SMiRT 27 and 28

18th International Seminar on FIRE SAFETY IN NUCLEAR INSTALLATIONS

Montrouge, France
May 20 - 22, 2025

GRS - 806

Gesellschaft für Anlagen-
und Reaktorsicherheit
(GRS) gGmbH

SMiRT 27 and 28

18th International
Seminar on
FIRE SAFETY
IN NUCLEAR
INSTALLATIONS

Montrouge, France
May 20 - 22, 2025

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September 2025

Remark:

This report refers to the in-house research project 4723R01450 which has been funded by German Federal Ministry for Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN).

The work was conducted by Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH.

The authors are responsible for the content of the report.

GRS - 806
ISBN 978-3-910548-99-2

Keywords

Experimental research, Fire PSA, Fire simulations, Future designs, Human factor, Nuclear fire safety, Operating experience, Regulation, Safety assessment, Standards

Kurzfassung

Im Rahmen des vom Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit (BMUKN) beauftragten Vorhabens 4720R31450 fand im Mai 2025 das achtzehnte internationale Seminar “Fire Safety in Nuclear Installations“ als Post-conference und Seminar der 27th und Pre-Conference Seminar der 28th International Conference on Structural Mechanics In Reactor Technology (SMiRT 27 und 28) bei edvance in Montrouge bei Paris, Frankreich statt.

Die vorliegenden Proceedings des Seminars enthalten alle Fachbeiträge des zweitägigen Seminars mit insgesamt 60 Teilnehmern aus insgesamt 12 Ländern aus Europa, Asien und Nordamerika. Sowie eine kurze Zusammenfassung der Erkenntnisse des Seminars und Schlussfolgerungen.

Abstract

In the frame of the project 4723R01450 funded by the German Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (BMUKN, German for: Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit) the eighteenth international Seminar on “Fire Safety in Nuclear Installations“ has been conducted as Post-cobngference Seminar of the 27th and Pre-conference Seminar of the 28th International Conference on Structural Mechanics In Reactor Technology (SMiRT 27 and 28) hosted by edvance in Montrouge, France.

The following Seminar Proceedings contain the entire technical contributions to the two days Seminar with a total of 60 participants from 12 countries in Europe, Asia, and Northern America as well as a brief summary of the seminar insights and conclusions.

Contents

1 Introduction

The meanwhile 18th International Seminar on ‘Fire Safety in Nuclear Installations’ was held as Post- and Pre-conference Seminar of the 27th and 28th International Conference on Structural Mechanics in Reactor Technology (SMiRT 27 and 28) hosted by edvance in Montrouge (a suburb of Paris), France in May 2025.

In total sixty participants from, Belgium, Bulgaria, Finland, France, Germany, Japan, the Netherlands, the Peoples’s Republic of China, Spain, Switzerland, the United Kingdom and the United States of America followed the 23 presentations that were given in the different scientific sessions and participated actively in a final panel discussion of the session chairs at the end of the seminar.

Fire safety in nuclear installations has significantly increased since the first seminar of this series in 1987, when the safety significance of fires in nuclear reactors had just been recognized following fire accidents in nuclear power stations with a risk potential to nuclear safety. In principle, this does not only concern the plant design, particularly of structures, systems and components (SSC) important to safety but also the operation of these reactor and non-reactor nuclear installations. Moreover, fires safety analysis and assessment includes experiences from testing, inspection and maintenance. Within the last nearly four decades, the methodological approaches for assessing the fire risk of nuclear installations as well as the corresponding analytical tools have been evolving and are continuously being enhanced and extended.

The two-days nuclear fire experts seminar started with a session on ‘recent developments’ covering regulatory expectations for strategic fire safety management, safety analyses in the design of new power reactors and a fire related safety case in a nuclear waste repository. The second session was devoted to one of the more recently identified and meanwhile clearly addressed topic of combinations of fires and other hazards. While the third session addressed new developments in the analyses of structural fire protection issues, the fourth session covered actual developments in probabilistic fire risk assessment.

As usual, in this seminar series further sessions were devoted to nuclear fire research presenting results from actual fire experiments for naturally ventilated compartment fires and different experimental programs with a specific focus on cable fires, and on recent experimental insights regarding the oil ignition behaviour.

Fire modelling insights and challenges were treated in the last topical session. The presentations focussed on applying artificial intelligence (AI) techniques and semi-empirical approaches in the modelling of cable fire, specific fire model developments for fire simulations of small modular reactors (SMRs) and in the different design stages of new reactors and the challenging issue of covering unburned gases in fire simulations for nuclear installations.

The seminar topics highlighted the quite broad scope of issues and challenges related to fire safety in the different types of nuclear facilities The presentations and discussions supported the general impression that fires remain an important topic to be addressed adequately in the safety assessment for various types of nuclear installations and sites. This topic is not limited to existing installations but needs to be appropriately considered in the most modern designs and operation of new built nuclear facilities.

After more than twenty years, this seminar was again organized in France, this time by edvance and EDF. The permanent organizers want to particularly thank the local hosts from edvance and EDF for organizing this valuable seminar. In addition, the seminar attendees were offered the opportunity to participate in technical tour of a the EDF Fire Lab in Chatou (a sub-urb of Paris) the day after the seminar itself. The organizers like to express their thanks to the EDF team for organizing the interesting tour of different experimental facilities as an add-on to the seminar.

Moreover, the organizers want to thank all speakers, co-authors and chairpersons as well as the entire seminar attendees for their highly active and fruitful participation and the variety of valuable, high-level contributions during this 18th International Seminar on ‘Fire Safety in Nuclear Installations’ which made this venue again a very successful one.

The next, 19th seminar of this series is intended to be held as SMiRT 29 Post-conference Seminar in France or Germany in late summer 2027.

Dr. Marina Röwekamp and Dr. Heinz-Peter Berg
– Scientific Chairs and Permanent Organizers –

2 Seminar Agenda

18th International SMiRT Seminar on

Fire Safety in Nuclear Installations

EDF / edvance, 97 Avenue Pierre Brossolette, 92120 Montrouge, France
May 20 – 22, 2025

Agenda

Monday, May 19, 2025

18:30 h to 2000 h	***Registration and*** ***SMiRT Fire Seminar Cocktail Reception at Hôtel Mercure Paris Porte d'Orléans, 13 Rue François Ory, 92120 Montrouge***

Tuesday, 20 May 2025

08:30 h	***Registration***		
09:00 h	***Organizers´ Welcome and Introduction***	***S. Dross (edvance, France)***	
09:15 h	***Recent Developments***	***Chairperson: K. Shirai (CRIEPI, Japan)***	
09:15 h	United Kingdom Regulatory Expectations for Strategic Fire Safety Management at Nuclear Licensed Sites – 'What Good Looks Like'	J. Plummer	ONR, United Kingdom
09:45 h	Fire Hazard Safety Studies in the Reactor Building for the EPR Hinkley Point C Project in the United Kingdom	L. Magnier	edvance, France
10:15 h	Safety Case for the Fire of a Battery Powered Electric Transport Vehicle for Nuclear Waste Packages in the Konrad Repository	F. Voigts, B. Forell	BGE, Germany GRS, Germany
10:45 h	***Coffee Break***		
11:05 h	***Combinations of Internal Fires and Other Hazards***	***Chairperson: H.-P. Berg (formerly BfS)***	
11:05 h	Wildfire Hazard and Vulnerability Assessments for Nuclear Power Plants	A. Lindeman	EPRI, USA
11:35 h	Deterministic Study on Seismically Induced Fires	K. Mai Quoc	Tractebel Engie, Belgium
12:05 h	Credible Combinations of Individual Hazards/Events in Deterministic Analysis for Combinations Internal Fire and Explosion: A Practical Approach for Existing Plants	E. Maillet	Tractebel Engie, Belgium
12:35 h	***Lunch Break***		

14:00 h	***Structural Fire Protection***	***Chairperson: A. Niggemeyer (edvance, Germany)***	
14:00 h	Use of Fire Protection Engineering Evaluations to Manage Separation Criteria	P. Boulden Jr	Appendix R Solutions, USA
14:30 h	Use of the Building Information Modelling Approach in Support of Fire Hazard Analysis	Y. Charefi	Tractebel Engie, Belgium
15:00 h	Application of ISO18195 for Justification of Fire Partitioning in French Nuclear Power Plants	D. Lévêque	EDF, France
15:30 h	***Coffee Break***		
16:00 h	***Probabilistic Fire Risk Assessment***	***Chairperson: M. Röwekamp (GRS, Germany)***	
16:00 h	Fire Compartmentation as a Key Element of a Probabilistic Fire Analysis	R. Grygoruk	Framatome, Germany
16:30 h	Converting A Fault Tree Based Fire PSA Model Into An Event Based One	T. Virtanen	FORTUM, Finland
17:00 h	Development of Fire PRA Infrastructures in NRRC – Participation and Promotion of the PRELUDE Program	K. Shirai	CRIEPI NRRC, Japan
17:30 h	**Summary of the first Seminar Day**	***Chairpersons of the first Seminar Day***	
17:45 h	***Photo and Adjourn of the first Seminar Day***		
19:30 h	***SMiRT Fire Seminar Aperitif and Dinner at Hôtel Mercure Paris Porte d'Orléans, 13 Rue Franis Ory, 92120 Montrouge***		

Wednesday, 21 May 2025

09:15 h	***Organizers' Remarks***		
09:30 h	***Experimental Fire Research***	***Chairperson: S. Thion (EDF, France)***	
09:30 h	Effects of A Vitiated Environment on the Burning Rates of Naturally Ventilated Compartment Fires	D. Alvear Portilla	University of Cantabria, Spain
10:00 h	OECD/NEA FAIR (Fire Risk Assessment Through Innovative Research) Project: Progress Two Years After Project Launch	P. Nerisson	ASNR, France
10:30 h	***Coffee Break***		
10:50 h	***Experimental Fire Research (contd.)***	***Chairperson: P. Nerisson (ASNR, France)***	
10:50 h	Thermal Behaviour and Characterization of Electrical Cables: Effects of Sample Orientation	A. Alonso Ipiña	University of Cantabria, Spain
11:20 h	Experimental Investigation on the Combustion and Spread Characteristics of Cable Fires in a Trough Box Cable Tray: Full-Scale Fire Experiment	G. Yang	CNPP, Republic of China

12:20 h	***Lunch Break***		
13:45 h	***Fire Modelling***	***Chairperson: W. Plumecocq (ASNR, France)***	
13:45 h	Enhancing Early Design Safety: Integrating Fire Modelling to Mitigate Risks	G. Georgiev, M. Seigneuret-Gaborit	newcleo, United Kingdom
14:15 h	A Unified 3D Framework for Zone Models and 3D Computational Fluid Dynamics Models for Fire Risk Assessment in Small Modular Reactors	R. Sampath	Centroid Lab, USA
14:45 h	Application of the COCOSYS Cable Fire Model on Long Cable Tray Fire Experiments in the DIVA and SATURNE Facilities	W. Klein-Heßling	GRS, Germany
15:15 h	***Coffee Break***		
15:45 h	***Fire Modelling (contd.)***	***Chairperson: W. Klein-Heßling (GRS, Germany)***	
15:45 h	Development of a Simplified Semi-Empirical Model for Fire-Induced Electrical Cable Failure	K. Tasaka	CRIEPI NRRC, Japan
16:15 h	Consideration of Unburned Gases Production and Combustion in Fire Modelling Tools	L. Vinçon	Framatome, France
16:45 h	Use of an AI Technique to Improve Cable Tray Fire Modelling	W. Plumecocq	ASNR, France
17:15 h	**Summary of the second Seminar Day**	***Chairpersons of the second Seminar Day***	
17:25 h	**Round Table Panel Discussion**	***Chairperson: M. Röwekamp*** ***Panelists:*** *H.-P. Berg,* *W. Klein-Heßling* *A. Niggemeyer* *P. Nerisson* *K. Shirai* *S. Thion* *W. Plumecocq*	
17:55 h	***Adjourn of the second Seminar Day***		

Thursday, May 22, 2025

Technical Visit of the EDF Fire Lab Chatou

10:00 h	***Welcome Coffee by EDF Research***		
10:15 h	Welcome and Introduction	S. Thion	EDF, France
10:30 h	Chatou Fire Lab Visit		
13:15 h	***Lunch***		
13:45 h	Final Discussion		
14:00 h	***Adjourn of the SMiRT Fire Seminar Technical Visit***		

3 Seminar Contributions

In the following, the seminar contributions prepared for the 18th International Seminar on ‘Fire Safety in Nuclear Installations’ held as Post-conference Seminar of the 27th and Pre-conference Seminar of the 28th International Conference on Structural Mechanics in Reactor Technology (SMiRT 27 and 28) are provided in the order of their presentation in the seminar.

3.1 Topical Session on Recent Developments

The topical seminar sessions started with a session on recent developments and activities regarding fire safety in different types of nuclear installations chaired by Koji Shirai from CRIEP NRRC in Japan.

The first presentation by Jacob Plummer from the Office for Nuclear Regulation (ONR) outlined some strategic aspects of fire safety management across nuclear licensed sites in the United Kingdom. The importance of leadership, organisational capability, and a strong safety culture in effectively managing fire risks effectively were emphasized. Furthermore, the presentation covered regulatory expectations under the goal-setting framework, highlighting the need for competence, capacity, and integrated management systems. Examples of good practice include apprenticeship programmes, systematic training approaches, and proactive obsolescence management strategies for fire protection systems.

The presentation also addressed fire performance data collection and escalation, stressing the role of safety performance indicators in informing strategic decisions. Leadership behaviour, as defined in ONR guidance, were presented as critical to sustaining high standards regarding fire safety. The author concluded that effective strategic oversight and leadership are essential for reducing risks and ensuring compliance with legal obligations.

The focus of the second presentation by Laurie Magnier from the French edvance was on the unique challenges of fire safety in the reactor building of the EPR (European Pressurized Water Reactor) under construction at Hinkley Point C in the United Kingdom. Conventional fire compartmentation methods are not applicable due to large volumes and non-fire-rated openings. A dedicated methodology involving justification of using a fire cell approach, a specific assessment non-mobilisable fire loads and a fire hazard analysis for safety was presented. A zero-fibre approach was adopted to minimize risks associated with cable protection, supported by a robust fire prevention strategy.

Analytical tools and correlation tables were used to define zones of influence (ZOI) for fire sources, while complex scenarios required computational fire dynamics modelling (CFD) with the Fire Dynamics Simulator (FDS). The presentation also detailed measures for hydrocarbon fire load assessment and outlined options for treating remaining risks. Overall, the methodology ensures compliance with the nuclear safety objectives and demonstrates that fire risks can be managed without compromising design integrity.

A safety case for replacing diesel-powered transport vehicles by battery-powered electric vehicles in the Konrad nuclear waste repository was presented by Florian Voigts from the German Bundesgesellschaft für Endlagerung (BGE) and Burkhard Forell (GRS, Germany). The original thermal design basis accident assumed a severe fire scenario defined by the so-called PTB curve (with a thermal load of 800 °C for 60 min). The modified design significantly reduces the fire loads. However, a comprehensive analysis was needed to confirm compliance with the licensing requirements. The approach combined full-scale battery fire experiments with CFD simulations using FDS to model worst-case scenarios.

The results show that even under conservative assumptions, the thermal load from a battery-powered vehicle fire remains well below the PTB curve. The study highlights the benefits of reduced fire loads and validates the safety of the redesigned transport process. Consequently, the Konrad repository can maintain its stringent safety standards while adopting modern, environmentally friendly transport solutions.

The corresponding five seminar contributions are provided hereafter.

Regulatory Expectations for Strategic Fire Safety Management at Nuclear Licensed Sites in Great Britain – 'What Good Looks Like'

Jacob Plummer*, Steve Hughes, Joe Nithsdale, Ray Cassar

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ABSTRACT

Effective fire safety management is a key consideration across nuclear licensed sites. The potentially large and diverse workforce, the unique nature of nuclear hazards and how they interface with life safety, and the long operational life spans of plant and systems can all lead to challenges in fire protection.

This paper discusses aspects of strategic fire safety management at nuclear licensed sites in the Great Britain. It reflects on the high level principles, plans and methods that licensee organisations employ in their management of fire safety at the enterprise wide level. This is distinct from the 'tactical' implementation of these measures at the working level.

The paper then discusses expectations of Greta Britain's Office for Nuclear Regulation (ONR) with regard to strategic fire safety management. It addresses key themes such as fire protection system health management, leadership and oversight, fire performance data and escalation, and fire safety competencies and training. Regulatory expectations are outlined with reference to practices that are recognised by ONR as relevant good practice (RGP) in these areas.

INTRODUCTION

The Office for Nuclear Regulation (ONR) is Great Britain's (GB's) independent regulator of nuclear safety, security, site health and safety, transport, and safeguards. Nuclear safety encompasses the topic of internal hazards of which internal fire (or challenges to nuclear safety from fire) is a key component. ONR is also the relevant enforcing authority for conventional or life fire safety on nuclear sites in Great Britain through the Regulatory Reform (Fire Safety) Order 2005 (RR(FS)O) in England and Wales [1] and the Fire Scotland Act 2005 in Scotland which is similar in content [2]. The paper generally refers to the RR(FS)O for brevity.

The regulatory framework in GB follows a goal setting, non-prescriptive approach for both nuclear and life fire safety, and this is reflected in ONR's regulatory expectations. ONR's regulatory expectations for nuclear safety are outlined within the Safety Assessment Principles (SAPs) [3]. There are also Technical Assessment Guides (TAGs) and the Technical Inspection Guides (TIGs) that provide guidance to inspectors on assessment and inspection in a broad range of technical areas, which include fire safety from a life fire safety perspective.

ONR's experience is that the expectation for duty holders to reduce risks So Far As Is Reasonably Practicable (SFAIRP) is typically achieved through an effective combination of tactical and strategic safety management approaches. Strategically speaking, effective leadership,

* Speaker

capability and engineering oversight are often key. ONR published guidance in these strategic areas offers transferable learning for life fire safety as described in this paper.

Strategic fire safety management at nuclear licensed sites means the high level principles, plans and methods that a licensee organisation employs to ensure it has adequate management of fire safety at the enterprise wide level. This should not be interpreted as the same as the 'tactical' implementation of these measures at the working level.

ONR's approach is risk-informed and goal setting for strategic aspects, setting expectations but allowing licensee's freedom to adopt the solutions that best fit their circumstances providing risks are demonstrably reduced SFAIRP. By placing regulatory attention on strategic aspects, such as the effectiveness of the overall leadership and corporate arrangements, ONR can influence proportionate safety improvements across the whole of the licensee's undertaking more efficiently. This is because the potential root causes or factors driving compliance shortfalls at facility / working level are often linked to the priority and resources given at the leadership strategic levels.

CAPABILITY

Under the Nuclear Installations Act 1965 (and thus the Energy Act 2013), ONR sets requirements for GB nuclear site licensees via site licence conditions [4]. License Condition 36 (LC36) addresses organisational capability and requires licensees to provide and maintain adequate financial and human resources to ensure the safe operation of the licensed site [5]. Safe operation in this context includes control of nuclear fire safety. Similarly, the RR(FS)O places a duty on licensees (as 'responsible persons' within the legislation) to appoint competent persons, and to ensure that the number of persons appointed, the time available for them to fulfil their functions and the means at their disposal are adequate having regard to the size of the premises, the risks to which relevant persons are exposed and the distribution of those risks throughout the premises [1].

The underlying requirements for a licensee to maintain a capable organisation to manage fire safety can be broken down into three major aspects; competence, capacity and culture. If a licensee organisation fails to exert strategic control over any one of these aspects, then it is likely that it will struggle to demonstrate adequate organisational capability to manage fire safety.

Competency

Competency in fire safety has been, and continues to be, a key topic in the United Kingdom. Following the 2017 Grenfell fire and the ensuing inquiry, the United Kingdom government has committed to strengthen regulation of competency in key fire safety roles, such as fire engineers and fire risk assessors across industry sectors [6]. While this is applicable to the industry as a whole, competency requirements and expectations are clearly relevant to those managing fire risks on nuclear licensed sites. Competence in the context of managing fire safety on a nuclear site includes both individual competence, i.e. are those with responsibility for fire safety suitably trained and experienced, and organisational competence, i.e. are adequate processes and arrangements in place to allow the licensee to manage fire safety.

It is important to note that fire safety is a specialist topic, and given its significance and topical nature, the nuclear sector competes in the market for experienced fire safety professionals in the post-Grenfell landscape. When combined with the relatively remote locations of many licensed sites, this can result in difficulty filling technical fire safety roles. Licensees opt to train technical resource internally providing a level of flexibility and opportunity to tailoring to the site needs and circumstances. However, there are also challenges inherent to this approach as commercially available training for fire safety is likely to be generic and will therefore require effort to capture the specific risk interactions present on a nuclear site. Additionally, when seeking accreditation for internal training courses or certification for staff on third party competency registers, licensees may find that nuclear site specific content and experience is not directly recognised by third parties without additional effort.

The RR(FS)O also defines a "*responsible person*" [1]. Article 8 of the order states that "*the responsible person must take such general fire precautions as will ensure, so far as is reasonably practicable, the safety of any of his employees*" [1]. Licensee organisations can be large and can manage complex estates. As a result, ONR at times finds that accountability for fire safety is delegated to senior managers with a large number of other safety and operational accountabilities. It is therefore important that the support and training available to these individuals, who manage fire safety with competing other priorities, is adequate to ensure the competence of responsible persons to comply with the RR(FS)O and licence conditions.

The large and varied estates managed by licensees can also pose challenges for organisational competence. It is therefore important that licensees' arrangements are flexible enough to manage fire safety where, for example, facilities on site differ significantly in age and lifecycle stage. Managing flexibly in this way reduces the risk that, by generating multiple bespoke processes and inflated documentation overhead, overall organisational competency is reduced by creating differences between plants and difficulty for operators to move roles between them.

Cognisant of the challenges faced by licensees, ONR sets expectations that allow licensees to develop their own unique competency arrangements. As per ONR TAG NS-TAST-GD-027 - Training and Assuring Personnel Competence [7], ONR does not assess the competence of licensee staff directly, or authorise, for example, reactor desk engineers, as is the case in some regulatory regimes. Similarly, ONR does not assess fire risk assessor competence at licensee sites (although competence is mandatory in the relevant legislation) but does expect robust arrangements to be put in place to ensure competence is maintained.

ONR expects licensees to maintain strategic oversight of fire safety competence in their organisations. ONR SAP EHF.8 states that a systematic approach to the identification and delivery of personnel competence should be applied [3]. License Condition 10 (LC10) addresses training and the LC10 TIG (NS-INSP-GD-01, Licence Condition 10 – Training) describes ONR's expectation that licenses implement a systematic approach to training (SAT) which involves identifying the competencies required for performing a role, then developing and implementing a training programme to achieve those competencies, and finally evaluating the training programme [5], [8]. This GB expectation aligns with international expectations detailed in IAEA SSG-75 [9].

At licensed sites a large number of roles will have fire safety responsibilities and accountabilities and as such ONR expects licensees to undertake analysis of the competence requirements to identify the training objectives, associated training needs and training periodicities. The fire safety competence requirements will be different for a building manager conducting local fire walkdowns, and a director making strategic fire safety implicated decisions. It therefore follows that training format, and contents should also be adapted to suit. The ONR SAPs address this expectation that licensees systematically consider training at all levels of the organisation in para. 65 [3].

"*Processes and systems should secure and assure maintenance of appropriate technical and behavioural competence of directors (both executive and non-executive), managers, leaders and all other staff and contractors with safety roles and responsibilities.*" [3]

Similarly, licensee's training needs analysis as part of applying a SAT should identify fire safety and fire systems competence requirements for maintenance and reliability engineers. This may be in addition to general fire safety training and should be sufficient to demonstrate compliance with requirements such as RR(FS)O article 13 and LC28 [1], [5].

- RR(FS)O Article 13: "nominate competent persons to implement those [fire-fighting and fire detection] measures and ensure that the number of such persons, their training and the equipment available to them are adequate, taking into account the size of, and the specific hazards involved in, the premises concerned" [1]
- LC28 (6): "*The licensee shall ensure in the interests of safety that every examination, inspection, maintenance and test of a plant or any part thereof is carried out*.

    a) by suitably qualified and experienced persons;" [5]

ONR expects competency to be developed and maintained by various means by the licensee with consideration of the choice of training methods to suit the scenario. Methods for on-job training should be demonstrated to be appropriate.

ONR expects licensee's strategic oversight of competence to take into account future conditions and changes in the organisation. For example, a project in construction may require a significant focus on construction fire safety competency but the licensee should look ahead to plan for competency requirements for commissioning and operational fire safety management. Similarly in facilities moving into decommissioning, licensees should consider the changing risk profile and competency requirements for fire safety. It is important that SAT is re-visited and applied in a proportionate way at each stage of the lifecycle giving cognisance to the risk and changing nature of activities being undertaken [7].

From an organisational competence perspective, ONR expects licensees to use an integrated management system. This approach is a requirement of IAEA GSR Part 2 [23] and as described in the LC17 TIG (NS-INSP-GD-017, LC 17 – Management [10]), is encouraged by ONR as it ensures safety is considered in all the licensee's activities and is not confined to the quality/safety management system [10]. For fire safety this means that life and nuclear fire safety aspects should be integrated into the management system alongside other statutory requirements to reduce the likelihood of incompatible arrangements.

ONR has found a number of good examples of the above expectations being implemented by GB nuclear licensees.

A licensee, in recognition of the difficulties faced when recruiting experienced fire safety professionals has taken steps to launch a fire safety apprenticeship programme. This meets ONR's expectations that competence gaps are systematically identified, and solutions put in place to ensure long term maintenance of competence.

A licensee that faced challenges bringing in external fire system design resource elected to bring design, installation, certification, maintenance and testing of fire detection and alarm systems in house. To support this change, the licensee conducted a training needs analysis which resulted in additional accredited external training in design and verification and installation, maintenance and commissioning for fire alarm systems being procured and assigned to the competency profiles of electricians and engineers. This meets ONR's expectations for ensuring that systems training forms part of the SAT such that the requirements of LC28 and article 13 of the RR(FS)O are met [1], [5]. The benefits associated with this change were found to be multi-faceted. Primarily they allowed for greater opportunities to support "*on the job*" learning at greater depth, as protocol level changes to fire alarm and detection logic could be completed by licensee staff (as an example). Additionally, the remoteness of the site in question had historically led to long delays in faults being addressed where external resource was required to attend site. This was largely addressed by upskilling and bringing design, installation, maintenance and testing in house. These benefits do require balance against the specifics of the asset in question particularly where spares may only be available through the original equipment manufacturer (OEM).

A licensee established fire safety as a specific part of its operational excellence programme with defined operational leaders as champions to ensure fire safety competence standards were maintained across operational personnel. This embedded fire safety as a key part of business as usual operational competence arrangements. This meets ONR's expectations for considering on-job methods for maintaining competency. It also demonstrates a commitment to maintaining competency in the organisation for the long term.

A licensee has reinforced the requirement to complete training by linking it to access permissions such that if training has not been completed, personnel cannot access particular parts of the site because training records are electronically linked to access control. Similarly, a licensee has achieved greater control of training by integrating fire risk assessments (FRAs) into a document management system which requires responsible and relevant persons to confirm that FRAs have been read and understood and records this information. The benefits of this are multiple, including legal compliance, but also engagement of persons responsible for buildings to drive fire safety improvement.

Capacity

Put simply, capacity relates to the expectation that licensees employ sufficient human resources to manage fire safety at their sites. This is inclusive of all roles relevant to fire safety such as fire risk assessors, fire engineers, reliability and maintenance engineers, building managers and emergency responders.

ONR finds that some licensees face challenges in this area. Related to the discussion of competency above, licensees compete in a limited pool for experienced fire safety resource, and this can lead to capacity issues. Remote site locations can exacerbate this issue.

ONR sets out expectations for capacity in its SAPs [3]. For example, paragraph 62 states:

"*The organisation should have adequate human resources. This includes having the necessary competences and knowledge in sufficient numbers to provide resilience and maintain the capability to govern, lead and manage for safety at all times*." [3]

This is also reflected in SAP EHF.11 which states that there should be sufficient competent personnel available to operate the facility in all operational states [3]. While the basis for this expectation is maintenance of nuclear safety, it remains relevant as a concept to life fire safety and the requirements of the RR(FS)O. Article 18 of the RR(FS)O relates to safety assistance and states [1]:

"*The responsible person must ensure that the number of persons appointed, the time available for them to fulfil their functions and the means at their disposal are adequate having regard to the size of the premises, the risks to which relevant persons are exposed and the distribution of those risks throughout the premises*." [1]

ONR sets out expectations on establishing and maintaining a nuclear baseline in guidance such as NS-TAST-GD-065 – Function and Content of the Nuclear Baseline [11] and NS-TAST-GD-061 – Staffing Levels and Task Organisation [12], but this does not necessarily capture all of the roles required to adequately maintain fire safety on a licensed site. For example, large sites may have many buildings with no radiological inventory that are unlikely to have associated nuclear baseline roles but are still subject to the RR(FS)O and whose resourcing should be considered as part of strategic oversight of fire safety capacity. ONR expects licensees to identify fire safety significant roles and to develop and maintain resourcing plans that provide resilience and ensure that delivery of fire safety management is not hampered by unfilled vacancies.

ONR has identified challenges with progressive small non-compliances linked to fire safety resource capacity. This can manifest as project details being missed during FRAs, drawings not being updated in line with building changes or signage not being appropriately maintained. At an individual level these non-compliances may appear low priority however, an amalgamation of such issues may present a significant issue in an emergency situation. ONR enforcement in this area has covered the appropriateness and availability of training as well as the level of cross-site resilience. Resilience, in this context, may include a tiered approach where staff responsible for e.g. fire system maintenance, may be upskilled to undertake fire risk assessments of simple buildings (large number) whilst more experienced assessors may focus on the more complex or high hazard facilities (small number). This approach can be further supplemented by engaging support from corporate resource or external contracts for the most complex cases.

Good practice that ONR has seen in this area includes systematic identification of deputies for fire key roles on licensed sites such as building managers. Licensees that employ this approach are more resilient to absence or staff movement and are better able to maintain a consistent level of fire safety management. Another example identified was the revision of conventional safety management structure, including compliance assessment roles, in the central function which enabled improved oversight of operations across multiple sites.

Culture

Safety culture at nuclear sites is a crosscutting topic that is much broader than fire safety alone. However, many day to day fire safety controls are effectively administrative, such as disciplined control of combustible load. These are therefore heavily impacted by behaviours and overall safety culture, and it is important for licensees to manage and maintain safety culture at a strategic level. ONR defines safety culture as:

“The underlying assumptions, which underpin the value placed upon safety by every individual and group at every level of the organisation, which interacts with the organisation’s structures and management systems, resulting in behavioural norms that consistently emphasise safety over competing goals.” [13]

This is related to expectations set out in the RR(FS)O regarding the general duties of employees at work, under Article 23, in that employees are required to take due care in regard to safety and cooperate with the employer's safety arrangements [1]. Enforcement history shows that safety culture issues specific to fire safety at licensed sites are not frequently singled out, but factors influencing fire safety have been observed. These include, for example, sites where construction/deconstruction activities involving large numbers of contractors exhibiting variability in fire safety behaviours and levels of familiarity with the site. Safety culture shortfalls can manifest for example as poor response to fire alarms.

Duty holders may contract operations that affect fire safety at nuclear licenced sites to third party organisations. In doing so, it is important that they achieve a good level of cooperation and coordination (as required by Article 22 of the Fire Safety Order) to enable a mutual understanding of risk and an effective management structure to be developed. The licensee retains responsibility for fire safety under the RR(FS)O at a nuclear licenced site and therefore adequate assurance of contractor operations needs to be applied. ONR has noted the benefit of groups designed to bring licensees and contractors from across the industry together as these help attendees to share experience and good practice thus improving safety culture.

ONR provides guidance for its inspectors to identify 'weak signals' that aid in diagnosing issues with safety culture in NS-INSP-GD-070 – Organisational culture guide for inspectors [14]. The guidance in this document provides 'warning flags' for inspectors to identify that allow safety culture to be investigated. Several of these 'warning flag' areas are highly relevant to fire safety can be interpreted to describe ONR expectations for a good safety culture in this regard.

Culture flag 'deviation from standards and behaviours' considers the drift away from accepted good practice or a duty holder's management system arrangements which includes aspects such as housekeeping discipline and combustible waste management [14]. Similarly, culture flag 'lack of personal ownership and engagement' reflects the behaviours by the staff at all levels throughout the organisation, including contractors and the supply chain, and concerns their engagement, ownership, participation and involvement in management arrangements [14]. This is directly relevant to the aforementioned challenges with integrating contractors into a strong safety culture.

Examples of positive safety culture flags that ONR has identified on fire safety inspections include good fire safety performance being rewarded and recognised via organisational schemes, direct feedback to 'rising stars' and enriching the jobs of strong performers with stretching developmental work.

Another relevant example of positive organisational culture is learning from experience (LFE) and event reporting. A licensee has established a series of briefing newsletters which are distributed estate wide and include event and LFE reports from both staff and contractors. Relevant reports are discussed at contractor and safety community forums which are attended by the licensee, support organisations and regulators. ONR has found that this inclusive approach promotes a culture of reporting and associated dissemination of learning. Safety culture is also fostered by the widespread adoption of safety representative bodies by duty holders who form a mechanism by which safety concerns may be identified by the workforce, as an addition to normal management practice, communicated to management and addressed.

FIRE PROTECTION SYSTEM HEALTH MANAGEMENT

Large nuclear licensed sites may have many hundreds of fire protection systems, encompassing fire detection and alarm, fire dampers, suppression systems and others. Some of these may be claimed either explicitly or implicitly in the safety case and some may be provided for life safety or property protection. In many cases systems will deliver more than one of these functions.

The RR(FS)O article 17 sets requirements on duty holders to ensure that any 'general fire precautions' are subject to a suitable system of maintenance and are maintained in an efficient state, in efficient working order and in good repair [1]. In defining 'general fire precautions' the RR(FS)O excludes measures to address fire resulting from nuclear processes where these are required to be taken to ensure any compliance with any requirement of nuclear legislation including The Energy Act 2013 [1], [4]. For these nuclear fire specific measures, a similar requirement is placed by LC28 [5]:

LC28 (1): *"The licensee shall make and implement adequate arrangements for the regular and systematic examination, inspection, maintenance and testing of all plant which may affect safety."* [5]

ONR finds that licensees experience some challenges in complying with these requirements. GB nuclear sites are for the most part long established and have many buildings, and systems that were not designed to the standards of today. These legacy facilities may contain aging fire protection equipment that either cannot be replaced with a modern equivalent or is yet to be replaced. Ongoing maintenance of this equipment may therefore require skills and experience that are not common outside of the nuclear industry due to the rarity of the equipment. This may introduce issues when, for example, licensees wish to bring maintenance contractors on to plant. Replacement of such systems represents a capital cost that competes with many other priorities on licensed sites. ONR finds that this may lead to delays in proactive replacement of older, but functioning, fire protection equipment. Notwithstanding the challenges discussed above, ONR's expectation is that duty holders achieve compliance with the legislative requirements of LC28 and Article 17 (RR(FS)O) that the risk is reduced SFAIRP.

Legacy plants and equipment may also introduce the issue of obsolescence. Obsolete equipment is that which the original manufacturer is no longer producing or supporting. ONR recognises that the presence of obsolete fire protection equipment at GB nuclear sites may cause issues with equipment availability, reliability and maintainability. This may place challenging critical spares demands on licensees that must be adequately managed. Additionally, ONR finds that spares requirements for legacy equipment puts licensees at increased risk of obtaining counterfeit, fraudulent and suspect items (CFSI) [15].

As a result of the age, size and complexity of some GB nuclear sites ONR finds that some licensees do not have a strong strategic oversight of the system health, obsolescence and spares picture for fire protection systems at an enterprise level. This means that the aggregated risk to operations and potentially to safety is not necessarily well understood.

ONR expects licensees to develop and maintain a strong understanding of fire system health across their facilities. Licensees should ensure that there is adequate strategic oversight of fire system health, that fire system replacement and upgrade is appropriately prioritised, and that obsolescence and system health is managed such that operations are not impeded, and legal obligations are met. ONR expectations are defined in the ONR SAPs, such as ONR SAP EAD.5 which states that a process for reviewing the obsolescence of structures, systems and components (SSC) important to safety should be in place [3]. This is supported by NS-TAST-GD-109 – Ageing and Degradation Management which sets out obsolescence management key expectations [16]. ONR expects licensees to:

- identify and record details of the equipment on the facility subject to obsolescence,
- identify the obsolescence status of the equipment,
- prioritise the obsolescence issues, and
- mitigate the obsolescence issues [16].

A specific ageing management programme should be implemented by licensees. This could be in the form of a dedicated programme or other written arrangements that manages the ageing of SSC. This programme should include systems that are important to nuclear safety and life fire safety (as well as security, safeguards and other conventional safety aspects), and should identify all systems potentially subject to obsolescence [16]. While the above requirements do apply at a specific plant and equipment level, ONR also expects licensees to monitor system health and obsolescence at an enterprise level to allow strategic decisions to be made on aggregation of risk and prioritisation of upgrades and replacements.

Positive examples identified by ONR in this area include a licensee that has launched a comprehensive asset management programme that introduces a new system health scoring that uses existing data to produce a more granular prioritisation score. The programme will include the production of a number of Asset Management Plans (AMPs) covering the majority of the site. Through the AMPs the licensee will seek to define the correct engineering data to enable accurate prioritisation and deliver adequate asset care broadly, and specifically inclusive of fire protection systems. ONR found that the improved tools and data represent a significant step forwards in asset management this will support the strategic management of fire systems.

A licensee proposed a proactive obsolescence management strategy aligned to IEC 62402 standards[17]. The licensee has engaged a third party obsolescence management software platform to review the obsolescence status of a large quantity of equipment, inclusive of the majority of fire protection systems. The data generated by this programme is used to underpin forward looking system health interventions in a long term asset management plan. For example, planning in fire alarm and detection system replacement 'need by' dates for facilities with expected lifetimes several decades into the future. Collecting system heath and obsolescence data holistically across all fire systems (and more broadly) allows licensees to prioritise interventions and to secure funding well ahead of the 'need by' date.

A licensee has developed a series of asset information cards covering fire alarm and detection systems onsite. The cards contain information on fault trends, the status of spares held on site and written description of the system architecture. Cards are linked to the sites online maintenance system and critical spares database and are readily accessible from generated maintenance requirements and work order pages. The primary goal of these cards is to aid the licensee in prioritising and planning system replacements in recognition of available site budgets. The collecting of trending and spares data also allows the licensee to predict cases where multiple simultaneous replacements or repairs may be required and plan accordingly rather than relying on reactive maintenance.

FIRE PERFORMANCE DATA AND ESCALATION

Collection and communication of fire performance data underpins the ability of senior leaders at licensee organisations to make strategic decisions about fire safety. In this context, fire performance data is wide ranging and resulting safety performance indicators (SPIs) may include events and incidents, risk assessment findings, maintenance status, training performance and system health. Importantly, fire performance data does not cover solely fire events on the licensed site. While it is important for data on such events to be collected, this is a lagging indicator that is of less use for strategic decision making than other, leading SPIs. It is also likely to be a small data set when compared to the other items monitored. Nevertheless, licensees are required to record incidents. LC7 – incidents on the site covers this specifically [5].

LC7(1): "*The licensee shall make and implement adequate arrangements for the notification, recording, investigation and reporting of such incidents occurring on the site:*

a) as is required by any other condition attached to this licence;

b) as ONR may specify; and

c) as the licensee considers necessary." [5]

A key legislative driver for fire performance data collection is the RR(FS)O. Article 9 of the RR(FS)O places a duty on responsible persons to make and regularly review a FRA and to record the results [1]. When following good practice in GB for production of such assessments, licensees generate a large amount of information on the fire performance of all of the facilities on the site that are subject to the RR(FS)O (the vast majority of buildings). This includes information on condition and housekeeping, system health and maintenance, structural fire performance, ignition sources and fire systems. FRAs also specifically identify shortfalls and rectifying actions. When aggregated across a whole licensed site the data from FRAs can provide a large bank of leading fire performance indicators that can be used to inform strategic decision making. By collecting, communicating and acting upon these leading indicators, licensees are able to exert strategic control over fire safety performance and direct enterprise level improvements.

For FRAs to be effective it is important that findings are identified clearly that SMART actions are assigned to findings and that these are systematically tracked. If findings are not systematically tracked, then not only can remedial action delivery be missed, but the opportunity to generate enterprise wide data to inform strategic decision making can be lost. FRAs occur at a facility or building level, and this undertaking may only involve lower-level operational staff and risk assessors. It is therefore important that the outcomes of FRAs are communicated upwards and shortfalls are escalated where this is required to allow senior leaders to monitor and regularly review safety performance. Discussion with duty holders has identified the benefit of applying additional clarity to the significance of FRA findings to allow managers responsible for sentencing and prioritisation of actions, across multiple areas of duty holder operations, to understand the significance of findings and therefore more effectively prioritise action.

The quality of FRAs can also be a challenge, particularly in the context of emerging risks, the incorporation of nuclear safety relevant aspects and projects with multiple phases. ONR finds that licensees often face challenges when applying generic guidance to the range of situations and projects encountered on nuclear licensed sites. The quality and specificity of FRAs can therefore be a challenge to usefulness and requires strategic guidance above the level of publicly available guidance on the production of risk assessments. ONR expects that those responsible for producing estate level guidance utilise regular reviews and updates which incorporate emerging issues and the latest LFE. This expectation is formalised within ONR SAP MS.4 [3].

While FRAs are point-in-time assessments of fire performance in a facility, licensees also generate a large amount of data through 'live' activities. This might include building manager walkdowns, operator rounds and daily plant status meetings and trackers. This data, if aggregated can also be used to inform strategic decision making at a facility and enterprise level. Licensees often track the live status of fire performance in facility specific dashboards. ONR recognises the importance of effective aggregation and communication of this data and that this process is best supported when dashboard format and contents are consistent across the facilities on a licensed site.

Fire protection system performance data includes availability, maintenance status and future system health, as discussed within the previous section. This is another important source of information to guide strategic decision making. Licensees are expected to maintain maintenance schedules under LC28 and the RR(FS)O and these will contain details of all planned, delivered and non-delivered maintenance of fire systems. Given there are many thousands of items within maintenance schedules it is crucial that fire safety implicated systems are appropriately tagged within the database via metadata to allow trending and strategic oversight.

ONR expectations in this area are underlined in the SAPs under ONR SAP MS.3 which states expectations that decisions made at all levels in the organisation affecting safety should be informed, rational, objective, transparent and prudent; and ONR SAP MS.4 which sets expectations that lessons should be learned from internal and external sources to continually improve leadership, organisational capability, the management system, safety decision making and safety performance [3].

In support of these SAPs, ONR guidance TD-HOC-GD-002 – Methodology for undertaking Leadership and Management for Safety (LMfS) reviews sets out specific expectations for safety performance indicators that are relevant to fire [18]. These include the following:

- Safety performance indicators (SPIs) are used at all levels within the organisation to monitor safety performance [18]. ONR guidance refers to nuclear safety performance which would include nuclear fire aspects, but this is a principle that is clearly applicable to fire safety holistically.

- SPIs have been developed which monitor the controls identified in the safety case(s), providing assurance that risks control systems are always operating effectively [18]. The reference to safety cases is directly relevant to nuclear fire, but this is equally applicable to controls identified in fire strategies and conventional fire assessments.
- SPIs are in place that can provide early indications of danger [18]. For fire safety this includes indicators arising from FRAs such as the status of transient combustible load in a facility. This factor has a direct impact on fire risk. Equally SPIs arising from maintenance and system health information provide key early indications. Failure (or even non-failure obsolescence) of a fire detection system on its own does not result in harm, but it can be a contributor to consequences. At an enterprise level, failure or degradation of many fire detection systems may pose an unacceptable contribution to overall risk that must be managed at a strategic level.
- SPIs are monitored routinely by the licensee's top management [18]. ONR expects that fire SPIs are routinely and effectively escalated to senior management. Fire SPIs should be given appropriate attention (alongside other SPIs) in high level fora such as executive safety committees.
- SPIs include leading indicators (predicators of future performance) as well as lagging indicators (evidence of past performance) [18]. Lagging indicators, as discussed previously, may be actual fire events. Leading indicators such as those discussed for combustible load and FRA outcomes are likely to provide more useful information for leaders setting safety direction.
- The organisation understands that not all SPIs have the same value, and that operational indicators (those linked to operating rules, safety mechanisms etc.) have a greater value and prominence than generic and programmatic indicators (number of people trained, audits completed to an agreed timescale etc.) [18]. A caveat to the example given here is where statutory fire safety matters fall into programmatic indicators. For example, undertaking and recording FRAs is a statutory duty under the RR(FS)O. As such, a programmatic indicator that measures delivery of FRAs is directly related to legal compliance.

Examples of good performance in this area identified by ONR include licensees providing an overall rating to each FRA (e.g. red, amber, green (RAG)) on large, licensed sites to allow easy visibility of areas with worse fire safety performance. In good examples, this information is regularly made available to senior leaders, and licensees are able to demonstrate that prioritisation decisions, e.g. on resources or additional oversight, are informed by this information.

A licensee completed a programme to rationalise fire safety dashboards across the site. Where previously a large number of bespoke dashboards were used to display operational fire safety data at a facility level this is now present in a largely consistent manner across the enterprise. This has the advantage of allowing easier aggregation of data, allowing staff to move across facilities more easily and allowing senior leaders to directly monitor and compare facilities within their areas more easily.

A licensee has established a series of focus indicators used to compare sites performance across the estate. These include directly comparable data fields such as number of defects raised and average timeframes to address defects as well as additional leading and lagging indicators such as number of nuisance alarms, reports of increases in fire load and fire safety health as reported by maintenance software. These metrics are accompanied by written feedback from oversight reports to provide context to perceived issues based on the trending data. As above, this approach allows leadership to more readily compare and contrast sites and seek further information as appropriate.

A licensee has introduced predictive FRAs on a major construction site. These consider the intended work packages, occupation, area ownership and potential clashes in risk activities. They contribute to the area FRAs which are completed by the contractors in primary control of an area. The size and complexity of major projects often requires innovative approaches to achieve compliance and to generate and escalate fire performance data.

The GB nuclear industry has a longstanding strategic and industry wide fire safety committee attended by representatives from multiple duty holders. The committee provides the opportunity to develop mutual support and understanding, review of changes to standards and to work in collaboration for the development of guidance and performance indicators.

International activities such as the ENSREG (*E*uropean *N*uclear *S*afety *Reg*ulators) second Topical Peer Review (TPR II) on “Fie Protection” also provide an opportunity for duty holders to identify and escalate fire safety performance data. An extensive depth and range of fire safety areas has been covered within the TPR II, where duty holders conducted extensive self-analysis leading to the development of improvement actions [19]. The project further allowed a comparison of methodology and performance at an international level with the associated benefit of additional expert review.

LEADERSHIP AND OVERSIGHT

Leadership is an aspect of fire safety management that ties all of the previously discussed strands together. Effective fire safety leaders are able to use fire safety performance data to underpin the strategies, policies, plans, goals, and standards for fire safety and then ensure that they are delivered throughout the organisation. Effective leaders are also seen to be visible champions for fire safety in their organisations.

Ineffective leadership can negatively impact fire safety outcomes when there is a disconnect between those setting strategic direction and those implementing process and policy at the work face. This maybe because performance indicators are not adequately collected and escalated or because of a lack of understanding of fire safety accountabilities among senior leaders. In large licensee organisations there will necessarily be significant delegation of responsibilities for managing fire safety from those with legal accountabilities such as executive members, to those with operational responsibilities at a plant level. This is unavoidable, but it is important that senior leaders retain understanding and are empowered through policy to exert strategic control when required.

ONR sets out expectations for effective safety leadership behaviours in the SAPs [3]. This guidance is aimed at the assessment of safety leadership with respect to nuclear safety, which is inclusive of nuclear fire safety. However, given the significant crossover between the various aspects of fire safety, the underpinning principles are also relevant to life fire safety leadership.

ONR SAP MS.1 establishes that: “*Directors, managers and leaders at all levels should focus the organisation on achieving and sustaining high standards of safety and on delivering the characteristics of a high reliability organisation*” [3]. SAP MS.1 acknowledges the role of leadership in achieving high levels of safety and identifies key leadership behaviours. ONR expands upon these expectations in NS-TAST-GD-107 – safety leadership, which sets out items for ONR inspectors to consider when assessing senior safety leadership [20]. ONR expects fire safety leaders to set and articulate clear standards and expectations for safety. Good fire safety leaders set out clear expectations that are directly linked to compliance with requirements set in the RR(FS)O and the license conditions but are suitably interpreted for the realities of the specific licensed site. TAG NS-TAST-GD-107 also sets out ONR expectations for leaders to develop their knowledge and understanding of high safety standards [20]. This relates directly to the topic of competence discussed previously. The TAG further details ONR expectations that leaders [20]:

- set demanding, but sufficiently incremental, safety goals,
- provide adequate financial and human resources, and support,
- monitor progress made in achieving safety goals,
- act where safety goals are at risk of not being met,
- check that safety goals, once met, have delivered the intended benefits.

For fire safety, these factors are directly linked to the aspects of strategic fire safety management previously discussed in this paper. To set goals, monitor progress and act where goals are at risk, leaders need to have suitable SPIs defined and underpinned by good quality data. To set and monitor fire safety goals at a strategic level, leaders need to have strategic oversight of performance. Indicators of poor or off-normal must also be adequately escalated to the licensee leadership. ONR expects that the actions that leaders take to meet safety goals and to provide adequate support and resources consider organisational capability including competence, capacity and culture.

ONR also recognises other relevant good practice in this area such as HSG65 [21], developed by the Health and Safety Executive (HSE). This guidance details a 'plan, do, check, act' (PDCA) cycle for safety leaders which is similar in application to that described in the ONR TAG. This is widely applied to non-nuclear safety matters and informs ONR's expectations for fire safety leadership on licensed sites.

ONR expects leaders at all levels to frequently and consistently exhibit good leadership behaviours. ONR applies the SAFER leadership model [22] to identify specific core behaviours of effective safety leadership whereby an effective leader [20], [22]:

- Speaks on safety,
- Acts safely at work,
- Focuses on maintaining safety standards,
- Engages others in safety initiatives, and
- Recognises individuals who adhere to safety.

These aspects are generic to safety leadership but are clear relevant to fire safety leadership. One measurable demonstration of these behaviours for fire safety is the inclusion of fire safety as a dedicated topic in 'leader in the field' activities. This provides positive reinforcement that licensee leaders understand and value fire safety matters on their licensed sites.

ONR has identified examples of good performance at licensees where strategic leadership within a duty holder has been strengthened by the development of oversight and management groups involving fire safety managers from across multiple sites and managers from central fire functions. This performs several functions including review of performance metrics, discussion of ongoing issues, and allows for effective setting and monitoring of fire safety goals.

ONR has identified examples of improvements in aspects of strategic leadership at one licensee, including the commissioning of compliance reviews designed to conduct a gap analysis between company standards and legislation to identify misalignment or omission. Reviews commissioned third party analysis bringing the benefit of a fresh perspective less likely be constricted by familiarity and more likely to challenge the status quo. The review established a baseline understanding of compliance arrangements which was then built upon by a process of restructuring which created several new compliance management and assurance roles thus enabling more effect management of compliance arrangements.

A licensee has delivered improvements in the monitoring and checking of safety goals by revising the process and guidance for in line assurance activities for fire protection. This has resulted in a significant increase in the number of these activities being undertaken by leaders with the assurance checklist being used by the licensee as a tool to track progress against sitewide fire safety improvements.

CONCLUSIONS

This paper has provided an overview of ONR's expectations for strategic fire safety management on licensed sites. It has detailed where ONR's expectations are recorded, where ONR has identified challenges that licensees face in meeting these expectations and where ONR has identified examples of good practice in strategic fire safety management.

The paper has discussed various aspects of strategic fire safety management, including organisational capability, fire performance data and escalation, and system health management. ONR expectations in these areas can be summarised as:

- Licensees should ensure that leaders are sufficiently trained to deliver their fire safety responsibilities, that senior managers have adequate strategic oversight of fire safety related training needs, and that key operational personnel have sufficient training and capacity to deliver the full scope of their fire safety responsibilities. Fire safety should be underpinned by a strong safety culture.
- Licensees should ensure that there is adequate strategic oversight of fire system health, that fire system replacement and upgrade is appropriately prioritised, and that obsolescence and system health is managed such that operations are not impeded, and legal obligations are met.
- Licensees should ensure that fire safety performance is measured, trends are identified and escalated, and that senior leaders have sufficient understanding of fire safety performance in their areas to enable delivery of strategic improvements.

The paper has also described how these aspects are encompassed by effective fire safety leadership underpinned by good safety leadership behaviours.

ONR expects that leaders use fire safety performance data to underpin the strategies, policies, plans, goals and standards for fire safety and then ensure that they are delivered, monitored, actions are taken when required, and their impact checked. Leaders should be visible champions for fire safety and exhibit good safety leadership behaviours such as those described in the SAFER model.

REFERENCES

[1] HM Government: The Regulatory Reform (Fire Safety) Order 2005, UK Statutory Instruments, 2005 N0. 1541, 2005, https://www.legislation.gov.uk/uksi/2005/1541/contents/made.

[2] HM Government: Fire (Scotland) Act 2005 (asp 5), Part 1 Fire and Rescue Authorities, 2005, https://www.legislation.gov.uk/asp/2005/5/pdfs/asp_20050005_en.pdf.

[3] Office for Nuclear Regulation (ONR): Safety Assessment Principles for Nuclear Facilities (SAPs), 2014 Edition, Revision 1, Bootle, Merseyside, United Kingdom, January 2020, www.onr.org.uk/saps/saps2014.pdf.

[4] HM Government: The Energy Act 2013, UK Public General Acts, 2013 https://www.legislation.gov.uk/ukpga/2013/32/contents.

[5] Office for Nuclear Regulation (ONR): License Condition Handbook, February 2017, https://www.onr.org.uk/media/gixbe2br/licence-condition-handbook.pdf.

[6] HM Government: Grenfell Tower Inquiry Phase 2 Report: Government response, Policy Paper, February 2025, https://www.gov.uk/government/publications/grenfell-tower-inquiry-phase-2-report-government-response/grenfell-tower-inquiry-phase-2-report-government-response-html.

[7] Office for Nuclear Regulation (ONR): ONR Technical Assessment Guide (TAG). Training and Assuring Personnel Competence, NS-TAST-GD-027, Issue 7, December 2022,

https://www.onr.org.uk/publications/regulatory-guidance/regulatory-assessment-and-permissioning/technical-assessment-guides-tags/nuclear-safety-tags/ns-tast-gd-027/.

[8] Office for Nuclear Regulation (ONR): ONR Technical Inspection Guide. Licence Condition 10 – Training, NS-INSP-GD-010, Issue 4, December 2022, https://view.office-apps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.onr.org.uk%2Fmedia%2Fdqljd1eo%2Fns-insp-gd-010.docx&wdOrigin=BROWSELINK.

[9] International Atomic Energy Agency (IAEA): Recruitment, Qualification and Training of Personnel for Nuclear Power Plants, IAEA Safety Standards; Specific Safety Guide SSG-75, STI/PUB/2029, ISBN 978-92-0-137422-6; Vienna, Austria, 2022, https://www-pub.iaea.org/MTCD/Publications/PDF/PUB2029_web.pdf.

[10] Office for Nuclear Regulation (ONR): ONR Technical Inspection Guide (TIG). NS-INSP-GD-017, LC 17 – Management, Issue 8.1, July 2023, https://www.onr.org.uk/media/hzsfivnr/ns-insp-gd-017.pdf.

[11] Office for Nuclear Regulation (ONR): ONR Technical Assessment Guide (TAG): Function and content of the Nuclear Baseline, NS-TAST-GD-065, Issue 5.2, January 2025, https://www.onr.org.uk/publications/regulatory-guidance/regulatory-assessment-and-permissioning/technical-assessment-guides-tags/nuclear-safety-tags/ns-tast-gd-065/.

[12] Office for Nuclear Regulation (ONR): ONR Technical Assessment Guide (TAG): Staffing Levels and Task Organisation, NS-TAST-GD-061, Issue 5, June 2023, https://view.office-apps.live.com/op/view.aspx?src=https%3A%2F%2Fonr.org.uk%2Fmedia%2Fbetbkwli%2Fns-tast-gd-061.docx&wdOrigin=BROWSELINK.

[13] Office for Nuclear Regulation (ONR): Safety Culture: Definition and Model, TD-HOC-GD-003, Issue 2, February 2025, https://www.onr.org.uk/media/g3jhg5nt/safety-culture-definition-and-model-1.pdf.

[14] Office for Nuclear Regulation (ONR): Organisational culture guide for inspectors, NS-INSP-GD-070, Issue 3.2, 2024; https://view.office-apps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.onr.org.uk%2Fmedia%2Fh0nc1bv5%2Fns-insp-gd-070.docx&wdOrigin=BROWSELINK.

[15] Office for Nuclear Regulation (ONR): ONR Technical Assessment Guide (TAG): Procurement and Intelligent Customer Capability, CNS-TAST-GD-41, Issue 2, May 2024, https://view.office-apps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.onr.org.uk%2Fmedia%2Fl2qnlzh0%2Fcns-tast-gd-41.docx&wdOrigin=BROWSELINK.

[16] Office for Nuclear Regulation (ONR): ONR Technical Assessment Guide (TAG): Ageing and Degradation Management, NS-TAST-GD-109, Issue 1, February 2023, https://view.office-apps.live.com/op/view.aspx?src=https%3A%2F%2Fonr.org.uk%2Fmedia%2Fnd1ca35h%2Fns-tast-gd-109.docx&wdOrigin=BROWSELINK.

[17] International Electrotechnical Commission (IEC): IEC 62402:2019: Obsolescence management, International Standard, Edition 2.0, 2019-05, 2019, https://webstore.iec.ch/en/publication/59531.

[18] Office for Nuclear Regulation (ONR): ONR Guidance: TD-HOC-GD-002, Methodology for undertaking Leadership and Management for Safety (LMfS) reviews, Issue 1.1, August 2024, https://view.office-apps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.onr.org.uk%2Fmedia%2Field4o1v%2Ftd-hoc-gd-002.docx&wdOrigin=BROWSELINK.

[19] Office for Nuclear Regulation (ONR): ONR-TD-GEN-23-02, ENSREG Topical Peer Review 2 – Fire Protection, United Kingdom National Assessment Report, Issue 0, 2023, https://onr.org.uk/news/all-news/2023/11/second-topical-peer-review-on-fire-safety-published/.

[20] Office for Nuclear Regulation (ONR): ONR Technical Assessment Guide (TAG), Safety leadership, Head of Profession: Human and Organisational Capability, NS-TAST-GD-107, Issue 1.3, 2024, https://view.office-apps.live.com/op/view.aspx?src=https%3A%2F%2Fwww.onr.org.uk%2Fmedia%2Fkzzahmy2%2Fns-tast-gd-107.docx&wdOrigin=BROWSELINK.

[21] Health and Safety Executive (HSE): Managing for health and safety (HSG65), Issue 3, Third Edition, ISBN 978-0-7176-6456-6, 2013, https://www.hse.gov.uk/pubns/priced/hsg65.pdf.

[22] Clarke, S., et al. (Eds.): The Wiley Blackwell Handbook of the Psychology of Occupational Safety and Workplace Health, ISBN: 978-1-119-14079-5, John Wiley & Sons, Ltd., Sons, Hoboken, NJ, USA, September 2015, DOI:10.1002/9781118979013.

[23] International Atomic Energy Agency (IAEA): IAEA Safety Standards, Leadership and Management for Safety, General Safety Requirements, No. GSR Part 2, 2016, https://gnssn.iaea.org/CSN/Relevant%20Documents/Safety%20Requirements/English/GSR%20Part%202.pdf.

Fire Hazard Safety Studies in the Reactor Building for the EPR Hinkley Point C Project in the United Kingdom

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ABSTRACT

The reactor building presents some specificities for the EPR (*E*uropean *P*ressurized *R*eactor) fire studies. The reactor building includes "large volumes" for which the usual fire methodologies and the two-zone MAGIC code, developed by EDF (*É*lectricité *d*e *F*rance), are not valid. Reactor building layout constraints do not allow the implementation of fire compartments but only fire cells with non-fire rated openings. In the frame of the Hinkley Point C (HPC) project, a "zero fibre approach" has been implemented for the reactor building, which means the conventional cable fire protection means (e.g., cable wrapping) are not allowed in this building and that the cable fire protection has to be reduced. Consequently, a specific methodology has been developed to perform fire verification studies for the reactor building including:

- justification of the safety fire cells,
- fire risk analysis on safety targets identified in the frame of the common cause functional failure analysis, and
- fire risk analysis for other purposes, for example the justification of the non-ignition of significant fire loads identified as non-mobilisable fire loads (NMFL).

These HPC fire safety studies for the reactor building rely on the fire prevention strategy developed for the HPC project to prevent large cable fires and hydrocarbon fire risks and to avoid late modifications of the design.

INTRODUCTION

The nuclear safety objective for the protection against internal fire hazards is to ensure that the required nuclear safety functions are performed during an event sequence including an on-site fire scenario. In any case, a sufficient number of suitable and reliable systems shall remain available allowing to reach and maintain a safe shutdown state, following a design basis accident. To meet this objective, fire compartmentation is implemented to prevent the spreading of fire by subdividing/partitioning the building into fire compartments. Usually, fire compartments are implemented to separate the different trains of the safety system. Due to the specific requirements regarding the management of transients from incidents or accidents in the reactor building, non-fire rated large openings must remain. Where a complete physical separation is not possible, fire cells have been defined. However, the usual two-zone MAGIC fire code developed by EDF is not applicable in the large volumes of the reactor building as it is out of its validity domain. For similar reasons, the EPRESSI *(E*valuation des *P*erformances *R*éelles des *E*léments de *S*ectorisation *S*ous Incendie - assessment of the real performance of partitioning elements in the event of fire) developed by EDF to demonstrate the integrity of fire compartments and based on the hot gas layer temperature cannot be applied.

An additional functional analysis is also performed to demonstrate that if the fire induces a design basis accident, a sufficient number of suitable and reliable systems remain available to reach and maintain a safe shutdown state. A potential common cause failure is identified if the same fire compartment or fire cell contains equipment of which the failure (in the event of fire) is likely to result in a design basis accident and components of a system required for the management of the design basis accident under consideration. The functional analysis determines whether the failure of the components is acceptable or not from a nuclear safety perspective. If not, the common cause failure is confirmed, and a fire risk analysis must be performed.

In case of a loss of coolant accident (LOCA) in the reactor building, debris can be released and clog some components such as strainers of the emergency core cooling systems (ECCSs) inducing the failure of the system in recirculation mode (see [1] for further details). The cable fire protection, typically cable wrapping used in EDF nuclear power plants (NPPs), either to remove the cable fire load or to preserve the functionality of the cable, contains fibre. In case of a LOCA, the cable wrapping is likely to be damaged and to release fibres inside the reactor building. In the frame of the HPC project, this kind of wrapping is not permitted to be implemented in the reactor building to strictly minimise the amount of fibre.

A fire prevention strategy has been developed for the HPC project to prevent large cable fires and hydrocarbon fire risks and to avoid late design modifications. If the fire risk cannot be easily mitigated, fire scenarios must be analysed; therefore, a specific methodology has been developed to perform the fire studies in the reactor building including:

- justification of the fire cells,
- fire risk analysis regarding safety targets identified in the frame of the common cause failure analysis, and
- fire risk analysis for other purposes, for example the justification of the non-ignition of large fire loads identified as non-mobilisable fire load.

FIRE COMPARTMENTATION IN THE HPC REACTOR BUILDING

Within the EPR (*E*uropean *P*ressurized *R*eactor) HPC (Hinkley Point C) project, the reactor building houses the primary circuit, comprising four loops. This is illustrated in Figure 1 below.

To ensure the that a sufficient number of redundant trains of the four loops of the safety system remain operable in the event of a fire, the reactor building has been subdivided into four main fire cells.

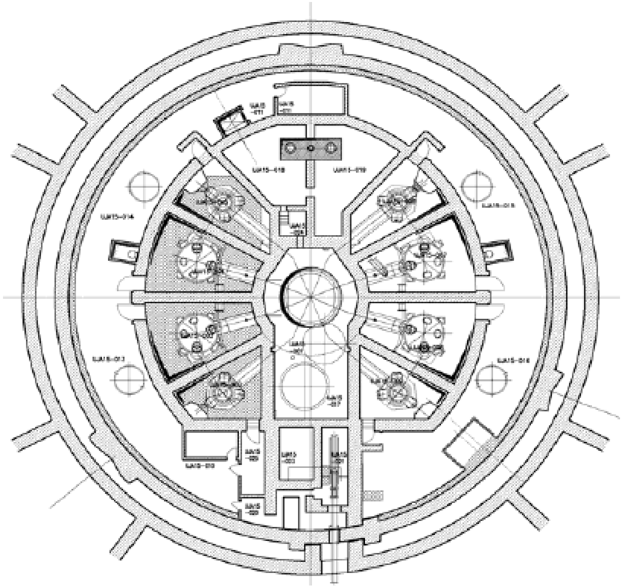

Figure 1 Reactor building plan view extract from the HPC Pre-construction Safety Report (PCSR) [2]

The rooms inside the fire cells are subdivided into two categories to define which methodologies can be applied for the analyses:

- “Standard Volumes” for which the volume of the room respects the criterion to remain in the domain of validity of the methodologies applied and of the zone model used in other buildings;
- “Large Volumes” for which the dedicated methodology for the reactor building must be used (outside of the domain of validity of the methodologies and tools).

This paper focuses on these “Large Volumes”.

FIRE PREVENTION STRATEGY

In the reactor building, two major fire risks have been identified: large cable fire scenarios and hydrocarbon fire risk. These fire risks are likely to lead to large fires in the large volumes that could jeopardise the fire cell integrity and lead to common cause failures. To prevent such risks, it has been decided within the HPC project to develop and apply the fire prevention strategy in the reactor building in line with the principles of defence in depth for fire protection as outlined in IAEA SSG-64 [3].

The following prevention measures are put in place to prevent large cable fire scenarios:

- Addition of local cable tray protections without fibre to limit large fire propagation scenarios;
- Operational rules preventing cable ignition caused by human actions and/or transient storage of combustibles;
- Addition of fire stops as additional prevention to limit fire propagation/ spreading along the cables.

The majority of the cable fire risks are captured by the fire prevention strategy; however, some complex cable configuration will need further assessment.

For the prevention of hydrocarbon fire risks, a specific analysis must be performed to ensure that the significant hydrocarbon fire loads identified as NMFL cannot be mobilised by a fire.

USE OF ANALYTICAL TOOLS

Analytical tools based on correlation tables are used to assess the impact of a single fire source on a target in the close vicinity. A screening of the fire sources within the reactor building has been performed ahead of the construction of the correlation tables to assess the most common fire sources in the reactor building.

A so-called zone of influence (ZOI) is defined for each fire source, considering the flame height, the plume zone and the radiated heat zone.

The correlation tables have been built based on the notion of the ZOI (see Figure 2):

- If a target is located outside of the ZOI corresponding to its malfunction or ignition criteria, the target can be considered as being not inadmissibly impacted by the fire source.
- If the target is located inside the ZOI it can be either considered as functionally unavailable, or modelling needs to be performed to confirm whether or not the target is unavailable or ignited (and by this also functionally unavailable).

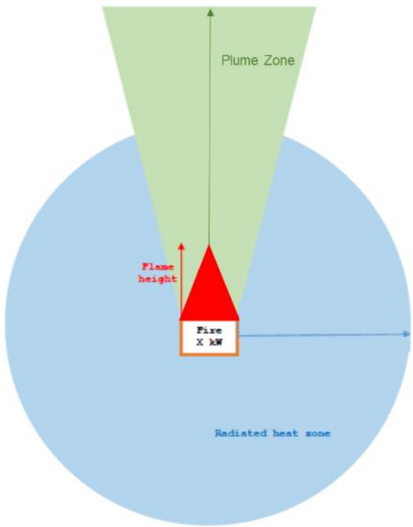

Figure 2 Example of a ZOI

These ZOIs have been built for each type of fire source with the MAGIC code in its validity domain. For the targets except fire barrier elements, the maximum temperature of the curves obtained with MAGIC is used as a dysfunction or ignition criterion. For each type of fire source, distances are provided, in a correlation table, beyond which the target sees a temperature lower than the specified threshold. For justification of the fire compartmentation the resulting temperature curves have been compared to the generic fire performance curve of the elements defined in the standard ISO 18195 [4]. Distances are provided in the correlation tables beyond which the fire barrier element will keep its fire performance.

JUSTIFICATION OF FIRE CELLS

In the large volumes of the reactor building, this justification is done in two steps:

- Each fire barrier element is assessed as a target,
- The non-fire rated openings are assessed applying the ZOI principle.

Step 1: Verification of the Performance of Fire Barrier Elements

The objective of the first step is the verification of the performance of fire barriers elements of fire cell boundaries, by checking that these elements are not impacted by fire sources located in the vicinity.

The fire barrier elements must be listed as input data for the analysis. Some examples include (see Figure 3 below):

- fire dampers,
- doors,
- penetration seals,
- gullies,
- joints,
- fire rated (cable) ducts.

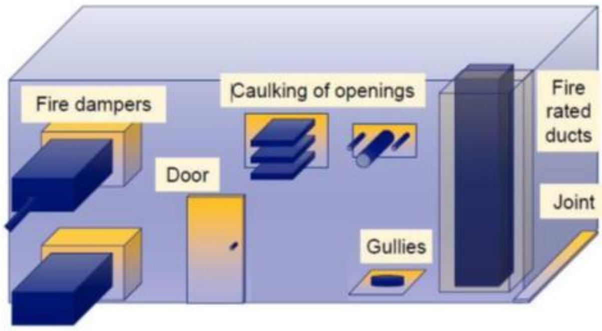

Figure 3 Schematic visualisation of the most common fire barrier elements

All fire sources present in the vicinity of the fire barrier element are identified inside the room and depending on the fire source type and target failure criteria between the rooms N+1 and N+4. For each fire source, a distance has been defined beyond which the fire barrier element performance is guaranteed. These “critical distances” were identified by using the maximum radiative ZOI and maximum plume effects ZOI.

The 3D model is used to apply the correlation tables by measuring distances between fire sources and targets (fire barrier elements in this case). For fire barrier elements beyond these critical distances, regardless of the fire source and provided there is no propagation that further adds fire load to the scenario, the fire barrier element performance is guaranteed, and no further analysis is required. If the fire barrier element is within the critical distance, its ZOI will be determined for that scenario and further analysis undertaken if needed.

Example of a Fire Damper Assessment

The target to be studied is a fire damper (fire barrier element) located in a large volume. All fire sources in the vicinity of the fire damper are analysed and their distances from the fire damper are measured (see Figure 4 below).

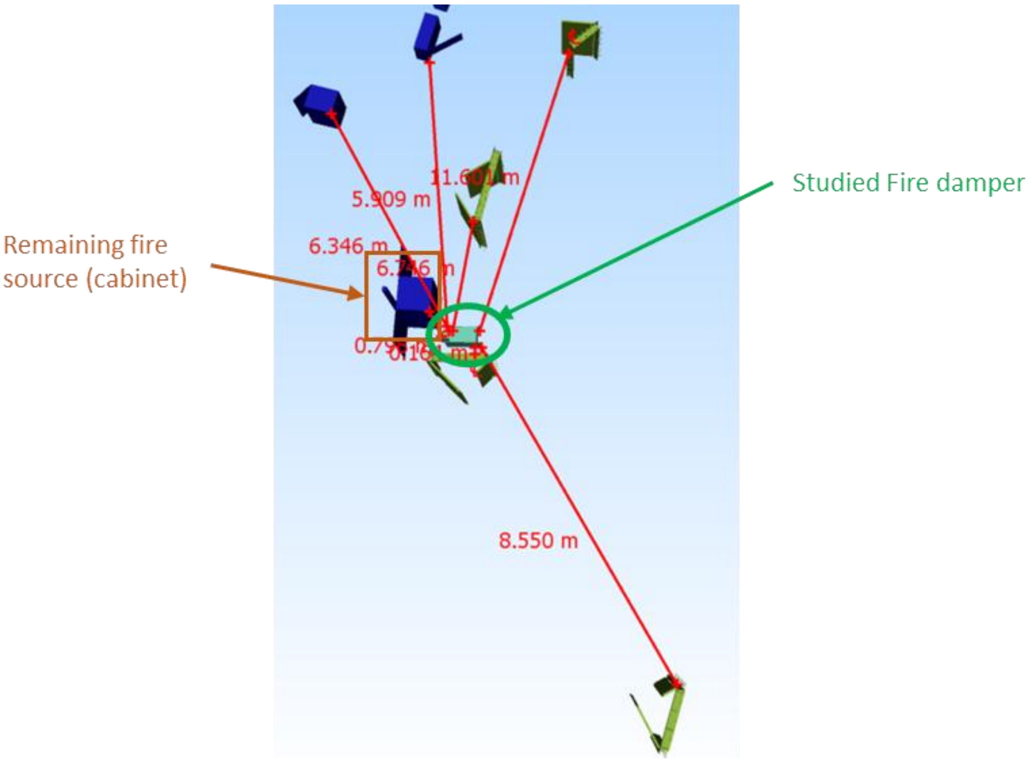

Figure 4 Example of a fire sources inventory and the respective distance measurement between fire sources and target

In this case, the fire sources screening has shown that only one fire source (an electrical cabinet) remains to be analysed as the other fire sources are located outside the critical distance of the ZOI. The correlation table corresponding to a cabinet fire with the closest characteristics to the true scenario is used to determine the ZOI of the cabinet fire.

As shown in Figure 5 below, the fire damper is located outside the ZOI of the cabinet fire. The fire damper integrity is therefore ensured for the assumed cabinet fire.

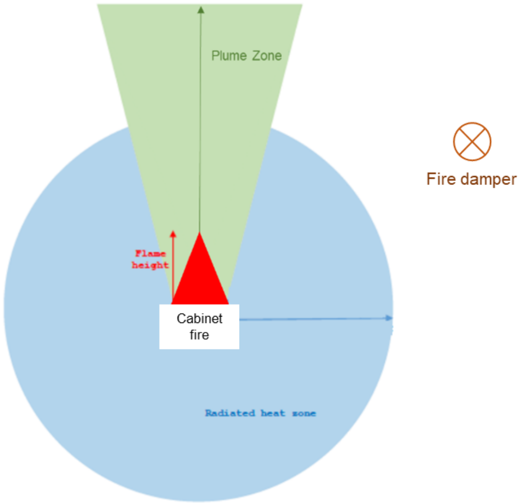

Figure 5 ZOI of the electrical cabinet fire

Step 2: Assessment of Non-fire Rated Openings

In the example, the fire related volumes inside the reactor building are not fire compartments but fire cells. Some openings in the fire barriers are not completely closed by fire-qualified fire barrier elements. A complementary analysis must be performed for all these openings. This analysis is done in three steps:

1. Verify the absence of fire spread from one fire cell to another,
2. Obtain the list of all components that are in the ZOI of a fire in an adjacent fire cell,
3. Assess the impact of the loss of the components through functional analysis.

Example of a Fire Cell Assessment:

In this case, no qualified physical barrier separates the two fire cells 1 and 2, the yellow line in the 3D model extract below represents the boundary between the two fire cells (see Figure 6).

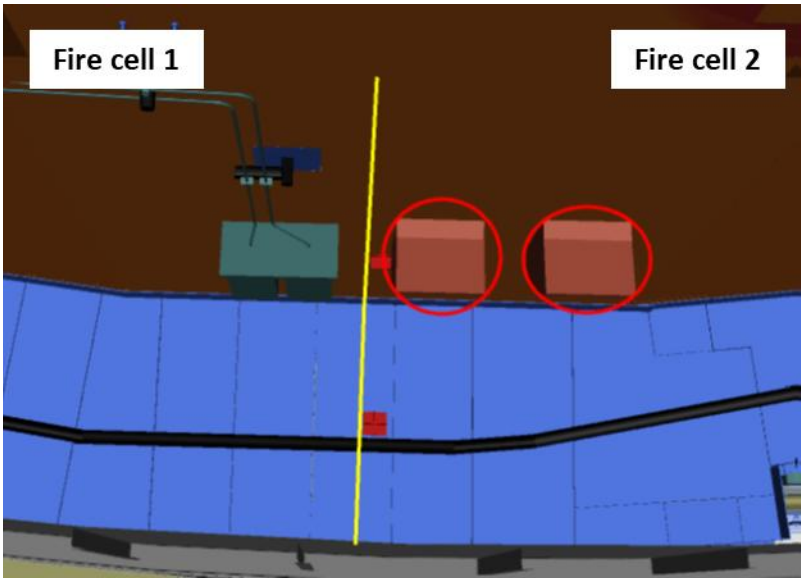

Figure 6 Example of boundary between two fire cells (3D model extract)

Two electrical cabinets in the fire cell 2 circled in red are located close to the compartment boundary. The fire scenario of these two cabinets burning together has been assessed. The ZOI has been determined and all the components in the fire cell 1 present in the ZOI have been listed. Based on their malfunction criteria, they have been considered as functionally unavailable. The consequences of losing these components are assessed in the functional analysis performed in the fire cell 2.

COMPLEX CABLE CONFIGURATIONS

The HPC EPR reactor building contains several complex cable configurations. These fire scenarios represent a risk of generalized (or flashover) fire scenarios through the cable trays despite the application of the fire prevention strategy. The objective is to assess the thermal effects of a distant major fire on any target studied, considering the risk of propagation of those fires beyond the initial fire source.

The fire scenarios analysed are the result of a screening phase performed in the reactor building with the analytic tool (correlation tables) used to determine the ZOI of each fire source and its impact on specific targets. The correlation tables can be used for simple configurations (single fire source or simple scenario of fire spread between single close fire sources) and do not cover complex configurations. Since such complex configurations are located in large volumes these scenarios are modelled using a CFD (*c*omputational *f*luid *d*ynamics) code such as the Fire Dynamics Simulator (FDS) [5].

The fire scenarios analysed with FDS can be sorted in two categories:

- High-voltage (HV) cable trays, for which the ignition can occur anywhere on the cable tray and for which the length of cable tray is not covered by the correlation tables;
- Electrical cabinets which can ignite a scenario which is neither a potential localised nor a generalised cable tray scenario in its ZOI.

The aim of the modelling is to check whether the fire prevention strategy is sufficient to limit the fire spread for those complex configurations. In case it develops into a large fire scenario, additional fire protection means or actions regarding the fire source (e.g., re-localisation) are required.

Figure 7 for example shows a cable fire scenario modelled with FDS (three cable trays).

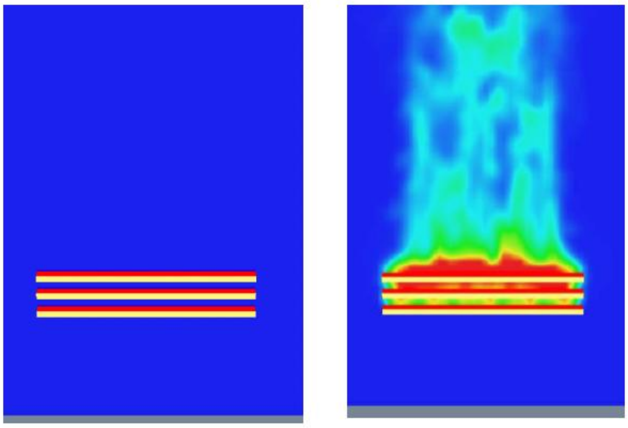

Figure 7 Example of cable trays on fire visualised with Smokeview [5]

Measurement devices are placed in the model at specific locations in the vicinity of the fire source to measure the physical parameters (temperature and heat flux). The modelling also provides a cartography of temperatures and heat fluxes around each configuration identified. In this way, it enables the assessment of the impacts of such cable tray fire scenarios on targets in the HPC reactor building.

The yellow dots in Figure 8 represent the location of the measurement devices. Once the simulation is completed, the results for temperature and heat fluxes are gathered along with the coordinates of each device (x,y,z) in the FDS computational domain. When the coordinates of a safety target are known, the most penalizing physical parameters of the closest device are compared to the failure criterion of the safety target.

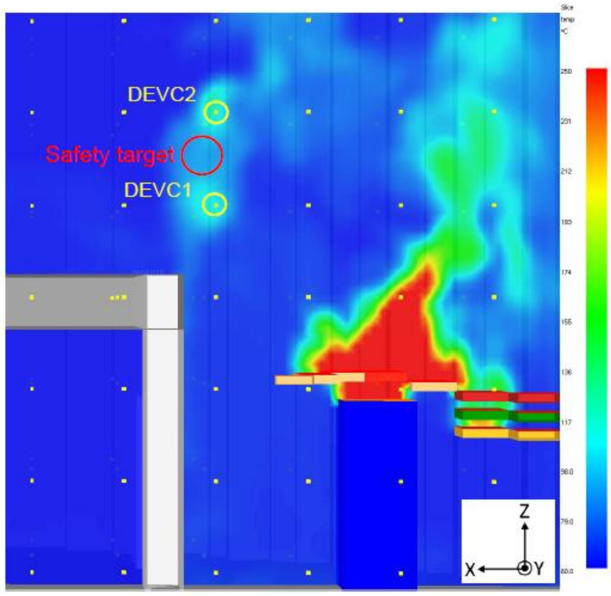

Figure 8 Example of a visualisation of a temperature vertical cut in Smokeview

If a safety target is located inside the red circle nearby the two dots circled in yellow (called DEVC1 and DEVC2), the parameters measured by both yellow dots are compared, with the most penalising ones then used to verify if the failure criterion of the safety target is met.

Example of the Assessment of a Target with the Cartography

A comparison between the 3D model and FDS model was performed to select the relevant reference point in the FDS model and in turn to obtain the maximum temperature for the fire scenario.

The most penalising value of the closest devices must be considered which, in this case for example, corresponds to the four devices in the blue square in Figure 9 below since they are the closest ones to the target identified. The maximum temperature measured by the four devices is retained and compared to the target malfunction temperature. If the temperature reached is higher than the malfunction temperature, the target is considered to be functionally unavailable as a result of the fire.

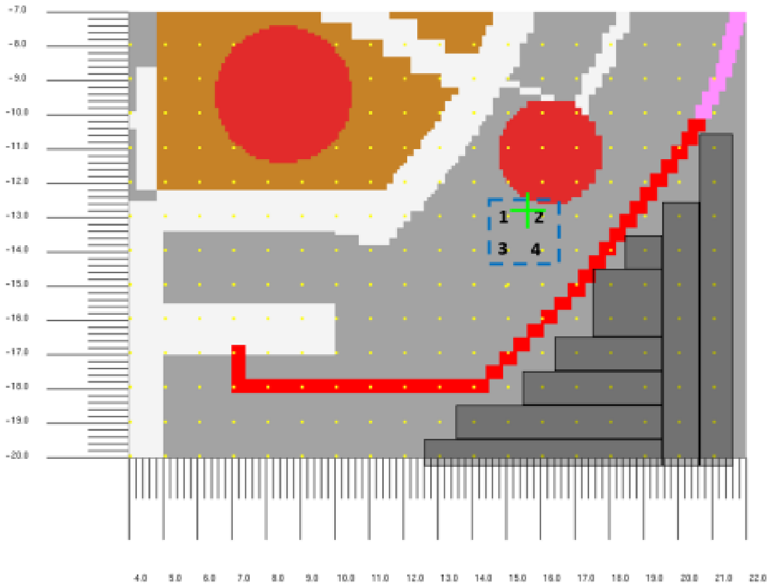

Figure 9 Example of a position of a target in the FDS model (green cross)

TREATMENT OF HIGH HYDROCARBON FIRE LOADS

High hydrocarbon fire loads represent a risk of large fires in the reactor building. A specific analysis is performed to demonstrate the absence of fire risk in the vicinity of those fire loads or that no residual fire risk can credibly mobilise these fire loads.

The principles of the robustness assessment of these high hydrocarbon fire loads consist of two parts:

- The assessment of the intrinsic robustness of the equipment containing the fire loads. This is done by providing evidence that adequate provisions are put in place in the design to reduce as low as reasonably achievable (ALARA) their risk of self-ignition (for example, the oil is contained within metallic frames with stringent mechanical resistance requirements or oil from oil leaks is collected in retention containers).
- The assessment via a dedicated fire risk analysis to demonstrate that no fire source located in the vicinity of equipment containing high fire loads can credibly mobilise these fire loads contained within such equipment.

For this last analysis, the inventory of the fire sources that could ignite each high hydrocarbon fire load is performed. Depending on the fire scenario, either it was studied using correlation tables or a FDS model was developed.

If the flash point of the oil remains below the temperature reached by the fire, it is considered that the fire load cannot be ignited, and thus is identified as non-mobilisable fire load. If the flash point of the oil is reached, measures are taken to mitigate the risk.

TREATMENT OF REMAINING ISSUES

If a target (fire barrier elements, common cause failure target, high hydrocarbon fire load, etc.) becomes functionally unavailable in a fire scenario several treatment options are considered in the analyses:

- Protection of the target, e.g. by a thermal screen or via fire protection to maintain the functionality of the target (cable tray fire protection for example);
- Relocation of the fire source;
- New detailed modelling, e.g., with a CFD code, or with refinement of the existing model, for example with more accurate information on the fire source and its power;
- Reduction of the fire risk, for example fire protection on cable trays;
- Justification of the acceptability of the functional loss of the target. For the fire barrier element, like a fire damper, this would mean performing the analysis with the assumption of a non-fire rated opening in the place of the fire barrier element. For the functional target (common cause failure), an in-depth functional analysis can be performed to justify that the loss of the equipment is acceptable.

CONCLUSIONS

The four fire cells in the reactor building house redundant trains of the safety systems connected to the primary circuit. In the frame of the safety demonstration, it must be justified that a fire does not lead to unacceptable consequences and does not jeopardise the safety objectives. In particular, it must be demonstrated that the integrity of safety fire compartments or fire cells is ensured, and it shall be demonstrated that the targets identified as confirmed common cause failure are not impaired by a fire. Consequently, the studies performed for the reactor building of the HPC EPR project using the dedicated methodology are essential.

Due to its specificities, the safety analyses performed for the reactor building are more complex and time consuming than for other buildings. The exhaustive list of fire barrier elements was difficult to gather as several databases needed to be cross-checked and considered. Each fire barrier element required individual assessment (around 200 fire barrier elements have been analysed). In some cases, the use of a CFD code was necessary which introduced another level of complexity in the analysis.

However, the fire prevention strategy was useful as a first approach to remove the risk of large cable fire scenarios from detailed analyses. The analytic tool with the correlation tables also reduced the time spent on the studies, they are robust, easy to use and sufficient for most of the assessments. The definition of the "critical distance" increased the efficiency of the fire barrier elements analysis.

The fire safety analyses for the reactor building of the HPC project are not yet finished. To date, all the studies performed for the reactor building in the frame of the EPR HPC project, combined with the application of the fire prevention strategy, have not resulted in any major issues for the safety demonstration.

REFERENCES

[1] Darby, J. L., et al.: GSI-191: The Impacts of Debris Induced Loss of ECCS (Emergency Core Cooling Systems) Recirculation on PWR Core Damage Frequency, NUREG/CR-6771, LA-UR-02-0279, Los Alamos, National Laboratory, United States Nuclear Regulatory Commission (U.S. NRC9 Office of Nuclear Regulatory Research, Washington, DC, USA, August 2002, https://www.nrc.gov/docs/ML0224/ML022410135.pdf.

[2] Électricité de France (EDF) Energy: PCSR – Sub-chapter 1.2 – General description of the unit, UKEPR-0002-012 Issue 03, August 2012, https://www.edfenergy.com/sites/default/files/sub-chapter_1.2_-_general_description_of_the_unit_0.pdf.

[3] International Atomic Energy Agency (IAEA): Protection against Internal Hazards in the Design of Nuclear Power Plants, Specific Safety Guide, IAEA Safety Standards Series No. SSG-64, STI/PUB/1947, ISBN 978-92-0-116121–5, Vienna, Austria, August 2021, https://www-pub.iaea.org/MTCD/publications/PDF/Pub1947_web.pdf.

[4] French Standard NF ISO 18195 – Method for the justification of fire partitioning in water cooled nuclear power plants (NPP), AFNOR Editions, July 2019, https://www.boutique.afnor.org/en-gb/standard/nf-iso-18195/method-for-the-justification-of-fire-partitioning-in-water-cooled-nuclear-p/fa178272/82969.

[5] National Institute of Standards and Technology (NIST): Fire Dynamics Simulator (FDS) and Smokeview (SMV),Version 6.6, FDS 6.6.0 SMV 6.6.0 - FDS6.6.0-131-g88ae75a, Gaithersburg, MD, USA, November 2017, https://github.com/firemodels/fds/releases/tag/FDS6.6.0.

Safety Case for the Fire of a Battery Powered Electric Transport Vehicle for Nuclear Waste Packages in the Konrad Repository

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ABSTRACT

The Konrad repository for low and intermediate level radioactive waste is currently under construction. Within the license process in the 1980s a thermal design accident of an unmitigated fire of a diesel-powered transport vehicle at a gas temperature of 800 °C engulfing the waste packages from all sides over 60 min (so-called “PTB curve”) was specified.

In the course of today's planning for the vehicle, a battery powered electric motor was chosen. It has been demonstrated that an unmitigated fire of the newly designed battery powered electric transport vehicle impacts the waste containers by a thermal load significantly below that of the PTB curve. The safety case is based on a fire simulation for the underground vehicle fire and a full-scale battery fire experiment to provide input data for the simulation. Thus, the design load for the nuclear waste packages for the Konrad repository, i.e. the PTB curve, is met by the new battery powered electric transport vehicle as well.

INTRODUCTION

The Konrad repository for radioactive waste located near the city of Salzgitter in Lower Saxony, Germany is currently under construction. It will be used for the final disposal of 303,000 m³ of low and intermediate level nuclear waste (LILW) from the German nuclear industry, research institutions and the German nuclear power plants being decommissioned. For this purpose, a former iron-ore mine is converted into a repository for radioactive waste. Emplacement will start at the beginning of the 2030s.

Konrad is the first repository in Germany that was completely licensed [1] under the nuclear law. The licensing procedure took about 20 years, the license to construct and to operate was granted in 2002. Applicator, licensee and operator of the repository is the Federal Company for Radioactive Waste Disposal (Bundesgesellschaft für Endlagerung, BGE), the German waste management organisation. It is owned by the Federal German government and is funded by the Federal budget as well as by fees from waste owners.

Konrad is a mine with two shafts. While Konrad 1 is used for personnel, material transport and air intake, Konrad 2 will be used for waste transport and air exhaust. The two shafts are located in a distance of about 1.5 km from each other.

Emplacement Process and Transport Vehicle

The transport and emplacement process of the waste has been planned in detail and represents an important input for the accident analysis as a part of the safety case for the repository. Waste is transported to the Konrad 2 site by train or truck in special waste packages or containers. The containers contain the waste products and protect these against mechanical and thermal loads. The containers pass through a thorough product control process in advance that demonstrates that the waste acceptance criteria for Konrad are met. In the shaft building, the containers are unloaded and transported through shaft Konrad 2 to the repository itself. At the shaft landing on the emplacement level, they are loaded on a transport vehicle and transported to the emplacement chamber. They are then stacked onto their spot with a forklift truck. The transport vehicle has been designed to be a mining transport truck with an articulated joint and a diesel engine. A visualization of the emplacement process can be accessed online [2].

Thermal Design Basis Accident

All transport processes and the necessary facilities, systems and components that are used for container transport are subject to a thorough quality control and have been examined during accident analysis. The thermal design basis accident for the underground transport is a fire of the transport vehicle. The accident analysis presumes that the onboard fire suppression systems and interventions from the driver and/or the mine rescue brigade will not be able to extinguish the fire. The waste containers and their waste products have therefore been constructed to survive an underground fire of the transport vehicle in the manner that the release of radionuclides is restricted to an amount that still meets the safety limit for an accident. The safety limit is defined by the Federal German Radiation Protection Ordinance [3] as 50 mSv for a reference person outside the repository in the case of an accident.

The worst-case scenario for the underground fire of the transport vehicle is a fire at the entrance of the emplacement chamber. The consequences at other fire locations are less serious due to the geometry of the tunnel and the ventilation there.

The thermal load from the underground transport vehicle fire is specified by a temperature-time curve. It is assumed that the fire will produce gas temperatures of 800 °C at the waste container for a period of 60 min. This design load is called the PTB curve as defined by the Physikalisch-Technische Bundesanstalt (PTB), Germany's national metrology institute, during the licensing process. The PTB curve is used as a construction constraint for all Konrad containers and is part of Konrad's license.

During the licensing process the fire load of the transport vehicle and other boundary conditions have been specified. The radiological consequence analysis has demonstrated the compliance with the safety limit mentioned above. The regulator has issued a requirement in Konrad's license to further improve the fire safety of the transport vehicle. For reducing the fire load, the vehicle is to be equipped with an electric motor instead of the diesel engine.

New Battery Powered Electric Transport Vehicle

To meet the requirement of reducing the fire load, the BGE has redesigned the transport vehicle by replacing the diesel engine by a battery powered electric motor. The battery powered electric transport vehicle (BPETV) has two axles, an articulated joint and a length of

11.2 m. The mass is up to 46 Mg, 20 Mg of that stems from the waste container. The propulsion is produced by wheel drives with the electric energy provided by four lithium-ion batteries. The weight of the batteries is approx. 1 Mg each, the electric energy content is 229 MJ. The design as used in the simulation is shown in Figure 1.

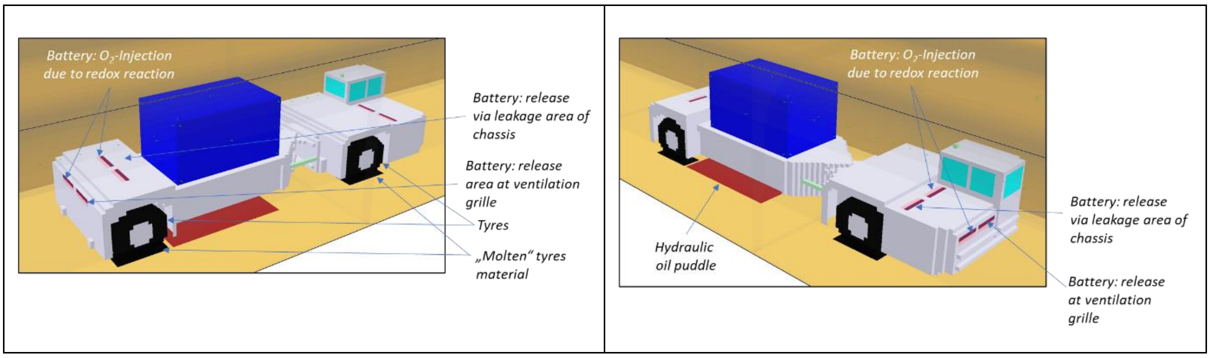

Figure 1 Location of fire loads and release areas

The redesign of the BPETV constitutes a change in the licensed emplacement process and has to be approved by the regulator. During this formal change procedure, the BGE has to demonstrate that all safety requirements that are defined by the nuclear law and the license are met and that the unmitigated fire of the BPETV still complies with the design load, i.e. the PTB curve. It has to be specifically demonstrated that the thermal load from a fire of the BPETV is covered by the PTB curve.

The BGE has decided to use a fire simulation for the underground fire as a tool to build the safety case for this change procedure, in combination with a fire experiment to provide input data for the simulation.

BACKGROUND OF THE PTB TEMPERATURE CURVE AND INPUT DATA

The waste packages are designed against a thermal load that is known as the PTB curve; the temperature-time curve shows

- a linear increase of the temperature at the beginning from 30 °C to 800 °C within 5 min,
- a 60 min plateau at 800 °C until 65 min, and
- a rapid temperature decrease to 30 °C at 65 min.

The PTB curve was derived from fire experiments with mock-ups representing diesel driven trucks in the mining industry (cf. Figure 2). These fire experiments were conducted in 1984 [4] in the experimental “Tremonia” mine in the city of Dortmund, Germany.

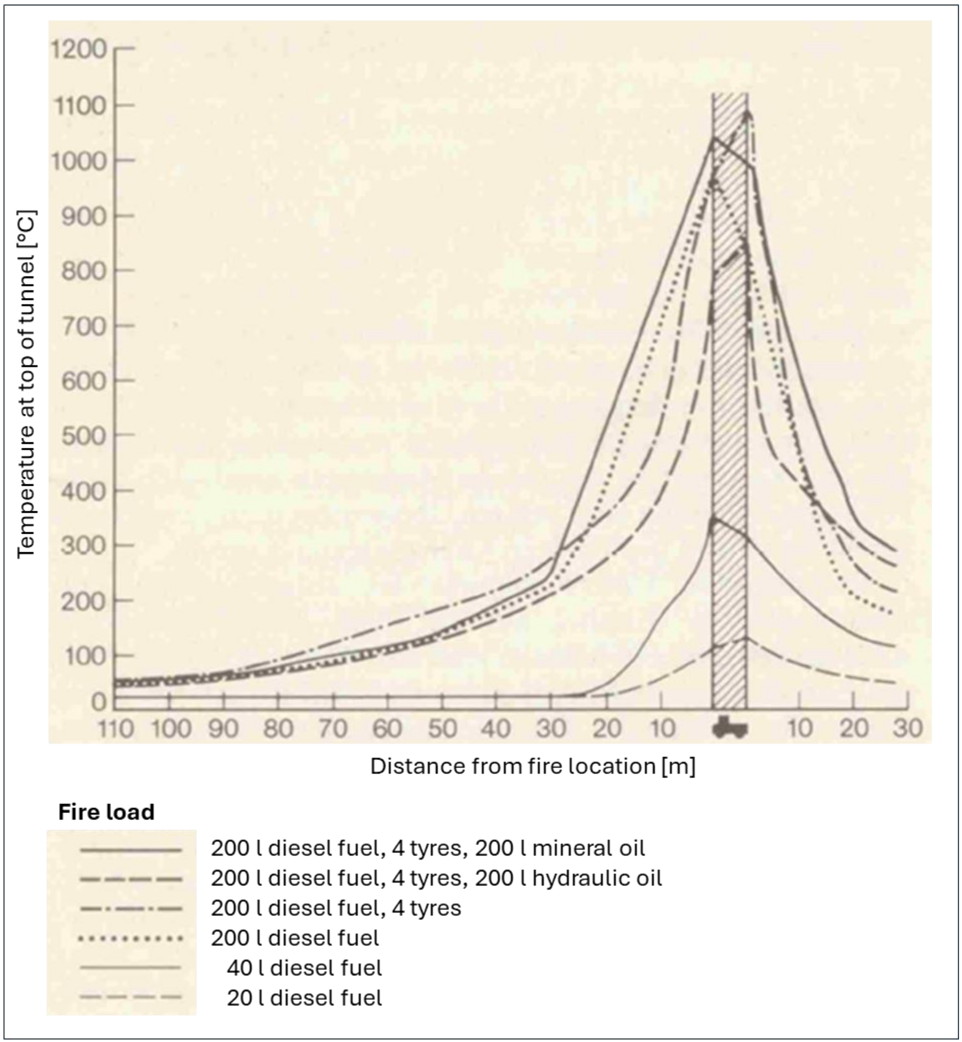

Figure 2 Temperature curves measured below the ceiling along a tunnel [4]

Even though in some experiments with high fire loads the maximum fire temperatures showed peaks at about 1,100 °C, the regulatory authorities [5] decided with reference to the IAEA transport regulations [6] that

"*In view of all these parameters, an exact theoretical determination of a temperature-time-function is impossible. This is the reason for the use of a model curve in order to describe more realistically the expected effects. A well-known example of such a model curve is the load assumption of 800 °C for a period of 30 minutes as contained in the IAEA transport regulations.*"

The IAEA design fire curve for type-B containers can be seen as a conservative, generic fire curve that is not intended to cover tunnel fires. In contrary, the PTB curve was intended to cover tunnel fire situations; however, this was achieved by an extension of the fully developed fire duration from 30 min to 60 min instead of increasing the fire temperature to more than 800 °C.

During the development of the PTB curve, two further temperature-time curves were under discussion (cf. Figure 3 below). The NUKEM curve started at 1,000 °C maximum temperature over 15 min with a linear temperature decrease to 200 °C at 45 min and further to an ambient level of 30 °C. The GRS curve showed a linear temperature increase at the beginning from 30 °C to 850 °C within 5 min, a temperature plateau until 35 min and a linear decrease from 850 °C to 200 °C at 90 min and further down to an ambient level of 30 °C.

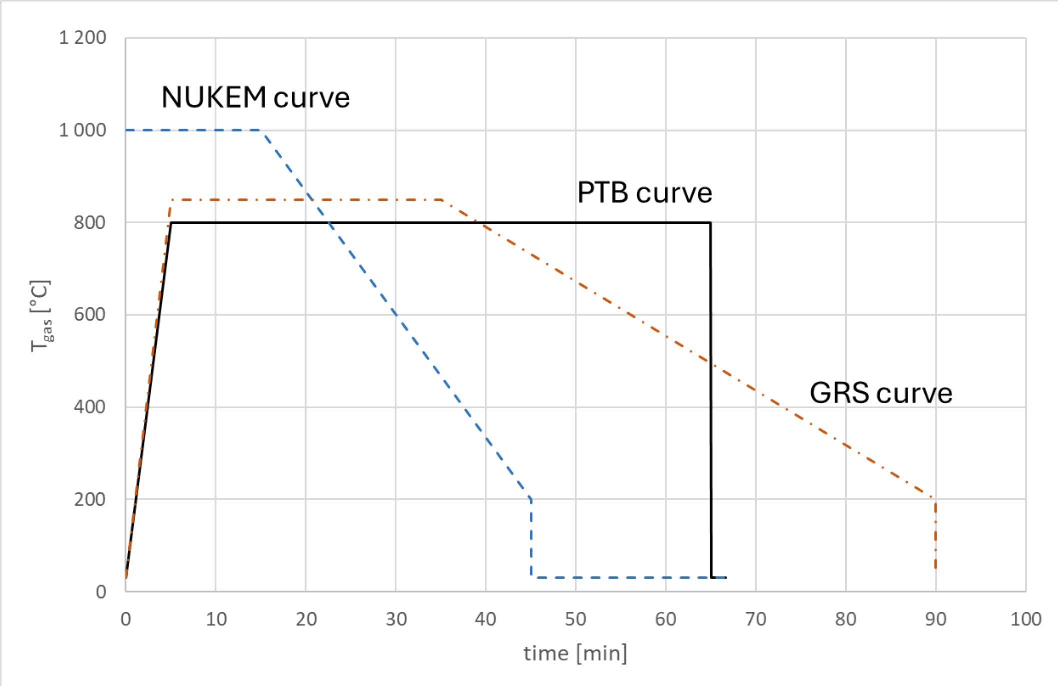

Figure 3 Comparison of three temperature-time curves

Regarding the resulting inside wall temperature of a cast iron vessel of 160 mm wall thickness (see Figure 4), particularly the PTB curve and the GRS curve show a quite similar effect on the nuclear waste packages. The NUKEM curve shows a lower maximum because of the earlier temperature decrease.

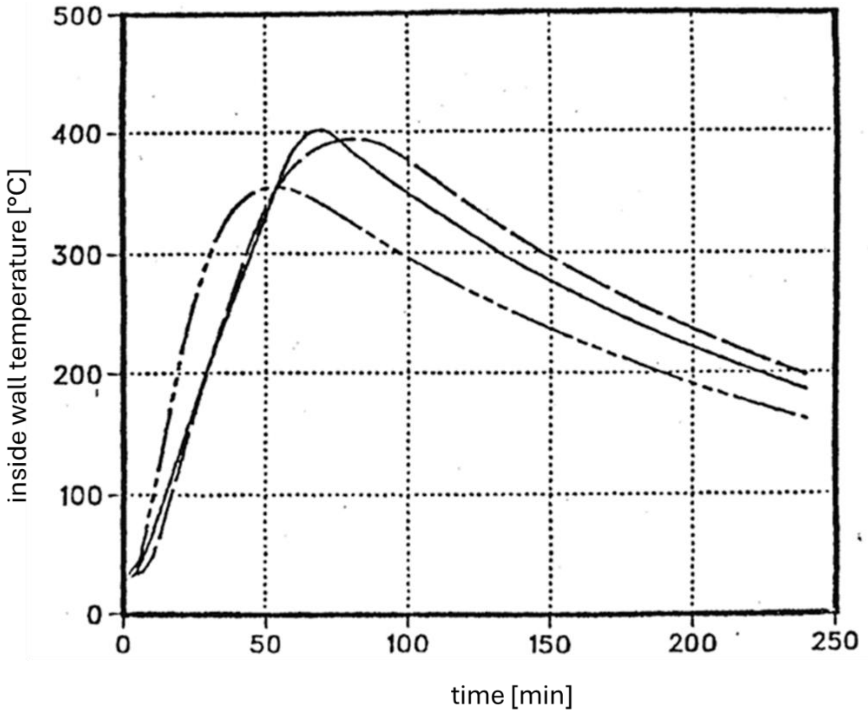

Figure 4 Calculated inside wall temperatures of a reference waste container with 160 mm cast iron walls from exposure according to the three temperature curves

The GRS curve is the most realistic fire curve because it consists of a fire spreading phase, a plateau and a decay phase. The reason is that it was developed based on a one-zone fire simulation model with heat release rate (HRR) source terms for different fire loads that are based on the fire loads according to the planning at that time of a diesel engine driven vehicle (cf. Table 1). The actual vehicle design consists of only single rear tyres instead of twin tyres, the amount of fluid from lubrication oils and diesel fuel is significantly reduced or replaced by batteries. Therefore, the reduction of the overall effective fire load is significant.

Table 1 Fire loads (effective heats of combustion in MJ) of the diesel driven transport vehicle compared to the battery powered electric transport vehicle

Fire Loads	Diesel TV	BPETV
4 Li batteries	-	9,160 MJ
Small parts (cables, paintings, plastics etc.)	not considered	9,226 MJ
Diesel fuel	9,524 MJ	-
Hydraulic, transmission oil, etc.	19,096 MJ	3,487 MJ
Front tyres	18,090 MJ	13,759 MJ
Rear tyres	34,170 MJ	13,759 MJ
Sum	**80,880 MJ**	**49,392 MJ**

Based on the fire loads of the diesel transport vehicle conservative HRR source terms were developed as input for the fire simulations for the GRS curve. For the liquid fuels a 10 m^2 pool fire was assumed below the vehicle to heat the waste containers and to provide a supporting fire for the tyres. The specific HRR was assumed to be 1,594 MW/m^2 as input for the GRS curve.

For the new BPETV the amount of fuel to be considered for the liquid fuel fire was significantly reduced (cf. Table 1) and the flashpoints are higher. When keeping the original fire area of 10 m^2 it was found that the reduced amount of liquids leads to a spill-like fire that, together with the higher flashpoints, results in a reduction of the HRR by a factor of two.

The tyre fire was estimated based on the tyre surface and a specific HRR of 0.373 MW/m^2. The outer tyre surface was assumed to be 6 m^2 and was increased to 9 m^2 at each corner of the vehicle to account for some fraction of the inner tyre surface. This resulted in a maximum $HRR_{tyres,diesel}$ of 4 x 9 m^2 x 0.373 MW/m^2 = 13.4 MW as input for the GRS curve.

For the new BPETV the contribution of a tyre fire was derived by the same approach; however, the intended tyre type has a reduced surface area of only 4.3 m^2 resulting in a $HRR_{tyres,BPETV}$ = 9.62 MW.

The contribution of the pool/spill fire and the tyre-fire is reduced from the change of a diesel transport vehicle to a BPETV, but the contribution of the battery fire had to be added. This is explained in the following.

FIRE SIMULATIONS

Procedure

The procedure as outlined in Figure 5 used to demonstrate compliance with the PTB curve is based on the procedure applied during the licensing process. In the fire simulations conducted, using the CFD (*c*omputational *f*luid *d*ynamics) code FDS (*F*ire *D*ynamics *S*imulator), the fire loads are taken into account by specifying the HRR. Here, the fire load of the transport vehicle from hydraulic oil and tyres is based on the licensed conditions or conservatively estimated using the experimental results of the battery fire experiment. The conservatism refers to the level of the HRR as well as to the fact that the fire of all combustibles starts simultaneously, i.e. all four batteries and the other partial fire loads (from the hydraulic oil puddle and the tyres) burn at the same time. The gas temperatures near the container surfaces are calculated by FDS. The resulting average gas temperature is compared to the PTB curve as an acceptance criterion (load assumption). The impact by the thermal load on the containers is calculated by FDS; however, these results are not used for the proof of fulfilment of acceptance criteria, because these results are depending on the type of waste package. It has been demonstrated during the licensing process that the waste packages are designed to withstand the thermal effects corresponding to the PTB curve.

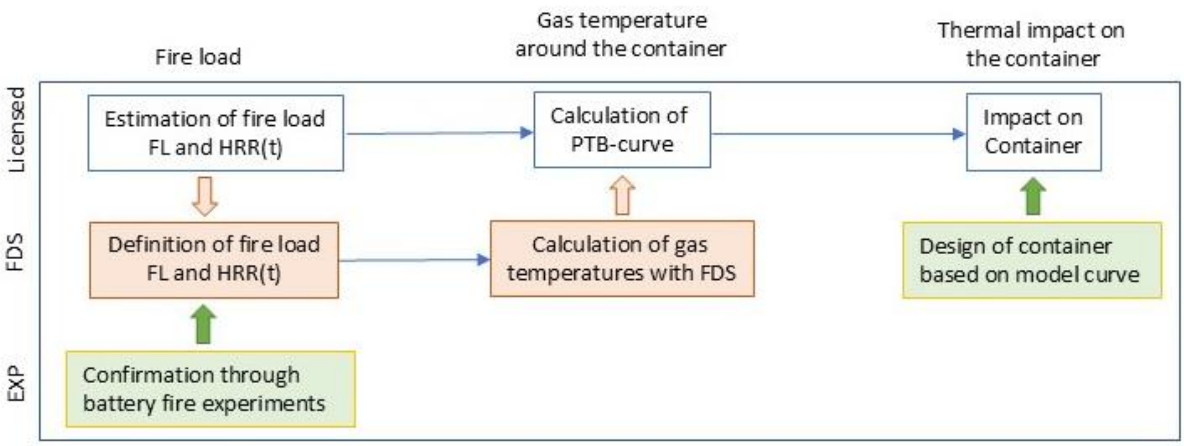

Figure 5 Scheme of the procedure used to demonstrate compliance with the PTB curve

Fire Load and Heat Release Rates

In the fire simulations with FDS the fire loads are represented by the integral of specified time-dependent HRRs. The existing fire loads of the BPETV are divided into a pool fire below the loading area, the tyre fires and the battery fires in the front and rear of the vehicle. The locations of the fire loads under consideration are shown in Figure 6. These consist of the discharge of battery gases (via ventilation grilles and leaks of the chassis), the liquid fuel pool (from hydraulic and transmission oils) and the tyres (including molten rubber pool). Other small fire loads were distributed among the above fire loads. Additional oxygen is injected near the release points of the battery gases in order to take into account the oxygen available in the battery for the redox reactions (light pink areas).

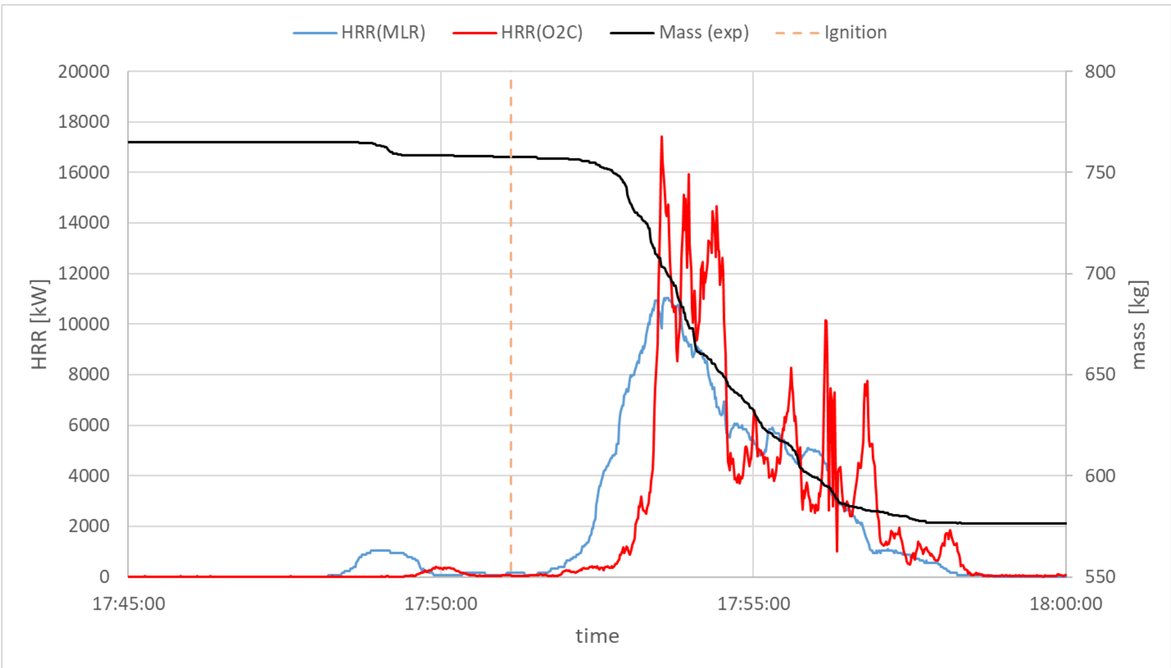

Figure 6 Experiment: mass loss, MLR and HRR; orange dashed line indicates the time of ignition (via a spark igniter)

A complete burnout of the four traction batteries is assumed for the analysis. This is a highly conservative assumption, as a failure and thermal runaway of all modules of a traction battery is very unlikely due to various active (e.g. the battery management system) and passive (e.g. encapsulation with aluminium housings at cell and module level) protective measures. Furthermore, it is assumed that all four traction batteries fail simultaneously, which is also not to be expected due to the spatial distance.

Although there are conservative estimates of the expected fire load of such a traction battery, there are uncertainties, particularly regarding the heat release time curve so that the source terms have been further validated by full scale fire experiments.

Each traction battery contains in total 21 modules which are connected in parallel in three strings of seven modules each (3 x 7 parallel). The fire in the experiment was initiated by battery overcharging. At the point in time of ignition the state of charge (SOC) was about 120 %. A spark igniter was used to ensure the ignition of flammable gases. During the thermal run-away, the test specimen lost 188 kg of mass within approx. 560 s. In addition to the mass loss, the HRR was measured by means of oxygen consumption calorimetry in accordance with ISO 9705 [7]. However, the method is calibrated for organic fire loads such as wood or plastics and cannot fully capture the heat release of lithium-ion batteries, in which redox reactions also take place. The measured heat release using oxygen consumption calorimetry (HRR_{O2C}) is therefore not complete. The measured results are presented in Figure 7.

During the thermal runaway of the first modules, flammable gases escaped without combustion occurring outside the battery (MLR peak before the orange line indicating the ignition of gases). In the course of the battery fire, the fire compartment became very smoky, therefore the ventilation volume flow was then increased. Before increase, this leads to lower HRR_{O2C} values compared to the HRR based on the MLR. Shortly after the increase, the smoke was removed out of the fire compartment, leading to high HRR_{O2C} values. Afterwards both values became quite similar. As a result, the HRR based on the MLR was used for the FDS simulations. The total heat release based on the typical oxygen consumption calorimetry (with 13.1 MJ per kg oxygen) is estimated to 1.82 GJ, which is approx. 8 times the stored electrical energy.

Regarding the energy release caused by redox reactions (without consuming oxygen from air) the work of Walters [8] and Scharner [9] show a proportion of about 1.88 to 1.6 in relation to the stored electrical energy. The same behaviour has been assumed for the traction battery because of a similar chemical composition, and the heat release due to redox reactions has been conservatively estimated with a factor of 2. Both together give a factor 10, so in total 2.29 GJ thermal energy for each traction battery.

The combined development of each fire load over time is presented in Figure 7.

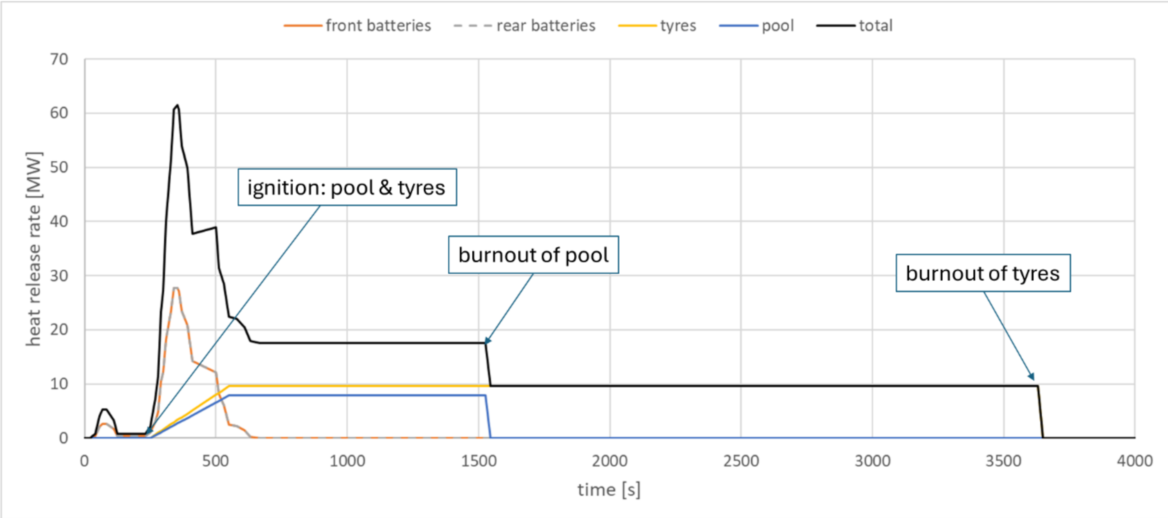

Figure 7 Development of the HRRs over time for each fire load

Boundary Conditions Used in the FDS Simulations

In order to minimize the influence of the boundary conditions, a tunnel section with a total length of 100 m is mapped in the FDS data set. Grid cells with the dimensions 0.1 x 0.1 x 0.1 m^3 are used in the vicinity of the fire. FDS offers the option of stretching the size of the grid cells. This function is used in the individual areas, whereby the cells are continuously enlarged or reduced in the direction of the distance (x-axis). The shape of the ridges is modelled as accurately as possible in the Cartesian grid. The size of the tunnel is about 4.5 m height and, and about 6 m width. The heat loss to the surrounding rock is taken into account. FDS offers the option of dividing the entire grid into several sub-grids and solving them in parallel. Five sub-grids, each with 100 x 68 x 48 = 326,400 cells, are used in the simulations, i.e. a total of 1,632,000 cells.

A distinction is made between two ventilation conditions. The first case corresponds to the licensed situation with a constant volume flow rate of 23 m^3/s at the intake side. The second case corresponds to the real situation with a constant volume flow rate of 17.25 m^3/s at the exhaust side. It has to be kept in mind that the volume expansion due to the heat up of atmosphere leads to an effective reduction of the mass flow rate in the second case, resulting in a lower deflection of the flames at the rear of the vehicle and a lower thermal load of the containers (cf. Figure 8).

Figure 8 Shape of flame at time point of maximum HRR for both ventilation situations

Table 2 lists the FDS calculations carried out for the assessment. The assumed fire development is the same in all cases. The total fire load is 49 GJ with a maximum HRR of 62 MW (cf. Figure 7). Regarding the ventilation, a distinction is made between the cases with a ventilation rate of 23 m^3/s at the intake and the downstream ventilation rate of 17.25 m^3/s. The first alternative corresponds to the boundary conditions considered in the licensed situation and is therefore designated as reference case. The second ventilation alternative corresponds to the planned procedure with a fan on the downstream side and a volume flow rate of 17.25 m^3/s. Due to the volume expansion of the gases occurring during the fire (reduction in density) the two alternatives lead to different results. In addition, two different types of vehicle loads are considered, two cylindrical packages on a transport frame for cases 1 and 2 (cf. Figure 8) or a rectangular container for cases 3 and 4 (cf. Figure 1).

Table 2 Overview of the FDS simulations carried out

No.	Ventilator Position	Fan Flow Rate	Load
1	at intake (push)	23.00 m^3/s	cylindrical package
2	at exhaust (pull)	17.25 m^3/s	cylindrical package
3	at intake (push)	23.00 m^3/s	Container
4	at exhaust (pull)	17.25 m^3/s	Container

FDS calculates local temperatures. To compare the results to the PTB curve it is necessary to average the local temperatures. In case of the container type package, for example, 25 monitor points were defined at the edges and centres of each side.

In addition, the so-called adiabatic surface temperature can be evaluated by FDS. This surface temperature T_{AST} is the computational surface temperature, at which the resulting heat transfer becomes zero, i.e.

$$\varepsilon\left(\dot{q}''_{inc,rad} - \sigma T_{AST}^4\right) + h\left(T_{gas} - T_{AST}\right) = 0$$

An exemplary result is shown in Figure 9.

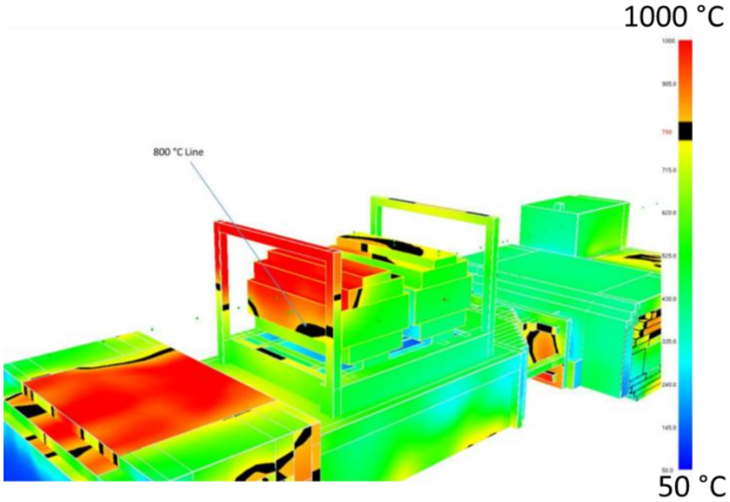

Figure 9 Case No. 1: 3D-view of an adiabatic surface temperature at 480 s

Results

In the following, exemplary results are discussed. The maximum gas temperatures of all monitor points are shown in red or blue and the minimum temperatures in orange or green in Figure 10. The difference between the two temperatures gives an impression of local effects. In the Case No. 1 with ventilation at the inlet side, the maximum temperatures exceed the PTB curve (800 °C) for approx. 210 s. In the Case No. 2 (ventilation at the exhaust), with the reduction in the velocities inside the tunnel and around the vehicle due to heat-up being considered, significantly lower maximum temperatures are calculated, because the inclination of flame is reduced (cf. Figure 8). These remain below 600 °C. The calculated minimum temperatures are very similar for both cases. It is remarkable that after the rear batteries have burnt down in the Case No. 1 the calculated maximum and minimum temperatures are practically the same and very low. That means that in the Case No. 1 the pool and the tyres have hardly any effect on the rear container. In contrary, in the Case No. 2, the rear tyres in particular lead to a thermal load on the rear cylindrical package.

The calculated average gas temperatures of the Cases No. 3 and No. 4 are shown in Figure 11. In the Case No. 3, average gas temperatures of approx. 800 °C are achieved for a time period of approx. 250 s. In addition to the PTB curve, this figure also shows the NUKEM curve and the GRS curve, with temperatures of up to 1,000 °C occurring in the NUKEM curve. The comparison of these model curves with the calculated average gas temperatures shows that, due to the assumed BPETV fire, the thermal load on the container is significantly lower than those corresponding to the model curves, which are used for the design of the waste packages.

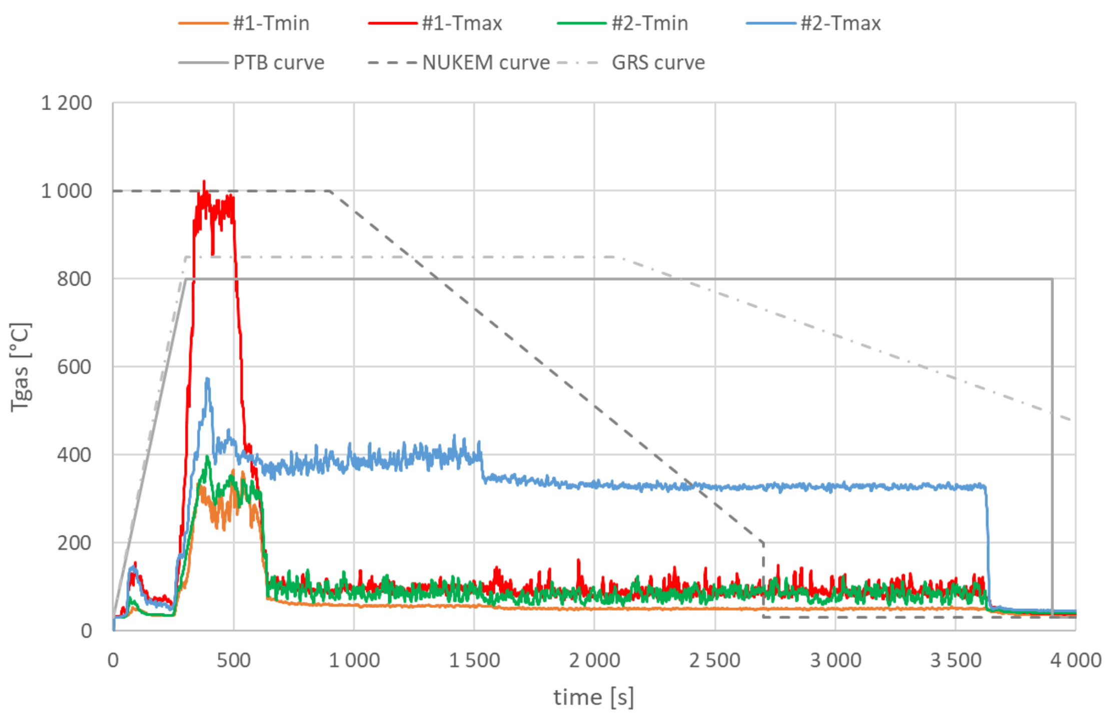

Figure 10 Cases No. 1 and 2: comparison of minimum (orange/green) and maximum (red/blue) gas temperatures near the surfaces of rear cylindrical package

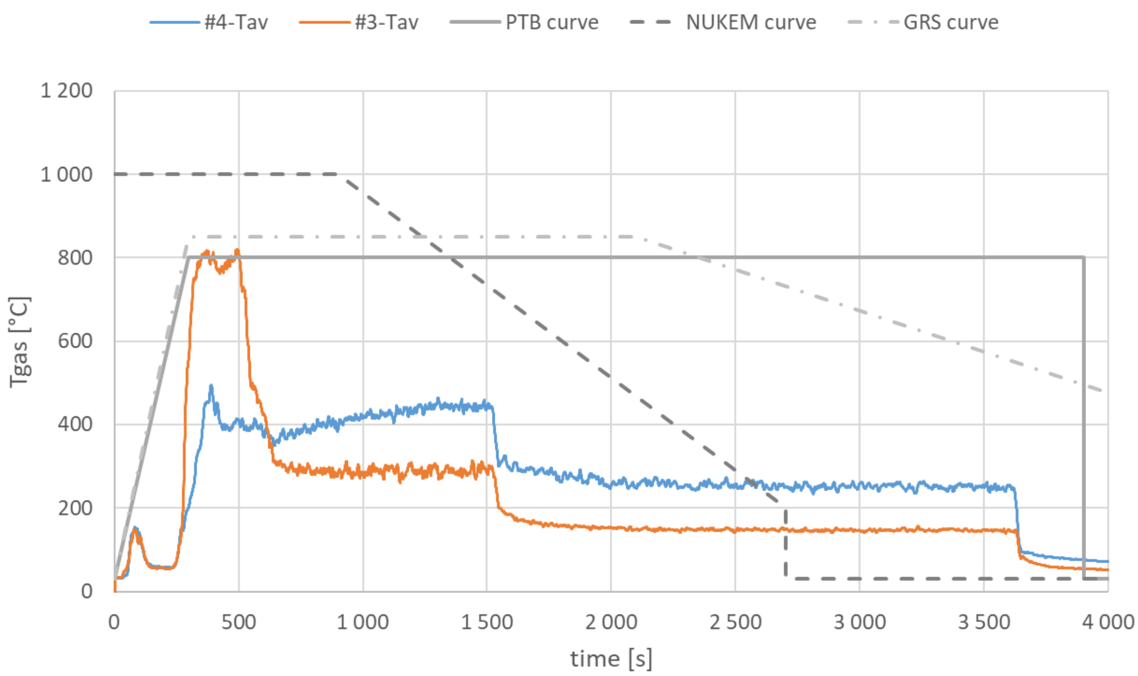

Figure 11 Cases No. 3 and 4: comparison of average gas temperature around the container

As a result, the gas temperatures at the container calculated by FDS under conservative assumptions lie significantly below this load assumption. The orange curve was calculated with the assumptions from the licensing process, the blue curve with the projected conditions (flow rate of 17.25 m^3/s at the exhaust side).

It has to be considered that the integral under the temperature-time curve is a measure of the thermal energy absorbed by the container. Therefore, the calculated thermal load on the container is far below the design load. The design load temperature of 800 °C is reached only during a very short period at the beginning of the simulation.

CONCLUSIONS

Is has been demonstrated that an unmitigated fire of the newly designed battery powered transport vehicle provides a significantly lower thermal load on the waste containers than the thermal load corresponding to the PTB curve (800 °C for 60 min), representing the design load for the thermal design basis accident assumed for the Konrad nuclear waste repository. The safety case is based on a fire simulation for the underground BPETV fire and a full-scale battery fire experiment to provide input data for the fire simulation. Thus, the requirements regarding the design load for the Konrad containers, i.e. corresponding to the PTB curve, are also met by the BPETV.

REFERENCES

[1] Niedersächsisches Umweltministerium: Planfeststellungsbeschluss für die Errichtung und den Betrieb des Bergwerkes Konrad in Salzgitter als Anlage zur Endlagerung fester oder verfestigter radioaktiver Abfälle mit vernachlässigbarer Wärmeentwicklung, Hannover, Germany, May 2002 (in German).

[2] Bundesgesellschaft für Endlagerung (BGE): Video Live-360°-Tour durch das Endlager Konrad: Der Weg der Abfälle, Peine, Germany, last access: 30 September 2021, https://www.youtube.com/live/xwSIoOWg4II.

[3] Ordinance on Protection against the Harmful Effects of Ionising Radiation – Radiation Protection Ordinance (Verordnung zum Schutz vor der schädlichen Wirkung ionisierender Strahlung – Strahlenschutzverordnung – StrlSchV)1 Radiation Protection Ordinance, Bundesgesetzblatt Jahrgang 2018 Teil I Nr. 41, Bonn, Germany, December 2018, English version in: https://www.bmuv.de/filead-min/Daten_BMU/Download_PDF/Gesetze/strlschv_en_bf.pdf.

[4] Heyn, W., and W. Foit: Die Auswirkungen brennender Gleislosfahrzeuge auf sonderbewetterte Strecken, Glückauf-Forschungshefte 47 (1986), pp. 146-148, 1986 (in German).

[5] Berg. H.-P.: Fire protection measures in the planned Konrad repository, Nuclear Engineering and Design, Volume 135, Issue 4, July 1992, pp, 403-41, 1992, https://www.sciencedirect.com/science/article/abs/pii/002954939290206B.

[6] International Atomic Energy Agency (IAEA): Regulations for the Safe Transport of Radioactive Material, 2018 Edition, Specific Safety Requirements No. SSR-6 (Rev. 1), STI/PUB/1798, ISBN N 978-92-0-107917-6, Vienna, Austria, June 2018, https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1798_web.pdf.

[7] International Organization for Standardization (ISO): ISO 9705: Reaction to fire tests — Room corner test for wall and ceiling lining products, Part 1: Test method for a small room configuration, Edition 1, 2016. https://www.iso.org/standard/59895.html.

[8] Walters, R. N.: Measuring Energy Release of Lithium-ion Battery Failure Using a Bomb Calorimeter, DOT/FAA/TC-15/40, Federal Aviation Administration William J. Hughes Technical Center, Federal Aviation Administration, New Jersey, USA, March 2016. https://www.fire.tc.faa.gov/pdf/TC-15-40.pdf.

[9] Scharner, S.: Quantitative Charakterisierung des Sicherheitsverhaltens von Lithium-Ionen-Zellen, BMW Group, Presentation, Batterieforum Deutschland, Berlin, Germany, 25. Januar 2018 (in German).

3.2 Topical Session on Combinations of Internal Fires and Other Hazards

The second seminar session chaired by Heinz-Peter Berg as one of the permanent seminar organizers addressed one of the most recent hot topics of deterministic and probabilistic specific topic, combinations of hazards, in this context fires and other hazards.

The first presentation by Ashley Lindeman from the Electric Power Research Institute (EPRI) in the United States of America (USA) addressed the emerging risk from wildfires to nuclear power plants, a hazard historically considered negligible, which unfortunately often results in consequential plant internal fires. Climate change has increased the frequency and severity of wildfires, posing threats such as damage to transmission infrastructure and loss of offsite power, which is critical for plant safety. The presentation highlighted that while internal fire hazards have been extensively analysed, impacts from external wildfires remain underexplored.

The methodology proposed by the authors involves assessing wildfire hazards site-specifically using recognised fire hazard maps and evaluating vulnerabilities such as power independence, access and egress to the site and plant, ventilation systems, structural integrity and cooling systems. A review of the available operating experience revealed that most wildfire-related impacts concern electrical systems, with events documented worldwide.

Mitigation strategies include vegetation management along transmission corridors, development of wildfire response plans and coordination with grid operators. The paper concludes that proactive risk management and periodic reassessment of wildfire hazards are essential to maintain nuclear plant resilience in a changing climate.

Xavier Leblanc of Tractebel Engineering (Belgium) presented a deterministic methodology for assessing seismically induced fire (SIF) hazards in Belgian nuclear power plants scheduled for shutdown. The study responded to regulatory requirements to consider credible combinations of hazards, such as earthquakes and internal fires. The primary safety objectives were to minimise the occurrence of SIFs and to maintain safe shutdown capability.

The approach presented builds on existing fire hazard analyses, integrating seismic interactions and screening potential ignition sources. Non-seismically classified components, combustible materials and lifting devices are examined through walkdowns and engineering evaluations. Fire protection systems, both passive and active, are assessed regarding their functionality following a seismic event.

Consequences of SIF scenarios are analysed using fire containment and fire influence approaches, supported by system-level evaluations to ensure residual heat removal (RHR) and reactor integrity. The methodology enables pragmatic hazard assessment and identification of improvement opportunities, reinforcing defence-in-depth for combined hazards.

In the presentation by Jo Rega from Tractebel Engineering e(Belgium) the challenge of addressing combined hazards in deterministic safety assessments for existing nuclear plants are explored. Prompted by lessons from Fukushima and WENRA's updated Safety Reference Levels (SRLs), the presentation focused on plant internal fire and explosion hazards combined with other events. In this context, hazard combinations are categorised as consequential, correlated, or independent (coincidental), applying screening criteria to identify credible scenarios.

Combinations of coincidental hazards are evaluated using deterministic and probabilistic screening criteria, including occurrence frequency threshold values. For consequential hazards, practical examples include internal missiles causing fires or explosions and high energy arcing faults (HEAFs) leading to fires. These scenarios are assessed through plant walkdowns and review of existing fire hazard analyses.

The underlying paper emphasises leveraging existing studies while applying targeted evaluations for combined hazards. Recommendations include implementing qualified barriers, refining fire compartmentation, and conducting detailed modelling as necessary. This pragmatic approach supports compliance with evolving regulatory expectations and enhances plant robustness against complex hazard interactions.

The three contributions of the second seminar session are provided hereafter.

Wildfire Hazard and Vulnerability Assessments for Nuclear Power Plants

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ABSTRACT

Historically, nuclear plants have not been exposed to the impacts of wildfires due to extended site perimeters, including owner-controlled areas, locations near large bodies of water, and the use of fire breaks to control the spread of a wildfire to the plant's vital areas. As regional climates shift, some regions have experienced or may in the future experience conditions which increase the potential likelihood and severity of wildfires – in particular, high temperatures, drought, and strong winds. The challenges associated with wildfires in the electric power grid is typically that power lines themselves can cause fires that can spread quickly, and wildfires can damage or destroy critical transmission and distribution infrastructure. From an operational and safety perspective, the availability of offsite power to nuclear power stations is imperative. Loss of offsite power could result in electrical impacts resulting in loss of generation capability and reliance on emergency power sources such as emergency diesel generators.

While internal fire hazards (originating from sources located in plant areas for normal and emergency operations) have been extensively evaluated, external wildfires and their potential impact on nuclear power plants have not. From a review of the operating experience, wildfires have occurred near nuclear power plant (NPP) sites. Most of the impacts are related to electrical power. This paper outlines a methodology that can be used to assess the vulnerability to the impact of a wildfire on a site-specific basis. Key attributes of the vulnerability assessment include determining whether the site is in a high fire prone area and, if so, assessing the potential impacts to electrical power, access/egress, vulnerability of air systems and vulnerability of water systems. If site-specific vulnerabilities are identified, potential strategies to reduce the identified vulnerability are also briefly introduced.

INTRODUCTION

Generally, nuclear plants have not been exposed to the impacts of wildfires due to extended site perimeters, including owner-controlled areas, locations near large bodies of water, and the use of fire breaks to control the spread of a wildfire. As regional climates shift, some regions have experienced or may in the future experience conditions which increase the potential likelihood and severity of wildfires – in particular, high temperatures, drought, and strong winds [1]. Assessing current and future wildfire potential can provide opportunities for strengthening plant resilience against those hazards that can challenge continued operations.

Wildfires can start by natural or human induced ignition sources, and the type and amount of vegetative fuels, topography, and weather dictate spread and severity. Over the past few decades, growth in the frequency, scale, and severity of catastrophic wildfires has highlighted the seriousness of an escalating global problem, particularly as these events cause increasing levels of devastation.

Wildfires may also pose a threat to nuclear power plants. While nuclear power plants are designed with stringent safety measures, wildfires can disrupt operations by damaging power lines, limiting access to facilities, and degrading air quality, and clogging water intake structures – all of which can affect operation of vital plant components and systems. Furthermore, the smoke and heat generated from a wildfire can pose risks to plant personnel and emergency response efforts. As many nuclear facilities are located in or near regions vulnerable to wildfires, proactive risk management, enhanced fire mitigation strategies, and robust emergency preparedness plans are crucial to ensuring the continued safety and resilience of nuclear power infrastructure.

Within the United States of America, the Committee on Energy and Natural Resources and the Committee on Environment and Public Works requested that the Government Accountability Office (GAO) undertake an analysis of how the United States. nuclear energy infrastructure may be impacted by natural hazards due to climate change. The study [2] evaluated the following hazards: heat, drought, wildfires, flooding, hurricanes, sea level rise, and extreme cold weather events at the 75 nuclear sites within the United States. At a high level, the GAO study concluded that increases in heat and drought due to climate change have resulted in NPP locations and overlayed with the U.S. Forest Service (USFS) 2023 Wildfire Hazard Potential map. This publicly accessible map is available here. This data set and map are used to inform evaluations of wildfire hazards or prioritization of fuel management needs across very large landscapes [3]. Based on the USFS data layer, the weighted average of the fire hazard potential surrounding each plant (0.5 mile / 0.8 km radius) was determined. Fire potential for each site was classified into three categories: none or low, moderate, and high or very high. Based on this ranking scheme, 16 of the 75 sites are assessed as having a high or very high hazard.

The Electric Power Research Institute (EPRI) is currently developing a methodology to assess the site-specific wildfire hazard and potential vulnerabilities given a wildfire occurs near a nuclear facility. This paper presents the current progress on this effort. The final EPRI technical report is subject to change as the process is tested and finalized.

OPERATING EXPERIENCE REVIEW

The project team conducted a review of operating experience using the Institute of Nuclear Power Operations (INPO) Industry Reporting and Information System (IRIS) database. The industry operating experience database was queried for the following key words: forest fire, wildfire, grass fire, and loss of offsite power and fire and external. The review found 19 events at commercial nuclear power plants between 1990 and 2024 that were categorized as a wildfire and these events were further studied to understand the plant impact.

The wildfire experience spanned worldwide and included the United States (13 events), South Korea (2 events), China (2 events), Brazil (1 event), and Argentina (1 event). The fire cause was not always documented, but in at least three events the fire cause was human-induced. Vegetation, grass, and brush were common materials that burnt and contributed to fire growth and spread. Most fire events were located in close proximity to transmission lines; for these fires – impacts were limited to electrical power. Four events were also in close proximity to the power plant site. As the fire approaches the site, in addition to electrical impacts, some impacts to air systems and access/egress were documented in the operating experience review.

When reviewing the wildfire experience, the plant impacts to offsite power were the most commonly observed. The availability of AC power is essential for normal and emergency conditions at nuclear power plants. Electrical distribution system design varies from site to site; however, it is common for balance of plant systems to be fed by offsite power. Perturbations in one or more lines can cause a trip of equipment necessary to maintaining the plant at power (e.g., voltage drops may trip main feedwater pumps and result in a turbine trip / reactor trip). The plant may also face a loss of offsite power (LOOP), where "the simultaneous loss of electrical power to all unit safety buses (also referred to as emergency buses, Class 1E buses, and vital buses) requiring all emergency power generators to start and supply power to the safety buses. The non-essential buses may also be de-energized because of this situation" [3]. There are several categories of LOOP, a wildfire is most likely to result in a grid-related LOOP where the initial failures occur in the interconnected transmission grid that is outside direct control of plant personnel [3].

When reviewing the wildfire events, 17 of the 19 events caused some perturbation of an offsite power source. A loss of offsite (LOOP) during shutdown conditions was observed in two events. Four events resulted in a reactor trip and seven events resulting in a downpower (with one ultimately resulting in a manual shutdown). Five events resulted in degraded electrical conditions where either a preferred, alternate, or startup power source was rendered unavailable by the wildfire.

WILDFIRE HAZARD

The first step is to understand the site-specific wildfire hazard. For this, obtain a fire hazard map layer from a nationally or locally recognized source. Within the United States a common model is the United States Forest Service (USFS) Wildfire Hazard Potential. At minimum, the fire hazard map should identify potential fire severity or intensity across the landscape (such as flame length, crown fire potential, fireline intensity or a combination of fire outputs). Ideally the fire hazard layer should account for both potential fire severity and fire frequency. To account for fire growth and spread, it is recommended that a 5 mile (8 km) radial analytical boundary be set from the centre of the plant.

Within this circular boundary calculate the percentage area of each fire hazard category (e.g., low, medium, high, very high) from the fire hazard data layer. The site is considered to be in a high-hazard/high-fire prone area if greater than 50 % of the land coverage area is classified as moderate or higher. For sites classified as high-hazard/high-fire prone, the process continues, and the analyst should review potential vulnerabilities.

For sites not classified as high-hazard/high-fire prone, the process is intended to be periodically assessed. Changes in vegetation, weather, etc. can potentially impact the classification in the future. At some periodicity, this classification should be updated to reflect the most recently available data and conditions.

POTENTIAL VULNERABILITIES DUE TO WILDFIRE FOR NUCLEAR POWER PLANTS

A nearby wildfire has the potential to impact the operational integrity and safety of a nuclear power plant. An understanding of the plant vulnerabilities to a wildfire can help inform nuclear operators and assist in resiliency planning. The list of vulnerabilities has been identified through reviewing of wildfire operating experience, external hazards experience, and engaging wildfire specialists. These include:

- Independence of power;
- Vulnerability of access/egress;

- Vulnerability of air systems to smoke;
- Vulnerability of site structures;
- Vulnerability of cooling systems and ultimate heat sink (UHS).

These potential vulnerabilities are further discussed in the subsequent paragraphs.

Independence of Power

From reviewing the nuclear operating experience, impacts to electrical power were frequently observed with a nearby wildfire. The transmission and distribution lines and associated equipment may be exposed to a variety of fire exposure conditions including high temperature, direct flaming, smoke, and embercast which may be further exacerbated by high winds and flying debris. These conditions can lead to physical infrastructure damage or trigger de-energisation events by transmission and distribution (T&D) operators. Faults in these lines have the potential to disrupt the normal plant environment (e.g., a fault in an offsite line can cause voltage instabilities and trip the feedwater pumps leading to a turbine trip and reactor trip). Depending on the local wildfire settings – topography, vegetation, and weather – and the spatial arrangement of utility infrastructure proximate to the plant, a single wildfire could impact some or all of the transmission lines. Understanding the physical layout of the incoming and outgoing power lines should be considered so appropriate mitigations can be developed and operationalized.

Smoke impacts from a nearby wildfire also have the potential to increase the likelihood of electrical arcing in high-voltage equipment such as transformers and switching equipment located in the switchyard. Smoke contains a mixture of fine particulate matter, soot, and conductive ions that, when concentrated in the air, can reduce the insulating properties of the surrounding atmosphere. This reduction in insulation can allow electrical current to leak across normally non-conductive gaps, leading to arcing. Arcing events pose serious risks, as they can result in short circuits, equipment failure, or even fires, further exacerbating the challenges faced by a nuclear facility during a wildfire event.

Vulnerability of Access and Egress

Access and egress to nuclear power plants are critical for emergency response, safe evacuation of personnel and continuity of staff change-overs necessary for plant operations during a wildfire event. These routes can be particularly vulnerable during a wildfire, as a wildfire can obstruct movement and delay essential operations. A primary risk is the rapid spread of fire, which can render roadways impassable due to extreme fire conditions (e.g., high temperature, exposure to flames, smoke), broken down vehicles, fallen trees, downed power lines, and accumulated debris.

Congestion and bottlenecks on limited access roads leading to and coming from the plant could be another concern. Many nuclear power plants are located in remote or semi-rural areas with few alternate evacuation routes. A single blocked road could prevent timely evacuation or impede first responders from reaching the site. If a wildfire threatens the surrounding community, simultaneous evacuation efforts may further strain available roadway and emergency response capabilities.

Vulnerability of Air Systems to Smoke

Wildfires in close proximity or within the site boundaries may result in deteriorating air quality. Personnel on-site, outside of structures, may experience reduced visibility and air quality degradations detrimental to long term health. Air quality hazards can be mitigated by the use of breathing apparatus which is maintained on the site.

The impact of smoke and particulates on individuals will be significantly lower inside structures. High efficiency particulate arresting (HEPA) filters are present in vital areas such as the control room; these filters ensure the ability of the plant operators to maintain control of the power plant systems despite air quality issues. Procedures exist to replace the filters should they become clogged with particulate matter. Clogging, if it occurs, will require a substantial amount of time before filter replacement will be required.

Air-cooled or air-operated systems which take air directly from outside (i.e., not from an air compressor or air tank) may be vulnerable to impacts from poor air quality (high concentrations of particulate matter). For example, diesel generators may be outside (not inside a structure) or draw air directly through ducts connected to the outside environment. In either case it is possible that particulate matter may clog the ducting or filters which are located on the diesel generators. However, as is the case for the HEPA filters, clogging would require a substantial amount of particulate matter over an extensive amount of time. Operation of equipment such as the diesel generators is monitored locally as well as in the control room; operators performing their rounds would see local indications of performance deficiency, while control room operators would be informed of such situations through annunciators and alarms in the control room. Maintenance personnel could be dispatched to clean (ducts) or replace (filters) as appropriate.

Vulnerability of Site Structures

NPP structures are inherently robust, particularly against external hazards such as fire, extreme weather, and seismic events. The primary plant buildings, including the reactor containment structure, auxiliary buildings, and control rooms, are typically constructed using reinforced concrete with fire-resistant properties. These materials provide significant protection against direct flame exposure, embers, and extreme heat. Additionally, nuclear facilities often implement buffer zones, such as cleared vegetation, gravel pathways, and firebreaks, to reduce the risk of wildfires encroaching on critical infrastructure.

However, despite these inherent protective measures, vulnerabilities still exist. Structures that are not part of the primary containment or essential operational buildings – such as warehouses, administrative offices, and support facilities – may be constructed with less fire-resistant materials, making them more susceptible to wildfire damage. Embers can infiltrate through vents, accumulate in roof gutters, and ignite combustible materials near or on these structures. Additionally, if a wildfire generates high heat levels near a nuclear plant, prolonged exposure could compromise external surfaces, degrade protective coatings, or lead to structural weaknesses, such as concrete spalling or steel softening under extreme temperatures.

Vulnerability of Cooling Systems and Ultimate Heat Sink

Operating nuclear power plants rely on UHSs to ensure that heat generated by the reactor process is safely and adequately removed, to prevent undesired impacts to the reactor fuel and plant systems and structures. A plant's UHS may take the form of large cooling towers (which in turn provide secondary cooling from local ponds or reservoirs), rivers, lakes, or (for plants in coastal regions), the ocean.

Wildfires may indirectly place demands on the debris removal mechanisms. Under the right conditions, fallen vegetation (such as trees, branches), ash, and soil could wash into the UHS (e.g., the river or lake). Conditions may include topography (for example, fire debris on the side of a slope adjacent to the water body), rainfall (resulting in debris flow), and distribution of particle size (too big to be dealt with by the screens and filters and their cleaning systems, or too small to be captured by the filters). Some of these conditions (rainfall, as one example) may occur following a significant time lag between the occurrence of wildfire and the existence of the condition of concern. The fire may occur in the summer months, with sufficient rainfall to cause subsequent debris flow not occurring until fall, winter or subsequent years after the burn.

MITIGATIONS TO IDENTIFIED WILDFIRE VULNERABILITIES

At a high level, a wildfire plan or procedure to respond to a nearby or onsite wildfire could provide guidance to operations to aid in decision-making when one or more of the required transmission lines are threatened by a wildfire or pre-emptive line de-energisation. A wildfire pre-plan would also establish jurisdiction for fire-fighting or other wildfire response strategies.

Coordination with transmission and distribution or the appropriate entities to enhance the vegetation management along high fire risk transmission right of ways may also mitigate wildfire spread and growth in and around utility corridors.

Table 1 provides a list of mitigations for identified grid vulnerabilities (e.g., independence of power) to wildfire. These strategies may be employed by nuclear plant operators to prepare for a wildfire event. Further mitigations for the grid, and remaining vulnerabilities are currently under development.

Table 1 Potential mitigation options for grid vulnerabilities

Vulnerability	Mitigation Category	Mitigation Description
Grid	Vegetation Management	Coordinate with appropriate entities to ensure vegetation management along the offsite power right of ways is appropriate given wildfire risks identified. Reduce wildfire risk to substations, generation facilities, and other electrical facilities, by ensuring defensible space is appropriate given wildfire risks identified. Coordinate with appropriate entities to ensure all downed wood and slash generated from vegetation management activities is cleared. Consider conducting a vegetation management inspection prior to wildfire season or during weather condition forecasts that indicate an elevated fire threat in terms of wildfire potential, of at risk offsite power lines.

CONCLUSIONS

As part of this ongoing project, a detailed wildfire hazard and vulnerability assessment was conducted at a United States nuclear power plant site. The conclusions of the hazard assessment (using the 5 mile radius) did align with the GAO report conclusions (both assessments classified the site as high-fire prone). To fully grasp the depth and breadth of the range of qualitative and quantitative wildfire tools, the team performed a landscape level analysis of the regional fire history, fire ecology, and climatology to better understand the history of ignition, past fire incidents and associated losses, as well as general wildfire environmental settings. Detailed wildfire behaviour modelling was conducted to better assess wildfire conditions proximate to the plant and how those conditions may impose risks on a variety of technical and operational systems. While this level of detail may not be required for the analyst to obtain a high-level understanding of wildfire vulnerabilities, there are certainly areas where this modelling can provide detailed insights to better inform future planning, such as vegetation management. Practical insights from this effort are actively being worked into the process. The goal of the project is to provide analysts a practical approach to understanding the wildfire hazard and vulnerability assessment.

ACKNOWLEDGEMENTS

EPRI would like to also thank and acknowledge Darlene Rini and Tim Metzger who provided practical expertise in wildfire impacts and wildfire behaviour analysis.

REFERENCES

[1] Electric Power Research Institute (EPRI): Evaluation of Wildfire Risk Assessment and Wildfire Smoke Datasets, Models, Tools, and Services, EPRI 3002030456, Palo Alto, CA, USA. June 2024.

[2] U.S. Government Accounting Office (GAO): Nuclear Power Plants, NRC Should take Actions to Fully Consider Effects of Climate Change, Report to Congressional Requestors, GAO-24-106326, April 2024, https://www.gao.gov/assets/gao-24-106326.pdf.

[3] United States Forest Service (USFS) United States Department of Agriculture (USDA): Wildfire Hazard Potential, Release Date: June 17, 2024. https://research.fs.usda.gov/firelab/products/dataandtools/wildfire-hazard-potential.

Deterministic Study on Seismically Induced Fires

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ABSTRACT

According to the 2020 edition of the Belgian Royal Decree [1]for the safety requirements of nuclear power plants and its article 17.3, the fire hazard analysis (FHA) has to take into account the credible combinations of a fire and other initiating events. One of the potential combinations to consider is an internal fire induced by an earthquake (safe shutdown earthquake). A seismically induced fire (SIF) is not aggregated with any internal or external accidents except the loss of offsite power that is also plausibly induced by the considered earthquake.

A methodology for performing a pragmatic deterministic study has been developed for operating NPPs that were to be shut down a few years later. The seismically induced fire hazard assessment aims to demonstrate that the fire safety objectives are met.

The SIF safety objectives for the operating reactors are:

- to minimize the occurrence and the effects of SIFs, and
- to maintain the capability for safe shutdown, residual heat removal (RHR) and monitoring of the plant state.

The goal of this paper is to present the main assumptions (such as the initial operational state of the plant), used references and the main steps of the methodology that has been followed to perform the study and in particular, the reuse of the conventional fire hazard analysis results for those NPPs concerned.

INTRODUCTION

This study has been performed in 2022 in the frame of the 2020 edition of the Belgian Royal Decree for the safety requirements of nuclear power plants. According to the article 17.3 of the Royal Decree, the fire hazard analysis (FHA) has to take into account the credible combinations of a fire and other initiating events(mainly hazards).

One of the potential combinations of hazards to consider is an internal fire induced by an earthquake.

A methodology for performing a pragmatic deterministic study has been developed for operating NPPs that were to be shut down a few years later. The SIF hazard assessment aims to demonstrate that the fire safety objectives are met.

The SIF safety objectives for the operating reactors are

- to minimize the occurrence and the effects of a SIF, and
- to maintain the capability for safe shutdown, RHR and monitoring of plant state.

As the objective is to reduce the SIF hazard to an “as low as reasonably practicable” (ALARP) level, the consequences of a SIF have only been taken into account if the seismically induced fire event could not be excluded or if protection measures could not be implemented. If needed, the results from the conventional FHA[1] have been reused as far as practicable.

In the paragraphs below, more insights will be provided on the approach used, the scope, the seismic interactions considered, and the consequences analysis that reuse the conventional FHA.

APPROACH APPLIED

The approach applied is based on the following documents:

- IAEA-TECDOC-1944 [2]: Fire Protection in Nuclear Power Plants (2021). The SIF is addressed in § 5.6.1 of TECDOC-1944 on the fire risk analysis;
- the contribution “Screening of Seismic-Induced Fires”, presented at the Probabilistic Safety Assessment and Management Conference PSAM 12 in June 2014 [3].

SCOPE

Earthquake Considered

The earthquake considered is the safe shutdown earthquake (SSE) which is used for the design of the plants concerned.

SIF Events Definition

First, it has to be pointed out that a SIF is a rare event as mentioned in the IAEA TECDOC-1944 [2]. In the present methodology, it is considered that the plants are in full power operation when the SSE occurs. Indeed, considering that

- the occurrence frequency of a SSE for the units considered is 1 E-04 /ry,
- the plant is in full power mode for most of the year, and

[1] A “conventional” FHA in this context is the FHA performed for all normal plant operational states (POSs) and for some combinations of independent hazards [4].

– the probability of an internal fire induced by a SSE is about 4 E-02 according to NFPA 804 [5] (§ A.7.3.2),

it is not considered credible to postulate a SIF during other plant operational states than full power operation. Indeed, the likelihood that an earthquake will induce a fire during a one-month outage is very low. It is also considered credible that a loss of offsite power (LOOP) could be induced by the SSE.

Buildings Included in the SIF Hazard Analysis

Only seismically classified buildings are taken into account in the assessment to achieve the safety objectives because these buildings host those structures, systems and components (SSC) that are designed and qualified to be functional in case of a SSE and required in the systems analysis. These components are therefore not considered as potential fire sources. In contrary, inside these buildings, the components that are not seismically classified are considered as potential sources of fire.

For the non-seismically classified buildings, it is only verified that a fire in these buildings will not compromise the SIF safety objectives. To perform this verification, it is relied on the fire resistance rating of the seismically qualified fire barriers between the seismic and the non-seismic buildings to prevent fire propagation in the event of a SIF.

Hazards Considered

According to the references [2] and [3] based on the operating experience feedback (OEF) for seismically induced fires[2]

- There is no indication of multiple, concurrent, seismically induced internal fires. Therefore, only a single internal fire has been considered [2];
- Non-seismically classified high voltage electrical equipment ($\geq$ 380 V), including transformers and high voltage electrical switchgear/breaker cabinets, have experienced seismically induced fires. Therefore, only non-seismically classified high voltage components ($\geq$ 380 V) have been considered as ignition sources [3];
- Seismically induced leaks from tanks and related pipework containing or transporting combustible liquids as well as from transformers of non-seismically classified system parts have occurred and may be considered as potential precursors to fires [3];
- Hazardous/flammable material stored in unanchored or unlocked fire resistant cabinets may be considered as potential precursors to fires [2];
- Unanchored combustible gas cylinders may be considered as potential precursors to fires [2].

As a particular consequence, no SIF has to be postulated inside the reactor buildings in Belgian NPPs because the primary pumps and the cable trays which constitute the largest fire hazard are seismically designed, and there are neither high voltage switchgear cabinets nor fire resistant cabinets nor combustible gas cylinders present. Walkdowns have been

2 The reference [2] was used to develop the methodology in 2022. More recent OEF and published documents are available in the meanwhile.

performed in the other buildings containing the SSC of the success path considered (see more information in the paragraph below about the systems analysis) to maintain the capability for safe shutdown, RHR and monitoring of the plant state in order to identify the potential non-seismically classified fire sources and to verify the seismic interactions.

SEISMIC INTERACTIONS

Interactions Due to Falling Objects

A falling object resulting from an earthquake can potentially initiate a fire. Specific attention is therefore given to the non-seismically classified lifting devices that could initiate a fire by damaging equipment located in their interaction zone. Indeed, lifting devices are in general located above the equipment they handle and can therefore not be disregarded. It is assumed that no lifting operation is ongoing when the earthquake occurs (it is a combination of two independent coincidentally occurring) and that the falling lifting devices would always cause a fire although there is not a one to one relation.

As a result, only the lifting devices that are not seismically classified have been considered as potential initiator of a fire in this assessment.

Seismic Walkdowns and Screening

The structural integrity verification against the SSE seismic level of

- lifting devices that could not be screened out based on previous studies (e.g., in the frame of periodic safety reviews (PSRs)) regarding potential seismic interactions or that are installed above non-seismically classified fire ignition sources,
- non-seismically classified equipment (e.g., pipes, tanks, etc.) containing combustible liquids (such as fuel, oil and other lubricants),
- fireproof storage cabinets and combustible gas cylinders not or poorly anchored, and
- fire barriers separating seismically qualified and non-qualified buildings (including not only walls but also fire barrier elements such as a cable or pipe penetrations, doors, dampers, etc.)

has been performed first during walkdowns by a seismic review team (SRT) of at least two experienced seismic capability engineers (SCEs). The objective of the seismic evaluation walkdowns is to screen out all items that have sufficiently high seismic capacities based upon combined experience and expert judgment and the use of earthquake experience data as appropriate.

With regard to the distribution systems (cables, pipes and ventilation ducts) that cross the boundaries between seismically qualified and non-qualified buildings, the walkdowns focused on their behaviour at the penetrations and close to them so as not to impact the penetrations themselves. Regarding the lifting devices, seismic evaluations performed in the past were used by the SRT to perform the screening during the walkdowns and to select the lifting devices for further analysis.

Analyses of Screened-in Items

Items that cannot be screened out on the basis of the walkdown evaluation or for which further analysis is required to support the engineering judgment are evaluated by calculation.

- For the lifting devices' anchorage verification, the calculations are performed based on the equivalent static method. The seismic design accelerations are applied at the equipment centre of gravity, peak accelerations are conservatively considered for a damping of 4 % according to the U.S. NRC Regulatory Guide (RG) 1.61 [6]. The horizontal and vertical components of the seismic action are combined by the square root of the sum of the squared values of the action effect due to each horizontal and vertical component according to the U.S. NRC RG 1.92 [7]. It is verified that the resultant forces considering the lifting device loaded with its payload without earthquake cover the resultant forces with the seismic load but without the payload. If it is not the case, the resultant forces with the seismic load shall be lower than the allowable loads of the anchors for all loading directions (tension, shear, combined tension and shear) as well as all relevant failure modes;
- The rocking evaluation of the fire resistant cabinets is performed according to the reserve energy method of ASCE/SEI 4-16 standard [8]: the horizontal spectral acceleration capacity shall be equal or exceed the maximum possible seismic demand, or the best estimate maximum rocking angle of the cabinet shall be sufficiently lower than the instability angle to avoid overturning. It has also been verified that the cabinets doors were locked close;
- Separation barriers made of reinforced concrete walls being part of the structure of a Seismic Category I building (i.e. designed against SSE loading) are considered to maintain their structural integrity in case of earthquake. When masonry walls are present, their stability verification is performed according to the EN 1996-1-1 standard (cf. [9] and [10]). The stability of the walls is evaluated by their capacity to resist an arch thrust between two floors or adjacent walls acting as their supports. This methodology is applicable as the concerned walls are well blocked by the adjacent elements (slabs or walls). Seismic design accelerations are taken for a damping of 7% according to RG 1.61 [6]. Peak accelerations are first conservatively considered, and if needed the first resonant frequency of the wall is estimated in order to consider more realistic seismic accelerations.

FIRE PROTECTION SYSTEMS

In order to be able to reuse the results of the conventional FHA, it is necessary to verify which fire protection means can still be considered in the event of a SIF and if not, it is then verified that they were not credited in the conventional FHA.

Water Supply

In general, the parts of the underground fire water main loop, that are intended to supply non seismically classified buildings, are not seismically classified. Manual or electrical motorized valves are installed to isolate the seismically classified parts from the non-classified parts in case of a SSE. It is therefore needed to verify that the procedures used in case of earthquake include a quick closure of those valves and that these valves are accessible in case of SSE.

Passive Fire Protection

The passive fire protection means of the considered units (fire barriers, fire doors, fire penetrations seals, fire dampers) were, by design, not required to ensure their fire safety function in case of earthquake. Therefore, where needed, an engineering judgement analysis has been performed to verify that the fire safety function of the considered fire protection means will not be impacted. It has been especially applied on the fire barriers between seismically classified building in scope and the non-seismically classified buildings. For the fire barriers inside the seismically classified buildings, it is considered that the fire barriers keep their fire resistance rating.

Active Fire Protection

For the active fire protection means, it has been verified that in the conventional FHA

- either the justification did not rely on the use of not seismically classified automatic extinguishing or on manual firefighting,
- or, where manual fire protection has been credited, that the fire detection is seismically classified, and that the coverage of seismically classified hydrants is adequate.

CONSEQUENCE ANALYSIS

For the case where SIF cannot be avoided, the fire consequence analysis and the system consequence analysis have been performed. In order to perform these analyses, the previous FHA analyses were reused as far as possible.

Fire Consequence Analysis

Fire Inside Seismically Classified Buildings

The “Fire Consequence Analysis” inside the seismically classified buildings follows mainly the methods called “Fire Containment Approach” (FCA), and “Fire Influence Approach” (FIA) (cf. [4]).

The FCA is a deterministic screening method that assesses the fire compartmentalization which is the third barrier of the fire safety defence-in-depth concept. It is a detailed analysis which is performed on the fire issues identified in the FCA analysis or on the cases that are out of the validation range of the FCA.

If the fire protection means identified in the conventional FHA are still available, the results of the conventional FHA can be reused. With respect to the development of the fire, the SIF will generally not lead to a significant modification of the heat release rate (HRR) than that considered in the conventional FHA.

This task has been performed firstly by identifying those barriers that are shared by seismically classified and seismically non-classified buildings or buildings that located in less than 16 m from each other without intervening combustibles. The fire resistance rating is assessed by one of the approaches mentioned above and it is verified by SCE's that the fire rating cannot substantially be affected in the event of a SSE. The 16 m distance criterion is based on the following calculation method which is used in the Belgian Royal Decree regarding the fire protection of buildings [12]:

The received heat flux *I* shall be less than 15 kW/m² (characteristic heat flux at where piloted ignition of wood occurs)

$$I = \emptyset \alpha I_{ec} < 15\ kW/m^2 \quad (1),$$

where:

- I is the received heat flux [kw/m²];
- $\emptyset$ is the view factor;
- α is the ratio between the total surface of the openings of the façade and the circumscribed surface of the façade containing the openings. Considering the collapse of the façade of the not seismically classified building, α is equal to 1.
- I_{ec} is the emitting heat flux which is considered to be 45 kW/m² according to Belgian Royal Decree [12] and some European regulations and standards (e.g. the NEN 6068 [11]). It corresponds to the situation of the collapse of the facade of the non-seismically classified building and the fire is "fuel controlled".

The view factor $\emptyset$ is calculated as follows:

$$\emptyset = \frac{2}{\pi}\left[\frac{X}{\sqrt{X^2+Y^2}}\ tan^{-1}\left(\frac{Z}{\sqrt{X^2+Y^2}}\right) + \frac{Z}{\sqrt{Y^2+Z^2}}\ tan^{-1}\left(\frac{X}{\sqrt{X^2+Z^2}}\right)\right] \quad (2),$$

where:

- X is the half length of the circumscribed surface of the non-seismically classified building facade [m];
- Z is the half height of the circumscribed surface of the non-seismically classified building facade [m];
- Y is the distance between the exposing facade and the exposure facade [m].

Considering the reference building of the Belgian Royal Decree [12] with the following dimensions: height 12 m and width 60 m, the minimal distance is 16 m.

Systems Analysis

The "systems analysis" addresses the importance of the losses of different items important to safety located in a fire compartment (comprising one or more rooms) potentially impacted by a SIF scenario.

This “systems analysis” analyse the capability of the plant to reach and maintain a safe shutdown state from the full power mode. The following safety functions are required for reaching and maintaining a safe shutdown state:

1. RHR,
2. Support RHR,
3. Safe shutdown capacities (cool down, criticality, reactor coolant system integrity, pressure control),
4. Support to safe shutdown capacities.

All safety systems and further equipment required to achieve those safety functions are already credited in the conventional FHA systems analysis and cover the SIF events described above. Indeed, in the conventional systems analysis only seismically classified SSCs were credited in one of the two success paths, and a combination of a fire occurring independently from a LOOP was taken into account, only the systems designed to remain operational under such conditions were credited in the conventional FHA [4]. This allows to quickly reuse the results of the conventional FHA and, where available and applicable, the previous justifications. The only difference is the success paths used. While in the conventional FHA the first success path was based on the first level safeguard SSC and the second path on the emergency SSC, in the SIF analysis only the success path based on the emergency SSC has been credited because it is designed to cope with a SSE.

Furthermore, there is no single failure criterion added to fire damages to the considered safety systems.

Establishment of the Needs and Opportunities for Improvement

Following the previous steps, modifications can, if needed, be proposed to eliminate, prevent or reduce the hazard. These modifications can be of different types such as the following ones:

- Adapting existing procedure;
- Reinforcing the anchoring of equipment;
- Installing passive fire protection means;
- Installing active fire protection features.

CONCLUSIONS

The proposed deterministic methodology developed for NPPs in Belgium scheduled to be shut down a few years later, allows to assess relatively quickly and in a pragmatic way seismically induced fires by, amongst others, reusing the results of the conventional FHA and, if needed, to propose needs or opportunities for improvement.

The assessment requires an integrated team of fire safety engineers, systems engineers and seismic capability engineers.

REFERENCES

[1] Arrêté royal complétant l'arrêté royal du 30 novembre 2011 portant prescriptions de sûreté des installations nucléaires pour ce qui concerne la conception des réacteurs existants, leur protection contre les phénomènes naturels et diverses dispositions annexes - Koninklijk besluit tot aanvulling van het koninklijk besluit van 30 november 2011 houdende veiligheidsvoorschriften voor kerninstallaties, voor wat betreft het ontwerp van bestaande reactoren, hun bescherming tegen natuurverschijnselen en diverse bijbehorende bepalingen, 19 February 2020, https://www.ejustice.just.fgov.be/mopdf/2020/02/28_1.pdf#page=10.

[2] International Atomic Energy Agency (IAEA): Fire Protection in Nuclear Power Plants, IAEA-TECDOC-1944, Vienna. Austria, February 2021, https://www-pub.iaea.org/MTCD/Publications/PDF/TE-1944web.pdf.

[3] Lin, J. C., et al., Screening of Seismic-Induced Fires, in: Proceedings of 12th International Probabilistic Safety Assessment and Management Conference (PSAM12), Honolulu, HI, USA, June 2014, https://iapsam.org/psam12/proceedings/paper/paper_590_1.pdf.

[4] Leblanc, X., P. Kwahou Kezembo, and E. Maillet: Development of a Fire Containment Approach of the Fire Hazard Analysis for the Belgian Nuclear Power Plants, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 24 15th International Seminar on Fire Safety in Nuclear Power Plants and Installations, October 4-5, 2017, Bruges, Belgium, pp. 82-94, GRS-A-3912, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, December 2017, https://www.grs.de/en/publication/grs-3912.

[5] National Fire Protection Association (NFPA): NFPA 804, Standard for Fire Protection for Advanced Light Water Reactor Electric Generating Plants, 2020 edition, SKU: 80420, 2020, https://www.nfpa.org/product/nfpa-804-standard/p0804code/nfpa-804-standard-for-fire-protection-for-advanced-light-water-reactor-electric-generating-plants-2020/80420.

[6] United States Nuclear Regulatory Commission (U.S. NRC): Regulatory Guide 1.61, Damping Values for Seismic Design of Nuclear Power Plants, Rev. 1, Washington, DC, USA, March 2007, https://www.nrc.gov/docs/ML0702/ML070260029.pdf.

[7] United States Nuclear Regulatory Commission (U.S. NRC): Regulatory Guide 1.92, Combining Modal Responses and Spatial Components in Seismic Response Analysis, Rev. 3, Washington, DC, USA, October 2012, https://www.nrc.gov/docs/ML1222/ML12220A043.pdf.

[8] American Society of Civil Engineers (ASCE): Seismic Analysis of Safety-Related Nuclear Structures, ASCE/SEI 4-16, Edition 2017, 2017, https://sp360.asce.org/personifyebusiness/Merchandise/Product-Details/productId/233131395.

[9] European Commission (EC): Eurocode 6 - Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures, EN 1996-1-1, 2005, https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-6-design-masonry-structures.

[10] National Belgian Norm (NBN): Eurocode 6 - Calcul des ouvrages en maçonnerie - Partie 1-1: Règles communes pour ouvrages en maçonnerie armée et non armée - Annexe nationale, NBN EN 1996-1-1+A1 ANB 2016, 2016, https://app.nbn.be/data/r/platform/frontend/detail.

[11] National European Norm (NEN): Standard NEN 6068, Determination of the resistance to fire movement between spaces, 2020, https://www.nen.nl/en/nen-6068-2020-a1-2023-ontw-nl-307685.

[12] Arrêté royal modifiant l'arrêté royal du 7 juillet 1994 fixant les normes de base en matière de prévention contre l'incendie et l'explosion, auxquelles les bâtiments doivent satisfaire, 20 mai 2022, https://www.securitecivile.be/sites/default/files/imported_files/1994-07-07r_normes_de_base.pdf.

Credible Combinations of Individual Hazards/Events in Deterministic Analysis for Internal Fire and Explosion: A Practical Approach for Existing Plants

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ABSTRACT

Lessons learned from the accidents affecting the Fukushima Daiichi nuclear power plant (NPP) units highlighted the importance of considering a NPP's robustness against the challenges from combined and consequential hazards. Such combinations of hazards have been addressed by the Western European Nuclear Regulators Association (WENRA) in a general manner since the first publications of the WENRA Safety Reference Levels (SRLs), combinations with internal hazards have been more clearly addressed in the 2020 WENRA SRLs concerning the internal hazards issue SV. The IAEA Safety Guide SSG-64 "Protection against Internal Hazards in the Design of Nuclear Power Plants" provides further information regarding the credible hazard combinations to be considered. These combinations for internal fire and explosion hazards are treated in the frame of the deterministic studies of a Periodic Safety Review (PSR) for the NPP.

This paper provides the global approach used to screen out some combinations of hazards/events and, in particular, the combination of independent hazards/events considering the hazard occurrence frequency and the duration of the event due to a single hazard or a combination of hazards.

The practical evaluation of screened-in combined hazards/events is illustrated for two combinations of consequential hazards:

- Internal missile inducing an internal fire or an internal (gas) explosion;
- High energy arcing fault (HEAF) inducing an internal fire.

INTRODUCTION

Lessons learned from the accident resulting from a combination of hazards affecting the Fukushima Dai-ichi NPP highlighted the importance of including the NPP's robustness against the challenges from combined and consequential hazards in the scope of the safety demonstration. Combinations with internal hazards were more clearly addressed in the 2020 WENRA safety reference levels SV 2.1 [1] concerning the internal hazards issue. Indeed, in the footnote about what is meant by "all internal hazards", the following is stated: "*the consequential hazards and causally linked hazards shall be considered, as well as random combinations of relatively frequent hazards*". Only the credible combinations of hazards (causally or non-causally related) have to be considered as mentioned in SV 4.1. In Belgium, the 2020 WENRA

SRLs are applicable to existing reactors by its transposition in a Royal Decree (from end-2023) and are expected to be considered in the frame of PSRs.

It is quite challenging to consider the combinations of hazards although the original safety demonstration of existing plants did not take most of such combinations into account and, on top of that, there was no obvious definition of the credibility of such combinations[1].

For the latter, the IAEA provides further information regarding the consideration of hazard combinations in several Specific Safety Guides, particularly SSG-64 [2], but also in SSG-68 [3], SSG-77 [4], SSG-3, Rev. 1 [5], etc., and doing so, supports specifying credible combinations of hazards. In particular, Appendix I of SSG-64 proposes to consider the following three types of hazard combinations (using the term "event" for the consideration of any single or combined hazard potentially resulting in an initiating event within the safety assessment):

- **Consequential (subsequent) events:** An initial event (e.g. an external or internal hazard) results in another event (e.g. an internal hazard). Examples are a seismic event and subsequent internal explosion and internal fire and subsequent internal flooding.
- **Correlated events:** Two or more events, at least one of them representing an internal hazard, which occur as a result of a common cause. The common cause can be any anticipated event, including an external hazard, or might be due to an unanticipated dependency. The two or more events connected by this common cause could occur simultaneously[2]. Examples include a tsunami as the common cause for external flooding, internal flooding and internal fire as three potential correlated events, and electromagnetic interference as the common cause for station blackout and internal fire as the two correlated events.
- **Unrelated (independent) events[3]:** An initial event (e.g. an external or internal hazard) occurs independently from (but simultaneously with) an internal hazard without any common cause. Examples are external flooding and an independent internal explosion, and a seismic event and an independent internal fire.

It is recognized in SSG-64 [2] that the hazard identification process could produce a long list of potential combinations and accordingly that pragmatic approaches should be applied to identify the credible hazard combinations.

It is the purpose of this paper to provide such an approach for identifying credible combinations of hazards in the frame of deterministic analysis for internal hazards and, in particular for the internal fire and explosion hazards. Note that the postulated initiating events such as a loss of coolant accident (LOCA) not representing external or internal hazards are not addressed in this paper.

In the proposed approach, it is important to understand that the plants did not systematically consider all combinations of hazards in the original design and/or safety demonstration. To illustrate this specific case, the main steps of the practical evaluation of two combinations of consequential hazards are described in this paper:

- an internal missile inducing an internal fire or an internal (gas) explosion, and
- a HEAF inducing an internal fire.

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[1] An IAEA TECDOC that will provide a specification of what is credible or not is expected by mid-2025.

[2] Simultaneously' in this case does not mean that the hazards occur exactly at the same time but rather that the second hazard occurs before the effects of the previous hazard have been completely mitigated.

[3] The IAEA meanwhile uses the more precise term "coincidental" instead.

LIST OF INTERNAL AND EXTERNAL HAZARDS TO BE CONSIDERED

The first step is to establish a list of internal and external hazards to consider. The list of internal hazards is expected to be the same for all pressurized water reactors (PWRs) as these hazards are quite general. Typically, this list includes the following hazards:

- Internal fire,
- Internal explosion (creation of an explosive gas atmosphere,
- High energetic electrical component such as a failure such as HEAF,
- Internal flooding,
- Internal missiles,
- Falling objects and collapse of structures.

From a general perspective, all types of external hazards should be considered; however, some of them are typically screened out already within the siting process, e.g. geological hazards like slope instability or volcanic hazards or do not pose a threat for the plant, for instance, ground settlement if the reactor unit is constructed on hard bedrock. Unlike the internal hazards, the list of external hazards can be quite easily reduced depending on their potential to impact the site or their extremely low likelihood to occur. For instance, external natural fires like forest fires are generally not relevant for plants located in an industrial area (e.g. a port) while the industrial activities near the site may result in human induced external fires which cannot be excluded so easily. Various meteorological hazards such as extremely high or low air temperatures, seismotectonic hazards, biological hazards like biological fouling, crustacean or mollusc growth, or hydrological hazards like external flooding are principally relevant for many nuclear plant site as the plant needs an adequate heat sink (usually river or sea for heat sink) to be safety operated.

In addition, the list of external hazards includes several human induced hazards such as accidental aircraft crash or impacts (mechanical, thermal or by releases of hazardous substances) from accidents in nearby industrial or military facilities or during transport, depending on the distance of the site to these sources of accidents.

In the frame of the present paper, the focus is on combinations of internal hazards with other internal or external hazards.

COMBINATIONS OF INDEPENDENT HAZARDS

The following criteria to screen out combinations of hazards occurring independently of each other by coincidence (based on [6], and consistent with [7], [8], [9] and [10]) are used:

- Criterion 1: The hazards are mutually exclusive. A combination is screened out if it is impossible for the hazards to occur simultaneously.
- Criterion 2: The hazards' effects are non-additive. In such case, the combination can be screened out as the effects due to the individual hazards do not produce aggregated loads on the same part of the plant and can therefore be handled independently of each other.
- Criterion 3: As the combinations of hazards to be considered are set up to further assess them, those combinations that are leading to consequences that are already included in the consequences of another single or combined hazard are analysed there.

- Criterion 4: The occurrence frequency of the combinations of independent hazards is lower than a given threshold which is typically 10^{-6} per year (cf. [8]).
- Criterion 5: The combination is considered credible but there is justification that the existing protection or alternative means are sufficient to deal with this combination without detailed justification.

Criterion 2 is relevant to exclude the independent occurrence of two hazards like, for instance, a pipe failure (leading to internal flooding) and an internal missile because the pipe failure does not interact with the protection against internal missile and vice versa.

Criterion 4 is very useful to screen out random combinations of hazards if the data needed are available or can be estimated based on, for instance, relevant operating experience feedback.

The probabilistic criterion 4 is only used if the deterministic criteria 1 to 3 have failed to screen out the combination. The combined probability is related to their respective occurrence frequency. Knowing that these events are, by definition, unrelated it is possible to quantify their simultaneous occurrence by multiplying their individual probabilities of occurrence. As only the occurrence frequency can be estimated, the switch between probability of occurrence and frequency of occurrence can be made by considering a Poisson distribution if the occurrence frequency is small. In the following, the P(A) notation is used for the annual occurrence frequency of an event A and its duration t_A.

The use of the occurrence frequency and the durations of two events A and B can be used to estimate, the credibility of their simultaneous occurrence in a duration equal to T. Namely, the combined probability is given by the following equations [3]:

$$P(A \cap B) =$$

$$1 - \frac{P(B) * e^{-P(A)*\frac{t_A}{T}} + P(A) * e^{-P(B)*\frac{t_B}{T}}}{P(A) + P(B)} + e^{-(P(A)+P(B))}\left[1 - \frac{P(A) * e^{P(B)*\frac{t_A}{T}} + P(B) * e^{P(A)*\frac{t_B}{T}}}{P(A) + P(B)}\right]$$

{1}.

This equation can be simplified as follows when t_A, t_B << T and P(A), P(B) <<1 (cf. [6], [11]):

$$P(A \cap B) = P(A) \cdot P(B) \cdot \frac{t_A + t_B}{T} \qquad \{2\}.$$

On an annual basis, T is equal to 1 year (or in average 8760 hours), the durations are given in hours and the frequencies are yearly based.

Applying this approach to assess the combination of a safe shutdown earthquake (SSE) with an independently of the SSE occurring internal fire. Considering conservatively that A is an internal fire with an occurrence frequency of about 1.14 10^{-1}/yr [12] and a duration of 2 hours and that B is a SSE with an expected occurrence frequency of 10^{-4}/yr and a duration of 72 hours (by conservatively considering aftershocks), using equation (2) a combined frequency of 1.1 10^{-7}/yr is obtained which is below the threshold value in criterion 4 (10^{-6}/yr). As a result, the independent combination of an internal fire with a SSE can be screened out.

Note that the doubling of t_A has a very small impact on the combined frequency (1.13 10^{-7}/yr) as it remains small with respect to one year.

COMBINATIONS OF CONSEQUENTIAL HAZARDS

As an internal hazard cannot induce a natural external hazard, the screening focuses on an internal hazard inducing another internal hazard or an external hazard inducing an internal hazard.

Regarding the combination of an internal hazard consequential to an internal hazard, the approach starts from the list of internal hazards.

The following general criteria are used:

- Criterion 1: Hazards are exclusive. A combination of consequential hazards is screened out if it is impossible for the initial internal hazard to induce the relevant internal hazard.
- Criterion 2: As the combinations of hazards to be considered are set up to further assess them, those combinations that are leading to consequences that are already included in the consequences of another single or combined hazard are analysed there.
- Criterion 3: The hazard combination is considered credible but there is evidence that the existing means are sufficient to deal with this combination without detailed justification. In that case, it is considered sufficiently justified that the protection against the combination is appropriate and the combination can be screened out from further consideration.

Examples of the application of each criterion to screen out a combination are provided in the following.

An internal flood will not induce an internal missile, this combination can therefore be screened out based on criterion 1.

An internal missile which strikes a lifting device and generates a drop of load is a very unlikely combination. Moreover, the consequences of such combination are not expected to induce more damage that the internal missile or the load drop individually. This combination can be screened out based on criterion 2.

An internal fire inducing an internal flooding due to the use of water for firefighting is a credible combination but is already included in the analyses for both hazards individually. As a result, this combination can be screened out based on criterion 3.

Examples of screened in, induced combination of hazards are

- an internal missile inducing an internal fire or internal explosion,
- a HEAF inducing an internal fire.

Both combinations of consequential internal hazards remain screened in in accordance with the operating experience feedback (for instance [13], [14]).

Regarding the combination internal hazards induced by external hazards, the same types of criteria as for an internal hazard inducing another internal hazard are used.

- Criterion 1: Hazards are exclusive. A combination of consequential hazards is screened out if it is impossible for the initial external hazard to induce the relevant internal hazard.
- Criterion 2: As the combinations of hazards to be considered are set up to further assess them, those combinations that are leading to consequences that are already included in the consequences of another single or combined hazard are analysed there.

- Criterion 3: The hazard combinations is considered credible but there is justification that the existing means are sufficient to deal with this combination if the existing means are designed to withstand the considered external hazard(s). In that case, the combination can be screened out.

For instance, the criteria can be applied as follows:

- An internal fire or internal explosion cannot be induced by biological fouling, or an extreme high air temperature (dry bulb) cannot induce an internal explosion. These combinations can be screened out based on criterion 1.
- An external flooding cannot induce an internal fire if the design of the plant ensures to prevent the presence of water on the site or inside safety related buildings by provisions against external flooding. This combination is screened out based on criterion 3.

A typical screened-in combination is an internal fire hazard induced by an earthquake as there are fire loads and/or ignition sources that are not designed to withstand an earthquake and could inadmissibly impair the required function of safety systems. The deterministic methodology used for treating this combination is presented in the paper [15].

The practical evaluation of screened-in combined hazards is illustrated in the following paragraphs for two exemplary combinations of consequential internal hazards:

- internal missile and consequential internal fire or internal (gas) explosion, and
- HEAF and consequential internal fire.

It is important to note that a fire hazard analysis (FHA) without consideration of these combinations is available. This FHA is strongly based on the fire containment approach (see [16]) and the fire influence approach as described in IAEA guidance documents.

Internal Missile Inducing an Internal Fire or an Internal Gas Explosion

In NPPs, there are different internal (or plant internally generated) missile sources that have to be considered in relation to their potential kinetic energy (see for instance [2] or [17]): turbine disc fragments or blades, fan blades, coupling bolts, pump impellers, valve bonnets on high energy line, temperature and pressure sensors on high energy lines and coupling between a diesel motor and its alternator. As an example, valve bonnets of high energy belonging to a non-nuclear safety graded system (e.g. the auxiliary steam system) are considered as potential internal missiles.

The combination of an internal missile and a consequential internal gas explosion is relevant if there is a potential for spatial interaction between an explosive gas pipe (e.g. a hydrogen supply pipe to the chemical volumetric control tank) or tank and a potential internal missile. A preliminary check based on the available site data allows to identify the rooms where explosive gas piping/tank and internal missile hazard(s) are present. The list of those rooms is used to perform walkdowns in order to take into account the real situation in the area and to assess if the concerned internal missile(s) could interact with the pipe or tank (i.e. without any solid obstacle that could significantly reduce the kinetic energy of the internal missile in such a way that there is not enough energy to damage mechanical equipment like a metallic pipe or tank) in the credible range of the missile trajectory. The internal missiles generated by fan blades are e.g. expected to be ejected in a solid impact angle perpendicular to the rotating axis.

Regarding the internal fire, the existing FHA studies are used to identify the cases where an internal missile could generate a fire hazard or a scenario that is not already covered by the fire containment or fire influence approach. The most credible situation that could not have been considered is an internal missile that would directly impact a combustible liquid pipe because the combustible liquid tanks themselves are already taken into account in the FHA. For the combustible liquid pipe, the fire scenario could be worse than the one considered in the FHA if the pipe is considered damaged by an internal missile and, consequently, the released combustible liquid inventory would become (significantly) larger than the one considered in the FHA (as a gravitational supply by a buffer tank see Figure 1).

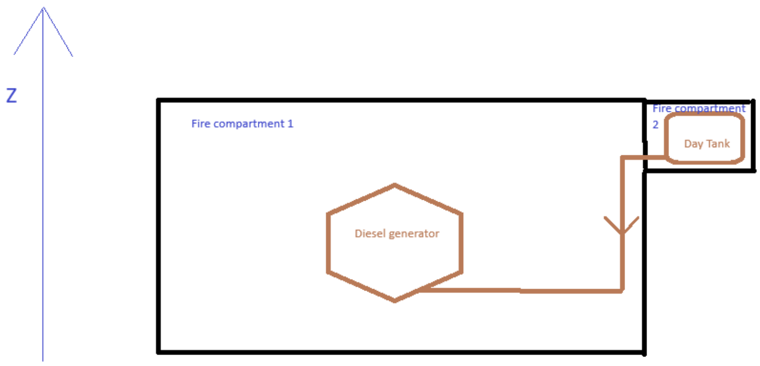

Figure 1 Gravity fuel supply to diesel generator – schematic view

As a result, a similar approach as for the gas pipe is used to identify the rooms where combustible liquid pipe(s) and internal missile hazard(s) are present. The obtained list of rooms is used to check in the FHA if the scenario is already bounding this case or if the additional fire load does not change the results. If needed, walkdowns are performed to assess the credibility of the combination similarly to what is done for the explosive gas piping.

From a general perspective, the implementation of a qualified barrier between the internal missile hazard and the target (an explosive gas pipe or a combustible liquid pipe) could resolve the issue if needed.

HEAF and Consequential Internal Fire

A HEAF occurring at 6 kV electrical supply boards could generate an overpressure in the affected room that could impact the weakest element(s) of the surrounding barriers. This is typically the case for doors that could open under the generated pressure. The advantage is that the doors opening will help to limit the pressure increase in the room by serving as pressure relief devices. As a result, the structural parts of the barriers can keep their integrity. However, when it concerns the opening of a fire door, the fire compartmentation is endangered and a fire induced by the HEAF could propagate faster outside the initial fire compartment. This scenario is depicted in the following figures (Figure 2 to Figure 6).

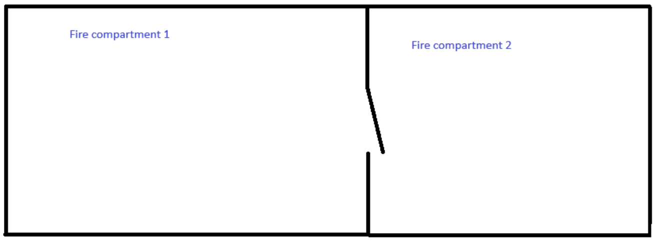

Figure 2 Schematic view of the fire compartment 1, in which the HEAF is postulated

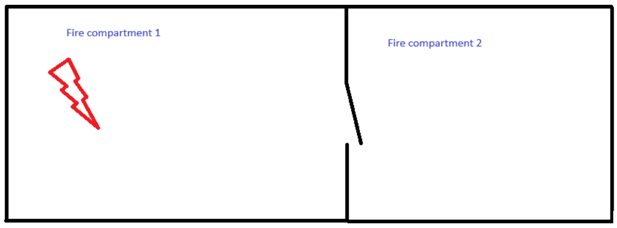

Figure 3 HEAF is postulated in the fire compartment 1

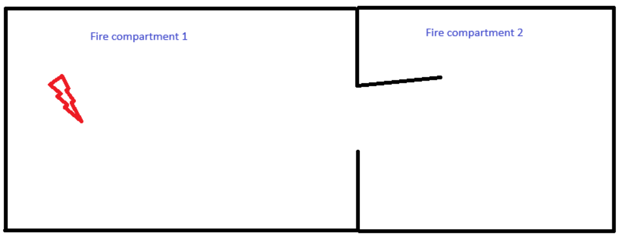

Figure 4 Fire door between the two fire compartments opens as a result of the rapid pressure increase in the fire compartment 1 by the HEAF

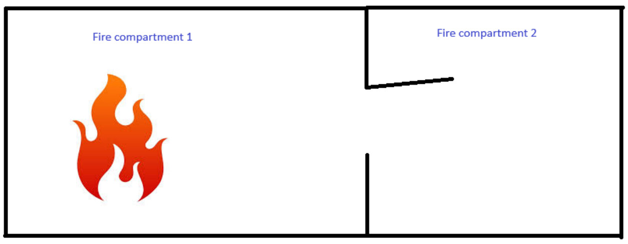

Figure 5 HEAF induces a fire in the fire compartment 1 while the fire door to the fire compartment 2 is open

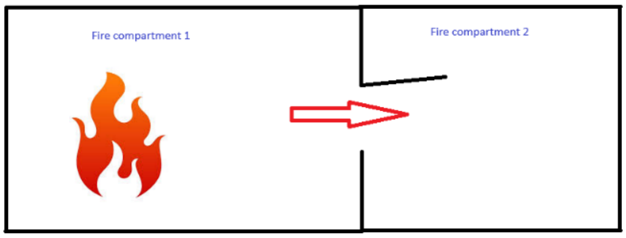

Figure 6 The HEAF induced in the fire compartment 1 could propagate via the open door to the fire compartment 2 igniting another component

The consequences of such combination of a HEAF and a consequential fire include not only the loss of the 6 kV electrical supply board by the HEAF (and the resulting fire) but also potential loss of other components y the consequential internal fire. In that case, considering that the redundant 6 kV electrical boards are installed in adjacent separate fire compartments, the consequences of the combination of two internal hazards, the initial HEAF at the component with an ensuing fire breeching the fire barrier by the rapid high energetic pressure increase resulting in a consequential fire of components in another fire compartment can be more severe than an internal fire inside a single fire compartment (assessed via the existing FHA and the fire containment approach (FCA)). This is due to the fact that a propagation of the fire can lead to damage(s) inside the adjacent fire compartment 2 also containing redundant 6 kV electrical boards. This is typically the case for a 3 x 50 % design for some systems. Indeed, the HEAF and fire damages could lead to the loss of a 2 x 50 % system capacity which may create a potential safety issue as only a capacity of 50 % would remain available.

Another potential issue can occur in case of a 2 x 100 % fire water supply design with two electric motor pumps of 100 % capacity per pump (such a 2 x 100 % fire water supply capacity is allowed in the U.S. NRC Regulatory Guide RG 1.189 [18]). Indeed, considering the case that it is needed to credit the firefighting with water to prevent fire propagation towards adjacent compartments via an open fire door, the fire water supply needs to be credited (to face the loss of fire compartmentation). In such a case and according to the WENRA SRLs 2020, a failure of a fire water supply electric motor pump has to be postulated in addition to the loss of the power supply of the other fire water supply electric motor pump due to the HEAF (loss of electrical power supply board) rendering the water supply unavailable and, as a result, the water based firefighting could be endangered.

In order to avoid such potential issues, a detailed analysis using appropriate tools like zone models or CFD (*c*omputational *f*luid *d*ynamics) models of the safety consequences following the induced fire by a HEAF needs to be performed.

CONCLUSIONS

The concerns about the combinations of hazards raised in the WENRA SRLs 2020 for existing plants is quite challenging for existing nuclear power plants. In a first stage, the identification of hazard combinations that are considered credible is needed. Using, among other documents, the IAEA Safety Guide SSG-64, an approach to select the credible combinations is presented in this paper especially for combinations including internal fire or explosion hazards. The criteria used to identify the combinations that require a more detailed analysis are presented for combinations of consequential hazards as well as for combinations of independent hazards. These criteria are deterministic, common sense or quantitative, based on occurrence frequencies, but do not include a probabilistic criterion such as the conditional core damage frequencies to remain in a deterministic assessment approach.

The approach proposed for the assessment of internal fire or explosion hazards combination for existing plants is presented for the two following combinations of consequential hazards as examples: internal missile and consequential internal fire or internal (gas) explosion and, HEAF with consequential internal fire. These are assessed by using, as far as practicable, existing studies and by performing plant walkdowns to assess more closely the credibility and/or the consequences of such hazard combinations.

REFERENCES

[1] Western Nuclear Regulators Association (WENRA): WENRA Safety Reference Levels for Existing Reactors 2020, 17th February 2021, https://www.wenra.eu/sites/default/files/publications/wenra_safety_reference_level_for_existing_reactors_2020.pdf.

[2] International Atomic Energy Agency (IAEA): Protection against Internal Hazards in the Design of Nuclear Power Plants, Specific Safety Guide, IAEA Safety Standards Series No. SSG-64, STI/PUB/1947, ISBN 978-92-0-116121-5, Vienna, Austria, August 2021, https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1947_web.pdf.

[3] International Atomic Energy Agency (IAEA): Design of Nuclear Installations Against External Events Excluding Earthquakes, Specific Safety Guide, IAEA Safety Standards Series No. SSG-68, STI/PUB/1968, ISBN 978-92-0-136221-9, Vienna, Austria, December 2021, https://www-pub.iaea.org/MTCD/publications/PDF/PUB1968_web.pdf.

[4] Protection Against Internal and External Hazards in the Operation of Nuclear Power Plants, Specific Safety Guide, IAEA Safety Standards Series No. SSG-77, STI/PUB/1991, ISBN 978-92-0-101522-8, Vienna, Austria, March 2022, https://www-pub.iaea.org/MTCD/Publications/PDF/PUB1991_web.pdf.

[5] International Atomic Energy Agency (IAEA): Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, Specific Safety Guide, IAEA Safety Standards Series No. SSG-3, Rev. 1, STI/PUB/2056, ISBN 978-92-0-130723-1, Vienna, Austria, March 2024, https://www-pub.iaea.org/MTCD/Publications/PDF/p15318-PUB2056_web.pdf.

[6] American Nuclear Society (ANS): ANS-2.12-1978: Guidelines for Combining Natural and External Man-Made Hazards at Power Reactor Sites, July 1978 (withdrawn), https://store.accuristech.com/ans/standards/ans-2-12-1978?product_id=1852497.

[7] International Atomic Energy Agency (IAEA): Assessment of Vulnerabilities of Operating Nuclear Power Plants to Extreme External Events, IAEA-TECDOC-1834, ISBN 978-92-0-108817-8; Vienna, Austria, December 2017, https://www-pub.iaea.org/MTCD/Publications/PDF/TE1834_web.pdf.

[8] Electric Power Research Institute (EPRI): Identification of External Hazards for Analysis in Probabilistic Risk Assessment: Update of Report 1022997, Palo Alto, CA, USA, October 2015; https://www.epri.com/research/products/000000003002005287.

[9] Knochenhauer, M., and P. Louko: Guidance for External Events Analysis, Statens Kärnkraftinspektion (SKI), SKI Research Report 2002:27, Stockholm, Sweden, January 2002, https://www.stralsakerhetsmyndigheten.se/en/publications/reports/safety-at-nuclear-power-plants/2002/0227/.

[10] American Society of Mechanical Engineers (ASME) / American Nuclear Society (ANS): ASME/ANS RA--2013: Addenda to ASME/ANS RA-S–2008 Standard for Level 1 / Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications, New York, NY / La Grange Park, Illinois, July 2013 (withdrawn).

[11] Institut National de l'Environnement Industriel et des Risques (INERIS): Probabilité dans les études de sécurité et études de dangers, OMEGA 24, DRA-18-171229-00933A, April 2018 (in French), https://www.ineris.fr/sites/ineris.fr/files/contribution/Documents/DRA-18-171229-00933A_Proba_OMEGA24_final_2bis.pdf.

[12] United States Nuclear Regulatory Commission (U.S. NRC): EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities, Final Report and Supplement 1, NUREG/CR-6850, EPRI 1011989, Washington, DC, USA, March 2021, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/index.html.

[13] Iancu, A., H.-P. Berg, and N. Fritze: Event Combinations with Fires – Update from the OECD FIRE Database, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 24, 15th International Seminar on Fire Safety in Nuclear Power Plants and Installations, October 4-5, 2017, Bruges, Belgium, GRS-A-3912, pp. 390 - 403, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, December 2017, https://www.grs.de/sites/default/files/publications/grs-a-3912_0.pdf.

[14] Röwekamp, M., et al.: The OECD/NEA FIRE Database: an update, Special Report, Nuclear Power Plant Fire Events, Nuclear Engineering International (NEI), April 2021, pp. 26 - 30, London, United Kingdom, 2021, www.neimagazine.com.

[15] Leblanc, X., Q. K. Mai, and P. D'Angelo: Deterministic Study on Seismically Induced Fires, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 27 / SMiRT 28 18th International Seminar on Fire Safety in Nuclear Installations, Paris Montrouge, France, May 20-22, 2025, GRS–806, ISBN 978-3-910548-99-2, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, in preparation June 2025.

[16] Leblanc, X., P. Kwahou Kezembo, and E Maillet: Development of a Fire Containment Approach of the Fire Hazard Analysis for the Belgian Nuclear Power Plants, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 24 15th International Seminar on Fire Safety in Nuclear Power Plants and Installations, October 4-5, 2017, Bruges, Belgium, GRS-A-3912, pp. 82-94,Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, December 2017, https://www.grs.de/sites/default/files/publications/grs-a-3912_0.pdf.

[17] United States Nuclear Regulatory Commission (U.S. NRC): Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition, NUREG-0800, formerly issued as NUREG-75/087, Chapter 3.5.1.1: Internally Generated Missiles (Outside Containment), Washington, DC, USA, March 2007, https://www.nrc.gov/docs/ML0703/ML070370569.pdf.

[18] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research: Regulatory Guide 1.189: Fire Protection for Operating Nuclear Power Plants, Washington, DC, USA, April 2001, https://www.nrc.gov/docs/ML0109/ML010920084.pdf.

3.3 Topical Session on Structural Fire Protection

The third session devoted to structural fire protection issues chaired by Andreas Niggemeyer from edvance (Germany) as co-organizer again included three presentations.

The first presentation titled 'Use of Fire Protection Engineering Evaluations to Manage Separation Criteria' by Paul Boulden Jr from Appendix R Solutions (USA) provided an approach for the application of Fire Protection Engineering Evaluations (FPEEs) in nuclear power plants, highlighting the importance of meeting regulatory fire protection separation criteria and addressing challenges faced by the utilities when conditions do not fully comply with the requirements. The author explained how evaluations conducted under U.S. NRC Generic Letter 86-10 provide a structured approach to justify existing configurations and ensure plant safety without unnecessary modifications.

The author categorised FPEEs into the following types: equivalency evaluations, adequate for the hazard evaluations, and change evaluations. Each type serves a specific purpose, such as demonstrating compliance, assessing mitigating factors or supporting program changes. The presentation also practical examples, including evaluations of containment penetrations, open hatches in turbine room, and non-labelled fire doors, illustrating how engineering judgment and technical analysis can maintain compliance with safety standards.

The technical content required in the evaluations was emphasized, including descriptions of configurations, assumptions, fire protection features, and safe shutdown capabilities. By incorporating rigorous analysis and referencing standards such as NFPA 805, these evaluations ensure that decisions are based on sound engineering principles. The approach allows utilities to prioritise resources effectively, focusing on measures that genuinely enhance safety. In conclusion, the presenter argued that FPEEs are a vital tool for managing fire protection in nuclear facilities. They provide flexibility within regulatory frameworks, reduce unnecessary costs, and support a risk-informed, performance-based strategy.

The second presentation entitled 'Use of the Building Information Modelling Approach in Support of Fire Hazard Analysis' by Youssef Charefi from Tractebel Engineering (Belgium) outlined the investigation of the integration of the so-called Building Information Modelling (BIM) with fire safety engineering tools. The presenter identified the limitations of traditional methods for transferring building geometry into fire simulation models and proposed a solution using BIM to streamline data exchange and improve accuracy.

The study performed focused on deterministic fire hazard analysis, where accurate building geometry is essential for simulation. BIM, combined with open standards such as Industry Foundation Classes (IFC), enables efficient sharing of geometric and material data. However, challenges arise due to the incompatibility between complex BIM representations and simplified zone models used in fire simulations. For addressing this, the author introduced algorithms that transform irregular room shapes into equivalent cuboid forms while preserving critical physical characteristics.

An interface application, including geometry transformation, repositioning of equipment and definition of fire scenarios, serves for automizing the process from BIM data extraction to fire simulation input generation. The tool significantly reduces manual effort, ensures consistency and enhances the quality of fire safety assessments. A case study has demonstrated the effectiveness of the approach, maintaining room volume and height while adapting geometry for zone model compatibility.

The author concluded that integrating BIM with fire modelling offers substantial benefits, including cost savings and improved data reliability. While the current implementation focuses on basic geometry, future developments aim to incorporate post-processing capabilities for detailed analysis of fire impacts on structural elements and equipment. This represents a promising step towards modernising fire safety design in nuclear installations.

The last presentation by Damien Lévêque from Electricité de France (EDF) was entitled 'Application of ISO18195 for Justification of Fire Partitioning in French Nuclear Power Plants'. The standard ISO 18195 is an international adaptation of the EPRESSI methodology, developed by EDF together with Efectis. It aims at providing tools and guidance for demonstrating the robustness of fire compartmentation, complementing standard fire rating classifications. The standard is under revision and remains based on EDF's experience.

Fire prevention in French nuclear power reactors relies on partitioning buildings into fire safety volumes (VFS) enclosed by qualified fire-resistant barriers. Minimum fire resistance ratings are established through conventional standard tests such as ISO 834 and NF EN 3501. The purpose of ISO 18195 is to confirm that fire barriers can withstand design basis fires, which differ from ISO 834 in duration and dynamics. Performance curves are developed for various fire scenarios to validate robustness.

The methodology involves creating a design basis fire curve for each room and performance curves for fire barriers. Robustness is confirmed if at least one performance curve exceeds the design basis curve at all times. The approach consists of two phases. In the first phase s standardised fire tests are analysed to identify failure criteria. The second phase uses modelling and experimental data to create performance curves, validate models, and develop qualification diagrams for fire barriers.

Current efforts include adapting the methodology for large volumes, implementing generic performance curves, refining ventilation modelling, and improving clarity for users unfamiliar with EPRESSI.

The seminar contributions prepared for this topical session are provided hereafter.

Use of Fire Protection Engineering Evaluations to Manage Separation Criteria

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ABSTRACT

Meeting the basic (required) fire protection separation criteria of various regulations such as the United States Nuclear Regulatory Commission (U.S. NRC) 10 CFR 50, Appendix R [1] is an important first step to managing fire risk. One of the challenges many utilities face over the life of nuclear power plant (NPP) operation is what to do with conditions that do not fully meet regulatory requirements and how to best apply plant resources to improve safety and comply with regulatory requirements.

The U.S. NRC issued Generic Letter (GL) 86-10 [2] "Implementation of Fire Protection Requirements" provided insights on the interpretation and implementation of the NRC fire protection requirements. GL 86-10 [2] also provides insights into the level of detail and staff expectations for documentation of evaluations of specific conditions where questions with compliance may be identified. These evaluations are required to be produced by a qualified fire protection engineer. The fire protection engineering evaluations (FPEEs) performed in accordance with GL 86-10 are a tool for the utility to judge whether existing configurations are adequate or whether costly modifications must be performed. Common conclusions for such evaluations may disposition a condition as being 'adequate for the hazard' or 'provides equivalent protection'. This type of disposition by a qualified fire protection engineer has the potential to allow the utility to focus their resources on issues that will improve plant safety.

The intent of these fire protection evaluations are not to subvert the regulatory requirements for an identified fire area[1] but to provide a process that allows for engineering evaluation to justify conditions that are acceptable and do not degrade the plant's ability to safely operate and achieve safe shutdown if necessary. This paper provides an overview of some examples that have been identified in the United States NPP experience, and how an engineered approach under the process defined by GL 86-10 [2] allowed for the plant fire protection engineers to better utilize plant resources where they will have the greatest benefit on plant safety.

INTRODUCTION

This paper describes the use of FPEEs to manage separation criteria in accordance with the U.S. NRC GL 86-10 [2]. Several examples are included to demonstrate real applications for implementation within the U.S. industry. GL 86-10 "Implementation of Fire Protection

[1] The term fire area used in the U.S. in accordance with fire boundary definition in accordance with Appendix R to Part 50 – Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979 [1] is synonymous to term fire compartment in the international framework (e.g. IAEA).

Requirements" was issued on April 24, 1986. This U.S. NRC document is the result of a series of discussions/workshops between the U.S. nuclear industry and the U.S. NRC on the implementation and interpretations of the U.S. NRC fire protection requirements. GL 86-10 requires evaluation by a qualified fire protection engineer for items not in verbatim compliance with 10 CFR 50.48, Appendix R [1]. The following terms may be used synonymously: 86-10 evaluation, engineering evaluation, FPEE, existing engineering equivalency evaluation (EEEE).

As part of the NFPA 805 Risk-Informed Performance-Based Initiative [4], NPPs were required to review EEEEs in accordance with NFPA 805 [4], subsection 2.2.7. When applying for a deterministic approach, the user shall be permitted to demonstrate compliance with specific deterministic fire protection design requirements in Chapter 4 for existing configurations with an engineering equivalency evaluation. These existing engineering evaluations shall clearly demonstrate an equivalent level of fire protection compared to deterministic requirements.

APPLICATION

There are three primary classifications of fire protection engineering evaluations:

- equivalency evaluations,
- adequate for the hazard evaluations, or
- change evaluations.

FPEEs are typically applied for the following applications;

- Fire area boundary evaluation/justification;
- Fire protection code equivalency evaluation;
- Partial area fire detection / fire suppression evaluation;
- Evaluation of a deviation from a tested configuration;
- Separation of redundant equipment.

FPEEs identified as 'equivalency evaluations' address non-fire rated features or conditions that as evaluated as being "equivalent" and therefore satisfy design requirements or commitments. An example is a fire door that has side gaps more than that allowed by the code of record (thereby not meeting design requirements), but which can be demonstrated to perform as a three-hour rated fire door by industry available testing data performed on doors with excessive side gaps. In this example using industry data, the fire door could be shown to provide equivalent level of protection and would be expected to perform its function.

FPEEs meeting the criteria for 'equivalency evaluations' should limit the technical data to those features directly associated with the device under review. These types of reviews should not include subjective features related to the general area.

FPEEs identified as 'adequate for the hazard' address conditions as being acceptable based on review of the features, construction, or conditions in conjunction with area mitigating factors. Specific types of mitigating factors may be credited as contributing to the acceptability including combustible loading, fire detection, fire suppression, proximity to safe shutdown components, etc. An example is an unsealed opening in a credited fire barrier (thereby not being in compliance with requirements). This opening may be determined to be 'adequate for the hazard' based on the small size of the opening, obstructions around the opening, depth of wall, low combustible loading within the fire area (and adjacent fire areas), and the presence of fire detection and fire suppression. These types of engineering evaluations should clearly identify the mitigating factors credited as a basis for the evaluation. The FPEE needs to identify the means to ensure that the credited mitigating factors are monitored and remain valid. For example, if the evaluation is based on the area being maintained free of combustibles, then the applicable monitoring program should be cited which governs that practice.

FPEEs identified as ‘proposed change evaluations’ to the approved fire protection program provide determination as to whether the change can be implemented in accordance with current licensing basis without prior regulatory approval. As stated in U.S. NRC RG 1.189 [5], Section 1.8.1 “Change Evaluations”, U.S. NPPs that have adopted the NRC “standard license condition for fire protection” (with some NRC specific criteria) may make changes to the approved fire protection program without the Commission’s prior approval only if those changes would not adversely affect the ability to achieve and maintain safe shutdown in the event of a fire. The fire protection evaluation is one tool the licensee may use to verify that a change would not adversely affect the ability to achieve and maintain safe shutdown in the event of a fire.

The following Table 1 provides an overview of the implementation of engineering evaluations within the U.S. industry.

Table 1 Overview of implementation where engineering evaluations are applicable for use within U.S. commercial nuclear industry

Evaluation Type	Deterministic		Risk-Informed, Performance-Based	
	Appendix R Plants	Appendix R Plants (BTP 9.5-1)	NFPA 805 Plants (Chapter 3)	NFPA 805 Plants (Chapter 4)
Complies	acceptable	acceptable	acceptable	acceptable
Equivalency	acceptable	acceptable	acceptable	acceptable
Adequate for the hazard	acceptable	acceptable	only for Sections 3.8, 3.9, 3.10 and 3.11	acceptable
Change evaluations	not applicable	not applicable	only for Sections 3.8, 3.9, 3.10 and 3.11	acceptable

ENGINEERING EVALUATION CONTENT

Under the NFPA 805 initiative [1] NPPs seeking to transition their license basis from the deterministic requirements of Appendix R to the risk-informed, performance-based requirements of NFPA 805 were required to review all aspects of their fire protection program. Specific reviews were required for all engineering evaluations that would be carried forward under the new plant license. This process allowed a fresh look at many legacy evaluations and a chance to upgrade documentation to meet current standards. During this period additional clarifications on the use and content of engineering evaluations were provided through the U:S: NRC Frequently Asked Questions (FAQ) process. FAQ 06-0003 [6] and FAQ 06-0008 [7] provide insight into regulatory expectations for the use and content of engineering evaluations. The following summary provides considerations for the content and use of engineering evaluations. The intent of these evaluations is to include enough technical rigor, that an independent reviewer can come to the same conclusion of the analysis.

- Description of the area/configuration
  - The description should provide enough description so that the reviewer has a clear image of condition and of the fire area.
  - The descriptive documentation of the equipment/area should provide an overview of the orientation and layout of the area, specifically with any elements for consideration within the evaluation.
- Assumptions
  - Plant operating conditions
  - Plant processes
- Safe shutdown capability
  - It is important to know if the subject area has a credited function, cables or equipment relevant to safe shutdown.
  - The safe shutdown plan is the methodology to maintain a reactor core geometry in a "safe and stable" condition as defined by 10 CFR 50.48(b) or 48(c).
- Fire protection
  - Available fire protection equipment relevant to the evaluation should be listed (e.g. automatic fire detection, automatic fire suppression, manual fire suppression)
    - Define full/partial coverage as applicable
  - Fire response procedure (and timelines as applicable)
- Combustible loading / identification of fire hazards
  - Discuss ignition sources relative to the target of concern (e.g. barrier opening)
  - Discuss fire severity of the area
- Analysis of installed configuration
  - Using the available information from above create a logical technical discussion to build an engineering decision based on sound engineering practices, engineering design, fire modelling, layout, design margins and capabilities, fire brigade intervention
  - Remember fire barriers have two sides – both must be discussed.
  - Validate all facts, by reference to station procedure, drawing or document.
  - Consider maintenance and transient combustible/ flammable loading.
  - Consider material condition.
  - Consider that changes to existing conditions and plant processes may be the most cost-effective solution than to minimize margin.
  - Use all the tools available to support a multi-layer "defence in depth" strategy towards a reasonable conclusion.
- Determination of evaluation: A conclusionary statement should be made that defines what determination was made as part of the analysis
  - Engineering equivalency evaluation
  - Adequate for the hazard
  - Change evaluation

ENGINEERING EVALUATION EXAMPLES

The following three examples provide an overview of typical types of GL 86-10 evaluations:

A. Cable Penetrations Through the Containment Building Boundary

Description

It was identified that there is a number of penetrations into the containment building from various adjacent buildings. Four primary penetration locations; electrical penetration area of each unit's cable vault/tunnel, mechanical penetrations in the auxiliary building, penetrations in the fuel building, high temperature mechanical penetrations in each unit's main steam valve house. Each of these four areas are separate fire areas from the respective unit's containment building. 10 CFR 50, Appendix R [1] requires that a three-hour fire rated boundary including walls, doors, penetration seals, dampers, etc., or at a minimum, a boundary that exceeds the fire loading in the area (per Generic Letter 83-33 [12]). The penetration seals in containment serve several purposes which, on a day-to-day basis, are as important, if not more important, than the fire protection duties of the penetration seal. The seals provide a radiation barrier from an airborne and surface contamination standpoint and to a lesser extent, a gamma and neutron radiation barrier. In addition, the penetration seals serve as a pressure boundary of the atmospheric containment and are seismically qualified.

No Underwriters Laboratory (UL) listed fire-rated penetration seal can do all the items required above. Therefore, an evaluation of the existing penetration seals (both electrical and mechanical) in terms of the seal's predicted performance under fire conditions is necessary to determine if adequate separation exists between adjacent fire areas.

This evaluation does not address the use of electrical penetrations for power cables feeding the residual heat removal (RHR) pumps to achieve cold shutdown. This analysis is contained in Section 2.7 of <Vendor Report Intentionally Left Blank>.

Evaluation: This evaluation is divided into two sections; the first deals with the electrical penetrations, and the second with mechanical penetrations.

Electrical Penetrations

The specification for containment electrical penetrations for <Power Plant Name Removed> design and testing requirements. The electrical penetrations were supplied by <Vendor Name Intentionally Removed>. Vendor information supplied on the electrical penetrations are given on drawings. Both the specification and the vendor drawings were reviewed as part of this evaluation.

The electrical penetrations are constructed of 8" – 12" diameter schedule 40 steel pipe through the width of the containment wall, which is just over 5'. All the penetrations have a steel plate approximately 1.5" thick on the outside of the containment wall. There are several variations on internal configuration of the penetrations. Some have a full-length canister in the sleeve. Others have a shorter canister in the sleeve. The canisters are filled with nitrogen. The sleeve is capped on the containment side by either an oversized steel face plate or one that fits into the sleeve.

The electrical penetrations have been subjected to numerous tests as outlined in the specification. The most important tests for the purposes of this evaluation are pneumatic pressure test, leak test, and pressure tests associated with the low-pressure containment testing. These tests show that the seals are airtight, which would prevent smoke and hot gases from flowing through the penetrations.

The electrical penetrations will provide separation between the containment and adjacent fire areas for the following reasons:

- Substantial construction. The penetrations are schedule 40 steel pipe. The faceplate that is placed over the end of the electrical penetration on the outside of the containment wall is steel and approximately 1.5" thick. In addition, it overlaps the sleeve by several inches. The face plate is connected by a minimum of eight bolts to a flanged connection on the sleeve.
- The containment wall is approximately 5' thick. This thickness provides a heat sink for the sleeve and a considerable distance for the heat to travel, allowing time for cooling. Flame propagation would be virtually impossible through this distance considering the relatively small diameter of the sleeves.
- The flanged and bolted connection described above will allow expansion of the face plate under fire conditions. The location of the face plate is also on the cable vault/tunnel side where the greatest heat potential exists.
- The various leak and pressure tests prove that the seal is airtight, which will prevent the passage of heat and gases.
- The containments, in the area around the electrical penetration and the cable vault/tunnel, have smoke detection systems. The cable vault/tunnel has a CO_2 total flooding system in the electrical penetration area that is automatically actuated by heat detectors.

Although no formal fire tests have been performed on the above electrical penetrations, the current configuration will provide separation equivalent to that required by 10 CFR 50 Appendix R [1], Section III.G.1.

Mechanical Penetrations

The mechanical penetrations are primarily located in the auxiliary building, but others are located in the main steam valve house and safeguards/quench spray pump house. There are several different types of piping penetrations. Some have sleeves and some were cast in place. Several penetrations are cooled with service water due to the high temperature liquid or steam that pass through the penetration.

This evaluation used the reactor containment piping penetration schedule as shown on drawing <Drawing Number Intentionally Removed>. Vendor drawings were also reviewed.

These mechanical penetrations will provide separation between the containment building fire area and the adjacent fire areas for the following reasons:

- The penetrations consist of pipe that was cast in place when the containment wall was poured. This is an accepted practice of penetration sealing around the outside of the penetration. In addition, the piping is schedule 40 or thicker (except for the containment spray recirculation service water piping which is schedule 30). No further evaluation is necessary on these penetrations.
- The remaining mechanical penetrations have sleeves with the pipe inserted through the sleeves. The piping through the sleeve is a minimum of schedule 40 steel or stainless steel.
- All of the penetrations are required to be airtight as explained in the introduction to the evaluation. This is achieved in the sleeves by the use of oversized face plates and the

service water cooling that circulates between the pipe and the sleeve. This seal will prevent the possibility of heat or gas entering through the penetration.

- The sleeved penetrations also have a number of other features that would prevent fire spread through the penetration. These items include substantial construction of steel plates; in some cases, 1" thick on the face of the penetration bolted to the wall, the thickness of the containment wall will act as a heat sink, and the fire loading on both sides of the penetration are relatively low.

It should be noted that containment penetrations have been classified by the Q-List as Appendix R “No”. The basis for this is that even though the penetrations are in an Appendix R fire area boundary, there are no unique Appendix R requirements beyond the Technical Specification requirements.

Conclusion

It can be concluded from this evaluation that the current arrangement of the electrical and mechanical penetrations provides separation of fire areas adjacent to the containment fire area equivalent to that required by Section III.G.1 of Appendix R to 10 CFR 50 [1], and meets the guidance provided by Generic Letter 83-33 [12] on fire area boundaries. This is based primarily on the Substantial construction of the penetrations, the thickness of the containment walls, use of water or nitrogen in the penetration, and the either low fire loading or fire protection systems in the areas.

B. Open Hatch in the HPCI Room

Description

According to the condition report, a fire protection engineering evaluation was performed to determine the acceptability of the sprinkler system in the HPCI turbine room in conjunction with a large open hatch directly above the high-pressure coolant injection (HPCI) turbine. The FPEE determined that there would be a delay in sprinkler activation, but this delay was acceptable because a fire in the HPCI turbine room is assumed to result in a loss of the equipment in the room. A condition report was issued to determine whether there was adequate technical justification for the sprinkler performance to be acceptable.

The purpose of this evaluation is to supplement the existing evaluation and provide a technical basis for the acceptability of the sprinkler system performance with respect to the open hatch in the HPCI turbine room. This evaluation concluded that the open hatch does not significantly delay the sprinkler activation, and both open and closed hatch configurations in the HPCI room are acceptable with respect to fire boundary temperatures. Issues regarding compliance with National Fire Protection Association (NFPA) codes are to be addressed in a FPEE, which this document provides, in accordance with NRC GL 86-10 [2].

Design Inputs

- Ambient temperature – 18.3 °C (65 F): The UFSAR (*U*pdated *F*ire *S*afety *A*nalysis *R*eport) states that the ambient temperature range for 03RB is 65 – 125 F. The lower bound of this range was used to provide a more conservative estimate for sprinkler activation.
- Fuel load – 155 gal of lube oil: The lube oil is provided for the HPCI pump and turbine and is expected to be contained in the diked area.

- Sprinkler activation temperature – 100 °C (212 F): Drawing <Plant Drawing Number Intentionally Removed> details the location of each sprinkler head. The notes section indicates that the sprinklers are standard ½” brass upright sprinklers that actuate at 212 F. Plant technical specification requirements specify that the sprinkler at node 82, near hangar 56, is an upright sprinkler in the upright position rather than a sidewall sprinkler as indicated on <Plant Drawing Number Intentionally Removed>.
- Boundary thermal properties – NUREG 1805 [10]: The walls and obstructions in the room were all modelled as either concrete or steel. Thermal properties for these materials were taken from NUREG 1805.
- Boundary dimensions – defined by plant drawings (drawing numbers intentionally removed): The room dimensions, location of obstructions, and location of openings were taken from the drawings listed above. All concrete was modelled to be as thick as the largest wall thickness of 1.22 m (4 ft), as shown in Drawing <Plant Drawing Number Intentionally Removed>. This value was used because it is representative of most of the concrete surface area on the 540’ elevation.
- Evaluation – Fire Dynamics Simulator (FDS) models were used to determine the acceptability of the sprinkler system performance with respect to the open hatch in the HPCI turbine room. Both elevations of 03RB were modelled together to evaluate the effects of the open hatch. Three fire sizes were modelled representing a transient fire (317 kW), a small lube oil spill (3 MW), and a complete lube oil reservoir spill (70 MW). Each fire size was modelled with both open hatch and closed hatch configurations.

Assumptions

The guidelines outlined in NUREG/CR-6850 [14] were used to provide consistent fire modelling assumptions. For example, a 317 kW transient combustible fire (e.g., trash can fire) is modelled as representative of a potential small fire for the area.

Assessment of Conditions

NFPA 13 1980 [11] is the code of record for the sprinkler systems. Section 4-4.8.1 of NFPA 13 1980 states: “When vertical openings are not protected by standard enclosures, sprinklers shall be so placed as to fully cover them. This necessitates placing sprinklers close to such openings at each floor level.” The system does not achieve exact compliance with this section because the hatch is surrounded by nine sprinklers on the lower level only, and not the upper level.

The requirements for vertical openings have changed over the years. NFPA 13 2010 [13] states that draft stops and reduced sprinkler spacing around the opening are required to protect vertical openings. The 2010 edition provides insight to the intent of the 1980 code. While the station is not committed to the 2010 edition, it reinforces the need for a technical evaluation of the sprinkler system performance.

Description of the Area/Configuration

Fire area[i] 03RB is a large area consisting of two rooms at different elevations. The HPCI room measures 45’ by 51.5’ on the 540’ elevation. Directly above the HPCI room is the control rod drive (CRD) room, which measures 30’ by 44.5’ on the 562’ elevation. There are two large openings in the concrete slab between the two rooms. An opening exists directly above the HPCI turbine and pump, which extends to the southeast corner of the CRD room. The other opening is an open stairwell along the north wall of the rooms. The stairs extend from an air lock at the 551' elevation up to the CRD room. A ladder is provided to access the 540' elevation from the air lock. The stairs are of an open grating construction.

The HPCI pump and turbine are located on a skid located in the south half of the room and is surrounded by a 6" wide by 3" tall concrete dike.

Combustible Loading / Fire Hazard

The major combustible load of the HPCI room is a reservoir, located within the diked area, containing up to 155 gal of lube oil. The contents of the reservoir are expected to be contained by the dike.

Transient combustibles are not precluded from the area, but they provide a less severe fire compared to the lube oil. A trash can fire was modelled to be characteristic of all transient fires in the area.

Fire Protection Features

The 540' elevation is protected with a sprinkler system, which covers the entire floor. There is no automatic suppression coverage provided for the 562' elevation or within the hatch and stairwell openings between the two elevations. Manual suppression is provided by hose stations and extinguishers.

Ionization detectors are provided for automatic detection on both elevations of 03RB.

The walls and ceiling of 03RB are constructed of reinforced concrete with a fire resistance rating of three hours.

Safe Shutdown Capability

All of the equipment and cables in fire zone 03RB would be assumed to be damaged in the case of a fire. Division I equipment outside the fire zone can be used to achieve safe shutdown for fires in 03RB. The reactor core isolation cooling turbine and pump as well as the core spray and the RHR pumps are located in other zones and serve a redundant function to the HPCI turbine, pump, and associated equipment.

Determination of Acceptability

To determine the effect of the open hatch on the sprinkler activation protecting the 540' elevation of 03RB, models were run using FDS, version 5.5.3. Six models were run with three fire sizes: a 317 kW transient combustible fire, a 3 MW design fire, and a 70 MW fire that would be the result of a spill filling the dike. Each fire size was modelled to compare results with the hatch open and with the hatch covered by a plug. Mechanical ventilation was not included in the model in order to simulate a worst case scenario for heating boundaries.

Table 3-4 of NUREG 1805 [10] states that transformer oil may be used as a surrogate fuel for lube oil due to its similar properties. Instead, kerosene was used due to being similar in nature to lube and transformer oil and having properties that were readily available, shown in the Attachment. While the heat release rate (HRR) would be slightly different between the fuels, a prescribed HRR was used for the 317 kW and 3 MW fires; this HRR would not be affected by the difference. For the 317 kW fire, an 8 min t2 growth time followed by a 12 min steady state burn was used to model a trash can fire in accordance with NUREG/CR-6850 [14] assumptions. The 3 MW prescribed steady state HRR fire was modelled to simulate a smaller fuel spill. The 70 MW fire was calculated using the ideal mass loss rate (MLR) for kerosene, which simulated a complete fuel spill. Due to the significant size of the fire, a small change in fuel properties by modelling one of the other fuels would not make a significant impact on the size of the fire.

Sprinklers were positioned in the model on the 540’ elevation as indicated on Drawing <Drawing Number Intentionally Removed>. Material properties for the concrete walls were taken from NUREG 1805 [10]. The ambient temperature range in 03RB is 18.3 – 51.6 °C (65 – 125 F), and the lower bound of the range was used for a more conservative sprinkler activation time.

The models were verified and validated to ensure their acceptability. The HRRs for the 317 kW and 3 MW fires were verified to work as prescribed by comparing their outputs to the expectations from the inputs. The 70 MW fire was verified against the mass loss rate, fuel surface area, and heat of combustion.

Table 2 shows activation times for sprinklers for each simulation. The 317 kW transient fires did not produce enough heat to activate the sprinklers either with or without the hatch cover. The 3 MW fires were able to activate the sprinklers at approximately 2 min with a small delay of 8 s in activation time due to the open hatch. Similarly, the large 70 MW fires, representing a complete spill, were able to activate the sprinklers within several seconds of ignition, and there was no delay for the open hatch. For a more detailed view of sprinkler activation, see the graph displaying sprinklers activated vs. time in Figure 4; Figure 5 and Figure 6.

Table 2 Sprinkler activation quantity and time, from simulations using FDS

HRR	Configuration	Number Activated	Time Activated	Delay
317 kW	open	0	N/A	N/A
	plugged	0	N/A	
3 MW	open	4	122 s	8 s
	plugged	7	114 s	
70 MW	open	18	9.6 s	0 s
	plugged	21	9.6 s	

The temperatures in the 03RB were monitored, in addition to sprinkler activation, with maximum temperatures shown in Table 3. The small transient fire did not pose any threat to the compartment boundaries being compromised due to temperature. A reasonably sized fire of 3 MW increased the gas temperature in the 562’ elevation but not to an extent capable of damaging unqualified cables, as per NUREG/CR-6850 assumptions [1]. The front side or fire side wall temperatures, shown in Table 2, were low enough to ensure that the back side or non-fire side wall temperature did not exceed a 121 °C (250 F) increase above ambient 18.3 °C (65 F), as per the ASTM E-119 standard [9]. Similarly, the front or fire side wall temperatures for the 70 MW fire were significantly below the requirements for ASTM E-119 [9].

While the gas temperature on the 562’ elevation was higher for the open hatch configuration for all fire sizes, the maximum wall temperature was not greatly affected by the hatch configuration. The peak fire boundary temperatures were located where combustion occurred by the stairwell in the closed hatch configuration and near the equipment hatch in the open hatch configuration.

Table 3 Maximum temperatures at and near the ceiling, from simulations using FDS

HRR	Configuration	Boundary Temperature	$dT_{boundary}$	562' Gas Temperature	dT_{gas}
317 kW	open	23.3 °C (73 F)	1 °C (3 F)	49.1 °C (120 F)	13.6 °C (24 F)
	plugged	24.3 °C (76 F)		35.5 °C (96 F)	
3 MW	open	38.5 °C (101 F)	5 °C (9 F)	114 °C (237 F)	12 °C (22 F)
	plugged	43.5 °C (110 F)		102 °C (215 F)	
70 MW	open	73.5 °C (164 F)	10 °C (18 F)	468 °C (874 F)	109 °C (196 F)
	plugged	83.5 °C (182 F)		359 °C (678 F	

The main difference between the two configurations (open hatch and closed hatch) was the time to suppression, seen in Figure 1, Figure 2 and Figure 3. For both the 3 MW and 70 MW fires, the fire was suppressed more quickly with the open hatch configuration than with the closed hatch configuration. The activated sprinklers entrained air down through the stairwell opening to provide circulation up through the open hatch, which allowed the upstairs section to benefit from the cooling effect of the sprinklers. This was not the case when the hatch was closed. These factors both together show that it is more beneficial, from a cooling standpoint, for the hatch area to be open.

Conclusion

Based on the FDS models and engineering judgment, the performance of the sprinkler system in the HPCI turbine room is acceptable with consideration of the maximum delay in sprinkler activation time for the open hatch configuration, as illustrated in Table 2. Additionally, the sprinklers maintain temperatures low enough, as per ASTM E-119 [9] criteria, for the fire barriers to prevent fire spread to other compartments. Due to the redundant systems available and the confinement of the fire to the fire area 03RB, the performance of this sprinkler system will not adversely affect the plant's safe shut down capabilities.

Supporting attachments to an open hatch in the HPCI room: These are included within this paper as a means to demonstrate the content that may be included within a FPEE.

Figure 1, Figure 2 and Figure 3 provide the results of a simulation run using FDS which demonstrate HRR profiles over time. Figure 4; Figure 5 and Figure 6 provide the results of a simulation run using FDS which demonstrates sprinkler activation vs. time.

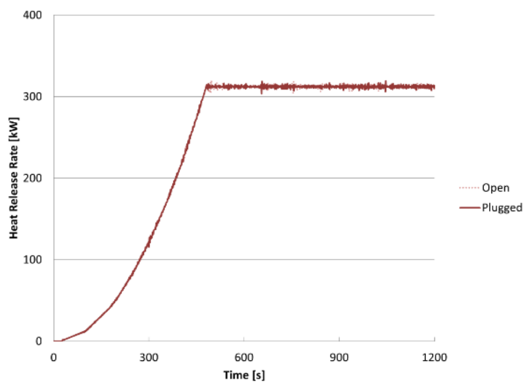

Figure 1 317 kW HRR profile

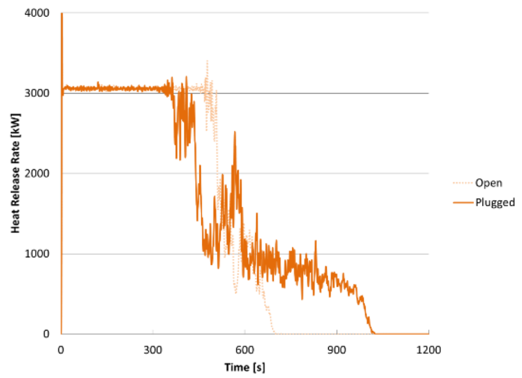

Figure 2 3 MW fire HRR profile

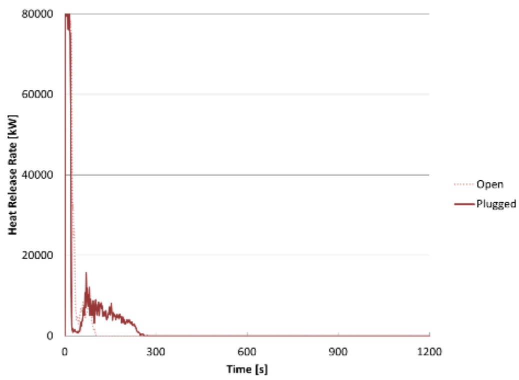

Figure 3 70 MW fire HRR profile

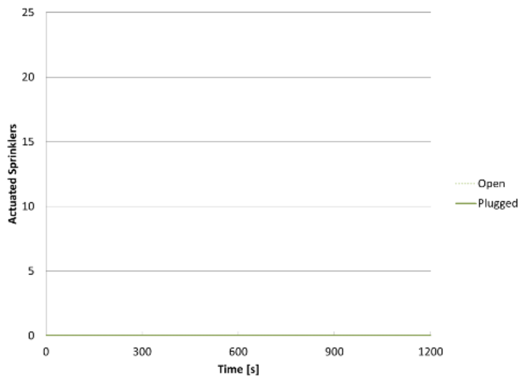

Figure 4 Sprinklers activated vs. time for 317 kW

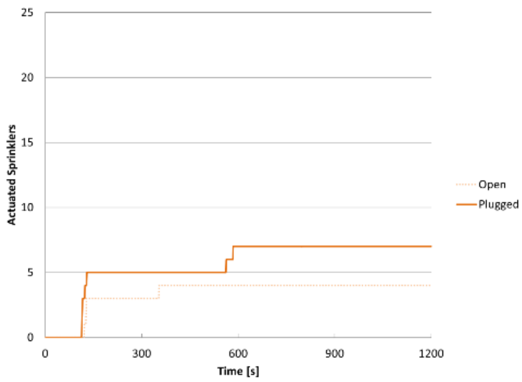

Figure 5 Sprinklers activated vs. time for 3 MW fire

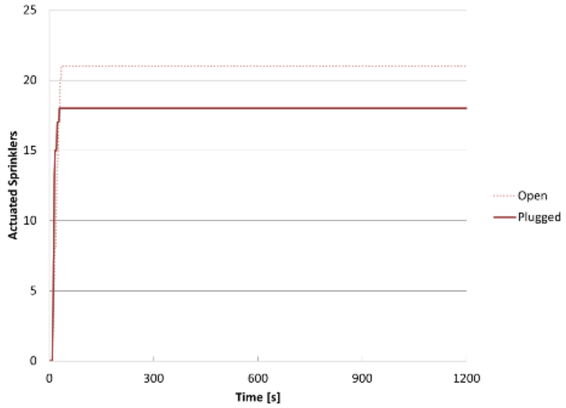

Figure 6 Sprinklers activated vs. time for 70 MW fire

C. Non-labelled Fire Doors in Concrete Walls

Description

Resulting from the utility self-assessment analysis of the power station's 10 CFR 50 Appendix R report, it was identified that there are a number of door assemblies in fire area boundary walls that do not have labels from recognized fire testing laboratory (e.g. UL). Most of these frames consist of steel channels that are an integral part of reinforced concrete or concrete block walls. The other frames consist of pressed steel frames that are rigidly attached to a reinforced concrete wall. These frames, although not labelled, are equivalent to labelled frames due to both their steel construction and their relationship to the wall.

This evaluation is being performed in accordance with Generic Letter 86-10 [2], Interpretations of 10 CFR 50 [1], Appendix R, Number 4, Fire Area Boundaries and Supplement 1 to Generic Letter 86-10 [3], Fire Endurance Test Acceptance Criteria for Fire Barrier Systems Used to Separate Redundant Safe Shutdown Trains Within the Same Fire Area. This interpretation states that "licensees must perform an evaluation to assess the adequacy of fire boundaries in their plants to determine if the boundaries will withstand the hazards associated with the area". This evaluation is not required to be submitted to the NRC staff for review; however, an earlier version of this evaluation was submitted and approved by the NRC (formerly filed as an Exemption Request).

The doors involved in this evaluation are the following:

- Door 7 – door from the turbine building to the turbine building lube oil storage room;
- Door 9 – door from the intake structure – oil tank room to the intake structure – emergency service water pumps.

Area Description

Fire areas are separated from each other by three-hour rated barriers or as otherwise evaluated by the engineering evaluations or Exemption Requests that are included in this report. Details concerning size and configuration of these areas are provided in the series of station drawings <Drawing Numbers Intentionally Removed>.

Fire Protection Features

All of the fire areas in this evaluation are equipped with smoke detection.

Most of the areas have fire extinguishers and hose stations are located in the area or just outside with ample hose to reach all parts of each area. The intake structure requires the use of the fire truck for manual firefighting.

Evaluation

This fire hazard analysis is divided into several sections. First, the two different types of door frames involved are examined. The frames are compared with UL Standard UL-63 [8] "Fire Door Frames". Second, the fire hazard associated with each individual door location (or group of doors in the same area) is examined. Each individual door location analysis will examine the following two factors that will influence the performance of the frame in a fire situation:

- Fire protection features present on each side of the door;
- Room and fuel configurations on each side of the door.

Door Frame Analysis

Most of the door frames in this evaluation consist of steel channels that are an integral part of a reinforced concrete or concrete block wall. Doors 7 and 9 are installed in concrete block walls; other channel steel frames are installed in reinforced concrete walls. Thickness of the steel channel used could not be verified but appears to be approximately 1/4 inch thick. The method of anchoring the channel into the wall is unknown; however, the channels appear to be cast in place in the concrete walls (i.e. the concrete fills the channel) or the steel is wedged tightly and grouted or anchored to the wall. A bar stock steel piece is attached to the channel steel piece in order to form the stop. The existing channel frames were compared with the required dimensions of UL-63 [8] Standard for Fire Door Frames for a single unit type steel channel frame. As can be seen from the comparison below, the existing steel frames meet or exceed the UL requirements. The doors also meet the associated requirement for maximum door opening size for this type of frame (6 ft x 12 ft for single door, or 10 ft x 12 ft for double door).

Table 4 Comparison of plant doors 7, 9 to UL 63 standard, from [8]

	Stop Width [inches]	**Stop Depth [Inches]**	**Throat Opening [Inches]**
Existing door	1 3/8 to 2	5/8	7 ¾, 8 or 12
UL standard	5/8	5/8	4 (minimum) 13 (maximum)
Existing door exceeds UL	yes	equals	equals

Fire Hazard Analysis Associated With Each Individual Door Location

The investigation concerns a turbine lube oil storage room door (fire door 7) and the intake structure – oil tank room door (fire door 9).

The above-mentioned doors separate the turbine lube oil room from the turbine building (fire door 7) and the Intake Structure – oil tank room from the rest of the intake structure (fire door 9). These doors both are installed in concrete block walls. Either one or both areas on each side of the door are equipped with a detection system and automatic suppression system. The impact of the combustibles located in these areas are considered to be minimized by the presence of the automatic suppression system discussed in the fire protection systems section.

Conclusion

The utility has determined that the current configuration of the fire door frames will provide equivalent protection to that required by 10 CFR 50, Appendix R [1] and GL 86-10 [2]. The technical bases which justify this conclusion can be summarized as follows:

- Fire detection and suppression systems are installed on at least one side of each fire door listed.
- The room and combustible configuration of most areas are such that the fire exposure in the vicinity of the doors will be minimized.
- Early notification provided by the fire detection systems and the room configuration will allow for prompt and effective fire brigade actions.
- The existing frames meet or exceed the UL standard on fire door frames (UL-63) [8] for most criteria.

CONCLUSIONS

FPEE provide an important tool that can be used to manage separation criteria. In the United States, fire protection programs have evolved to include a variety of treatments for use in these evaluations taking into consideration operational experience and new methods.

The use of FPEE can improve safety by

- focusing plant modifications/repairs on systems that improve plant safety,
- reducing the compensatory measures that may be required for inconsequential deficiencies,
- including a roadmap for dealing with apparent conditions that may not be in verbatim compliance with fire protection requirements.

ACKNOWLEDGEMENTS

I am extremely grateful for the mentorship provided by the ARS Fire Protection group, specifically Lee Warnick, P.E., Harold K. Lefkowitz, PE, and Barry Collyer. Without their years of guidance and training this paper would not have been possible.

REFERENCES

[1] United States Nuclear Regulatory Commission (U.S. NRC): Appendix R to Part 50 – Fire Protection Program for Nuclear Power Facilities Operating Prior to January 1, 1979, 10 CFR 50, Appendix R, Washington, DC, USA, 1979, https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appr.html.

[2] United States Nuclear Regulatory Commission (U.S. NRC): Implementation of Fire Protection Requirements, Generic Letter 86-10, Washington, DC, USA, April 1986, https://www.nrc.gov/reading-rm/doc-collections/gen-comm/gen-letters/1986/gl86010.html.

[3] United States Nuclear Regulatory Commission (U.S. NRC): Fire Endurance Test Acceptance Criteria for Fire Barrier Systems Used to Separate Redundant Safe Shutdown Trains within the Same Fire Area, Supplement 1 to Generic Letter 86-10, Washington, DC, USA, March 1994, https://www.nrc.gov/reading-rm/doc-collections/gen-comm/gen-letters/1986/gl86010s1.html.

[4] National Fire Protection Association (NFPA): NFPA 805 Performance-Based Standard for Fire Protection for Light Water Reactor Electric Generating Plants, 2025 edition, 2025, https://www.nfpa.org/codes-and-standards/nfpa-805-standard-development/805.

[5] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research: Regulatory Guide 1.189: Fire Protection for Operating Nuclear Power Plants, Washington, DC, USA, April 2001,

[6] United States Nuclear Regulatory Commission (U.S. NRC): Frequently Asked Question FAQ 06-0003, Greater than Minimal (ADAMS # ML063170355), Washington, DC, USA, 2006, https://www.nrc.gov/docs/ML0631/ML063170355.pdf.

[7] United States Nuclear Regulatory Commission (U.S. NRC): Frequently Asked Question FAQ 06-0008, Fire Protection Engineering Analysis (ADAMS # ML073380976, ML090560170), Washington, DC, USA, 2009, https://www.nrc.gov/docs/ML0733/ML073380976.pdf.

[8] Underwriters Laboratory (UL): UL-63 Standard Outline of Investigation for Fire Door Frames, Edition 2, 1991.

[9] ASTM International: ASTM E-119 Standard Test Methods for Fire Tests of Building Construction and Materials, 2011, https://store.astm.org/e0119-11.html.

[10] United States Nuclear Regulatory Commission (U.S. NRC): Fire Dynamics Tools (FDTs) – Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program, NUREG-1805, Washington, DC, USA, March 2021, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/index.html.

[11] National Fire Protection Association (NFPA): NFPA 13 Standard for the Installation of Sprinkler Systems, 1980 edition, Quincy, MA, USA, 1980, https://www.nfpa.org/product/nfpa-13-standard/p0013code/nfpa-13-80-pdf/1380pdf.

[12] United States Nuclear Regulatory Commission (U.S. NRC): NRC Positions on Certain Requirements of Appendix R to 10 CFR 50, Generic Letter 83-33, Washington, DC, USA, October 1983, https://www.nrc.gov/reading-rm/doc-collections/gen-comm/gen-letters/1983/gl83033.html.

[13] National Fire Protection Association (NFPA): NFPA 13 Standard for the Installation of Sprinkler Systems, 2010 edition, Quincy, MA, USA, 2010, https://www.nfpa.org/codes-and-standards/nfpa-13-standard-development/13.

[14] United States Nuclear Regulatory Commission (U.S. NRC) / Electric Power Research Institute (EPRI): EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Plant Facilities, Final Report, NUREG/CR-6850, EPRI 1011989, Washington, DC, USA, March 2021, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/index.html.

Use of the Building Information Modelling Approach in Support of Fire Hazard Analysis

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ABSTRACT

For any fire simulation model, getting an accurate building geometry is a fundamental and essential requirement, yet this can often be a challenging process. The conventional approach of transferring building information from printed drawings and databases to computer software applications is inefficient and time-consuming, error-prone and difficult to keep up to date. Therefore, there is a growing trend in the industry to use so-called "Building Information Modelling" (BIM) with the idea to be used throughout the entire building lifecycle enabling the recording, preservation and exchange of information. However, to create a "golden thread of information" in BIM from the fire safety engineering (FSE) perspective, many significant challenges and limitations must be resolved. This paper provides the basis for geometry and equipment position data transfer between a BIM to a fire zone code software as entry data. This enables designers to perform fire and smoke propagation simulations starting from a 3D model.

INTRODUCTION

In the international nuclear regulatory framework of nuclear power plants (NPPs) and more generally for nuclear installations, the license is required to perform a Fire Hazard Analysis (FHA) [1] which needs to be updated regularly within Periodic Safety Reviews (PSRs). The primary objective of the FHA is to demonstrate deterministically that the safety systems required to safely shut down the reactor, to remove the residual heat and to contain the radioactive materials are protected from external and internal fire for a specific set of conditions called a fire scenario. Specifically to the internal fire assessment, the scenario includes details of the room configurations (dimensions, contents, materials of construction, fire protection means, ventilation systems, arrangement of rooms in the building, etc.) but also the main fire scenario and targets inside or in the adjacent rooms. The outcome determination can be made by expert judgment, by probabilistic methods using data from past incidents, or by deterministic means either qualitative or quantitative approach such as fire models. In this work, the focus is on the deterministic quantitative approach, where fire simulations are used.

For any fire simulation model, getting an accurate building geometry is a basic and essential requirement, yet this can often be a challenging process, especially for 2D zones fire models. The conventional approach of transferring building information from printed drawings and database to computer software applications is inefficient, time consuming, and error-prone and difficult to keep up to date. Therefore, there is a growing trend in the industry to use BIM tools, which are the new generation of object-based CAD software applications capable of constructing and assembling building elements in a virtual environment. The BIM data produced by these tools come in various formats. Industry Foundation Classes (IFC) is a standardized non-proprietary data model which has started to be adopted as an international interoperability standard for sharing building information. The IFC data model allows the building geometry and materials property information to be exported from a BIM authoring tool to a standard format such as the IFC-compliant STEP (Standard for Exchange of Product Model Data) physical data file.

In this work, the IFC open standard BIM in combination with the fire simulations is used. A set of algorithms that overcome the incompatibility issues between the BIM and 2D zone fire model is developed. This enables designers to perform fire and smoke propagation simulations directly from a BIM model import. The algorithms automate the majority of the simulation workloads: from extraction of the necessary information from an IFC file to generation of the input file for the fire simulation code. The possibility to add the missing information regarding the thermal properties of different objects (like the walls) and fire loads from an external library is also developed. The capabilities and outcome of this data-sharing process will be illustrated using a test case building and performing a fire simulation for a pre-defined scenario.

Building Information Modelling (BIM)

BIM involves creating a virtual model of a building by defining its components and associated information. This model is stored in a database with parameters and relationships, which helps identify conflicts and design issues. BIM uses building components such as walls, windows, doors, roofs, vent system, etc. to represent a building. These building components contain geometric information and, in some cases non-geometric information such as materials and the properties of the materials. In addition, BIM also stores the relation information between multiple components. The structure that BIM stores data enables the supply of the necessary information throughout the lifecycle of a building: design, construction, operation and demolition.

OpenBIM, an initiative by buildingSMART (a non-profit organization), supported by leading software vendors, introduced a data model known as Industry Foundation Classes (IFC) to overcome data sharing and interoperability problems. IFC is an open standard for BIM data exchange and sharing among collaborators in a building project. It consists of four conceptual layers (resource, core, interoperability, and domain), each containing various schemas to capture and share both general and discipline-specific building data.

However, when it comes to sharing data between BIM and FSE tools (specifically fire and evacuation modelling tools), while certain levels of support for necessary FSE input data exist within BIM tools, no FSE-specific information exchange is available. It is worth noting that despite this limitation, certain BIM software like Autodesk Revit® allows users to include custom data to elements. Nonetheless, having explicit support in the IFC Model is crucial for ensuring a consistent approach across various BIM platforms that is not tied to a specific project.

On the other hand, the level of support for BIM data within fire modelling tools is quite restricted [2]. Only a limited number of FSE modelling tools can extract building geometry from IFC files.

Therefore, the focus of this work is to present the strategy for BIM integration and steps taken to enhance the level of support for BIM data within the fire modelling where the main development steps are described below.

Fire Modelling

In FSE, the fire modelling tools can be classified as zone models (2D) or field models (3D), also known as CFD (*c*omputational *f*luid *d*ynamics) models. The two types of models are inherently different. Zone models are simpler, and the simulation running time is very short, usually below a few minutes. On the other hand, CFD models are more complex, and the simulation running time is much longer, usually days to weeks.

In this work, the two-zone model CFAST (free and open-source software provided by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce) is used. It is a two-zone code internationally used for fire safety development, fire compartmentation or fire probabilistic risk assessment (FPRA). This kind of codes are used for FHA of operating as well as future nuclear power plants. 2D zone model codes are based on the stratification of a hot layer above a cold one, where mass and heat balances are solved, and the upper zone is filled up with hot gases and smoke by the thermal plume (cf. Figure 1). The mass and energy balance equations carried out on each area, together with the equation of the heat diffusion in the walls meshed according to their depth, allow calculation of aerothermal conditions of the rooms during the postulated fire.

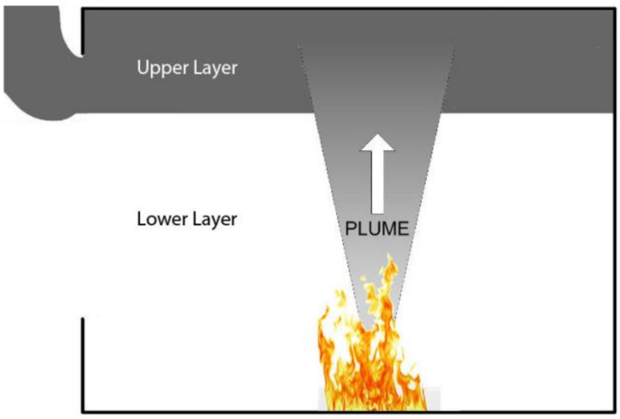

Figure 1 Two-zone model illustration

Although this kind of model has a big advantage of being fast comparing to CFD models, its simplified simulation model places a different challenge to the integration with BIM. The type of model used in this study describes the shape of a room with only three parameters, width, depth, and height. With these three parameters, the only shape of rooms that can be simulated is cuboid, despite the variety of shapes of rooms in real-world buildings. This simplification causes incompatibility between real-world buildings, their representation in BIM and the zone models. In this work, a set of algorithms was provided to solve the incompatibility between BIM and the simplified zone models.

Overcoming Geometry Limitations

Zone models describe the shape of a room with only three parameters, width, depth and height. With these three parameters, the only shape of rooms can be simulated is cuboid. Conventionally, users must manually transform the rooms of various shapes to cuboids in order to perform smoke propagation simulation in a 2D zone model code. This transformation process is time-consuming and likely to generate different results depending on the methods each individual uses to transform the shapes. Therefore, to reconcile the different geometry representations between BIM and 2D zone model codes, a transformation algorithm is developed and implemented in this work. This algorithm automatically transforms any shape of non-cuboid rooms to be compatible for 2D zone model codes simulation.

This operation consists of transforming rooms with complex shape into an equivalent parallelepipeds retaining both the physics of fire and its interaction with the equipment (fire exposed one = targets) present in the room. The following elements that are taken into account in a fire scenario:

- Fire: source of ignition, flame, thermal plume, ceiling jet, hot layer;
- Ventilation: openings or mechanical ventilation;
- Interactions between fire and targets.

In order to ensure that the scenario simulated y the zone model is not altered by geometric transformation operation, certain constraints must be respected. These are grouped into two main categories:

- Constraints of geometric transformation of the room:
  - The volume of air present in the room affects the power of the fire. The volume of the room is therefore kept constant during the geometric transformation. This ensures that the amount of oxygen available remains the same before and after transformation. It also ensures that the filling of the room by the hot smoke remains the same.
  - In order to have the same characteristics of the ceiling jet, the height of the room is kept constant as well.
  - The transformation of the rooms preserves the surface of these different openings as the air available through the openings strongly influences the power of the fire. This air supply depends on the geometry of the openings (surface, height). Openings can also influence the kinetics of smoke spread and the fire propagation to neighbouring premises. Because of these reasons the neighbouring rooms communicating with the room which is part of the scenario are also taken into consideration.
- Constraints of positioning of elements inside the room – the objects/equipment located in the room before the transformation are re-positioned inside of the room if they are located outside of it after transformation.

Figure 2 illustrates some of the main principles of the transformation listed above.

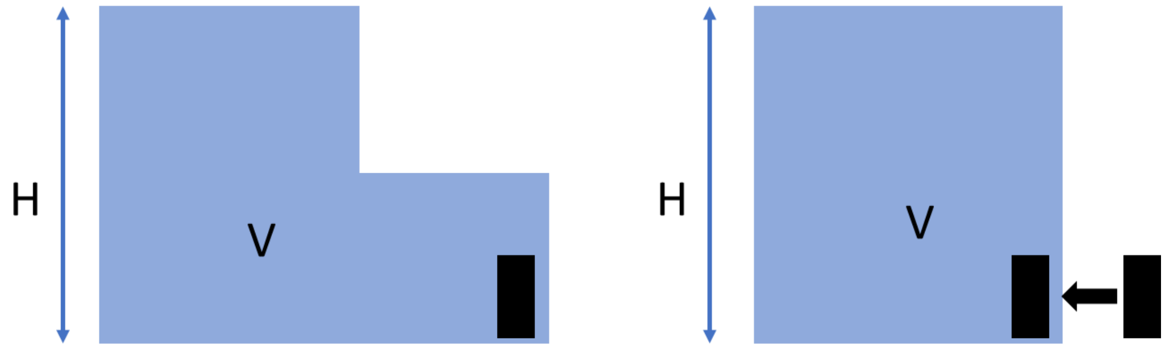

Figure 2 Illustration of the geometry transformation (not scaled)

The algorithm calculates the new length and width of the transformed room. The transformation can be applied to any shape of the room.

Automation: BIM-2D Zone Model Tool

An interface application is developed in order to integrate the smoke propagation simulation and the BIM using the algorithm for the geometry transformation described above. The flowchart in Figure 3 shows the main principle of the application developed.

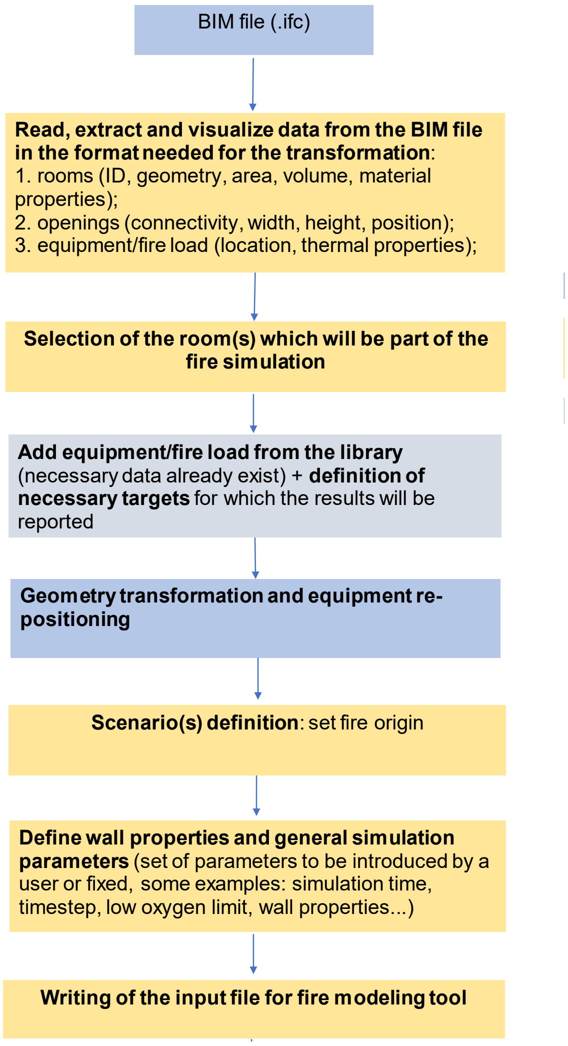

Figure 3 System diagram

With the user interface, the user gains the capability to access the input file, initiating a smoke propagation simulation with just a few simple actions. As the simulation finishes, the 2D zone code tool generates an output file which compiles the results of the conducted simulation.

Figure 4 depicts the user interface where it is also possible to visualize the geometry after transformation.

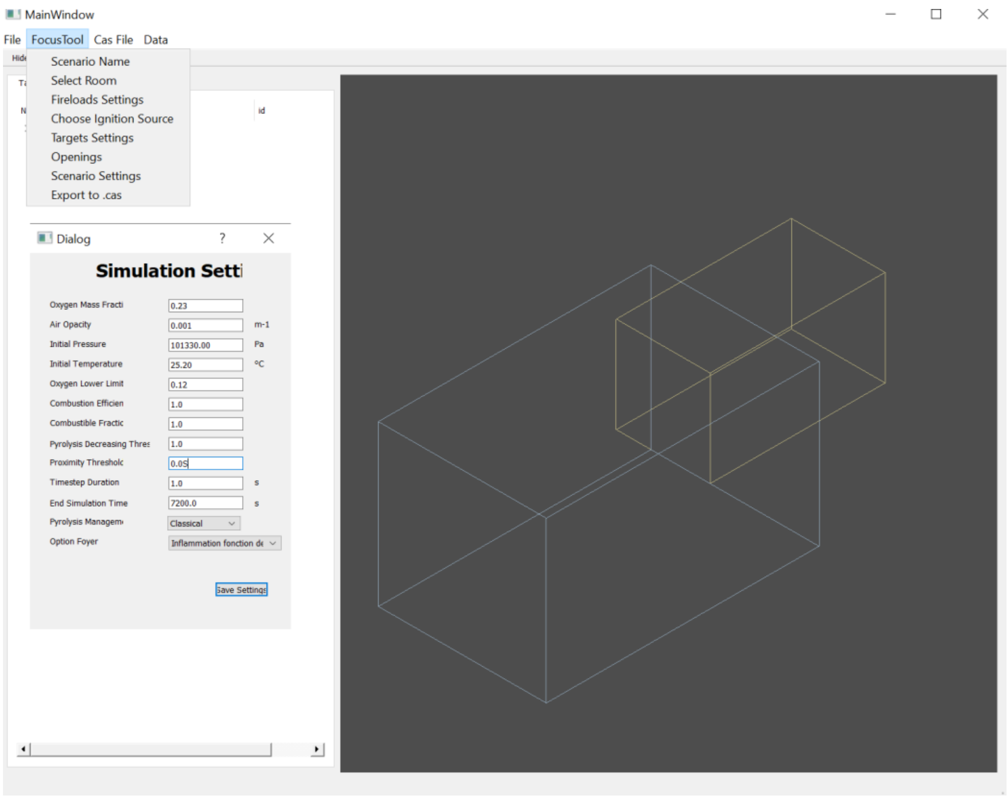

Figure 4 Screenshot of the application developed with the graphical view of the model and the simulation parameters filled in

RESULTS

An IFC file available in the literature is chosen for this work. It considers a large building where two rooms with an opening in between were selected in order to test the tool. The rooms (room where the fire is located and the adjacent room) are shown in Figure 5 before and after the transformation.

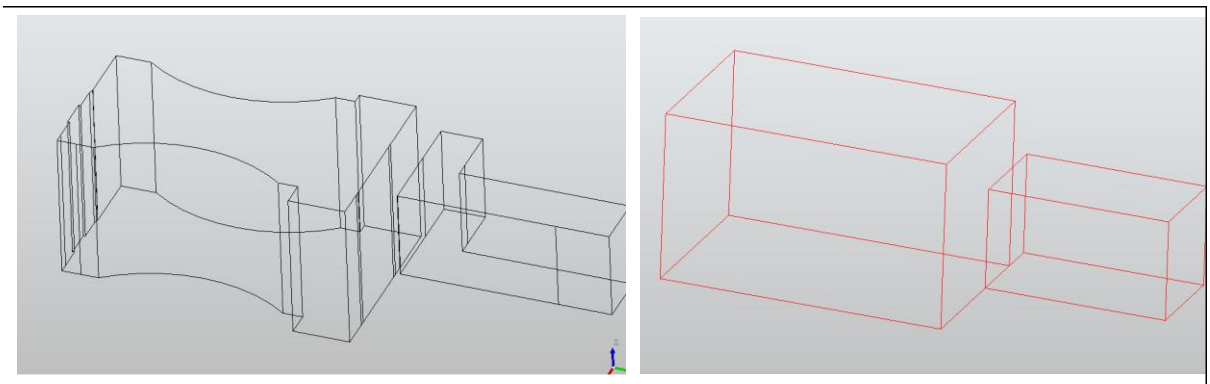

Figure 5 Rooms before (left) and after transformation (right)

Table 1 gives the lengths and widths before and after transformation. As it can be seen the volume of the rooms and height are fixed while the new length and widths are recalculated.

Table 1 Room configuration before (left - red) and after transformation (right - green)

Room	Room 1 (2AC1)		Room 2 (2AC2)	
Transformation	before	after	before	after
Length [m]	varies	4.89	varies	2.73
Width [m]	9.79	7.94	6.71	5.09
Height [m]	4.68	4.68	2.8	2.8
Volume [m^3]	181.86	181.86	38.99	38.98

CONCLUSION

A new software system architecture has been developed in order to allow the use of BIM information in fire simulations.

The incompatibility between smoke propagation simulation models that use simplified building representations and BIM that uses complex and complete building representations, is the primary challenge of the integration. This work implemented the algorithm that overcomes the incompatibility issue and thus enables to perform smoke propagation simulation directly on a BIM model. Given the complexity of the IFC data model and the variants in the current BIM methods and data interoperability standards, the data mapping implementation is currently limited to basic building geometry and detection of the surrounding rooms.

The initiatives taken by the developed interface application provide a considerable cost saving and improvement in the quality of data exchanged for fire simulations and fire safety design in general.

The software prototype developed in this work can be generalized to other zone models and BIM authoring applications.

Further work is needed on post-treatment of data to fully implement the tool. By transforming data (new coordinates of the fire source and targets) and analysing the temperature of the fire plume, ceiling jet as well as hot and cold layers, the tool can assess whether targets are lost or saved.

REFERENCES

[1] International Atomic Energy Agency (IAEA): Protection against Internal Hazards in the Design of Nuclear Power Plants, Specific Safety Guide, IAEA Safety Standards Series No. SSG-64, STI/PUB/1947, ISBN 978-92-0-116121–5, Vienna, Austria, August 2021, https://www-pub.iaea.org/MTCD/publications/PDF/Pub1947_web.pdf.

[2] Siddiqui, A: A., et al.: Building Information Modelling for performance-based Fire Safety Engineering analysis – a strategy for data sharing, Journal of Building Engineering, 42(3):102794, 7, 4, pp. 697 - 717, May 2021, DOI: 10.1016/j.jobe.2021.102794.

3.4 Topical Session on Probabilistic Fire Risk Assessment

Probabilistic fire risk assessment is another topic with increasing interest in the nuclear fire safety experts' community. The fourth topic session of the seminar was accordingly chaired by Marina Röwekamp (GRS, Germany) as one of the permanent organizers of the seminar and Vice Chair of the OECD Nuclear Energy Agency (NEA) Working Group on Risk Assessment (WGRISK).

The presentation by Roman Grygoruk (Framatome, Germany) discussed the significant role of fire compartmentation within probabilistic fire safety analysis (Fire PSA) for nuclear power plants, with specific reference to the Olkiluoto Unit 3 (OL3) nuclear power plant in Finland. Fire compartmentation, which involves subdividing plant buildings into compartments surrounded by qualified fire barriers, is a cornerstone of the defence-in-depth strategy for fire protection, ensures that fires do not compromise redundant safety systems essential for safe shutdown and containment of radionuclides.

The authors explained the design principles of the OL3 fire protection concept, which is in accordance with the EPR Technical Codes and the Finnish YVL Guides. The concept incorporates both fire containment and fire influence approach, depending on spatial constraints. Safety fire compartments and fire cells are defined to prevent redundant trains of the safety systems against common cause failures, by suitable fire resistance ratings ranging between 60 and 120 min.

The underlying paper also outlines the deterministic Fire Hazard Functional Analysis (FHFA), and the Fire PSA performed during different project phases. The FHFA demonstrates that sufficient redundancy remains operable after a postulated fire, while the Fire PSA provides quantitative insights into the fire risk. The Fire PSA evolved through three stages, increasing in detail and complexity, from compartment-based assumptions to room-level partitioning.

Key findings highlighted in the presentation are the balance between detailed plant partitioning and model complexity. While finer partitioning improves the accuracy of the results; however, increases computational demands. The study concluded that fire compartmentation significantly influences the outcomes from Fire PSA and that careful consideration of cables, spatial separation, and fire barriers is essential for credible risk assessment.

Another presentation from Finland, by Timo Virtanen from FORTUM provided an approach for converting a fault tree based Fire PSA model into an event tree based one. The presentation outlined the process and implications of such a conversion fi for the Loviisa nuclear power plant in Finland. While the original Fire PSA for Loviisa, Unit 1 used fault trees, the newer model for Unit 2 employed event trees. Differences in the modelling approaches led to discrepancies in risk estimates for similar rooms, prompting the need for harmonisation.

The conversion aimed at maintaining logical consistency between fire scenarios, initiating events, and mitigation measures while improving readability and updateability. Event trees allow better integration with Level 1 and Level2 PSA and facilitate more precise modelling of cable routes and component losses. Unlike the older approach, which relied on predefined boundary condition sets, the new methodology dynamically accounts for cable failures based on room-level fire scenarios.

Findings indicated that the conversion increased the overall fire risk estimate by approximately 24 % for power operation, primarily due to more comprehensive consideration of cable routes. Benefits of the event tree approach include enhanced flexibility, easier updates, and better linkage between PSA levels, although this approach also resulted in larger event trees and longer computation times. Overall, the new approach supports more robust risk-informed decision-making.

The third and last presentation in this session by Koji Shirai from CRIEPI NRRC (Japan) described the development of fire probabilistic risk assessment (FPRA) infrastructures in Japan and the collaborative PRELUDE program between EDF and CRIEPI. The PRELUDE program, conducted at the IGNIS experimental platform of EDF, focuses on large-scale fire tests in confined environments to improve the understanding regarding the fire behaviour and its impact on electrical equipment. The PML campaign within this program investigates smoke stratification and thermal effects in a multi-room gallery configuration.

The first research area of the campaign involved four fire experiments using different liquid fuels. The results showed that diesel fuel produced the highest soot concentrations and significant thermal output, making it suitable for subsequent tests on electrical equipment. Measurements included heat release rates, temperature profiles, heat flux, and soot concentrations, providing valuable data for validating fire simulation models.

The applicability of the BRI2-CRIEPI zone model for predicting compartment fire behaviour under mechanical ventilation was also analysed. Comparisons between experimental results and model predictions demonstrated good agreement for mass loss rates and interface heights, though some discrepancies in hot gas temperatures were noted. These findings support the use of the model n FPRA for nuclear facilities.

Future work in the second research area will assess the combined effects of smoke, heat and radiation on electrical cabinets under diesel pool fire conditions. In conclusion, the PRELUDE program enhances FPRA capabilities by providing realistic fire scenarios and validating advanced simulation tools, thereby supporting risk-informed safety improvements in nuclear power plants.

The seminar contributions of this topical session are provided hereafter.

Fire Compartmentation as A Key Element of A Probabilistic Fire Analysis

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ABSTRACT

In general, the fire protection approach in nuclear power plants (NPPs) is based on the arrangement of redundant equipment in physically separated fire compartments, where possible, surrounded by qualified fire barriers. If the physical separation is not possible due to the nature of the system, e.g. within the reactor building, the fire influence approach can be applied. By the fire influence approach, redundant equipment can be located within the same fire compartment but is safeguarded by providing sufficient spatial separation between the redundant trains and/or by using protective enclosures, fire-resistant coatings or flame-retardant insulation.

The principles of fire compartmentation of the NPP buildings are established in the fire protection design. The fire compartments form the fundamental basis for the subsequent deterministic fire safety analysis and a probabilistic fire risk/safety analysis (Fire PSA). In the frame of the Fire PSA, fire compartments have been transferred into fire areas which are physical analysis units specific to the Fire PSA.

This paper provides insights gained during the development of the Fire PSA for the Olkiluoto NPP, Unit 3 (OL3). In the frame of this development the scope and the level of detail of the Fire PSA have been gradually extended. In particular, special attention has been given to the level of plant partitioning, i.e. definition of fire areas within fire compartments, and its effects on the Fire PSA results.

INTRODUCTION

Not all large NPP fires are significant from a safety point of view, nor are all safety significant fires large. Differences in such details such as the routing of electrical cables, the separation and orientation of cable trays, the fire protection means implemented in a particular compartment, and the procedures employed by the plant operators in response to a fire can drastically alter the risk significance of real and postulated fires. Fire PSA is a quantitative tool for addressing all these details composing a fire protection concept and showing how they relate to risk, [1].

The fire protection concept at the OL3 NPP establishes the fire protection provisions required for the protection of structures, systems and components (SSC) important to safety as well as the procedures, equipment and personnel required to implement these. The general design of the fire protection concept of OL3 is based on the requirements of the EPR Technical Codes for Fire Protection [2]. The detailed design, however, is based on the Finnish regulations that govern the safe use of nuclear energy – the YVL Guides (particularly [3]). Whenever it is possible from a nuclear safety viewpoint, the design of the fire protection concept also meets the requirements of conventional Finnish fire related codes/standards. Although the design of the fire protection concept is influenced by the building characteristics specific to nuclear facilities.

The OL3 fire protection concept ensures through a defence-in-depth design that the occurrence of a fire will not prevent bringing the plant to and maintaining it in a safe shutdown state and will not significantly increase the risk of radioactive releases to the environment. The defence-in-depth strategy for fire protection is applied with maintaining a balance between the following levels:

1. Fire prevention
   Limit fire ignition sources by using non-combustible and fire resistant or flame-retardant materials as much as possible throughout the plant area in order to prevent fires from starting.
2. Fire containing
   Provide protection for structures, systems, and components to ensure the operability of redundant safety system equipment essential to safety.
3. Fire controlling
   Promptly detect, control, and extinguish those fires that do occur.

Fire compartmentation which corresponds to “fire containing” is a crucial concept in the field of fire safety in general which aims at reduction of the likelihood of fire and other effects spreading to other SSC important to safety. As such, fire compartmentation is a key element of a probabilistic fire risk analysis.

TERMINOLOGY

Fire Barrier

Walls, floor, ceiling or devices for closing passages such as doors, hatches, penetrations and ventilation systems, etc., used to limit the consequences (the spread) of a fire. A fire barrier is characterized by a pre-defined fire resistance rating.

Fire Compartment

A building or part of a building comprising one or more rooms or spaces, constructed to prevent the spreading of fire to or from the remainder of the building or part of the building for a given period of time. A fire compartment is completely surrounded by qualified fire barriers.

Note: The terms fire compartment and fire cell are essentially analogous to the fire area and fire zone terms used in codes, standards and guidance documents in the United States of America. Therefore, this definition is different from the same in [4] where “*A fire compartment is a well-defined enclosed room, not necessarily with fire barriers. Fire compartments generally fall within a fire area…”.*

Fire Cell

A fire cell is a subdivision of a fire compartment in which fire separation between items important to safety is provided by fire protection provisions (such as limitation of combustible materials, spatial separation, fixed fire extinguishing systems, qualified fireproof coatings or other features) such that consequential damage to other separated systems is not expected.

Foreign Cable

A foreign cable is a cable in a division (redundant train) but is allocated to another division (redundant train).

(Probabilistic) Fire Area

The term fire area is specifically defined for Fire PSA and maps plant fire compartments and/or cells, defined for the plant and based on the fire protection design and/or operations considerations, into discrete physical analysis units that form the fundamental basis of the Fire PSA.

Note: This definition is different from that in [4], where a *fire area is an area that is bounded by non-combustible barriers where heat and products of combustion from a fire within the enclosure will be substantially confined.*

Separation, spatial

Spatial separation is the separation of items important to safety of different redundant trains / divisions by installing them in different rooms or in a sufficient distance free of any combustible products, in order to prevent the simultaneous loss of both systems and components by a single fire.

Separation, physical

Physical separation is the separation of items important to safety of different redundant trains / divisions by installing them either in two separate rooms of which at least one constitutes a fire compartment in order to prevent the simultaneous loss of more than one redundant item by a single fire.

DESCRIPTION OF THE FIRE PROTECTION CONCEPT

The fire protection concept at OL3 establishes the fire protection measures required for the protection of SSC important to safety; and the procedures, equipment, and personnel required to implement them. The fire protection measures have been designed to ensure that in the event of a fire the reactor can be safely shut down and radioactive releases to the environment are minimized.

The main safety systems intended to achieve safe shut down of the reactor and to remove residual heat from the core are divided into redundant safety trains or divisions that are physically and/or spatially separated. Each redundant safety train / division is contained within one building, where possible. This divisional separation is provided for all mechanical and electrical systems including instrumentation and control.

There are two design approaches used to ensure the operability of redundant safety system equipment, which are based on room arrangements and fire compartmentation: fire containment approach and the fire influence approach. With the first approach, redundant items important to safety are actually located in separate safety fire compartments. The fire containment approach assumes that all combustibles within a fire compartment can be consumed during a fire. If the use of the fire containment approach cannot be realized due to the overall layout of the facility the fire influence approach is often used subdividing the compartments into the fire cells.

The partitioning of buildings into fire compartments and fire cells offers different levels of protection against fire. Fire compartments are completely enclosed by qualified fire barriers and their elements such as fire-resistant walls, floors and ceilings as well as openings, penetrations, etc. are protected with fire resistant materials. Fire compartments are designed to contain a fire without compromising the integrity of the fire barriers. Therefore, the fire resistance rating of the fire barriers for each fire compartment may vary, depending on the type of fire compartment, the fire load (or fire load density) and the level of protection required. There are different types of fire compartments defined for OL3 having fire resistance rating as required by Finnish fire protection legislation:

- Safety fire compartments (SCOs) are designed to safeguard the redundant trains responsible for performing safe shutdown operations against a common cause failure. The fire barriers of safety fire compartments have a minimum fire resistance rating of 120 minutes.
- Protected rescue (access and escape) route fire compartments (RCOs) are designed to provide protection for the evacuation of personnel in the event of a fire or to provide protection of the fire brigade during emergency response situations. The fire barriers of protected rescue route fire compartments have a minimum fire resistance rating of 60 minutes.
- Unavailability limitation fire compartments (UCOs) are designed for further separation to limit fire spread inside the facility, to enable safe escape of the plant personnel and to facilitate prompt response from the fire brigade. The fire barriers of most unavailability limitation fire compartments have a minimum fire resistance rating of 60 minutes. However, based on larger fire loads, some unavailability limitation fire compartments have a minimum fire resistance rating of 90 minutes or 120 minutes.

All fire compartment boundaries are used to provide a means of separation from adjacent fire compartments, and each fire barrier is constructed to withstand the exposure to fire for the minimum duration indicated by the associated fire resistance rating classification.

Fire cells are used in limited instances where the design and layout of systems and equipment prevent certain portions of the facility from being systematically subdivided into fire compartments. Therefore, such compartments are subdivided into fire cells to provide SSC important to safety with protection against the spread of fire. This is accomplished by maintaining adequate spatial separation between the redundant trains and/or using protective enclosures, fire-resistant coatings or flame-retardant insulation. Safety fire cells (SCEs) are designed to safeguard the redundant trains responsible for performing safe shutdown operations against a common cause failure.

To ensure the adequacy of the fire protection measures for the safety SSC during all operational states of the plant, a Fire Hazard Analysis (FHA) was performed, prior to the construction of the facility [5]. The FHA demonstrated the adequacy of the fire barriers between different redundant trains as well as the common fire protection concept so that the general safety design requirements set forth in the Fire Protection in Nuclear Power Plants Safety Standard [6] and the Code on the Safety of Nuclear Power Plants: Design [7] are adequately met.

Further analyses on fire safety are provided in the deterministic Fire Hazard Functional Analysis (FHFA) and in the probabilistic fire risk analysis (Fire PSA) as described below.

DESCRIPTION OF FIRE ANALYSES

Deterministic Fire Hazard Functional Analysis

For the licensing of the OL3 reactor unit both deterministic (FHFA) and probabilistic (Fire PSA) fire analyses have been performed.

The primary objective of the FHFA is to demonstrate that the plant can be brought to and maintained in the safe shutdown state after a postulated fire. Consequently, FHFAs demonstrate for all safety related buildings that a sufficient number of redundant systems remains operable to reach and maintain safe shutdown and to cope with the fire in a safety fire compartment or safety fire cell, respectively.

In the FHFA the functional failure of all equipment is conservatively assumed within the safety fire compartment or safety fire cell where the fire is postulated, except if protected by qualified fire barriers, designed to or able to resist the fire consequences.

The FHFAs are carried out considering certain boundary conditions such as:

- Fire barriers between the different redundancies are adequate to withstand the fire and prevent the fire spread to adjacent redundant trains.
- No credit is taken from automatically actuated fire extinguishing systems and manual firefighting equipment.

The FHFAs are elaborated with regard to the subdivision of the buildings into SCOs and SCEs.

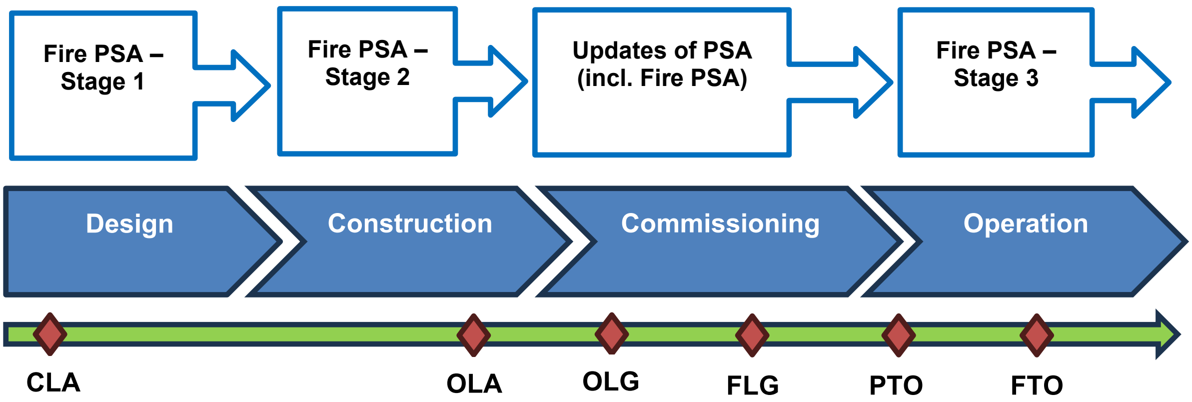
Probabilistic Fire Safety Analysis (Fire PSA)

The OL3 PSA has been developed from the very beginning starting already from the OL3 basic design and went through different project phases – detailed design, construction and commissioning phases. The OL3 PSA was latest updated by the plant supplier to the as-built configuration and submitted to the customer as part of final documentation for the plant provisional take-over. During the construction and commissioning phases of the OL3 unit the PSA model was mainly used for the safety assessment of design changes and licensing purposes as well as for risk-informed applications. After the OL3 plant had started commercial operation the OL3 PSA model is intended to be used additionally for plant operation tasks and within the decision-making processes.

The OL3 Fire PSA has been gradually performed starting already from the plant design phase to provide probabilistic insights for the design. The Fire PSA has been requested as well for licensing purposes [8]. During the basic design of a NPP, however, not all information usually needed for a detailed Fire PSA is available. Cable fires are playing an important role in the Fire PSA, but the cable routing was not planned during the basic design phase. Therefore, a methodology has been developed which made use of the strict divisional separation of redundant trains in the design of the OL3 unit and did not need the detailed cable routing within the divisions but used conservative bounding assumptions that all equipment fails due a fire in the division concerned. Thus, the methodology applied provided conservative results [9].

To align the Fire PSA development to the plant design, construction and commissioning progress it was being performed in several stages (cf. Figure 1):

- Stage 1 is performed on a component level started already during the plant basic design phase without detailed information on cable routing. It is based on a so-called "compartment-based approach" assuming that any ignition, if not timely suppressed, grows to a developed fire and once it reaches the closest target all components within the fire area are lost due to fire. In this stage the fire area corresponding to a SCO or SCE, it means the entire safety division is unavailable as consequence of the fire. Thus, the stage 1 of the Fire PSA follows the level of the plant partitioning applied in the FHFA.
- With Stage 2 (the so-called extended Fire PSA) the information on cables was incorporated into the modelling. It consists not only of analysing and screening the cables from the source to the destination (target) but also considering failure modes related to the cable failures (circuit analysis).
- Stage 3 is currently in progress and considers plant repartitioning from SCO/SCE level to the UCO/RCO level or in some case even to the room level.



CLA – Construction License Application; FLG – Fuel Loading Granting;
OLA – Operating License Application; PTO – Provisional Take Over;
OLG- Operating License Granting; FTO - Final Take Over.

Figure 1 Fire PSA development scheme

FHFA AND FIRE PSA INTERFACE ANALYSIS

Aim of the interface analysis is to determine the consistency between the above-mentioned analyses – FHFA and the Fire PSA. Both types of analyses partly share a set of components assumed to fail or to be inadmissibly impaired by the fire hazard. In the interface analysis also both methods are compared – for example, their boundary conditions, scope and the failure modes applied. The differences between the Fire PSA and the FHFA have been justified case -by case.

PLANT PARTITIONING IN THE FRAME OF FIRE PSA

A fire area concept is a concept used in the Fire PSA to map the fire compartments and fire cells into suitable entities from the Fire PSA modelling point of view. In some cases, a fire compartment is equal to a fire area; however, a fire area may be composed of several fire compartments or a fire compartment or even fire cell may be divided into more than one fire areas.

For the purposes of the Fire PSA, the plant is subdivided into a number of probabilistic fire areas (PFA). The analysis considers the impact of fires in a given fire area and fires that might impact multiple PFAs. Hence, the definition of probabilistic fire areas is critical to the analysis. It is important that fire areas be defined in a reasonable manner that appropriately supports the Fire PSA.

As recommended in [4], a starting point is the identification of the fire compartments defined in the context of the plant's regulatory compliance fire protection program. The fire compartment definitions used in regulatory compliance should then readily satisfy the PSA fire area partitioning criteria. Another factor that is considered in the partitioning exercise is the level of detail available for mapping Fire PSA components including cables within the plant. If the information available cannot support the mapping to the level of partitioning exercised at a given project stage, the value of the additional partitioning is reduced. Retention of larger and more clearly delineated fire areas is generally considered in the more conservative approach.

Like that, with the Stage 1 of the Fire PSA the definition of a fire area basically followed the definition of a safety fire compartment/cell within the fire protection concept.

Within Stage 2 the subdivision of a few fire areas analysed in the Stage 1 into smaller units was performed. The necessity to do so was, for example, through the identification of "foreign" cables which would lead to the fire impact on more than one division (redundant train) if the former fire area remains unchanged. However, the plant partitioning remains at the level of safety fire compartments/cells. With the update of the PSA including Stage 2 of the Fire PSA during the plant commissioning phase, the definition of UCOs inside SCOs was considered in the way to localise the ignition. However, after fire grows and propagates the entire SCO is assumed as affected. In conjunction with a "compartment-based approach" it is assumed that all components within the SCO are lost due to fire. Thus, the Stage 2 of Fire PSA remains far conservative with respect to the definition of the fire area.

The change in plant partitioning came later within Stage 3 of the Fire PSA where the definition of probabilistic fire areas changed from the SCO level to the unavailability limitation fire compartments (UCOs) and protected RCOs or in several cases to the room level. Stage 3 of the Fire PSA is however, limited to the most important buildings with respect to their contribution to the Fire PSA results (graded approach).

Table 1 presents a rough comparison of the modelling complexity in terms of elements in Fire PSA model such as number of fire areas and integral number of targets (basic events affected by fire) for different stages of the Fire PSA. The increasing modelling complexity with each next stage negatively affects the computation time and challenges the minimal cut sets (MCSs) searching engine of the related PSA tool. Therefore, the balance between the expected results determined by the level of the plant partition and consequential model complexity should be kept in mind when developing the Fire PSA.

Table 1 Comparison of the modelling complexity for different Fire PSA stages

Development Stage	Single-Compartment Analysis		Multi-Compartment Analysis	
	Number of PFA	**Number of Targets**	**Number of PFA Pairs**	**Number of Targets**
Stage 1	about 40	about 1900	about 10	about 1400
Stage 2	about 50	about 2100	about 20	about 1600
Stage 3	more than 180	more than 5000	*(not yet available)*	*(not yet available)*

Presenting the results of the Fire PSA obtained for each probabilistic fire area the contribution of each fire area can be summed-up to the contribution of corresponding plant building. Figure 2 presents the distribution between different plant buildings dominantly contributing to the Fire PSA results[1] in each stage. The five "most important" buildings are compared:

Building 1 houses safety related systems relevant to reach and maintain a safe shutdown state and has strict physical separation of redundant safeguards.

Building 2 houses systems relevant to normal plant operation and has strict physical separation of redundant system trains.

Building 3 houses both system relevant to normal plant operation as well as safety-relevant components/cables but the separation between redundant system trains is mainly spatial.

Building 4 houses systems relevant to normal plant operation without strict physical separation of redundant system trains.

Building 5 houses systems relevant to normal plant operation but has neither physical nor spatial separation of redundant system trains.

[1] Results are for single-compartment scenarios with the fire occurring when plant is at power.

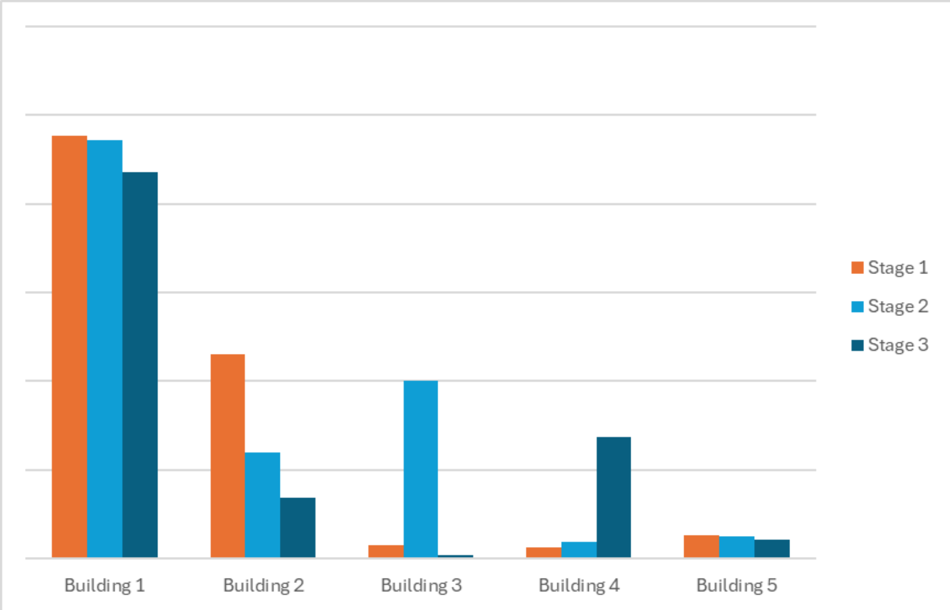


Figure 2 Contribution of plant buildings to the Fire PSA results at different stages

The following insights are gained when comparing the results:

1. For buildings having strict physical separation between redundancies the "deeper" plant partitioning is the less conservative results can be obtained. "Foreign" cables, however, are playing an important role when performing partitioning.
2. For buildings having only spatial separation between redundancies the information on the routing of cables, however, is crucial as it can impact the significance of the fire area under discussion.
3. Incorporation of cables into the Fire PSA has not only an impact on the plant partitioning but also provides new considerations for the analysis, e.g. new failure modes and/or scenarios.
4. The PSA significance of buildings related to fire safety may be drastically increased if the partition is only limited to the particular plant area[2].
5. The location of fixed fire protection provisions is essential when performing plant partitioning.
6. There is no benefit from a "deeper" partitioning of the building providing neither physical nor spatial separation for redundant system trains.

It can be expected that the combination of single-compartment analyses and multi-compartment analyses will provide the same final numerical estimates of the plant-wide fire risk, regardless of how the partitioning was performed. In practice, however, an ideal consistency may be difficult to achieve and/or demonstrate. Furthermore, the partitioning decisions impact the presentation and interpretation of the Fire PSA results in terms of single- and multi-compartment fire scenario contributions [4].

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[2] Note: Buildings 4 and 5 are not subject to the Stage 3 of the Fire PSA. Their absolute contributions have been taken from the results of the Stage 2.

CONCLUSIONS

The paper provides an overview of the gradual development of the Fire PSA for the Olkiluoto NPP, Unit 3 progressively to the plant design, construction, commissioning and finally the plant operation phases.

As the project progresses, the level of detail of Fire PSA is correspondingly increasing to reflect the current plant design. It is especially characterized by plant partitioning performed within different stages of the Fire PSA. The level of the plant partitioning influences the credibility of the PSA results but also impacts the model complexity and consequently the computational overhead. Therefore, a balance between the expectations from the Fire PSA results and the model complexity should be achieved when developing the Fire PSA.

REFERENCES

[1] OECD, Nuclear Energy Agency (NEA) , Committee on the Safety of Nuclear Installations (CSNI): CSNI Technical Opinion Paper No. 17: Fire Probabilistic Safety Assessments for Nuclear Power Plants: 2019 Update, Nuclear Safety 2019, NEA No, 7417, Paris, France, https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/7417-csni-top17.pdf.

[2] Électricité de France (EDF): ETC-F, EPR Technical Code for Fire Protection, Design and construction rules for fire protection of PWR nuclear plants, November 1998.

[3] Radiation and Nuclear Safety Authority (STUK): Fire Protection at a Nuclear Facility, STUK Guide YVL 4.3, Helsinki, Finland, November 1999, superseded by: Radiation and Nuclear Safety Authority (STUK):"Fire Protection at a Nuclear Facility, STUK Guide YVL B.8, Helsinki, Finland, November 2013, http://www.finlex.fi/data/normit/41792-YVL_B.8e.pdf.

[4] United States Nuclear Regulatory Commission (U.S. NRC) / Electric Power Research Institute (EPRI): EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Plant Facilities, Final Report, NUREG/CR-6850, EPRI 1011989, Washington, DC, USA, 2005, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/v1/index.html.

[5] International Atomic Energy Agency (IAEA): Preparation of Fire Hazard Analyses for Nuclear Power Plants, IAEA Safety Reports Series, No. 8, STI/PUB/1059, ISBN 92-0-102798-2, Vienna, Austria, 1998, https://www-pub.iaea.org/MTCD/Publications/PDF/STIPUB1059-66258162.pdf.

[6] International Atomic Energy Agency (IAEA): Protection against Internal Fires and Explosions in the Design of Nuclear Power Plants, IAEA Safety Standard Series, Safety Guide No. NS-G-1.7, Vienna, Austria, 2004, ISBN 92-0-103304-4, superseded by: International Atomic Energy Agency (IAEA): Protection against Internal Hazards in the Design of Nuclear Power Plants, Specific Safety Guide, IAEA Safety Standards Series No. SSG-64, STI/PUB/1947, ISBN 978-92-0-116121-5, Vienna, Austria, August 2021, https://www-pub.iaea.org/MTCD/publications/PDF/Pub1947_web.pdf.

[7] International Atomic Energy Agency (IAEA): IAEA Safety Standard Series, Requirements No. NS-R-1, Safety of Nuclear Power Plants: Design, International Atomic Energy Agency (IAEA), ISBN 92-0-101900-9, Vienna, Austria, 2000, superseded by: International Atomic Energy Agency (IAEA): Safety of Nuclear Power Plants: Design, Specific Safety Requirements, IAEA Safety Standards Series Nno.SR-2/1, Rev. 1, STI/PUB/1715, ISBN 978-92-0-116121-5, Vienna, Austria, February 2016, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1715web-46541668.pdf.

[8] International Atomic Energy Agency (IAEA): Treatment of Internal Fires in Probabilistic Safety Assessment for Nuclear Power Plants, Safety Reports Series, No. 10, STI/PUB/1062, ISBN 92-0-103298-6, Vienna, Austria, 1998, https://www-pub.iaea.org/MTCD/Publications/PDF/P062_scr.pdf.

[9] Blombach, J., and H. Kollasko: Methodology for Fire PSA During the Design Process, in: Proceedings of 10th International Probabilistic Safety Assessment and Management Conference (PSAM10), Seattle, WA, USA, June 2010.

Converting A Fault Tree Based Fire PSA Model Into An Event Tree Based One

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ABSTRACT

The Loviisa nuclear power plant (NPP) consists of two reactor units. The first Probabilistic Safety Analysis (PSA) for Loviisa, Unit 1 was completed in 1989 and in 2009 for Loviisa, Unit 2. The Loviisa, Unit 1 fire scenarios were first modelled outside PSA software and later converted into a fault tree based model whereas the newer model for Loviisa, Unit 2 was built with event trees. Differences in the plant configuration, modelling approaches and age of the Loviisa 1 model caused discrepancy in the results for similar rooms in different units even though the rooms serve the same purpose with same equipment. This resulted in a need to convert the Loviisa 1 model into an event tree based one in order to unify the modelling approaches and to make the differences in plant configurations more identifiable for recognizing needs for possible plant modifications.

The primary approach in converting fault trees into event trees was to keep the logic between means of mitigation and initiating events caused by the fire the same because both approaches are based on the same fire analyses unless there have been plant modifications that call for changes. At the same time, the event trees for the matching rooms of Loviisa 2 were looked into for possible differences or simplification opportunities of the model.

Losses of safety systems and components due to fire damaging them was handled differently in the approaches. In the fault tree model the losses of components were determined in boundary condition sets (BC sets) for each scenario with a finite amount of separately identified loss and initiating event combinations. In the event tree model, they are modelled by generating fault trees for the cables of all relevant components and using the rooms the cables are routed through as inputs. Basic assumption is that a fire that either started in the room or spreads from another room is assumed to cause loss of cables within the room.

Possible differences in the results from the two approaches were identified by analysing the cut sets. In some cases, the results increased primarily due to taking the cable routes into account more comprehensively but in other cases the results decreased due to reduced amount of conservativity. The results for some rooms remained unchanged.

After the update, multiple modelling discrepancies between the results for the two units were reduced and actual differences in the plant configurations were better identified. The event tree model provides better readability, the losses of safety systems and components are considered more widely and precisely, the model is easier to update and the linking between Level 1 and Level 2 PSA is more convenient. However, due to multiple fault trees being now converted into a single event tree, the event trees can get quite large. Also due to the abundance of house events in the cable route fault trees, the calculation time increases slightly when the model is updated based on the states of the house events.

INTRODUCTION

The Finnish Loviisa NPP consists of two reactor units, Loviisa 1 (LO1) and Loviisa 2 (LO2), both of which are VVER-440 type. The first PSA for LO1 was completed in 1989 and in 2009 for LO2. The first fire PSA was completed in 1997 for power operation. It was created outside PSA software, but it was integrated with the PSA model in 2005 as a fault tree model, and shutdown states were assessed in 2011. The Fire PSA for LO2 was completed in 2019 for power operation and in 2020 for shutdown states. The LO2 Fire PSA was built with event trees for better readability and updateability compared to the LO1 fault tree model and to improve the linking between Level 1 and Level 2 PSA. The current PSA software used is RiskSpectrum® PSA.

The purpose of the Loviisa Fire PSA is to identify the risk, including core damage frequency (CDF), large release frequency (LRF) and early release frequency (ERF) due to plant internal fires at the NPP. In addition to common PSA applications, Fire PSA results have been utilized in identifying significant fire doors and designing cable routes for power supply or automation renewal projects. The fire risk consists of the fire frequency, the initiating event caused by the fire, losses of safety systems and components due to the fire, and unavailability of the safety systems. In this paper, the term "initiating event" is used to refer to the initiating event that a fire causes rather than the fire itself except when initiating event records within the PSA application are referred to.

The two units are similar in their design and plant configurations, therefore the logic between fires, the initiating events, mitigation and consequences should be similar. However, there are discrepancies in the Fire PSA results for rooms and buildings that serve the same purpose in each plant unit. Some of the differences arise from actual differences between the plant configurations but others are a result of differences in modelling approaches. The modelling approaches needed to be unified to make the actual differences more identifiable in the results and to make suggesting and rationalizing plant modifications more feasible. The means to achieve this was selected for updating the older LO1 Fire PSA. Another motivation for the update was the age of the LO1 Fire PSA which ignored some of the newer plant modifications.

This paper will first introduce features of the old fault tree approach and then the new event tree approach. Afterwards, details on how the actual conversion was conducted and what findings were observed will be discussed.

OLD AND NEW APPROACH

Initiating Event Identification

A fire in a room can damage equipment the losses of which will lead to initiating events recognized in the internal events PSA. The initiating events for each room were identified by utilizing a separate model built for the purpose. This model consisted of fault trees that modelled how losses of components could cause different initiating events. Knowledge of the locations of the components and their cabling could then be used to find the room and initiating event combinations. These combinations were mostly kept the same in the old and new models.

There has been minimal screening of the rooms to be included in the Fire PSA due to the use in applications and the full risk significance being found only after the calculations are done. However, the original analyses were carried out in two general phases where the first analyses were coarser, and the second ones focused more on the rooms of high importance or with large fire loads. Some conservative assumptions were made, such as the initiating event identification model only focusing on the more important initiating events and assuming that fires in each room cause at least a reactor trip (RT) or a loss of the main feedwater (LMFW) depending on the building. For rooms where the fire could only cause a RT, the analysis was limited to rooms where the fire can cause additional damage to necessary safety systems in mitigating the accident. Other fires were assumed to be included in the basic RT frequency. The LO1 Fire PSA currently covers a total of 248 rooms.

Fire Frequencies

Fire frequencies have been estimated by using the events in the OECD Nuclear Energy Agency (NEA) FIRE (*F*ire *E*vents *R*ecords *E*xchange) Database [1], the operating experience of LO1 and LO2 and operating times of observed plants from the IAEA-PRIS database [2]. Plant unit specific total fire frequencies for room types, (e.g., process rooms, cable corridors), are estimated first. The room type fire frequencies are then partitioned for individual rooms of that type based on parameters (e.g. number of electrical components, total length of cables in the room). The previous update of fire frequencies took place in 2020, and they were not changed in this update.

Fire Scenarios

A fire scenario describes how a fire in a room can lead to an initiating event and later to core damage and release of radioactive materials from the containment as shown in Figure 1. The scenario starts with the initial incipient fire in a room which can cause an initiating event. The conditional probability of a fire resulting in an initiating event can consist of events of multiple types, including fire extinguishing means, spreading of the fire, pumps that are in use and recovery opportunities.

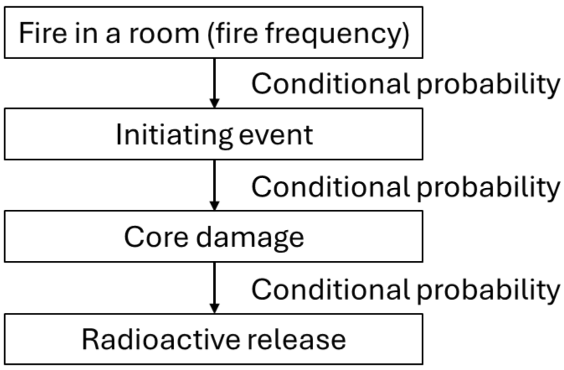

Figure 1 Fire scenario

A unique fault tree was generated for each scenario in the older approach. A simplified example is given in Figure 2, where the fire in room 1 causes an extra small loss of coolant accident (XSLOCA) if the sprinkler system in the room fails and problems arise with the primary circuit pump (PCP) seal water cooling. The first input is a basic event that models the fire frequency. The following inputs represent the conditions for the fire to cause an initiating event. The last gate represents the conditional probability after an XSLOCA which is also used for the internal events XSLOCA calculations. XSLOCA could also be caused by multiple different conditions, and other conditions could lead to other initiating events. Each scenario needed its own fault tree and the total CDF from fires in a room would be calculated by adding up the CDF results for each analysis. Also, if the spreading of the fire could cause additional damages to relevant safety systems, a separate fault tree would be built for the scenario. Different fault trees were also built for the hot and cold plant operational states.

In the new approach, two event trees were needed for each room, one for the hot plant operational states and one for the cold states. A simplified example is given in Figure 3 where the fire always causes a RT and can cause either an XSLOCA or a loss of instrumentation room ventilation (LIRV). On the top, there is first an initiating event - record that in this case refers to the fire in the room. The conditions for fire leading to PSA initiators are identified as function events after the initiating event. A downward branch in the tree models the failure of the system represented by the function event. The initiating events a fire can cause are listed in the "Conseq" column and a path through the event tree is called a sequence. The consequences are linked to event trees used for the initiating events in the internal events PSA. In the actual model, the most complex fire event trees include more function events and tens of sequences.

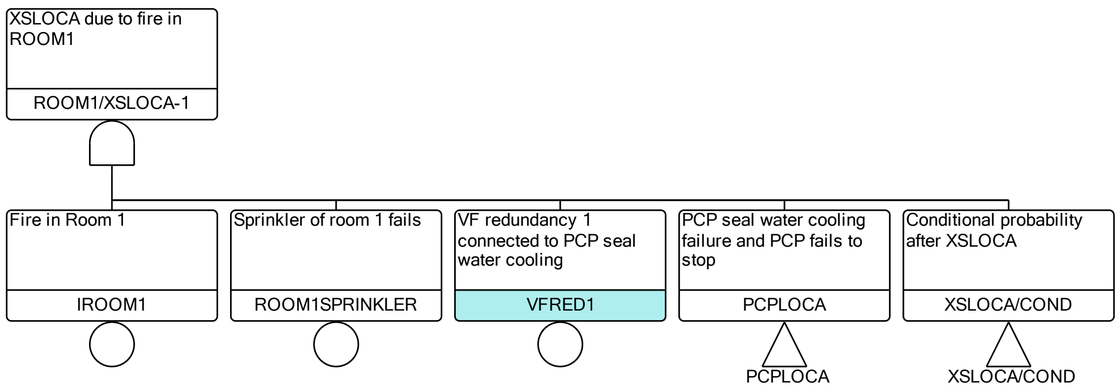

Figure 2 Simplified fault tree example for a fire scenario in room 1

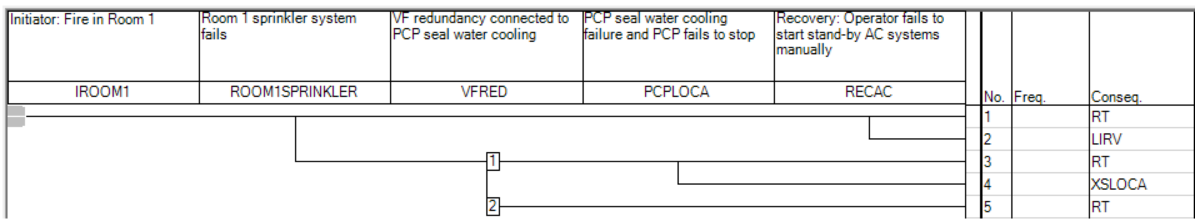

Figure 3 Simplified event tree example for a fire in room 1

Losses of Safety Systems

The initiating event leading to core damage follows the same conditions as in internal events PSA and the same models are used. However, a fire can damage the necessary safety systems, and these losses need to be taken into account in the modelling. A fire in a room can cause losses by either damaging

1. the components directly,
2. their power or instrumentation and control cables,

3. the power supply,
4. the automation equipment, or
5. the relevant control stations causing erroneous controls.

In the old approach, states of basic events or gates describing a failure of a component were set to true in relevant BC sets. A BC set allows modification of fault tree models with analysis case specific conditions. BC sets can be connected to multiple types of records, including fault tree analysis cases that are used to calculate the top event frequency of a fault tree. These conditions for BC sets had to be determined outside of PSA software and imported into the PSA model separately.

In the new approach, the cable routes are modelled explicitly in the fault trees representing the component failures as shown in Figure 4. The cable route fault tree includes all the rooms the cable or cables pass through. In general, this is done on room level, but in rooms of high importance the details are increased. For example, automation cables might be less likely to be lost since they are routed on different cable trays than power cables that are the more likely ignition source. Fire protected cables usually also require the failure of fire protection for the cables to be lost. In larger rooms the fire sources are more spread out and distances to the cable trays vary. A simplified example of a cable route fault tree is given in Figure 5 where the cable passes through rooms 1 to 3 and is fire protected in room 2.

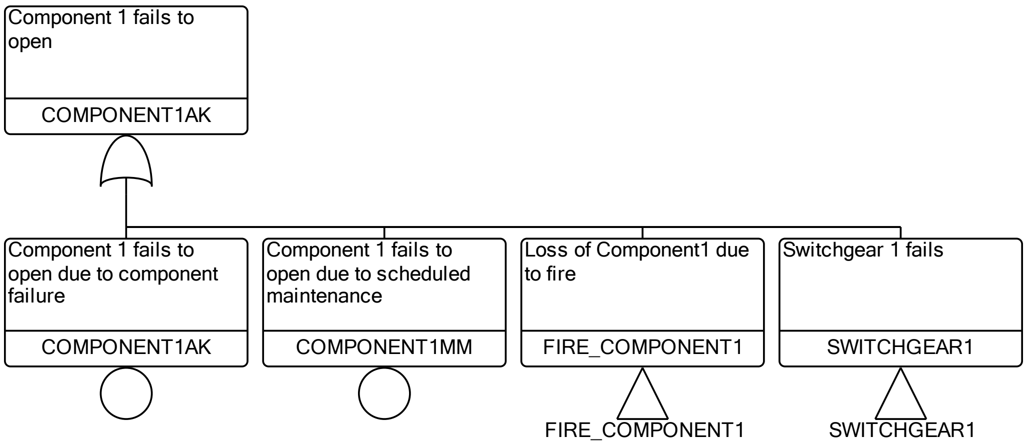

Figure 4 Simplified fault tree for component 1; the third input representing the cable route

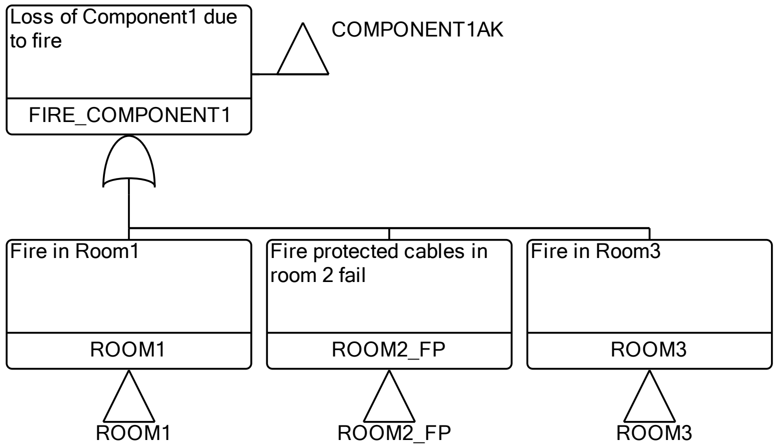

Figure 5 Simplified cable route fault tree of component 1

The cables in a room can generally be lost if the fire originates within the room or it spreads into the room through a fire door. An example of this is shown in Figure 6 where the first input is a house event for the room and its state is set to true in the event tree. Figure 7 shows the common conditions for fire spreading, which are failure of extinguishing and an open fire door. For the most part, fires were not assumed to spread between non-adjacent rooms.

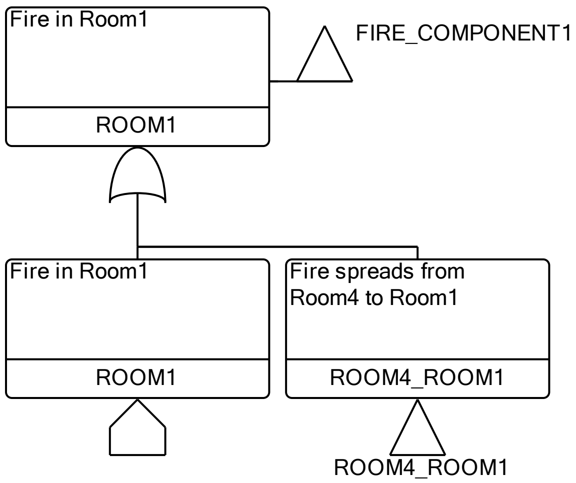

Figure 6 Simplified fault trees modelling how the cables in room 1 can be lost

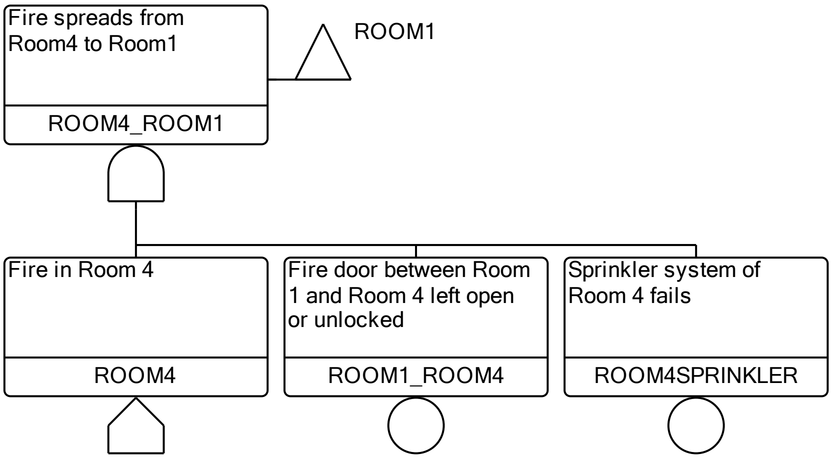

Figure 7 Simplified fault tree modelling how the fire can spread from room 4 to room 1

CONVERSION FROM FAULT TREES TO EVENT TREES

The Conversion Process

The conversion from fault trees into an event tree was performed manually room by room. Fault trees were first filtered for the ones relevant to the room, which was usually simple due to the naming conventions used. There was some overlapping between the fault trees where the only difference was the safety systems lost due to fire spreading to another room. The fault trees were inspected for such overlapping and only those ones with minimum conditions were used in the event tree.

It was necessary to then look into possible plant modifications and expired assumptions that could affect the scenarios. There have been multiple modifications to process, electrical and automation systems, and also structural changes like a new building throughout the years. These changes affect how the fires actually impact the plant. There have also been changes in analyses that might not be directly related to the fires but to dependency between systems. These changes have an impact on the PSA results and their accuracy even if the plant configuration remains the same.

Another important reference was the event tree model of an almost identical room within LO2. The plants are similar to each other so rooms that serve the same purpose should have similar event trees. Looking into the LO2 event trees was also necessary for identifying aspects that could be updated in those trees. Opportunities for simplification of the scenarios were also identified.

The initial event trees were then built. Since the fault trees normally included all the inputs in an AND-gate, using them in the event tree was simple. The basic event representing the fire frequency was used for input in the initiating event record of an event tree. The conditions before the initiating event were used as inputs for the function events and the conditional probability gate was used to identify the consequence. In some cases where the initiating event would be a total loss of a system, only partial loss was chosen as the initiating event and other losses that would make it a total loss were considered as losses of safety systems. Generally, a single fault tree became a single sequence within the event tree unless there were OR-gates within the fault tree. In those cases, the OR-logic was replicated in the event tree and multiple sequences were created.

Fault trees for the cable routes were built by utilizing

- old PSA databases for the cable routes,
- installation plans for new cables or modified cable routes, and
- conditions determined in the BC sets of the old model.

Building of the cable route fault trees was done quite automated to avoid having to create hundreds of fault trees manually. After having a structured list of components and rooms that the cables go through, code could be used to convert it into a text formatted import file with predetermined structure. The file was imported into the PSA software and the fault trees were created.

The list of fault trees for fires spreading was also made as complete as possible. For this purpose, all the rooms considered as fire sources and all rooms included in the cable routes were highlighted on layout pictures of the plant. Then fault trees were created for all possible spreading scenarios between the rooms.

Manual work was still necessary when going through an implementation plan and listing the rooms mentioned. Attaching the cable route fault trees to the fault trees modelling failure of the component also required lots of manual work. It could not be automated due to there being component specific exceptions and inner gate logic within the fault trees. There can be recovery possibilities for a component or there can be lots of time to manually control it.

The age of LO1 imposed some challenges. The level of documentation of the cable routes varies because the oldest cable routes were chosen decades ago. Even if the room level documentation might be lacking, some general rules were followed. For example, the rooms are divided into redundant trains which should only include cables for components of the same redundancy. There are exceptions but in these cases the cables in the wrong redundancy should be fire protected. Due to lack of information, it was necessary to use more generic routes for specific components. In these cases, the cable route was assumed to include all rooms through which the cable could go through. For example, if a valve of first redundancy is located in the reactor Building and the power supply is in the so-called control building, which also contains the switchgear rooms, a conservative assumption is to include all rooms for first redundancy of both of these buildings. Some of the buildings could still be ignored and most significant buildings could be also split into floors or levels. If the floor of the power supply and the direction where the cable would head are known, the other floors above or below could be ignored.

After the initial event trees and cable routes were completed, test calculations were made for each room and compared to the results of the fault tree model. A primary means was to identify the differences in minimum cut sets. The goal was to identify the reasons for valid changes in the results and to fix the unreasonable differences.

Findings

Even though the model logic should remain mostly the same between the new and old approach, there were lots of changes in fire risk estimate and the changes were in both increases and decreases depending on the room. The total fire risk estimate increased by 24 % on power operation including other model changes and contributes a third of the total CDF. Final results for shutdown have not been calculated by event trees yet, but preliminary estimates are at around 10 % increase. The three most important buildings for the Fire PSA are the control building, the diesel building and the turbine building in the respective order. Out of the initiating events, primary circuit leakages through primary coolant pump seals due to seal water and protective automation failures contribute most to the fire risk. This is due to the relevant cables being located in a large number of rooms.

The differences between the LO1 and LO2 Fire PSA results were reduced, but the results still differ from each other. Some of the differences are due to plant configuration, e.g., location of equipment, cable routes and locations of cable tunnels. There are still some modelling differences too. The level of documentation is also slightly better for LO2 thus reducing the number of necessary conservative assumptions in the modelling. Some LO2 rooms were now also taken into account in the LO1 Fire PSA if the fires can cause initiating events in LO1. There were some rooms where modifications of the LO2 model were needed.

Changes in plant configuration that have decreased the fire risk include splitting the emergency feedwater system into redundancies rather than having it all as one redundancy. A new building next to the control building resulted in a gap being formed between the buildings that has been analysed as a possible route for heat and smoke from fires on the lower levels of the control building to cause damages on the upper levels of the control building and slightly increased the fire risk.

Modelling of component losses increased the fire risk in multiple rooms. In the old approach, the number of combinations of initiating events and component losses were fixed. The new approach takes into account all cables imported into the model in each fire scenario and the impacted components are solved by the PSA software each time the analyses are run. This makes it more likely that all relevant components are taken into account since previously the losses of components were determined outside the PSA software which made the listing prone to errors and very difficult to keep up to date. Plant modifications or new analyses can make new components relevant for mitigation of an initiating event. Now losses due to fire are automatically taken into account when the initiating event is caused by a fire.

The generic and redundancy specific cable routes caused some increases in conservativity of the fire PSA. Some previously ignored fire spreading options also caused slight increases in risk, but most of the relevant options were already considered in the old approach. Conservativity was decreased in some cases due to the old approach using constant multipliers for certain scenarios that are now solved through component losses.

Including the cable routes into the component fault trees also improved readability. Both the missing and excess cable routes can now be identified when viewing the fault tree structure. There have been occurrences where a cable route for a valve has been identified unnecessary to model due to the time window for operating it being long enough for manual operation or the valve being intended to be operated manually.

However, solving the cable routes takes more computing power and thus increases the total calculation time. If a room is included in many cable routes, setting the matching room house event true will modify as many fault tree states. Total calculation times for old and new model were not recorded, but they could be more than doubled for most calculation heavy rooms and remain the same for rooms with little cabling. The calculation time is also affected by there being only one consequence analysis case to calculate rather than multiple fault tree analysis cases for each room. The number of analysis cases was also decreased because component losses due to fire spreading do not need separate analysis cases anymore.

Due to the analysis case changes, the minimization of cut sets is now done correctly compared to calculating the fires with multiple fault tree analysis cases which can result in overlapping cut sets existing in different analysis case results. This should not have an effect on the total CDF level of the plant since it is calculated with a separate MCS analysis case which should consider the overlaps correctly and remove the excess cut sets.

The new approach offered more flexibility with flag events that can be set to true or false depending on the plant state. With the old approach, these flags could be set only in the first BC set and they would be applied throughout the whole sequence from initial fire to core damage or release. The new approach allows attaching boundary condition sets also to individual function events so that certain flags would be enabled only after the fire has caused an initiating event or at a certain point after the initiating event. This changed some results since flags that should be enabled way later in the fire scenario used to make cut sets possible when they would not even cause the initiating event in the new approach.

Changes that did not directly affect the PSA results included better readability and updateability of fire scenarios. Rather than having all the fire scenarios of one room and the same plant operating state in different fault trees, all the scenarios are within a single event tree. This makes adding new function events or adjusting the sequences simpler for the whole room and reduces number of modelling mistakes made. Other modelling convenience comes from the ability to link the Level 1 and Level 2 event trees to each other rather than having to use workarounds. However, the older approach showed better how the fire risk in a room is split among different initiating events. In the new approach all the results are in the same analysis case and this information is less convenient to dig out.

CONCLUSIONS

Two alternate methods to model fire scenarios with PSA software and the conversion process between them were presented. The old method was based on fault trees while the new one is based on event trees. The conversion process included lots of manual modelling, but some parts could be automated.

The new modelling approach was found to have lots of benefits compared to the older one, including making it easier to keep up to date with plant modifications and new analyses. The conversion increased the total fire risk estimate, but for some rooms the results decreased. The results for LO1 and LO2 became more uniform to each other. More accurate modelling of cable routes were the primary reason for changes in the Fire PSA results.

REFERENCES

[1] Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA): OECD/NEA FIRE Database Version 2019:01, Paris, France, May 2021 (limited to FIRE Database Project member countries).

[2] International Atomic Energy Agency (IAEA): PRIS (Power Reactor Information System) database, Vienna, Austria, 2024, last access: 2020, https://pris.iaea.org/pris/home.aspx.

Development of Fire PRA Infrastructures in NRRC - Participation and Promotion of the PRELUDE Program

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ABSTRACT

The PRELUDE program has been launched by Électricité de France (EDF) on the IGNIS platform, specially designed for large scale fire tests in confined environments. One of the campaigns of this program, called PML campaign, has been launched within the French Japanese joint test program between EDF (Électricité de France) and the Central Research Institute of the Electric Power Industry (CRIEPI) from the beginning of 2024 to the end of 2026. In this campaign, a 78.75 m^3 gallery configuration with a mechanical ventilation system was implemented in the ME2 test facility. The PML campaign consists of two research areas. The topic of the first area is the stratification and propagation of smoke during a fire in the gallery configuration. Four tests had been carried out by the end of 2024 using three types of liquid fuel and one type of gaseous fuel. The topic of the second area is the assessment of the consequences of smoke and heat on the operation of electrical or electronic equipment. Three tests will be carried out on this aspect by the end of 2025. This paper presents some specific findings obtained in the first research area, focusing on the fire propagation phenomena in the gallery configuration and the applicability of the BRI2-CRIEPI fire simulation model.

INTRODUCTION

Japanese utilities have implemented fire protection measures in their own nuclear power plants (NPPs) to ensure fire safety. One method to evaluate the design and effectiveness of the fire protection means is to identify potential vulnerabilities related to internal fires by applying the internal fire probabilistic risk assessment (FPRA) methodology. Therefore, it is important to prepare the FPRA infrastructure to promote practical FPRA and support risk-informed decision making among Japanese industries. The CRIEPI has been continuously improving the fire simulation zone model called "BRI2-CRIEPI" to enable highly predictive analysis considering the characteristics of a compartment fire and to provide more realistic fire scenarios during fire risk assessment.

The PRELUDE program has been launched by EDF R&D (France) on the IGNIS (French: *I*nstallation *g*randeur *n*ature *i*ncendie *s*ûreté) platform as shown in Figure 1 specifically designed for large scale fire tests in confined environments [1]. One of the campaigns of this program, called PML campaign, has been launched within the joint test program of EDF and CRIEPI from the beginning of 2024 to the end of 2026.

The PML campaign, which is the French acronym for multi-room propagation, aims at setting up a configuration that is realistic for existing NPPs. The main objective of this campaign is to investigate the effects of both soot concentration and thermal feedback on an electrical target located in the fire room or the adjacent room. In this campaign, a 78.75 m^3 gallery configuration with a mechanical ventilation system has been implemented in the ME2 test facility, which is 2.50 m wide, 10.50 m long (a portion of the fire room separated by a wall was excluded from this campaign). and 3.00 m high with three rooms (R1, R2 and R3), see Figure 2. The walls are made of two layers of concrete with a total thickness of 0.40 m.

The PML campaign consists of two research areas. The topic of the first research area is to characterize the fire behaviour in the gallery configuration in terms of heat release rate (HRR), soot concentration, and gas temperature distribution to ensure that the chosen fire source is suitable for our study. As a result, four tests were conducted using three types of liquid fuel (ethanol, heptane, and diesel fuel) and one type of gaseous fuel (propane) by the end of 2024. The topic of the second research area is to assess the effects of smoke and heat on the operation of electronic equipment. Three tests will be conducted by the end of 2025.

This paper summarizes some specific results obtained in the first research area, focusing on the fire characteristics in the gallery configuration, the selection of the fuel type for the main tests in the second research area, and the applicability of the BRI2-CRIEPI fire simulation model with the selected fuel type. In addition, a brief overview of the second research area is presented including the main test outline.

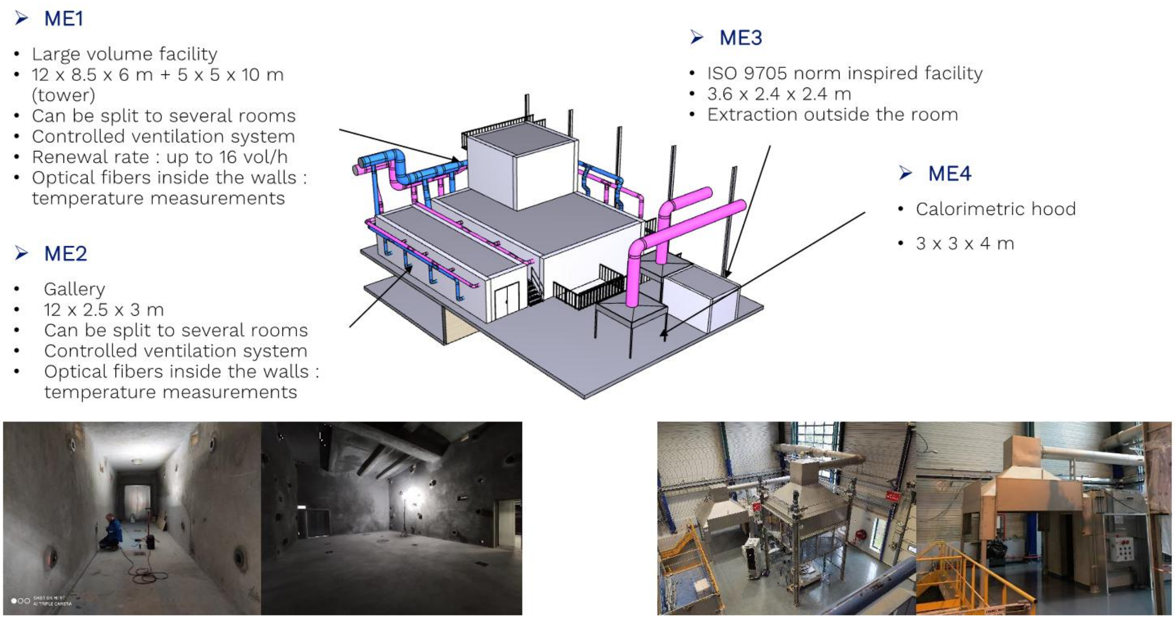


Figure 1 IGNIS fire safety experimental platform operated by EDF

FIRST RESEARCH AREA

Test Conditions

Table 1 shows the test conditions.

- Tests #1 and #2: These burning tests using propane and ethanol fuel were conducted to validate the HRR measurement.
- Tests #3 and #4: These burning tests using heptane and diesel fuel (GNR) were conducted to obtain the soot and temperature profiles in the gallery configuration.

Table 1 Test matrix of the fire tests in the first research area

Test No.	Fire Source			Renewal Rate	Notes
	Room	Fuel	Size		
#1	R1	Propane	0.4 m x 0.4 m	10 /h	HRR measurement validation
#2	R1	Ethanol	0.7 m		HRR measurement validation
#3	R1	Heptane			Base case to obtain the soot and temperature profiles
#4	R1	Diesel			

Figure 2 shows the test configuration. Room R1 is a 4.00 m long, 2.50 m wide and 3.00 m high enclosure in which various fire sources are lit. It is directly connected by a 2.00 m high, 0.80 m wide opening to a target compartment. The target compartment is divided in two zones delimitated by a smoke retaining structure set on the ceiling. The two zones are 3.25 m long, 2.50 m wide and 3.00 m high. The fire source was placed in the canter of the R1. The entire facility is ventilated at an air renewal rate of 10 /h and the flow rate is divided equally between the three rooms of the configuration. The 2VR12 exhaust ducts and the 2VR14 inlet ducts remain closed during the tests to avoid disturbing the airflow around the smoke retaining structure. The fire source is ignited using an 8 kW premixed propane burner.

The instrumentation installed in the ME2 facility for the PML campaign is as follows:

- Vertical temperature profile measurements inside the flame and at three locations inside each compartment;
- Temperature of the inlet and outlet gases and volumetric flow rate for each ventilation duct;
- Pressure inside the ME2;
- O_2, CO_2 and CO concentration at two height (1.0 m and 2.0 m) in R1 and R2, at one height in R3 and in the exhaust pipe of the facility;
- Soot mass concentration in R1, R2 and R3;
- Fuel mass loss rate.

Vertical gas velocity profile measurement at the opening between R1 and R2:

- Incident heat flux at horizontal distances of 0.5 m and 1.0 m from the fire source edge;
- Heat flux from the hot gas layer (HGL) reaching a height of 2.00 m in R1.

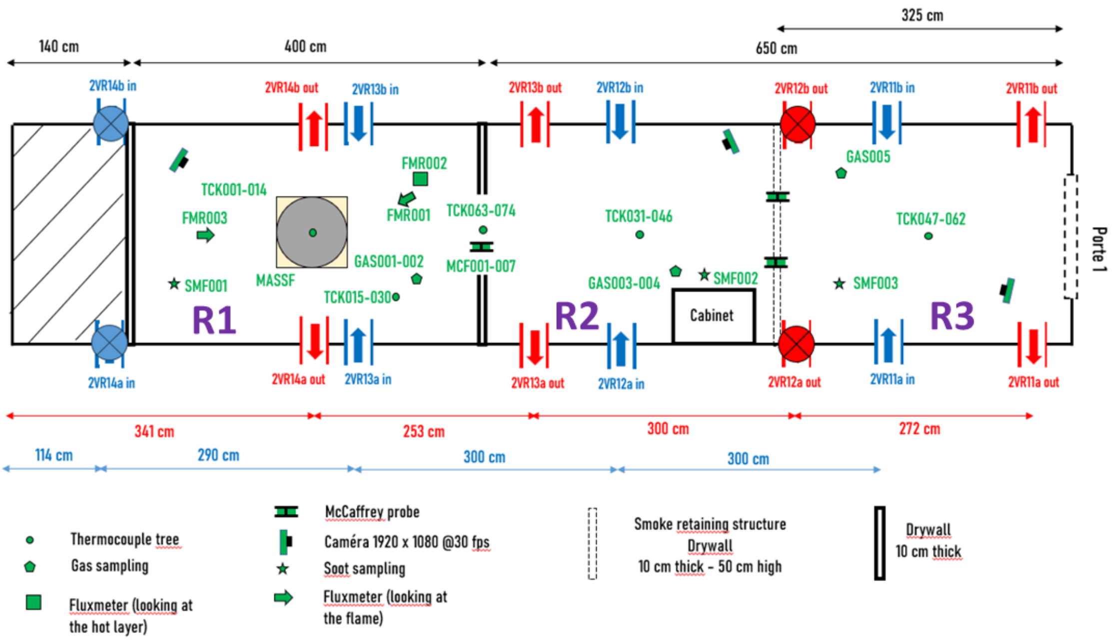


Figure 2 Configuration of the test gallery ME2

Test Results

Behaviour of Flame and Smoke

Figure 3 shows the flame behaviour for four tests. The propane and ethanol flames are very similar in geometry and produce almost no smoke. The heptane flame is larger and the visibility in the room decreases more than for ethanol and propane, but even after 240 s the flame remains visible. The diesel flame is similar in geometry to the heptane flame but produces large amounts of smoke. After 240 s, there is no visibility due to the smoke.

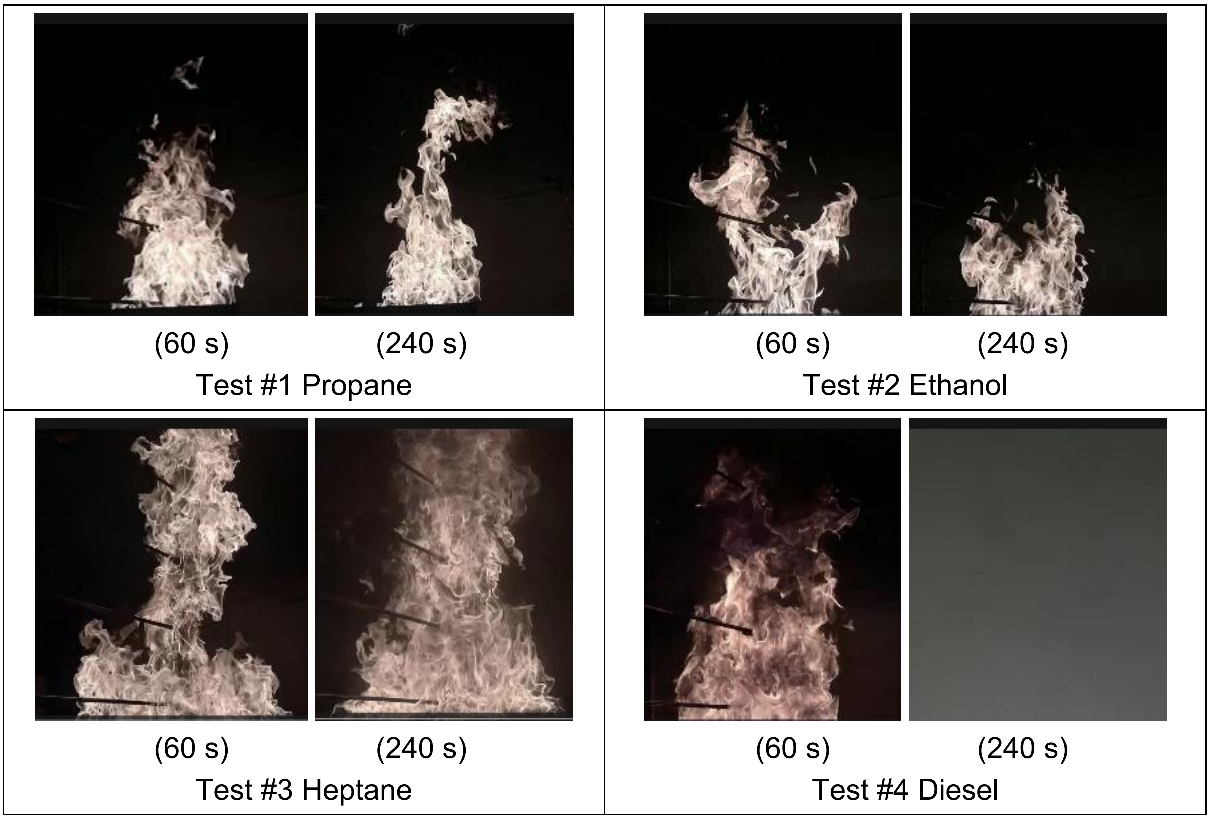


Figure 3 Recorded flame behaviour for the four tests

Heat Release Rate

Figure 4 shows the time profile of the HRR for four tests. The first two tests were performed specifically to validate the HRR measurement method. In both tests, the HRR obtained mechanically by the mass loss rate (MLR) and the HRR estimated by thecarbon dioxide generation (CDG) method are in good agreement. In case of the heptane and diesel fuel, HRR time profile shows similar shape representing ventilation controlled fire, for example, after ignition, although the rapid increase of HRR appeared, the decrease and the steady state of HRR was found. In both tests, the mechanical HRR and the estimated HRR in the steady state agree well except the peak value and reached up to 400 kW.

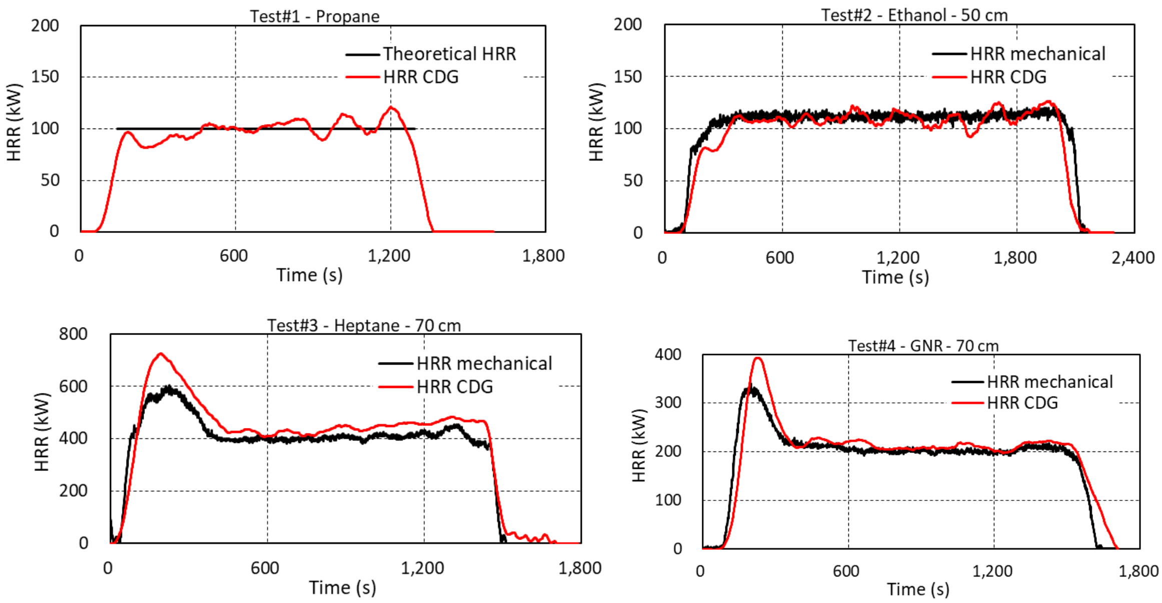


Figure 4 Time profile of the HRR for the four tests

Thermal Stratification, Heat Flux Profile and Soot Concentration

Figure 5 shows the thermal stratification within each room 1000 s after ignition for tests #3 and #4. The highest temperature occurred in fire room R1 and the temperature is almost constant between 2.00 m and 3.00 m height due to the influence of the opening (2.00 m high and 0.90 m wide) existing between R1 and R2. In case of heptane the temperature exceeds 400 °C, for diesel fue, the temperature exceeds 250 °C.

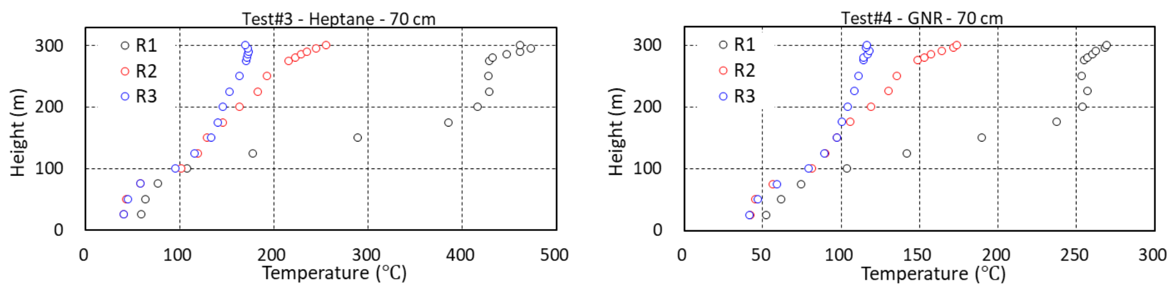


Figure 5 Temperature stratification for Tests #3 and #4

Figure 6 shows the heat flux profile for Tests #3 and #4. The trends observed by the heat flux meter located at 1.00 m (FMR001) and 0.50 m (FMR003) from the edge of the fire source are very similar and agree well with the trend observed in the HRR curves. The FMR002 heat flux meter was set to measure the flux from HGL reaching a height of 2.00 m in R1.In the case of Test #4, the measured value is very small.

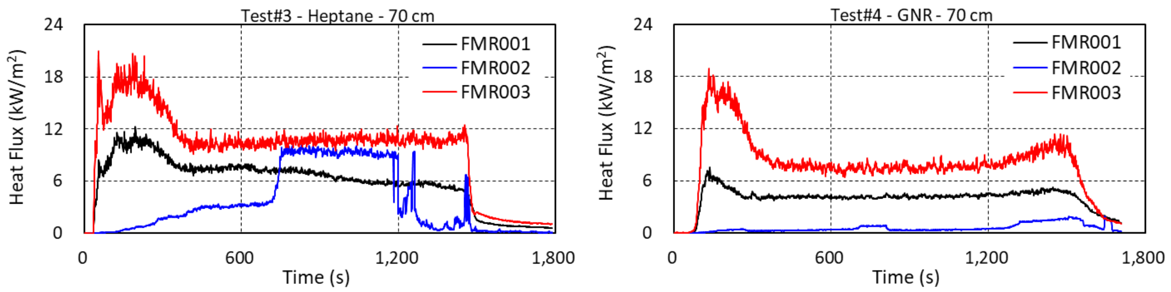


Figure 6 Heat flux profile for Tests #3 and #4

Figure 7 shows the soot concentration inside the R1 for Tests #3 and #4. It is obvious that the large amount of soot was measured in Test #4. The maximum soot concentration obtained during Test #4 with diesel fuel is close to 14 g/m^3.

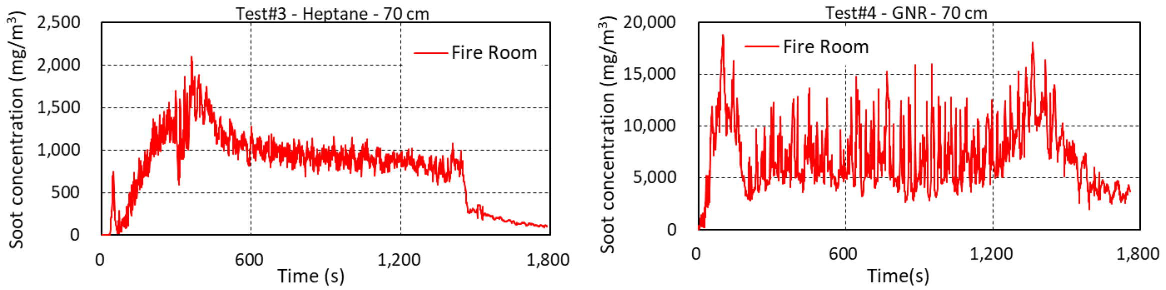


Figure 7 Soot concentration for Tests #3 and #4 in the fire room R1

Discussion

M. Piller et al. [3] proposed the failure map related to the combined effect of the soot concentration and the hot gas temperature based on experimental programs using electrical elements to investigate the malfunctions of real electrical equipment exposed to a fire environment. To check the likelihood of the failure occurrence of the target, we combined Test #4 results and the failure map described before. Figure 8 shows the combined map, which is divided into a domain of good operation (grey range) or into a malfunctioning domain linked to a combined effect of temperature and soot (green field), or into a malfunctioning domain linked to a combined effect of temperature, soot and heat flux (purple field), or in a thermal malfunction domain (in red). Although the single damage mode caused by high-temperature gases is not applicable, it is considered that the combined effects of temperature, heat flux, and soot on the target damage can be sufficiently verified in this experimental condition.

As a result, diesel fuel seems to provide the necessary conditions in terms of soot production and thermal output to submit electrical targets to conditions that could lead to thermal failure, or smoke related failure.

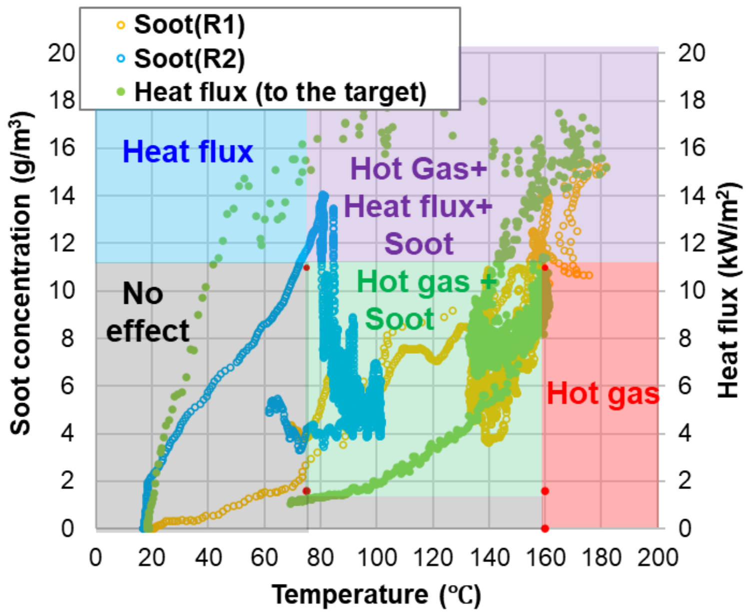


Figure 8 Combined effect map among hot gas temperature, soot concentration and heat flux from the flame

Applicability of the Zone Code BRI2-CRIEPI

In the event of compartment fires in NPPs under mechanically ventilated conditions the fire characteristics may change from fuel-controlled to ventilation-controlled due to the oxygen depletion resulting from the fire growth. Additionally, the changes in the MLR due to the degradation of the oxygen concentration in a compartment have a clear limit and affect the HRR from a fire source. The fire simulation zone model BRI2-CRIEPI has been continuously improved to allow analysis considering the characteristics of compartment fires under mechanical ventilation conditions [4].

To verify the applicability of the BRI2-CRIEPI zone model to the diesel fuel pool fire, a numerical analysis was performed to compare with the experimental data obtained in Test #4, as shown in Figure 9. Moreover, the Babrauskas correlation between the MLR [kg/m²/s] and the pool diameter D [m] as shown in Figure 10 was applied, using the heat of combustion per unit mass ΔH = 42.7 MJ/kg.

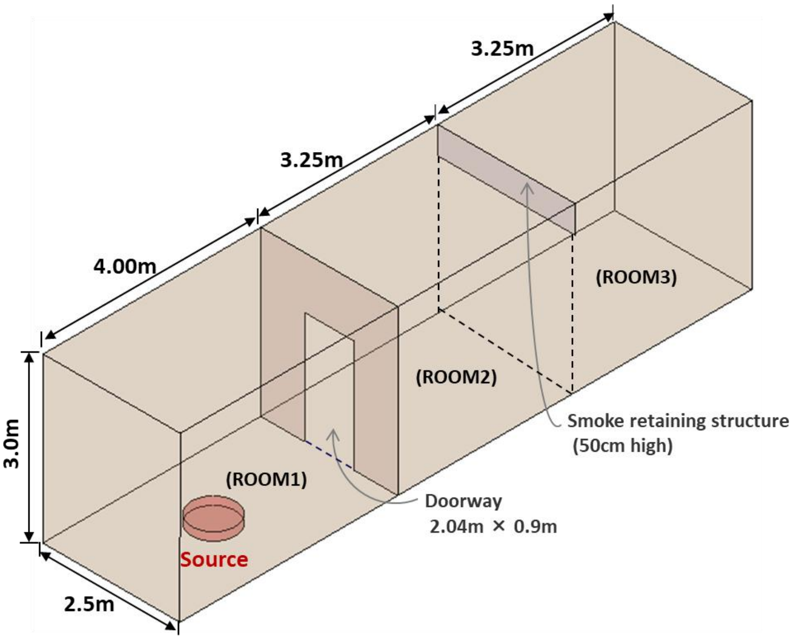


Figure 9 Analysis configuration for the BRI2-CRIEPI simulations

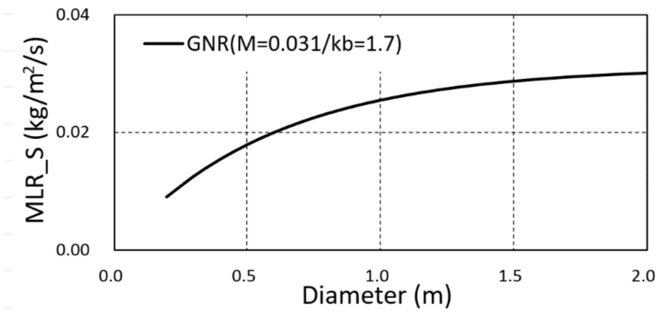
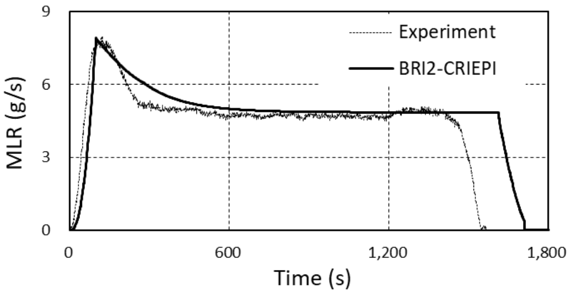
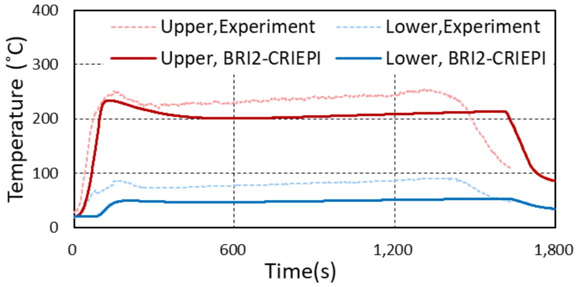


Figure 10 MLR for diesel fuel (GNR)

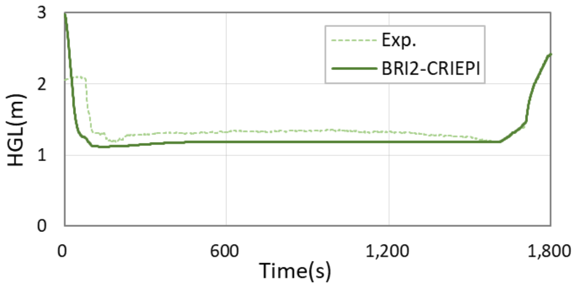
Figure 11 shows the calculated time history of the MLR, the HGL the temperature and interface elevation compared to experimental values. As a method to estimate the interface elevation, the N% rule was applied [5]. In this study, N = 50 % was adopted and compared to the calculations of BRI2-CRIEPI. The calculated first peak and the quasi-steady state of the MLR were in good agreement with the experimental values. However, although the calculated variation of the interface height was similar to the measured values, the calculated hot gas temperature was slightly lower than the measured value.



(a) MLR



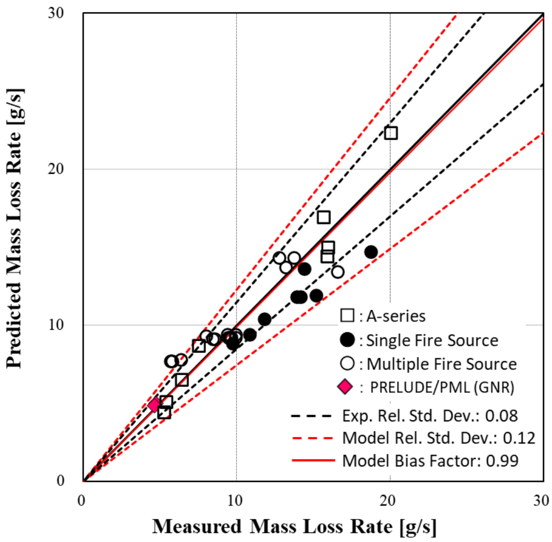
(b) HGL temperature



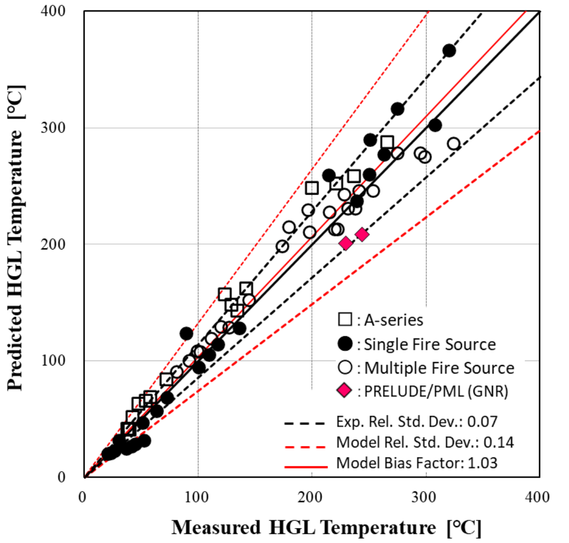
(c) interface height

Figure 11 Analysis results for Test #4 using BRI2-CRIEPI

Figure 12 shows the mapping of the current prediction results onto the existing validation results [4] for the MLR and hot gas layer temperature prediction performance of BRI2-CRIEPI. It seems that there is no particular systematic trend in the model prediction.



(a) MLR



(b) HGL temperature

Figure 12 Validation of calculation results against MLR and the HGL temperature

KEY TOPICS OF THE SECOND RESEARCH AREA

The topic of the second research area is to evaluate the effects of smoke and heat on the operation of electrical or electronic equipment. In this study, an electrical test cabinet will be subjected to a diesel fuel (GNR) pool fire using the test gallery ME2 with three rooms (R1, R2, and R3). Some specific test conditions and the test cabinet specifications are presented below.

Test Conditions

Table 2 shows the test conditions. Three tests are considered according to the expected combined effect map as shown in Figure 8.

- Test #5: The target electrical cabinet will be set in R2 to investigate the effect of smoke propagated from the fire source.
- Test #6: The target electrical cabinet with the radiation shielding panel will be set in R1 close to the fire source to investigate the effect of smoke and high temperature gas originating from the fire source.
- Test #7: The target electrical cabinet without the radiation shielding panel will be set in R1 close to the fire source to investigate the combined effect of smoke, high temperature gas and heat flux radiated from the fire flame.

Table 2 Test matrix in the second area

Test No.	Fire Source			Renewal Rate	Electric Cabinet	Notes
	Room	Fuel	Size			
#5	R1	Diesel	0.7 m	10 /h	R2	Soot effect (thermal radiation blocking with pane)
#6	R1	Diesel			R1	Soot and temperature effect (thermal radiation blocking with pane)
#7	R1	Diesel			R1	Soot, temperature and radiation effect

Electrical Test Cabinet

In the fire room, the electrical test cabinet, which is 0.55 m wide, 0.30 m deep and 1.43 m high, will be installed without the door as a target exposed to a diesel fuel pool fire. This cabinet is placed on the handling pallet, which has a height of 0.15 m. Figure 13 shows the external appearance of the cabinet and its dimensions. The total weight of the test cabinet including the handling pallet is 150 kg. To measure the heat flux radiating from the flame and smoke to the cabinet and temperature inside the cabinet, two heat flux meters are installed in the upper part of the cabinet and twelve thermocouples are also installed in close proximity to the component inside the cabinet.

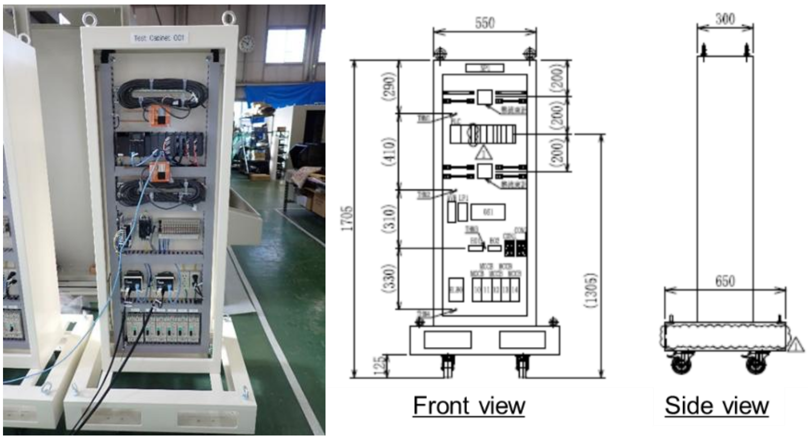


Figure 13 Exposure targets installed in the fire compartment

During the fire test, this cabinet will be powered by the single-phase AC 100 V (60 Hz) power supply. The system monitors the malfunction of electrical or electronic components by digital control, analog control and data communication as shown in Figure 14. The digital control including optical media convertor and optical fiber cables is ordered to switch between the on and off states every second. Analog control is ordered to change the voltage level from 0 to 10 V and the current value from 0 to 20 mA. Data communication is ordered to send data 1000 times every 10 seconds. All signal responses are logged in the monitoring system.

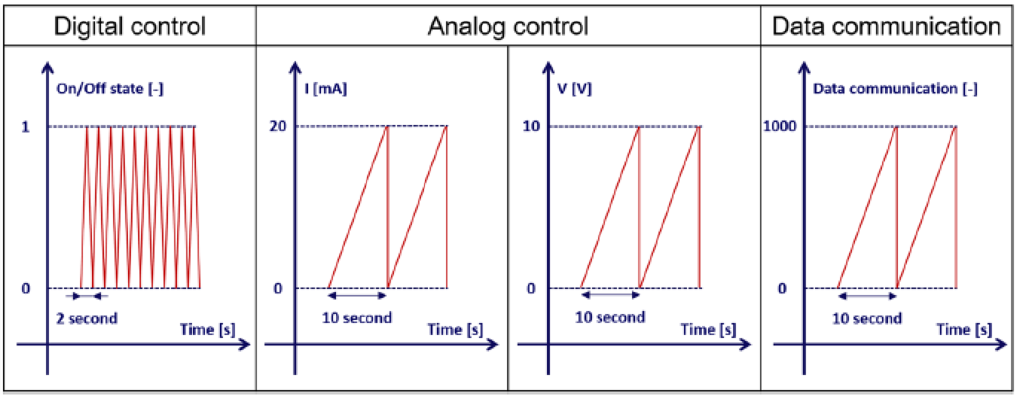


Figure 14 Different types of monitoring signals

CONCLUSIONS

The PML campaign of the PRELUDE program has been launched within the framework of the French Japanese joint test program between EDF R&D and CRIEPI from the beginning of 2024 to the end of 2026 using the ME2 test facility with the gallery configuration implemented in the IGNIS platform.

The PML campaign is composed of two research areas. The topic of the first area is the stratification and propagation of smoke during a fire in the gallery configuration and four tests have been successfully completed by the end of 2024 using three types of liquid fuel and one type of gaseous fuel. According to these preliminary fire tests, diesel fuel (GNR) appears to provide the necessary conditions in terms of soot production and thermal output to subject electrical targets to conditions that could lead to combined thermal and smoke failure. In addition, the two-zone fire model, BRI2-CRIEPI, has been validated by the test results to estimate the fire behaviour in the gallery compartment with the diesel fuel fire source for the MLR and the HGL temperature.

This paper also presents the key topics of the second research area, regarding the test condition and the electrical target, from the point of view of assessing the consequences of smoke and heat on the operation of electrical target.

REFERENCES

[1] Thion, S., et al.: IGNIS: A New Experimental Platform Dedicated to Real Scale Fire Studies, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 26, 17th International Seminar on Fire Safety in Nuclear Power Plants and Installations, October 24-25, 2022, Westerburg, Huy, Germany, GRS-705, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, November 2022, https://www.grs.de/sites/default/files/2023-02/GRS-705.pdf

[2] Prétrel, H., W. Le Saux, and L. Audouin: Experimental determination of fire heat release rate with OC and CDG calorimetry for ventilated compartments fire scenario, Fire and Materials, Volume 38, Issue 4, Wiley Online Library, June 2014, https://onlinelibrary.wiley.com/doi/abs/10.1002/fam.2193.

[3] Piller, M., and M. Coutin: Effects of smoke and thermal stress on electrical equipment failure, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 24, 15th International Seminar on Fire Safety in Nuclear Power Plants and Installations, October 4-5, 2017, Bruges, Belgium, GRS-A-3912, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, December 2017, https://www.grs.de/sites/default/files/publications/grs-a-3912_0.pdf.

[4] Shirai, K., et al.: Development of two-layer zone model BRI2-CRIEPI applicable to fire PRA for nuclear power plants, Fire Safety Journal, Volume 141 (1):103948, December 2023, https://doi.org/10.1016/j.firesaf.2023.103948.

[5] Cooper, L. Y., et al.: An Experimental Study of Upper Hot Layer Stratification in Full-Scale Multiroom Fire Scenarios, ASME Journal of Heat and Mass Transfer, Volume 104, Issue 4, The American Society of Mechanical Engineers (ASME= Digital Collection, 1982, https://asmedigitalcollection.asme.org/heattransfer/article-abstract/104/4/741/414185/An-Experimental-Study-of-Upper-Hot-Layer?redirectedFrom=fulltext.

3.5 Topical Session on Experimental Fire Research

The topical session on experimental fire research covered in total five presentations and was chaired by Sebastien Thion (EDF, France) and Philippe Nerisson (ASNR, France).

The first presentation by Daniel Alvear Portilla from Universidad de Cantabria, Spain showed the study the influence of oxygen depletion and radiant heat flux on heptane pool fires in naturally ventilated compartments. Two experimental campaigns, a bench-scale using a fire propagation apparatus (FPA) and medium-scale in a typical compartment, provided the result that the external heat flux significantly increases heat release and burning rates, while the ventilation conditions govern the combustion sustainability. The study validated a modified Tewarson method for estimating mass loss rates and emphasised the need for improved predictive models to enhance fire safety in enclosed spaces. The experimental findings highlight the complex interaction between oxygen availability, heat flux and compartment geometry in determining fire behaviour.

The presentation by Philippe Nerisson from ASNR, France provided an update of the status of the OECD/NEA experimental project FAIR (*F*ire Risk *A*ssessment through *I*nnovative *R*esearch). This project builds on previous studies within the PRISME (French: *Pr*opagation d'un *i*ncendie pour des *s*cenarios *m*ulti-locaux *é*lémentaires) projects to address knowledge gaps in fire safety assessment for nuclear installations and focuses on cable tray fire propagation including ageing effects, combustion in hot and oxygen-depleted compartments and multi-source fire scenarios. Large-scale tests at the GALAXIE experimental platform and medium-scale analytical experiments aim to replicate realistic conditions and support model development. First results have confirmed the significant impact of oxygen vitiation and heat flux on the fire behaviour.

FAIR also addresses smoke propagation in interconnected rooms with mechanical ventilation, a significant factor in nuclear safety. The project, running until 2028, combines experimental campaigns with an analytical working group to interpret the findings and to enhance predictive modelling. This collaborative approach ensures that the data generated will improve fire safety strategies and regulatory frameworks on an international level.

In the third presentation entitled 'Thermal Behaviour and Characterization of Electrical Cables – Effects of Sample Orientation and Testing Conditions' Alain Alonso Ipiña (Universidad de Cantabria, Spain) provided insights from investigations how the cable orientation during FPA tests affects the ire behaviour. While the critical heat flux remained consistent across orientations, vertical samples exhibited higher peak heat release rates, faster ignition and an increased flame spread compared to horizontal samples. Oxygen enrichment further amplified combustion intensity. The thermal response parameter and the fire propagation index confirmed an increased fire risk for vertical configurations.

The findings suggest that current standards may underestimate hazards associated with vertically routed cables, calling for revised testing protocols and safety evaluations. These results underpin the importance of considering the installation geometry in fire safety assessments, particularly for nuclear power plants.

Another presentation devoted to cable fires was given by Guanghua Yang from China Nuclear Power Plant Engineering Co. Ltd. The study presented addresses the combustion and flame spread characteristics of cable fires in trough box cable trays, a common configuration in nuclear power plants. Current fire hazard analyses often assume similar behaviour between trough-type and ladder-type trays, but limited research exists for trough trays. To close this gap, full-scale fire experiments under varying conditions of cable filling rates and tray bottom types were conducted at a comprehensive fire platform featuring multiple compartments and ventilation systems. Four test configurations were examined: trays with solid bottoms at 8 % and 30 % cable filling rates, and trays with open bottoms at 30 % and 20 % filling rates. A propane burner was placed beneath the tray as ignition source. The experimental results revealed that flame spread of approx..1.5 m occurred only at the lowest filling rate. Higher filling rates restricted the airflow, preventing flame propagation.

Temperature analysis indicated that ignition required localized heating above 500 °C, and multi-peak temperature curves suggested complex combustion stages. The findings challenge existing assumptions in fire hazard analysis: trough-type trays exhibit significantly lower flame spread potential compared to ladder-type trays, particularly at high cable densities.

The last presentation by Sebastien Thion from EDF, France presented research on ignition scenarios involving Mobil DTE Medium oil, commonly used in primary coolant pumps of French nuclear power plants. Liquid pool fires represent critical fire hazards due to their high heat release rates, yet current safety analyses often neglect oil ignition resistance, leading to conservative assumptions. To address this, seven large-scale experiments were conducted at EDF's IGNIS fire test platform, focusing on oil preheating effects and dripping ignition scenarios.

The results demonstrated that oil ignition is highly dependent on temperature: a threshold of approximately 200 °C must be reached for combustion to occur. Tests with preheating at 150 °C showed delayed ignition after prolonged exposure to a pilot flame, while preheating at 200 °C or more resulted in immediate ignition. The heat release rate peaked at 300 kW during ignition but stabilized at around 125 kW regardless of initial preheating temperature. Heat flux measurements confirmed the moderate thermal impact on surrounding targets, with polyvinyl chloride (PVC) and high-*d*ensity *p*oly*e*thylene (HDPE) samples heating up more than steel due to material properties.

A dripping test simulating flaming oil spilling onto a preheated slick revealed no ignition, even after 90 min of continuous flow suggesting that scenarios involving secondary ignition from leaks are unlikely under realistic conditions.

The five contributions of this seminar session are provided hereafter.

Effects of Vitiated Environment on the Burning Rates of Naturally Ventilated Compartment Fires

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ABSTRACT

Combustion in vitiated atmospheres, characterized by a reduction in available oxygen for combustion and an increase in surrounding temperature, remains as a key issue in fire science. The Global Equivalence Ratio (GER), which relates the mass loss rate (MLR) of the fuel with the oxygen available for combustion, has been commonly employed to assess the combustion regimes (under-ventilated or fuel-controlled). However, there is a limited number of experimental studies and the effect of the GER on combustion and extinction is not completely assessed.

This work presents a comprehensive experimental campaign aimed at analysing combustion in vitiated atmospheres of a heptane pool fire situated within a naturally ventilated enclosure compartment. The experimental campaign was divided into two scales. First, a (*F*ire *P*ropagation *A*pparatus) campaign analysed the effect of oxygen concentration and incident heat flux on a heptane pool fire of 0.01 m². Then, a medium-scale setup was developed studying different opening size conditions on naturally ventilated enclosure compartments.

The results demonstrate the influence of different ventilation conditions on combustion regimes, from fully developed to extinction due to oxygen depletion. The findings provide valuable insights for improving fire safety measures and developing more accurate predictive models for fire behaviour in enclosed spaces.

INTRODUCTION

Combustion in vitiated atmospheres has been mainly analysed in small and bench-scale test were boundary conditions such as oxygen concentration of gas flow can be adjusted to define the desired condition for the analysed [1], [2]. These controlled studies have allowed the development of parameters that analytically correlate the oxygen availability with the combustion typology. One of the most employed parameters is the GER that correlates the fuel mass loss with the oxygen inflow and the stoichiometric combustion relation, to define whether a combustion is under-ventilated or fuel controlled. However, these studies are often based on bench-scale tests, such as the FPA where other compartment factors (e.g. effects from hot layer) are not affecting the combustion. Additionally, the Equivalence Ratio, related to the GER, is estimated by different analytical equations defined experimentally for different particular cases as mechanical or natural ventilated compartments [3].

Some studies have developed laboratory scale experimental campaign to evaluate the compartment boundary conditions in the combustion. In [4], the effect of radiative heat fluxes in the burning rate of elevated dodecane pool fire in a well-ventilated compartment was analysed by using a reduced scale compartment of 1.8 m^3 with a mechanically ventilation system. The results showed that, if the flame does not impinge on the ceiling, the MLR remains quasi-constant, while when the flame impinges on the ceiling, the MLR increases drastically. Additionally, in [5], the same experimental setup was employed to analyse the effect of ceiling on burning rate of heptane and ethanol pool fires. The results confirmed the increase in MLR with the elevation for all fuel types. In [6] an analysis on the effect of a ceiling opening into the auto-extinction of heptane pool fire was presented. This study employed a compartment of 0.75 m^3 and the section of the pool and the opening was modified finding an exponential correlation between extinction and ceiling opening section. A study of self-extinction time of n-heptane pool fire in closed compartments was included in [7]. The experiment considers a compartment of 0.75 m^3 and pool fire diameters varying between 0.1 m and 0.3 m. They found that the fire self-extinction occurred when local oxygen mole fraction in the vicinity of the flame decreased to a level of 10.7 – 5.3 %.

The present study aims to analyse: 1. the influence of boundary conditions such as external radiant heat flux and O_2 concentration in the burning rates of heptane in controlled conditions as the defined in the FPA; 2. the influence of natural ventilation in compartments on the evolution of the GER and the burning rates, analysing extinction conditions.

METHODOLOGY

Physical Fundaments

Enclosure fires are affected by a large number of physical phenomena interconnected to each other. These phenomena are not insulated, and it is well known that they are affected by external factors, such as reradiation from hot surfaces and smoke layer, that can increase the fuel MLR. Another relevant factor is the oxygen availability to mix with the pyrolysis gases and allows combustion.

In fire science, it is widely used the equivalence ratio in order to analyse combustion reactions. This parameter defines the ratio of the fuel mass flow rate to the air mass flow rate divided by the same ratio at the stoichiometry of the reaction considered.

$$\phi = \frac{[\dot{m}_f/\dot{m}_a]}{[\dot{m}_f/\dot{m}_a]_{st}} = \frac{[\dot{m}_f/\dot{m}_a]}{r} \quad (1).$$

This equation is valid to analyse gas combustion conditions where fuel inflow ($\dot{m}_f$) and air inflow ($\dot{m}_a$) can be adjusted, being r the stoichiometric fuel-air-ratio. To calculate r we need to define a theoretically perfect reaction of the fuel with oxygen. Then, we define the stoichiometric combustion and calculate the stoichiometric moles of O_2 per moles of heptane consumed.

$$C_7H_{16} + 11(O_2 + 3.76N_2) \rightarrow 7CO_2 + 8H_2O + 41.36N_2 \quad (2),$$

$$r = \frac{(moles\ fuel)(M_f)}{(moles\ Air)(M_{air})} \quad (3).$$

Nevertheless, this approach is not easily applicable in fire safety engineering where the complexity of scenarios disables an accurate quantification of the air mass flow contributing to the combustion and neither the fuel mass flow. As a consequence, fire science has been using some analogous expressions for equivalence ratio to consider the global conditions of the fire scenarios. In ventilated compartments, the GER can be defined with the previous equation considering $\dot{m}_f$ as the instantaneous fuel MLR, and $\dot{m}_a$ as the total air flow rate into the compartment. In naturally ventilated compartment fires, it is not really hard to directly impose and measure the air flow, but estimations can be made based on well-known equations [7]:

$$\dot{m}_a = \frac{1}{2} A_0 \sqrt{H_0} \quad (4),$$

where A_0 is the area of the opening [m^2] and H_0 the height of the opening (m). In compartment fires, oxygen concentration in the combustion atmosphere is not necessarily constant. Therefore, in the GER calculation associated with compartments fires [7], the oxygen concentration in the inlet should be considered (γ_{O_2}), and the stoichiometric fuel-oxygen ratio (r_o):

$$\begin{cases} \phi = \frac{\dot{m}_f}{\dot{m}_a \gamma_{O_2} r_o} & mechanical\ ventilated \\ \phi = \frac{\dot{m}_f}{\frac{1}{2} A_0 \sqrt{H_0} \gamma_{O_2} r_o} & natural\ ventilated \end{cases} \quad (5).$$

If $\phi < 1$ the compartment is considered "well-ventilated", as there is an excess of oxygen available for combustion and all gases released from the fuel pyrolysis have available oxygen atoms for combustion. On the other hand, if $\phi > 1$, the compartment is considered "under-ventilated", since there is not enough oxygen for the combustion of all pyrolysis fuel gases, and unburned gases are being releasing.

The heat released during the combustion, as well as the flame temperature, are governed by the thermodynamics of energy conversion between reactants and products. The dependence of these two parameters on the fuel / air ratio is studied in [8]. This study shows that the heat released during fuel combustion remains constant for lean mixtures (excess oxidant), as all the fuel released through pyrolysis is consumed. However, for rich mixtures (excess fuel), the heat release decreases due to insufficient oxygen to completely burn the fuel. The flame temperature reaches its maximum under stoichiometric conditions (fuel oxygen ratio for complete combustion) and decreases for mixtures with excess air (more air to heat) and mixtures with air deficiency (less fuel burned).

Experimental Campaign

The experimental campaign has been designed in two sub-campaigns at bench-scale and at medium scale to analyse the effect of vitiated environment on burning rates. First one was performed in the FPA and the second one in an ad-hoc setup of 0.125 m^3.

The first sub-campaign, performed in the FPA aimed to analyse the influence of O2 concentration and of the external heat flux in the combustion. This apparatus was employed in the analysis of the GER in the combustion [2]. The FPA allows precise control of key parameters, such as the inlet gas flow rate (set at 200 l/min is this test), the O_2 and the measurement of the MLR, which are the three main parameters used to estimate the GER.

Table 1 summarizes the definition of the FPA experimental sub-campaign. As it is shown values of O2 concentration vary from 15 % to 21 % (air atmosphere) and two values of incident heat flux are considered, 0 and 15 kW/m^2. The fuel chosen in the study was heptane. Heptane is a very common combustible in nuclear facilities studies and its use is very common in this context. Three repeatability tests were conducted for each configuration.

Table 1 Characteristics of the FPA experimental sub-campaign cases

Case	Atmosphere	Incident Heat Flux [kW/m^2]
FPA_Hep-1	Air	0
FPA _Hep-2	18 % O_2	0
FPA _Hep-3	15 % O_2	0
FPA _Hep-4	Air	15
FPA _Hep-5	18 % O_2	15
FPA _Hep-6	15 % O_2	15

As FPA equipment allows the imposition of a specific gas flow inlet, the definition of the species concentration in the inlet gas flow, and the measurement of mass loss during the test, the direct equation of equivalence ratio (ϕ) can be applied under mechanical ventilated scenarios.

In a second step, a medium scale experimental setup was also developed and included in the present study. In order to understand and analyse ventilation and MLR in the combustion behaviour under vitiated atmospheres in a natural ventilated compartment, the influence of varying the opening height was analysed, as this parameter is closely related to ventilation. An ad-hoc setup was designed and developed for this purpose. The geometry of this equipment consists of a cube of 0.5 m size, which define an available volume of 0.125 m^3. Table 2 collects the definition of the boundary conditions of the medium scale sub-campaign. As mentioned, the aperture height was modified to assess its influence on ventilation and the fuel MLR.

Table 2 Characteristics of the medium-scale experimental campaign cases

Case	Opening height [m]	Pool Fire Section [m^2]
ME_Hep-1	0.05	0.10 x 0.10
ME_Hep-2	0.10	0.10 x 0.10
ME_Hep-3	0.25	0.10 x 0.10

A total of three repeatability tests were performed for each case in order to ensure the reliability and consistency of the results. Here, the pool fire size selected was the same employed in the FPA sub-campaign. According to literature [9] the mass burning rate of heptane is 0.101 kg/m^{2}s which, according to the Fire Dynamics Tools (FDTs), corresponds to a heat release rate (HRR) of approximately 5.26 kW for a 0.01 m^2 pool fire. In this case, as air gas flow inlet is unknown, and equation (5) for calculate the GER under natural ventilated scenarios must be used. The following Table 3 shows an estimation of the theoretical GER for the different cases to be analysed in the experimental campaign.

Table 3 Theoretical GER and combustion conditions in the medium scale tests

Case	HRR [kW]	A_0 [m^2]	H_0 [m]	GER	Combustion
ME_Hep-1	5.26	0.0375	0.25	0.182	well-ventilated
ME_Hep-2	5.26	0.0150	0.10	0.719	well-ventilated
ME_Hep-3	5.26	0.0075	0.05	2.035	under-ventilated

Adapted Tewarson Methodology

In order to estimate MLR from experimental tests, we defined a methodology based on the main principles of [10] by the use of following equations:

$$M_{t_i} = \left(\frac{E_{t_i}}{E_T}\right) M_T \quad (6),$$

$$MLR_{t_i} = \left(\frac{dM}{dt}\right)_{t_i} \quad (7),$$

where M_{t_i} is the mass at time t_i, and M_T the initial heptane mass.

RESULTS AND DISCUSSION

The following figures present a comparison between the average MLR directly measured by the FPA (dashed lines) versus the values estimated using the adapted Tewarson's methodology (continuous lines). It can be observed an accurate approach of the MLR curves obtained through the adapted Tewarson's methodology and those measured by the FPA, with the added advantage of reduced signal noise in the estimated curves.

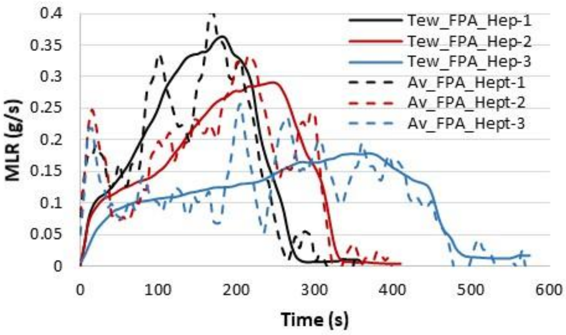

Figure 1 Comparison of the experimental MLR average versus the estimated one for the FPA tests 1 to 3

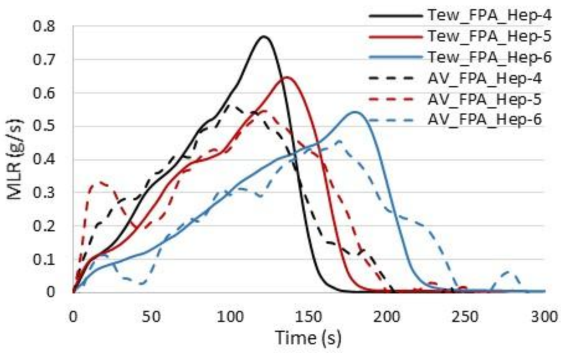

Figure 2 Comparison of the experimental MLR average versus the estimated one for the FPA tests 4 to 6

FPA Results

Table 4 includes the average values of the maximum HRR, MLR estimated using the adapted Tewarson's methodology and the theoretical GER.

Table 4 Summary results of FPA sub-campaign

Measure	FPA_Hept-1	FPA_Hept-2	FPA_Hept-3	FPA_Hept-4	FPA_Hept-5	FPA_Hept-6
Max HRR [kW]	14.99	12.57	8.52	38.15	28.61	28.80
Max Tew MLR [g/s]	0.366	0.290	0.179	0.768	0.646	0.543
Max Tew GER	1.43	1.33	0.98	3.02	2.95	2.98

A maximum HRR value of 38.15 kW was obtained in case FPA_Hept-4, with an external heat flux of 15 kW/m^2 under an air atmosphere. Average values of around 28 kW were obtained in cases FPA_Hept-5 (18 % O_2) and FPA_Hept-6 (15 % O_2) with the same external heat flux.

Cases without external radiant heat flux obtain lower HRR peak values, 14.99 kW, 12.57 kW and 8.52 kW for cases FPA_Hept-1 (21 % O_2), FPA_Hept-2 (18 % O_2) and FPA_Hept-3 (15 % O_2), respectively.

These results indicate that the presence of external heat flux leads to higher HRR values, which is also associated with increased MLR and GER. In cases without external radiant heat flux, GER values are higher with the higher O_2 concentration of the gas inflow. Only FPA_Hept-3 obtained a GER value lower than 1, but it was 0.98, very close to 1.

Figure 3 shows the average MLR for the cases with an external radiant heat flux of 15 kW/m2 (in black) and without it (in red). The MLR curves show a tendency of decreasing MLR values and longer combustion time as the oxygen concentration decreases. Additionally, the results show that increasing the external radiant heat flux leads to higher burning rates and shorter combustion durations. Combustion in cases with external radiant heat flux finished before 250 s, while cases without it reached up to 500 s.

Figure 4 compares the GER values for the different tests. Higher values of the GER were obtained for cases with the external radiant heat flux. The GER curves follow a similar trend to the MLR ones, although in cases with external radiant heat flux, the same peak value for the different O_2 concentrations was obtained.

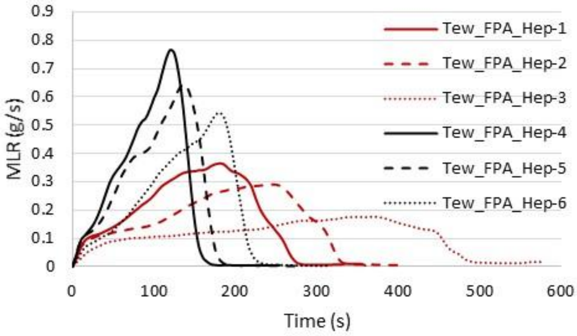

Figure 3 Comparison of the average experimental MLR of the FPA sub-campaign

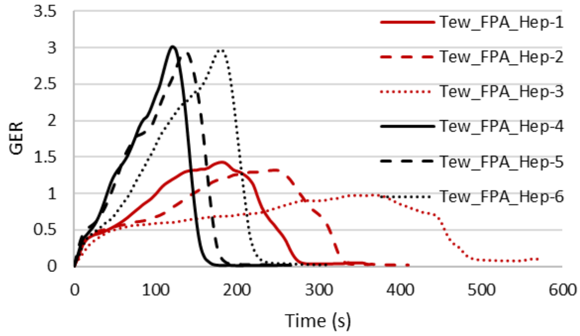

Figure 4 Comparison of the average experimental GER of the FPA sub-campaign

Medium-scale Results

Figure 5 shows the comparison of the average MLR for the different cases, from the largest opening (ME_Hep-3) to the smallest (ME_Hep-1). The three repeatability tests of case ME_Hep-1 extinguished due to oxygen depletion around 120 s after ignition, leaving an average of the 68 % of the initial heptane unburned. The setup conditions of ME_Hep-3 test boosted the combustion obtaining the greatest MLR values. The maximum MLR value was 0.424 g/s, which is a 15 % higher than the peak value observed in FPA_Hept-1 (performed in air atmosphere without external heat flux).

Figure 6 presents the calculus of the GER for the three scenarios. In case ME_Hep-1, extinction occurs when the GER exceeds a value of 1. Comparing ME_Hep-2 and ME_Hep-3, it is observed that ME_Hep-3 yields lower GER values (below 0.8).

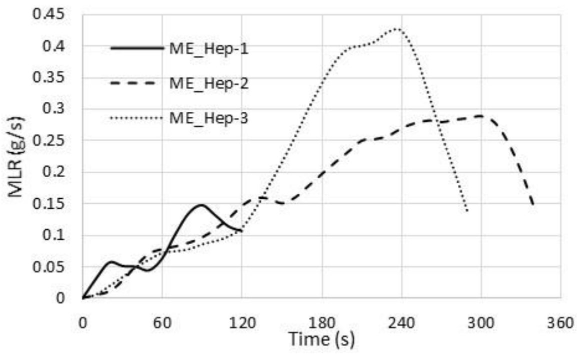

Figure 5 Comparison of the average experimental MLR of the medium scale sub-campaign

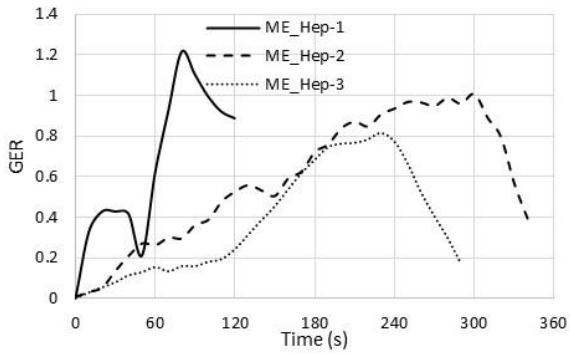

Figure 6 Comparison of the average experimental MLR of the medium scale sub-campaign

Figure 7, Figure 8 and Figure 9 show the visual evolution of the combustion in three tests of the different cases. As observed in Figure 7, at 60 s there was a weak flame scarcely visible over opening height. Figure 8 illustrates the flame evolution for the ME_Hept-2 case. Time evolution of the flame shows a displacement to the surroundings while decrease the flame height. At 240 s, we can see that there is no flame in the upper layer. Nevertheless, the calculated GER does not overpass the value of 1, and the fuel was completely consumed during all repeatability tests.

Figure 7 Photos of ME_Hept-1b at 30 s, 60 s, 90 s and 120 s

Figure 8 Photos of ME_Hept-2b at 60 s, 120 s, 180 s and 240 s

Figure 9 Photos of ME_Hept-3a at 60 s, 120 s, 180 s and 240 s

This effect is also reflected in case ME_Hep-3, as shown in Figure 9. At 60 s, there is no flame in the upper layer, and the flame is distributed along the lower part of the compartment. By 240 s, combustion areas are clearly visible. As in the previous case, the GER remains below 1, and the heptane is fully consumed.

CONCLUSIONS

This study highlights the significant influence of ventilation and oxygen concentration on the combustion behaviour and burning rates of naturally ventilated compartment fires. The effect of the vitiated atmospheres on burning rates has been studied by the development and analysis of two experimental sub-campaigns. The first one, a bench-scale sub-campaign performed in the Fire Propagation Apparatus (FPA), focused on assessing the influence of the O_2 concentration and external radiant heat flux on burning rates and the global equivalence ratio. The second one, a sub-campaign involved a medium scale ad-hoc setup (0.125 m^3) to analyse the effect of opening in the generation of vitiated atmospheres, and the effect on burning rates of naturally ventilated compartments. Furthermore, to determine additional data from the medium scale tests, such as MLR, a modified version of the Tewarson's method [9] was proposed and validated.

Results from the FPA sub-campaign showed a significant influence of the external radiant heat flux on burning rates and HRR of the heptane. Additionally, it showed that higher oxygen concentrations resulted in more intense combustion under conditions without external radiant heat flux, as in FPA_Hept-1 (21 % O_2), FPA_Hept-2 (18 % O_2) and FPA_Hept-3 (15 % O_2) tests. However, when an external radiant heat flux of 15 kW/m^2 was applied, this trend was not appreciated. Although the peak HRR was highest for FPA_Hept-4 (21% O_2) test, the peaks for FPA_Hept-5 (18% O_2) and FPA_Hept-6 (15% O_2) tests were similar.

Despite significant effects on combustion, variations in O_2 concentration had minimal impact on the GER values, highlighting limitations in the current analytical equations. While increasing external radiant heat flux elevated the fuel gasification rates and the proportion of unburned gases (yielding GER values closer to 3). The decrease in the O_2 concentration was not clearly reflected in the GER curves, which showed similar peak values.

In cases without external radiant heat flux, lower O_2 concentrations were associated with lower GER values, suggesting an apparent excess of oxygen. This outcome may stem from the use of equation (5), originally developed for mechanically ventilated conditions. According to this equation, the product $\dot{m}_a Y_{O_2}$ ranged between 0.896 g/s, 0.770 g/s and 0.641 g/s for 21 %, 18 % and 15 % O_2 concentration tests respectively. The analysis indicates that a 6 % reduction in the O_2 concentration theoretically increases the GER by 40 %, while in actual results, it had a larger effect on combustion. For instance, the peak HRR increased by 76 % between FPA_Hept-3 and FPA_Hept-1 tests. Under external radiant heat flux conditions this effect is less pronounced, as gasification was influenced by the compartment effect.

In the medium-scale sub-campaign, certain configurations led to fire extinction due to oxygen depletion, underscoring the importance of adequate ventilation to maintain combustion. The extinction was observed when the GER for natural ventilation exceeded a value of 1. Among these tests, the ME_Hep-3 test setup favoured the combustion obtaining the greatest MLR values. The maximum MLR value was 15 % higher than the peak value observed in the FPA_Hept-1 test. This can be associated with the re-radiation effect of the medium scale compartment employed, which increased the burning rate of fuel.

The GER results from the medium-scale sub-campaign showed better alignment with equation (5) for naturally ventilated conditions than those from the FPA tests. In the case of ME_Hep-1, extinction occurred when the GER exceeded 1, followed by a decrease in the GER as the MLR dropped. Comparing ME_Hep-2 and ME_Hep-3 tests, the latter exhibited lower GER values, consistent with its improved ventilation conditions.

Overall, the results provide valuable information for improving fire safety measures in naturally ventilated compartments. Understanding the interaction between oxygen concentration, radiant external heat flow and compartmentation can help develop more accurate predictive models of fire behaviour, enhancing safety protocols and fire management strategies.

ACKNOWLEDGEMENTS

The authors would like to thank the Consejo de Seguridad Nuclear for the cooperation and co-financing of the project “Análisis de modelos numéricos y experimentales para la investigación de incendios en centrales nucleares” (FIRENUC) and for the research project SUBV-18/2022 “NUCLEVS - Validación, calibración y aplicación de modelos de propagación de incendios en escenarios reales de Centrales Nucleares”.

REFERENCES

[1] Lázaro, FD., et al.: Influence of the STA boundary conditions on thermal decomposition of thermoplastic polymers, Journal of Thermal Analysis and Calorimetry, Volume 138 (1) , pp. 2457 - 2468, September 2019, DOI: 10.1007/s10973-019-08787-4.

[2] Khan, M. M., A. S. Tewarson, and M. Chaos: Combustion Characteristics of Materials and Generation of Fire Products, in: SFPE Handbook of Fire Protection Engineering, 5th Edition, pp. 1143 -1232, New York, NY, USA, Springer, 2015.

[3] McGrattan, K., and S. Miles: Modeling Fires Using Computational Fluid Dynamics (CFD), in: SFPE Handbook of Fire Protection Engineering, 5th Edition, pp. 1034 -1065, New York, NY, USA, Springer, 2015

[4] Georges, E., et al.: Burning rate of elevated pool fire in a well-ventilated compartment: Effects of radiative heat fluxes, Fire Safety Journal, Volume 141 (5-6):103933, September 2023, DOI: 10.1016/j.firesaf.2023.103933.

[5] Prétrel, H., et al.: Experimental investigation at reduced scale of the effect of a ceiling on the burning rate of a pool fire, Journal of Fire Sciences, Volume 43(1), pp. 18 - 32, October 2024, DOI: 10.1177/07349041241285775.

[6] He, Q., C. Li, and S. Lu: Vent size effect on self-extinction of pool fire in a ceiling vented compartment, Procedia Engineering, The 9th Asia-Oceania Symposium on Fire Science and Technology, Volume 62, pp. 242 - 249, Springer, 2013, https://www.sciencedirect.com/science/article/pii/S1877705813012435.

[7] Zhang, J., et al.: On the Self-extinction Time of Pool Fire in Closed, Procedia Engineering, Procedia Engineering, The 9th Asia-Oceania Symposium on Fire Science and Technology, Volume 62, pp. 266 - 274, Springer, 2013, https://www.sciencedirect.com/science/article/pii/S1877705813012460.

[8] Fernández-Pello, A. C.: On Fire Ignition, in: Fire Safety Science 10, Proceedings of the Tenth International Symposium, pp. 25 – 42,2011 DOI: 10.3801/IAFSS.FSS.10-25.

[9] United States Nuclear Regulatory Commission (U.S. NRC): Fire Dynamics Tools (FDTs) – Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program, Final Report, NUREG-1805, Washington, DC, USA, 2004, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/index.html.

[10] Tewarson, A. S., and M. M. Khan: Fire Propagation Behavior of Electrical Cables, in: Fire Safety Science: Proceedings of the Second International Symposium, pp. 791 – 800, 1989,DOI: 10.3801/IAFSS.FSS.2-791.

OECD/NEA FAIR (Fire Risk Assessment Through Innovative Research) Project: Progress Two Years After Project Launch

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ABSTRACT

The international OECD Nuclear Energy Agency (NEA) FAIR (*F*ire Risk *A*ssessment through *I*nnovative *R*esearch) Project has been launched in June 2023. Its main objective is to obtain additional and/or complementary data to those of the previous three OECD/NEA PRISME (French: *Pr*opagation d'un *i*ncendie pour des *s*cenarios *m*ulti-locaux *é*lémentaires) Projects performed between 2006 and 2021 (PRISME 1: 2006 – 2010, PRISME 2: 2011 – 2016, and PRISME 3: 2017 – 2022) for a better fire risk assessment in nuclear power plants (NPPs) and other nuclear facilities.

Based on the conclusions of a PIRT (*P*henomena *I*dentification and *R*anking *T*able) type exercise, aimed at identifying the topics for which there was a shared interest both from the point of view of safety issues and need for knowledge, the partners in the former PRISME projects have drawn up the content of the new FAIR project, which comprises the following three main topics:

- Fire propagation along cable trays;
- Effects of hot and vitiated environments on fires in confined, mechanically ventilated compartments;
- Complex multi-source and multi-compartment fire scenarios.

The experimental campaigns of the FAIR Project are being carried out in the GALAXIE platform facilities (operated by ASNR at Cadarache, France). A short overview of the project is presented.

INTRODUCTION

The international PRISME (which means "fire propagation for multi-room scenarios") Projects were conducted as Joint Projects under the auspices of the of the Organisation for Economic Co-operation and Development (OECD) NEA from 2006 to 2022.

The first OECD/NEA PRISME Project (2006 – 2011) concerned smoke movement from a fire compartment to adjacent rooms, the effects of under-ventilated conditions on the fire source (mainly liquids), and the behaviour of electrical cables exposed to high thermal stress [1]. The second OECD/NEA PRISME 2 Project (2012 – 2016) allowed the completion of studies on smoke movement from the fire compartment to adjacent rooms through a horizontal opening, fires of complex sources such as cable trays, fire spreading from an electrical cabinet to targets, such as cable trays or electrical modules, and the efficiency of water-based fire extinguishing systems for fire control 0. The third OECD/NEA PRISME 3 Project (2017 – 2022) investigated new scenarios of smoke propagation in a mechanically ventilated multi-room facility using multiple and elevated fire sources, the spread of fire from an open door electrical cabinet to neighbouring cabinets with closed doors, and new configurations of cable tray fires in open and confined atmosphere, including configurations involving a long corridor representative of a service gallery 0, 0.

After PRISME 3, a new Project FAIR was launched in mid-2023. Its objective is to obtain additional and/or complementary data to those of the previous three OECD/NEA PRISME Project series by addressing new fire scenarios and new topics of interest for an improved fire risk assessment in NPPs and other nuclear facilities.

In order to achieve the above-mentioned objectives, the experimental programme FAIR is organized in the following three major topics:

- Propagation along cable trays with a focus on the effects of long cables trays (LCT) and cable ageing;
- Fires in confined and mechanically ventilated compartments, with a focus on the effects of hot and vitiated environments (HVE) on the combustion and the re-inflammation of unburned material;
- Multi-source and multi-compartment complex scenarios, with a focus on fire propagation between discrete sources and smoke propagation in complex room configurations.

The safety issues associated with each of the topics identified above and the outline of the experimental program planned within the FAIR Project for improving the state of our knowledge for each of them have been described already in a contribution to the previous SMiRT post-conference Fire Seminar in 2022 by March et al. 0.

The experimental campaigns of the FAIR Project are carried out in the GALAXIE platform facilities presented below and operated by the French Nuclear Safety and Radiological protection Authority ASNR (formerly IRSN), at Cadarache, France. In this paper, a short overview of the Project is given.

GALAXIE PLATFORM

As mentioned in the introduction, the experimental work within the OECD/NEA FAIR Project is performed in the GALAXIE platform of ASNR at Cadarache in France.

Large-scale tests are performed in facilities briefly described in the following paragraphs.

DIVA Facility

The DIVA facility is used to conduct highly instrumented tests on fires in configurations involving several confined and mechanically ventilated rooms which could affect nuclear laboratories and factories just as much as nuclear power reactors. Figure 1 shows a general view of the DIVA facility. For the FAIR Project, most of the large-scales tests planned are performed in the DIVA facility. It should be noted that the separation between Room 2 and Room 3 has been removed, notably to be able to perform long vertical cable tray fires (in the LVCT campaign).

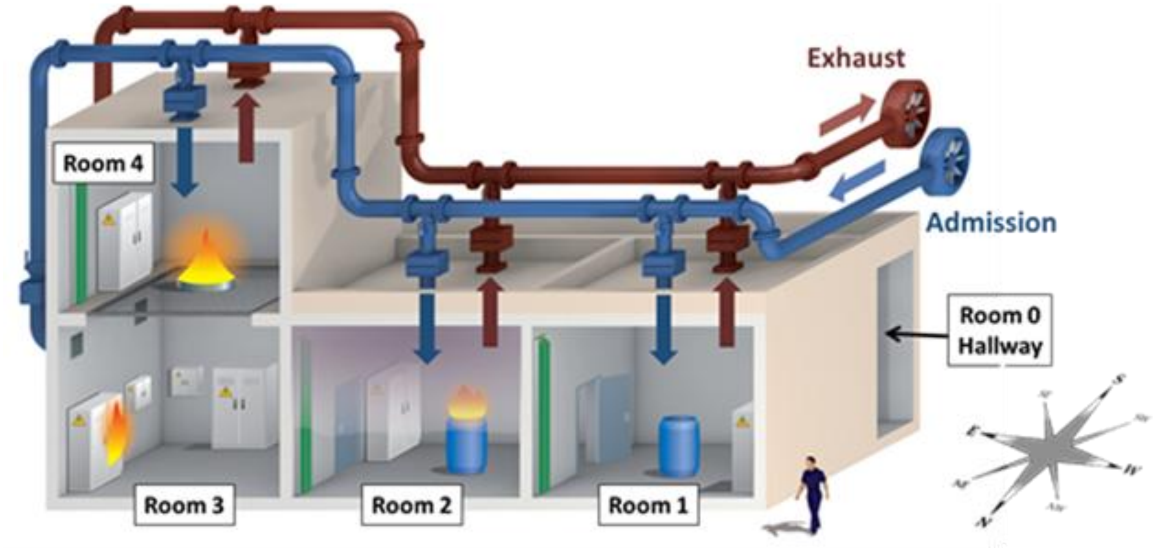

Figure 1 DIVA facility

SATURNE Facility

The SATURNE facility (2,000 m^3 volume), equipped with a large-scale calorimetric hood, allows to perform fire tests in open atmosphere conditions (oxygen limitless) to reach a full development of the fire on the studied fuels. Figure 2 shows the lower part of the hood with the concrete slab where the fire to be characterized is placed. For the OECD/NEA FAIR Project, SATURNE will be used in the multi-source test campaign to characterize fire sources (see test matrix below).

Figure 2 SATURNE facility

PLUTON Facility

This single-room facility is composed of a large-scale enclosure coupled with a complex ventilation network to simulate high-power fire scenarios in different representative configurations of nuclear facilities. Figure 3 shows the interior of the enclosure. For the OECD/NEA FAIR Project, PLUTON is intended to be used to install a new device dedicated to the study of unburned gases´ combustion (see test matrix below).

Figure 3 PLUTON facility

Some experimental campaigns of the FAIR Project also involve tests in medium-scale test devices:

NYX Test Device

The NYX test device is small-scale enclosure designed to provide a detailed understanding of fire scenarios in confined and mechanically ventilated enclosures. The device is modular and allows the study of the characteristics of the ventilation network (flow rate, position of vents), of the fire (gas, liquid or solid fire, position in the room) and of the nature of the walls. Figure 4 shows a picture and a schematic outline of the NYX test device. For the OECD/NEA FAIR Project, NYX is used in the HVE campaign (see test matrix below).

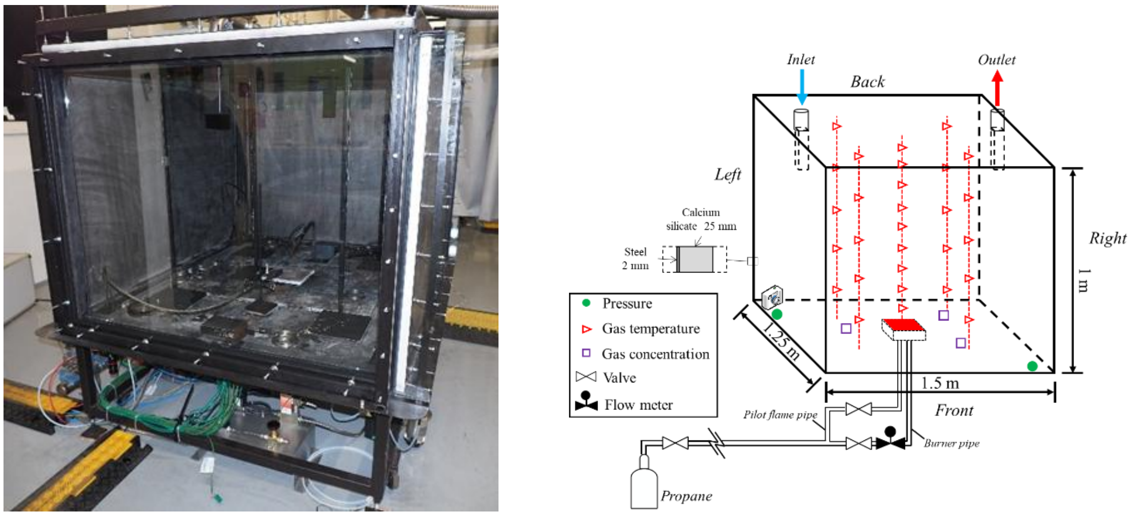

Figure 4: Photo and schematic outline of the NYX test device

CISCCO Test Device

The CISCCO test device allows the study of the pyrolysis and flame spread on preheated fuel surfaces (electric cable layer, polymeric material plates, etc.) that can be either horizontally oriented or inclined. Figure 5 shows the CISCCO test device. For the OECD/NEA FAIR Project, tests dedicated to cable ageing study will be performed in the CISCCO test device (see test matrix below).

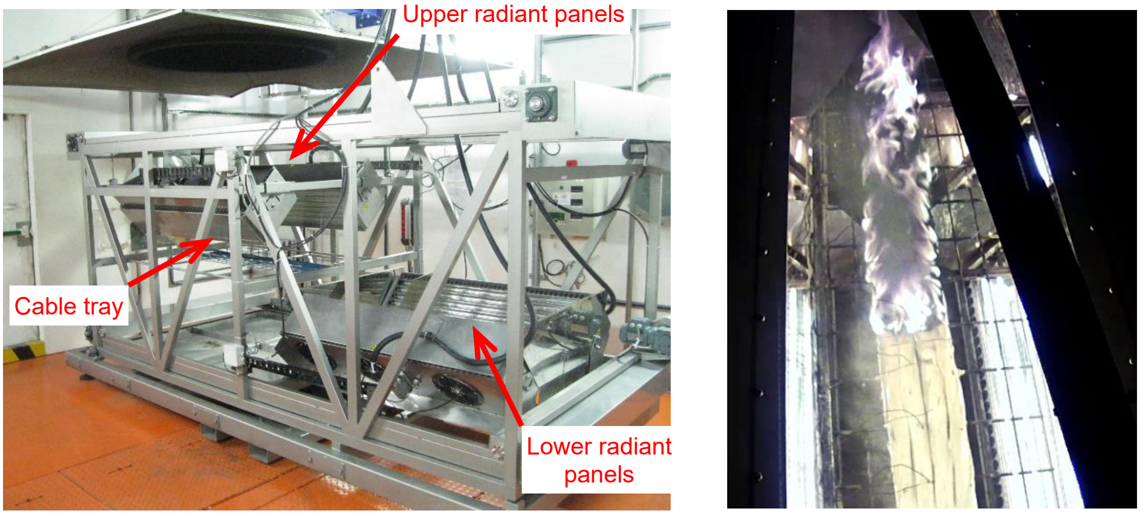

Figure 5 CISCCO test device, left: an overview of the upper radiant panels located above the cable tray while the lower ones were moved to the relocation area, right: top view showing the flame front spread along the cable tray and the lower radiant panels

EXPERIMENTAL GLOBAL TEST MATRIX

The global test matrix of the OECD FAIR Project is presented in Table 1.

Table 1 Global test matrix of the OECD/NEA FAIR Project

Experimental Campaigns	Large-scale Tests	Medium-scale Tests
A1 – Long horizontal and vertical cable trays (LHCT, LVCT)	7 (DIVA)	0
A2 – Cable ageing effects (CAE)	0	10 (CISCCO) + 10 (cone calorimeter)
B1 – Combustion in vitiated and hot environment (HVE)	3 (DIVA)	10 (NYX)
B2 – Combustion of unburned gases (UGC)	0	10 (new, possibly inside PLUTON)
C1 – Propagation between discrete sources	4 (DIVA or PLUTON) 2 (SATURNE)	0
C2 – Smoke propagation in multi-compartment scenarios	3 (DIVA)	0

In addition to the tests listed in the test matrix in Table 1, each campaign includes a series of support tests, conducted to qualify the installations/facilities/devices, metrology, fuel behaviours and fire scenarios.

PROJECT SCHEDULE

Figure 6 presents the FAIR Project schedule. The Project started in mid-2023 for an expected duration of five years until mid-2028.

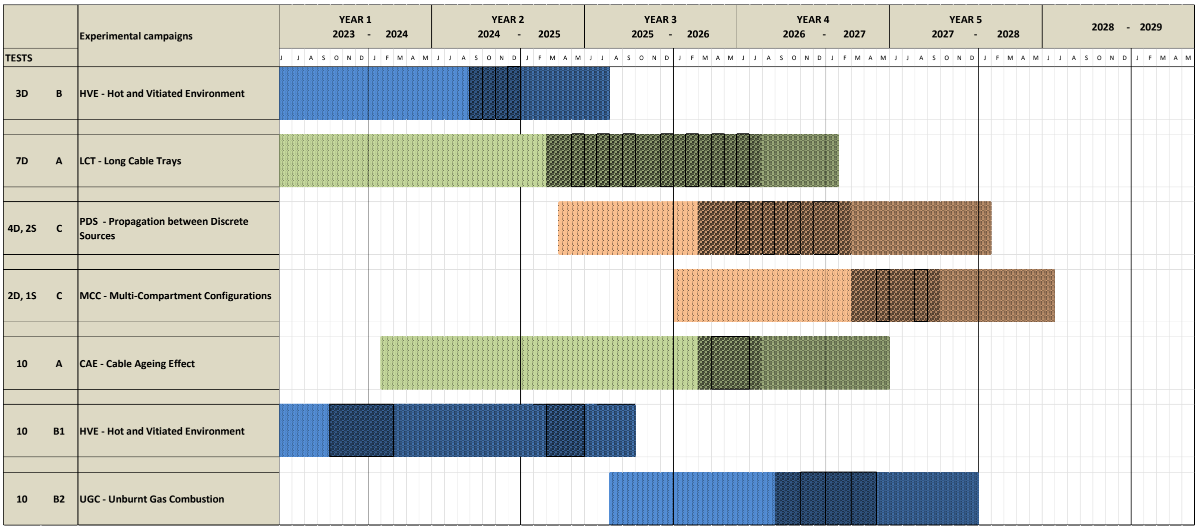

Figure 6 OECD/NEA FAIR Project schedule

DESCRIPTION OF THE EXPERIMENTAL WORK

The OECD/NEA FAIR experimental campaigns are described in March et al. 0. The main objectives of each campaign are recalled below.

Fire Propagation along Cable Trays

Long Horizontal and Vertical Cable Trays (LHCT, LVCT)

A first of large-scale tests is proposed to address the full characterization of fire propagation over long horizontal cable trays in mechanically ventilated confined compartments. These tests will complement the most recent OECD/NEA PRISME 3 CFP (Cable Fire Propagation) 0 corridor test campaign that involved 6 m long horizontal cable trays in the corridor of the ASNR DIVA facility (see Figure 1). These tests showed that longer cable trays are more suitable to avoid any edge effect and thus allow a more extensive validation of the analytical models. Taking into account the feedback of these tests regarding the DIVA safety criteria, tests using 8 m to 10 m long cable trays will be performed in the corridor of the DIVA facility.

A second series of large-scale tests is proposed to study both the fire spread over long vertical cable trays and the consequences of such fires in mechanically ventilated confined compartments. To this end, tests using a vertical cable tray of at least 6 m length will be considered in room 34 of the DIVA facility. This second test series will complete the previous works that all involved 2 m to 4 m long vertical cable trays 0, 0, [8], 0.

Cable Ageing Effects (CAE)

The FAIR Project proposes to provide information on the effects of ageing of sheathing (Insulation) materials on the fire behaviour of cables and fire propagation 0, 0, 0.

Two tasks are proposed:

- Task 1: In the frame of this task the impact of ageing on the fire behaviour of naturally aged cables shall be determined in order to receive representative outcomes. The main challenge is to be able to collect appropriate cables from nuclear facilities: cables neither contaminated nor activated and with the knowledge of the fire standards they initially satisfied.
- Task 2: Within this task the impact of ageing on the fire behaviour of artificially aged cables shall be studied. This allows a wide selection of cables and the choice of the ageing source(s). However, the main challenge is to specify representative accelerated ageing tests.

A selection will be performed among the proposed cable candidates for the ageing study, depending on what is specified above.

Fire characterizations will be conducted both in cone calorimeter and, at medium-scale, with tests using the CISCCO test device (cf. Figure 5). The cone calorimeter tests will allow to analyse the ageing impact on the time to ignition and the HRR of cable samples. The CISCCO tests will allow to assess the ageing impact on the flame spread velocity along a horizontal cable tray and the related HRR.

Fires in Confined and Mechanically Ventilated Compartments

Combustion in Hot and Vitiated Environment (HVE)

The FAIR Project proposes to provide insights from the combined influence of oxygen depletion 0 and gas temperature (or external heat flux) increase on the development of the fire and the conditions of ignition and extinction for a fire developing in a very hot and strongly under-oxygenated atmosphere 0, 0. A twofold experimental approach is proposed: a first approach based on large-scale experiments in order to gather real scale realistic fire scenarios and a second one based on a medium-scale analytical approach in order to support both the analysis and understanding of large-scale test results and the development of a modelling methodology.

The first test series will include large-scale experiments involving one or several mechanically ventilated compartments of the DIVA facility (cf. Figure 1). The objective is to reproduce configurations for which the external heat fluxes towards the combustibles are significant and can compensate the negative effect of the oxygen vitiation. Typical examples are cable trays or electrical cabinets under the ceiling engulfed within the smoke layer.

A second series of medium-scale experiments will be performed in a controlled atmosphere device. Simple fire sources are considered as liquid pool and homogenous solid. The intermediate experimental device that is considered is the NYX test device (cf. Figure 4). The design of the experiments at both large and reduced scale will be conducted in order to demonstrate the performance of scaling laws.

Unburned Gases Combustion (UGC)

Smoke explosions were observed during large-scale cable tray fire tests that were conducted in representative rooms of NPPs within the frame of the OECD/NEA PRISME 2 experiments 0. Several deflagrations, characterized by overpressures exceeding 100 hPa, and fast flame propagation occurred while there was no sudden change in the ventilation. Smoke explosion therefore cannot be excluded from fire safety analyses performed for rooms of NPPs. The FAIR Project proposes to provide insights in the smoke explosion phenomenon and especially concerning the conditions that promote the formation of a premixed gas mixture and the conditions that lead to deflagrations.

It is foreseen to conduct medium-scale experiments that will be more favourable than large-scale experiments to provide a detailed characterization of both the conditions for the occurrence of deflagrations and their development.

The reduced-scale test device should be similar to NYX (see Figure 4) with a volume of about 2 m^3 corresponding to a one-quarter scale model of one room of the DIVA facility. The proposed reduced-scale test device will also be equipped with two ventilation ducts for simulating either air leakages or moderate ventilation flow rates that both will contribute to gradually form the premixed gas mixture as observed prior to the smoke explosion phenomenon. Several fuel types will be considered, from the simplest one (liquid hydrocarbon) to the more realistic ones (electrical cable samples). The second purpose of the medium-scale experiments will be to highlight the conditions that lead to deflagrations (e.g., the related temperature and concentration criteria) and to characterize their development (e.g., the premixed flame propagation velocities).

Multi-source and Multi-compartment Complex Scenarios

Propagation Between Discrete Sources

This campaign of the FAIR Project will focus on the propagation between several discrete sources in the same environment, leading to a displacement of the fire location in the compartment or to the occurrence of several simultaneous fires.

This campaign will involve some large-scale experiments performed in the GALAXIE platform, focusing on both real configurations and academic scenarios, either in confined atmosphere (DIVA or PLUTON facilities) or in open atmosphere (SATURNE facility). The practical configurations will focus on two scenarios of fire spreading. The first one will focus on vertical spread, mainly induced by convection because of the smoke motion. The second one will focus on horizontal spread, mainly induced by radiation from the flame. The fire source will be a real fire source such as cable trays, but one or two large-scale fire tests will deal with more academic fuels. The objective of this approach is to focus on the physical mechanisms involved and to propose academic cases for code validation. The fire source will be well-mastered as pool fire or homogenous solid for which the thermal characteristics are known (critical heat fluxes and ignition temperatures). The configuration will concern simple source arrangements such as horizontally or vertically aligned sources.

Another important issue in assessing fire risks and in simulating fire scenarios is not only due to the complexity of the fire source but also to the complexity of configurations and geometries specific to nuclear facilities. Fire scenarios mostly concern assemblies of several interconnected rooms equipped with mechanical ventilation to ensure dynamic confinement with pressure cascade.

The fire tests will include large-scale experiments in the DIVA facility, involving various compartment arrangements and mechanically ventilated scenarios. The main topics proposed for being studied are the smoke propagation and deposition in multi-compartment arrangements with various room shapes and the interaction between smoke flow and the geometrical obstacles (e.g., grid flooring).

PROJECT PROGRESS

To date, the HVE campaign is being finalized: as shown in the Project schedule outlined in Figure 6, large-scale tests have been carried out in the DIVA facility (see Figure 7) and the final small-scale tests are underway. Besides, the preparation of the large-scale tests of the LCT campaign (vertical and horizontal cable trays, LVCT and LHCT) in the DIVA facility and associated first qualification tests are currently being performed. These tests will be carried out until early 2026.

Figure 7 Example of a cable fire during the FAIR HVE tests in the DIVA facility

CONCLUSIONS

The ongoing FAIR Project will investigate three major topics described in this paper, namely fire propagation along cable trays, fires in confined and mechanically ventilated compartments, and multi-source/multi-compartment scenarios.

The experimental campaigns of the FAIR Project will include tests carried out in the GALAXIE platform facilities (operated by ASNR at Cadarache, France), either on a large scale in the

DIVA, SATURNE and PLUTON facilities, or with more analytical devices on a medium scale, such as CISCCO, NYX or still to be designed devices (as for unburned combustion). The Project started in mid-2023 has an intended duration of five years.

In parallel to the experimental work described in this paper, an Analytical Working Group (AWG) has been launched, to provide an expert forum for exchanges between analysts from the FAIR partner organisations concerning the interpretation of the Project results. The activities carried out in the frame of the AWG do significantly enhance the value of such a project, thanks to the added value of the discussions and work carried out by specialists on the complex subjects studied experimentally in the FAIR Project.

ACKNOWLEDGEMENTS

The authors warmly thank all partners of the OECD/NEA FAIR Project.

REFERENCES

[1] Audouin, L., et al.: PRISME Project: Fires in confined and ventilated nuclear-type multi-compartments – Overview and main experimental results, Fire Safety Journal, Vol. 62, pp. 80 - 101, 2013, https://doi.org/10.1016/j.firesaf.2013.07.008.

[2] Suard, S., et al.: Fire development in multi-compartment facilities: PRISME 2 Project, Fire and Materials 43, pp. 433 - 435, 2019, https://doi.org/10.1002/fam.2754.

[3] Suard, S., P. Zavaleta, and H. Prétrel: Overview of the OECD PRISME 3 Project, Fire Safety and Emergency Preparedness for the Nuclear Industry, Presentation at the at FSEP 2019 – 3ed Conference on Fire Safety and Emergency Preparedness, Ottawa, ONT, Canada, October 28-30, 2019.

[4] Prétrel, H., P. Zavaleta, and S. Suard: Experimental study on the effect of the mechanical ventilation on cable tray fires in compartments, Fire Safety Journal, Volume 138, 103792, ISSN 0379-7112, Elsevier, July 2023, https://doi.org/10.1016/j.firesaf.2023.103792.

[5] March, P., et al. FAIR: A New OECD/NEA Fire Risk Research Project Under Development as a Follow-Up to PRISME 3, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 26, 17th International Seminar on Fire Safety in Nuclear Power Plants and Installations, Westerburg Huy, Germany, October 24-26, 2022, GRS–705, ISBN 978-3-949088-96-4, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, November 2022, https://www.grs.de/aktuelles/publikationen/grs-705.

[6] Riese, O., D. Hosser, and M. Röwekamp: Evaluation of Fire Models for Nuclear Power Plant Applications, Benchmark Exercise No. 5: Flame Spread in Cable Tray Fires, International Panel Report, G GRS-214, ISBN 978-3-931995-81-2, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Köln, Germany, November 2006, https://www.grs.de/en/news/publications/grs-214-evaluation-fire-models-nuclear-power-plant-applications.

[7] McGrattan, K. B., and S. D. Bareham: Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 2: Vertical Shafts and Corridors, NUREG/CR-7010, Vol. 2, prepared for United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research, Washington, DC, USA, December 2013, https://www.nrc.gov/docs/ML1334/ML13346A045.pdf.

[8] Passalacqua, R., et al.: Experimental characterisation of ITER electric cables in postulated fire scenarios, Fusion Engineering and Design 88 (9-10), pp. 2650 - 2654, Elsevier, October 2013, https://doi.org/10.1016/j.fusengdes.2013.01.026.

[9] Audouin, L., and J. L. Torero: Special issue on PRISME – Fire safety in nuclear facilities, Fire Safety Journal, Volume 62, Part B, pp. 7, November 2013, https://doi.org/10.1016/j.firesaf.2013.11.002.

[10] Kim, J.-S.: Evaluation of Cable Aging Degradation Based on Plant Operating Condition, Journal of Nuclear Science and Technology, 42:8, pp. 745 - 753, 2005, https://doi.org/10.1080/18811248.2004.9726444.

[11] Subudhi, M., and S. K. Aggarwal: Literature Review of Environmental Safety-Related Qualification of Electric Cables, NUREG/CR-6384, BNL-NUREG-52480, Vol. 1, prepared for: United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear regulatory Research, Washington, DC, USA, April 1996, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6384/index.html.

[12] Nowlen, S. P.: An Investigation of the Effects of Thermal Aging on, the Fire Damageability of Electric Cables, NUREG/CR-5619, SAND90-2121; prepared for: United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research, Washington, DC, USA, March 1991, https://www.nrc.gov/docs/ML0625/ML062510133.pdf.

[13] Peatross, M. J., and C. L. Beyler: Ventilation Effects on Compartment Fire Characterization, Fire Safety Science 5, pp. 403 - 414, 1997, https://doi.org/10.3801/IAFSS.FSS.5-403.

[14] Suard, S., et al.: Analytical Approach for Predicting Effects of Vitiated Air on the Mass Loss Rate of Large Pool Fire in Confined, in International Symposium of Fire Safety Science, 2011, https://doi.org/10.3801/IAFSS.FSS.10-1513.

[15] Nasr, A., et al.: Fuel mass-loss rate determination in a confined and mechanically ventilated compartment fire using a global approach, Combust. Science Technology, Vol. 183, no. 12, pp. 1342 - 1359, 2011, https://doi.org/10.1080/00102202.2011.596174.

[16] Zavaleta, P-, S. Suard, and L. Audouin: Cable tray fire tests with halogenated electric cables in a confined and mechanically ventilated facility, Fire and Materials, 43, pp. 543 - 560, 2019, https://doi.org/10.1002/fam.2717.

Thermal behaviour and Characterization of Electrical cables: Effects of Sample Orientation and Testing Conditions

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ABSTRACT

Electrical cables are essential components in buildings and infrastructures, playing a crucial role in power distribution and data transmission. In nuclear power plants (NPPs), they are particularly vital for operational control and the safe functioning of critical systems. Before new cable products enter the market, they must undergo rigorous testing to ensure compliance with safety and performance standards. Given the extensive number of tests required, bench-scale experiments are commonly conducted to analyse thermal behaviour and fire properties. Apparatus such as the cone calorimeter and fire propagation apparatus (FPA) are widely used for this purpose, typically following standardized horizontal testing configurations. However, vertical testing can be performed by simply adjusting the sample holder's orientation. This study investigates the influence of sample orientation in FPA testing. The results indicate some minor but interesting differences between horizontal and vertical configurations for both tested cables, despite being composed of the same materials. While critical heat flux values remained consistent across both configurations, thermal response parameter (TRP) varied with positioning, and significant differences in heat release rate (HRR) were observed. These findings highlight the impact of sample orientation on fire performance assessments. Although standards for bench-scale tests specify that combustion and ignition tests should be conducted in a horizontal position, the differing behaviour of cables due to their orientation once installed in buildings suggests that testing in multiple positions should be considered.

INTRODUCTION

Electrical cables play a fundamental role in modern infrastructure, ensuring reliable power distribution and data transmission across various applications. Their performance and safety are particularly critical in high-risk environments such as NPPs, where they support operational control and essential safety systems. To guarantee compliance with safety and performance regulations, electrical cables must undergo rigorous testing before market approval. The Construction Products Regulation (CPR-305/2011) [1] establishes the framework for fire safety classification, requiring full-scale testing according to EN 50399 [2], which subsequently determines cable classification under EN 13501-6/2019 [3]. Nonetheless, the extensive number of tests required under these standards presents challenges in terms of cost and feasibility, necessitating alternative approaches to optimize the testing process.

Among these research initiatives, the CHRISTIFIRE project [4], funded by the U.S. Nuclear Regulatory Commission (NRC), has provided valuable insights into the fire behaviour of electrical cables, particularly in cable tray installations. This project has focused on quantifying mass loss, energy release, heat release rates, smoke production, and flame spread characteristics using both bench-scale and large-scale tests. Similarly, the FIPEC (*Fi*re *P*erformance of *E*lectric *C*ables project [5] has contributed to refining testing methods for evaluating the fire performance of electrical cables through small- and large-scale experiments.

Building on these large-scale studies, several works have demonstrated the effectiveness of bench-scale tests in characterizing cable fire behaviour. For instance, in [6] the researchers explored the correlation between small-scale fire test data and intermediate-scale fire propagation behaviour. Additionally, in [7] new and aged building wires using a cone calorimeter bench-scale tests were used to evaluate the fire behaviour of flame-retardant PVC cables. Other studies have investigated variations in testing conditions, such as the work [8] which examined how different levels of external heat flux influenced fire characteristics. Similarly, in [9] the authors analysed the impact of cable spacing on fire behaviour and associated risks. Furthermore, in [10] the effects of parameters such as heat flux, cable quantity, and spacing were evaluated.

Considering the findings from these previous studies, it is evident that variations in testing conditions significantly influence fire behaviour parameters. While ISO 12136:2011 [11] / ASTM E2058-19 [12] standards specify a horizontal position for ignition and combustion tests and a vertical position for fire propagation tests in the FPA, further investigation into the influence of sample orientation on test results could be valuable. This is particularly relevant given that electrical cables in buildings and infrastructure are commonly installed in both vertical and horizontal positions, and previous cone calorimeter studies have shown that the test set-up can significantly affect fire behaviour outcomes.

To address this gap, the present study investigates the influence of sample orientation using the FPA, which offers greater versatility than the cone calorimeter. The FPA allows for varied sample positioning, accommodates larger sample sizes, and enables atmospheric control by adjusting both the external heat flux and oxygen concentration. Unlike the cone calorimeter – where vertical orientation is possible but not standard – the FPA is specifically designed to support both horizontal and vertical orientations. Moreover, it facilitates propagation analysis in samples up to 810 mm in length. This flexibility enables a more comprehensive assessment of material behaviour under varied fire scenarios.

This study aims to assess key fire behaviour parameters under varying test conditions by obtaining properties such as chemical heat release (Q_{chem}), effective heat of combustion (ΔH_{eff}), critical heat flux (CHF), and time to ignition (t_{ign}). Additionally, based on the experimental results, parameters such as the TRP, the fire propagation index (FPI), and thermal inertia (ρkc) are calculated. These findings contribute to a deeper understanding of electrical cable fire performance based on their orientation in service.

EXPERIMENTAL SET-UP

The FPA was used for all tests conducted in this study. Three types of tests were executed: (1) ignition, (2) combustion, and (3) propagation. According to [11], [12], ignition and combustion tests should be performed with the specimen in a horizontal position, while fire propagation tests are conducted in a vertical position. In addition to the standard methodology, this study also included ignition and combustion tests with the specimen positioned vertically. Due to their larger specimen size (810 mm), fire propagation tests were necessarily performed in the vertical orientation.

The ignition tests determine the CHF required to ignite a sample by exposing it to an external radiant heat source while monitoring the time to ignition (t_{ign}). The procedure involves subjecting the sample to a series of heat flux levels, starting from a low value and gradually increasing until ignition is observed. At each heat flux level, a pilot flame is introduced to determine whether the sample ignites. Once ignition occurs, two additional tests are conducted at the same heat flux to confirm the minimum heat flux for ignition. The test provides crucial data on time to ignition (t_{ign}) and establishes the CHF, which is the lowest radiant heat flux that causes sustained ignition.

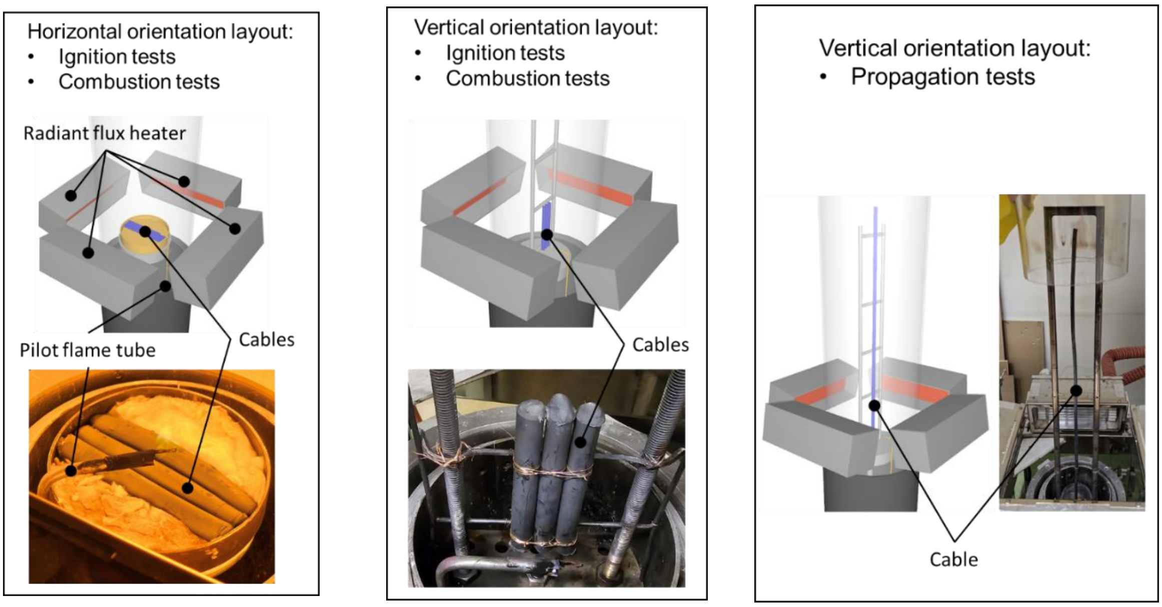
The combustion tests evaluate a material's fire behaviour by measuring chemical heat release (Q_{chem}), mass loss rate (MLR), and effective heat of combustion (ΔH_{eff}), under controlled conditions. The sample is subjected to a constant external heat flux to sustain burning, while a pilot flame ensures continuous ignition. Gas analysers in the exhaust system measure carbon monoxide (CO), and carbon dioxide (CO_2) production, which are used to calculate the effective heat of combustion and assess combustion efficiency. The test also records the mass loss rate (MLR).

The propagation tests assess a material's ability to sustain and spread the fire under controlled heat flux and varying atmospheric conditions. In this test, the sample is continuously exposed to an external radiant heat source, with a pilot flame ensuring ignition. Once ignited, the material's flame spread behaviour and burning rate are analysed by monitoring the HRR, similar to combustion tests, along with flame dynamics. A key feature of the FPA propagation test is its ability to vary the atmospheric oxygen concentration, allowing researchers to study fire behaviour in well-ventilated, oxygen-limited, or oxygen-enriched environments.

The three types of tests conducted, along with their respective boundary conditions, are summarized in Table 1 and the Figure 1 indicates the position of the samples. The standard-specified configurations for each test type are underlined. Two types of monopolar electrical cables were tested, and their properties are detailed in Table 2.

Table 1 Tests conducted in FPA apparatus

Test	**Sample Orientation**	**External Radiant Heat Flux [kW/m²]**	**Oxygen Level [%]**	**Number of Samples**	**Length of the Sample [mm]**
Ignition	horizontal	variable up to ignition is produced	21	5 (cable A) / 3 (cable B)	10
	vertical				
Combustion	horizontal	25, 40, 45, 50	21	5 (cable A) / 3 (cable B)	10
	vertical				
Propagation	vertical	50	20, 35, 40	1	810



a) b) c)

Figure 1 Cable layout for testing, experimental schematic, and actual photograph: a) horizontal layout for ignition and combustion tests, b) vertical layout for ignition and combustion tests, and c) vertical orientation for propagation tests

Table 2 Tested cables

Test	Type	Cross section [mm²]	External diameter [mm]	Sheath thickness [mm]
Cable A	monopolar	16	12.2	1.67
Cable B	monopolar	50	6.7	1.12

EXPERIMENTAL RESULTS

Ignition Tests

Table 3 presents the results of the ignition tests. Based on these findings and following the CHF estimation method described in the Ignition Handbook (Quintiere's procedure) [13], the CHF for Cable A was determined to be 17 kW/m² (16/18 = 17) in both horizontal and vertical orientations. Similarly, for Cable B, the CHF was 19 kW/m² for both orientations.

Table 3 Results of ignition tests

Cable A				Cable B			
Horizontal		Vertical		Horizontal		Vertical	
External radiant heat flux [kW/m^2]	Time to ignition [s]	External radiant heat flux [kW/m^2]	Time to ignition [s]	External radiant heat flux [kW/m^2]	Time to ignition [s]	External radiant heat flux [kW/m^2]	Time to ignition [s]
14	∞			18	∞	18	∞
16	890, ∞	16	∞	20	665, 792	20	709, 780
18	627, 734	18	416, 451	23	464, 614		

"∞" indicates no ignition after 10 minutes of test

Regarding time to ignition, considering only the heat flux levels that resulted in ignition, Cable A exhibited slightly faster ignition in the vertical position. However, for Cable B, no clear trend was observed between the horizontal and vertical orientations, making it difficult to determine which position facilitated ignition more readily.

Combustion Tests

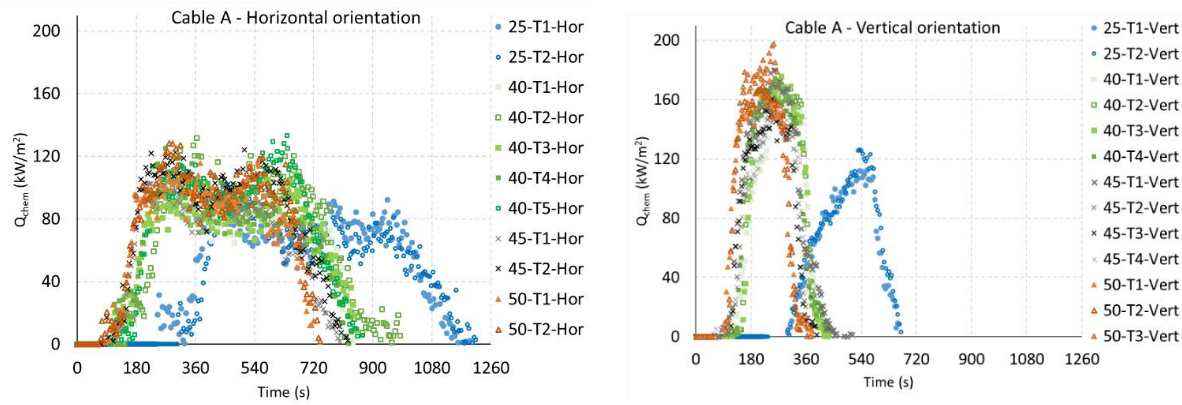
The results of these tests for Cable A are summarized in Table 4. For both orientations, the table includes the time to ignition (t_{ign}), the peak HRR (pHRR), and the total heat released (THR) during the burning period. Due to the limitations of the vertical test setup – specifically, the use of the propagation test sample holder, which occasionally made contact with the FPA's aluminium support tube total heat released – mass loss measurements in the vertical orientation were unreliable. As a result, the effective heat of combustion could only be determined from the horizontal orientation tests. The energy release curves (Q_{chem}) for both orientations are presented in Figure 2.

Table 4 Results of combustion tests for Cable A

Cable A									
External Radiant Heat Flux [kW/m^2]	Initial Mass [g]	Mass Loss [g]	ΔH_{eff} [kJ/kg]	T_{ign} [s]	pHRR [kW/m^2]	THR [kJ]	T_{ign} [s]	pHRR [kW/m^2]	THR [kJ]
	Horizontal Orientation						Vertical Orientation		
25	81.9	8.9	20826	242	100.7	185.3	218	112.2	169.3
	82.5	8.6	20767	306	102.3	178.6	239	126.1	183.0
40	82.2	8.8	20826	109	114.8	183.9	99	165.4	207.1
	82.2	8.8	23532	147	131.4	207.8	117	172.4	222.7
	82.7	8.1	22353	109	108.2	181.1	120	175.3	214.6
	82.2	8.9	20771	106	125.0	184.9	80	174.1	220.5
	81.9	8.6	23387	102	133.1	201.1			

Cable A									
External Radiant Heat Flux [kW/m^2]	Initial Mass [g]	Mass Loss [g]	ΔH_{eff} [kJ/kg]	T_{ign} [s]	pHRR [kW/m^2]	THR [kJ]	T_{ign} [s]	pHRR [kW/m^2]	THR [kJ]
	Horizontal Orientation						Vertical Orientation		
45	82.1	*		87	107.4	167.9	77	179.6	245.8
	82.1	8.7	23077	86	124.1	200.8	83	152.7	184.5
							59	160.4	190.7
							60	155.7	200.8
50	81.7	8.2	21029	66	115.9	172.4	52	179.4	210.7
	82.6	8.8	21449	72	128.2	188.8	56	169.1	203.1
							69	197.6	215.7

"*" error in mass measurement.



a) b)

Figure 2 HRR curves for combustion tests of Cable A: a) horizontal orientation, b) vertical orientation

Regarding Cable A, for the horizontal orientation, the total mass loss across all tests ranged from 8.1 to 8.9 g. The t_{ign} varied between 306 s at the lowest external heat flux (25 kW/m²) and 66 s at the highest heat flux (50 kW/m²). The pHRR ranged from 100.7 to 133.1 kW/m², increasing with the applied heat flux. The THR varied from 172.4 kJ at 25 kW/m² to 188.8 kJ at 50 kW/m², with an average THR of approximately 180.6 kJ. The heat of combustion varied from 20686 to 23532 kJ/kg, with an average of about 22108 kJ/kg. Similar effect of the external radiant flux was observed in the results for the vertical orientation tests. The t_{ign} ranged from 239 seconds at the lowest heat flux (25 kW/m²) to 52 s at the highest (50 kW/m²). The pHRR increased with heat flux, from 112.2 to 197.6 kW/m². The THR spanned from 169.3 kJ at 25 kW/m² to 222.7 kJ at 50 kW/m².

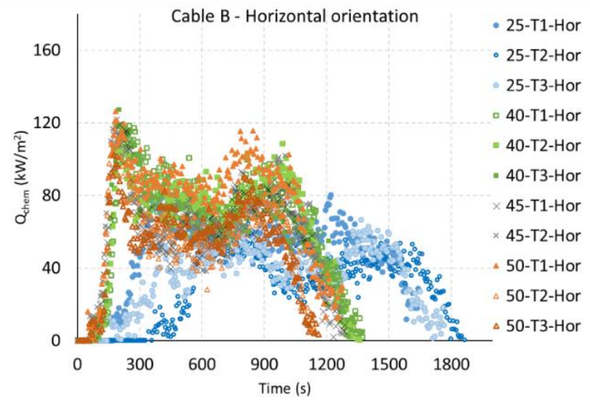
The curves in Figure 2 show a clearly different behaviour at an external radiant heat flux of 25 kW/m². However, although increasing the external heat flux led to higher total energy release and greater HRR peaks, the differences between the 40 kW/m² and 50 kW/m² tests were not significantly pronounced.

Cable B tests exhibited the same issue with mass loss measurements, and their results are organized following the same structure as Cable A: values are provided in Table 5, and the corresponding HRR curves are shown in Figure 3.

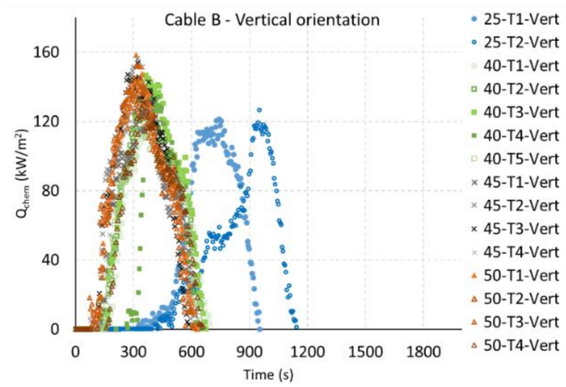
Table 5 Results of combustion tests for Cable B

Cable A									
External Radiant Heat Flux [kW/m²]	**Initial Mass [g]**	**Mass Loss [g]**	ΔH_{eff} **[kJ/kg]**	T_{ign} **[s]**	**pHRR [kW/m²]**	**THR [kJ]**	T_{ign} **[s]**	**pHRR [kW/m²]**	**THR [kJ]**
	Horizontal Orientation						**Vertical Orientation**		
25	146.4	16.7	17291	175	88.0	288.8	232	121.3	271.4
	146.5	12.6	15589	331	64.2	196.4	399	126.5	271.6
	148.5	13.3	16778	144	66.5	223.1			
40	148.0	*		89	118.2	324.4	137	132.3	291.0
	148.0	12.9	24510	78	110.9	316.2	118	137.1	315.3
	146.3	13.6	21951	62	127.1	298.5	125	146.5	344.1
							102	121.6	290.0
							137	167.3	368.1
45	146.1	12.4	21860	55	121.8	271.1	106	132.6	300.4
	146.3	12.9	21521	60	117.4	277.6	83	156.2	345.2
							78	153.5	337.4
							70	139.7	329.5
50	146.8	12.8	27104	49	126.3	346.9	76	158.4	343.8
	146.1	13.1	17463	50	116.7	228.8	81	152.1	332.3
	148.4	14.0	16091	55	102.3	225.3	71	138.2	322.9
							71	141.5	310.4

"*" error in mass measurement.



a)



b)

Figure 3 HRR curves for combustion tests of Cable B: a) horizontal orientation, b) vertical orientation

The HRR curves in Figure 3 show a clearly different behaviour at an external radiant heat flux of 25 kW/m². Despite the increasing the external heat flux increased the total energy release and greater HRR peaks, the differences between the 40 kW/m² and 50 kW/m² tests were not significantly pronounced.

For horizontal tests, the total mass loss varied between 12.4 g and 14.0 g across all external heat flux levels tested (25, 40, 45, and 50 kW/m²). The heat of combustion ranged from 15589 kJ/kg to 27104 kJ/kg, with an average value of approximately 20754 kJ/kg. The THR across these tests ranged from 196.4 kJ to 346.9 kJ, with an average THR of about 277.6 kJ. These results reflect the effect of increasing heat flux on combustion behaviour in the horizontal orientation. For vertical tests, the heat of combustion ranged from 16091 kJ/kg to 27104 kJ/kg, similar to horizontal cases, with an average value of approximately 21677 kJ/kg. The THR ranged from 271.4 kJ to 368.1 kJ, and the average THR was approximately 323.8 kJ. The tests were also conducted under external radiant heat fluxes between 25 and 50 kW/m², and mass loss values were in a comparable range to the horizontal orientation, though specific mass loss values for all vertical samples were not individually listed.

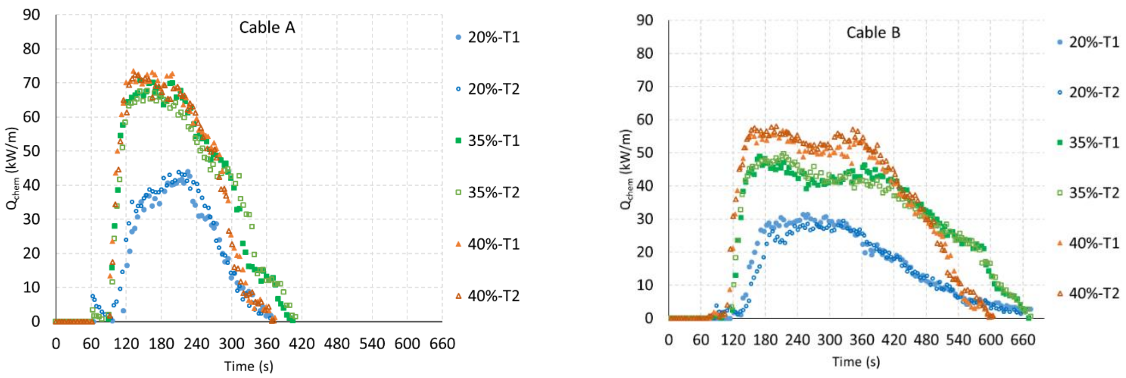
Propagation Tests

These tests were only executed in exclusively in vertical position and 50 kW/m^2 of external radiant flux but employing three different oxygen concentrations. Table 6 and Figure 4 contain the results for both cables.

Table 6 Results of combustion propagation tests of both cables

Oxygen level [%]	T_{ign} [s]	pHRR [kW/m]	THR [kJ]	Damaged length [mm]	T_{ign} [s]	pHRR [kW/m]	THR [kJ]	Damaged length [mm]
	Cable A				Cable B			
20	67	44.0	137.8	350	120	31.3	352.4	300
20	62	43.7	151.2	350	87	29.4	326.0	300

Oxygen level [%]	T_{ign} [s]	pHRR [kW/m]	THR [kJ]	Damaged length [mm]	T_{ign} [s]	pHRR [kW/m]	THR [kJ]	Damaged length [mm]
	Cable A				Cable B			
35	62	70.7	294.5	550	78	48.9	701.0	550
35	62	67.6	290.7	550	72	49.6	697.8	550
40	61	73.4	286.4	550	78	56.7	729.3	550
40	62	72.3	273.4	550	74	57.9	762.0	550



a) b)

Figure 4 HRR curves for propagation tests of Cable B

Both cables demonstrated relatively stable t_{ign} values under varying oxygen concentrations. For Cable A, the t_{ign} ranged from 61 to 67 s, whereas Cable B exhibited a broader range between 72 and 120 s. Both cables demonstrated significant differences in pHRR and THR when comparing an oxygen concentration of 20 % to higher concentrations of 35 % and 40 %. However, the differences between 35 % and 40 % were negligible, with Cable B showing more appreciable variations. For Cable A, the pHRR increased with higher oxygen concentrations, ranging from 43.7 to 73.4 kW/m², an increase of approximately 1.67 times. Similarly, the THR rose from 137.8 to 294.5 kJ, nearly doubling. The highest THR values were observed in tests with 35 % oxygen, while the highest pHRR values occurred at 40 % oxygen concentration. Cable B exhibited a comparable trend, with pHRR values increasing from 31.3 to 57.9 kW/m² and THR values rising from 326.0 to 762.0 kJ as oxygen concentration increased. At higher oxygen concentrations, the differences of Cable B became more pronounced, with higher pHRR and THR values observed at 40 % oxygen concentration.

At an oxygen concentration of 20 %, the damaged lengths were 300 mm for Cable A and 350 mm for Cable B. In oxygen-enriched atmospheres, the damaged length significantly increased, consistently reaching 550 mm – the full length of the sample above the pilot flame – at higher oxygen concentrations.

DISCUSSION AND CONCLUSIONS

Regarding the calculation of CHF, for both cables, the orientation of the samples did not have a significant influence. In other words, there were no substantial differences based on the sample's position that consistently caused the CHF to increase or decrease. Concerning ignition times for Cable A, the vertical position facilitated ignition, meaning the cable ignited more quickly in a vertical orientation. This trend was not consistently observed for Cable B, as at 20 kW/m² the ignition times for the vertical orientation were longer than or similar to those in the horizontal orientation.

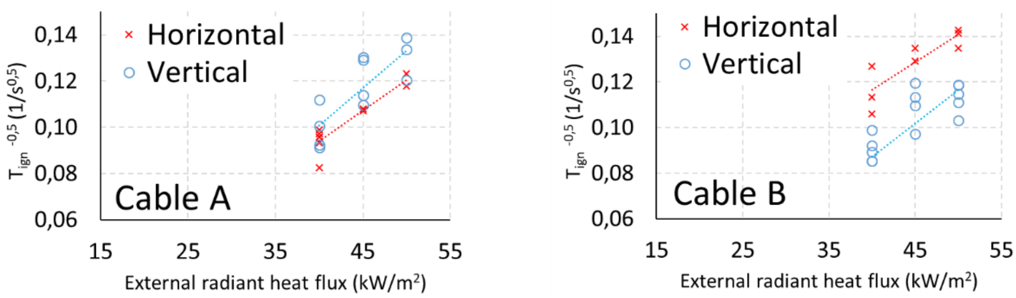
As to combustion tests, the next conclusions raised from the results obtained:

- Time to ignition. For Cable A, the t_{ign} consistently decreased with increasing external heat flux, following the expected trend of faster ignition under higher thermal loads. Across all flux levels, vertically oriented samples generally ignited more rapidly than those in the horizontal orientation. This effect was particularly pronounced at lower radiant heat fluxes. Cable B also exhibited an inverse relationship between t_{ign} and applied heat flux, with longer ignition times observed at lower flux levels. However, unlike Cable A, the horizontal samples of Cable B generally ignited slightly faster.

  Based on the t_{ign} values and following the procedure outlined in [11], [12], the TRP was calculated. This parameter, derived from the linear regression of the inverse square root of t_{ign}, quantifies a material's resistance to ignition under external heat flux. A higher TRP value corresponds to greater resistance to ignition, indicating a higher energy requirement to reach ignition. The TRP values for both cables and orientations are summarized in Table 7 and illustrated in Figure 5. The results show that vertical orientation generally yields lower TRP values, indicating a higher propensity for ignition. This trend is likely due to the broader surface area exposed to the radiant source in the vertical configuration, promoting more efficient heat absorption.

Table 7 Values of the TPR

TPR [kW·s$^{1/2}$/ m^2]	Horizontal	Vertical
Cable A	418	353
Cable B	470	389



a) b)

Figure 5 TPR curves: a) Cable A, b) Cable B

- The HRR and its peak (pHRR) for Cable A tended to increase with higher external heat flux, indicating more intense combustion. However, no significant differences were observed among the 40, 45, and 50 kW/m² tests. Vertical orientation consistently resulted in significantly higher pHRR values than the horizontal orientation across most flux levels. At 40 kW/m², vertical samples reached pHRRs above 170 kW/m², while horizontal samples remained below 135 kW/m². This trend persisted at higher fluxes, with vertical samples at 50 kW/m² peaking at approximately 197.6 kW/m², compared to the values of 115.9 to 128.2 kW/m² for horizontal samples. These differences highlight the influence of sample orientation on combustion dynamics, where vertical positioning enhances combustion intensity.

  Cable B exhibited a similar behaviour to Cable A. The pHRR increased systematically with rising heat flux in both orientations, as expected due to the greater energy available for combustion. Nonetheless, the differences among external heat fluxes of 40, 45, and 50 kW/m² were not substantial for either orientation. At 25 kW/m², pHRR values for horizontal samples ranged between 64.2 and 88.0 kW/m², while vertical samples reached up to 126,5 kW/m². This disparity became more pronounced at higher fluxes. At 50 kW/m², vertical samples achieved a pHRR of 158.4 kW/m², compared to 126.3 kW/m² in the horizontal configuration. Across all flux levels, vertical orientation consistently resulted in higher pHRR values.

  The most significant differences between orientations were observed in the HRR curves. For both cables, the curves obtained from horizontal orientation tests exhibited a slower combustion profile, characterized by a longer duration between ignition and flameout and lower HRR values compared to the vertical orientation tests.

- The THR for Cable A increased slightly with higher heat flux in both orientations. However, similar to the pHRR values, the differences among the 40, 45, and 50 kW/m² tests were not substantial. At lower heat flux (25 kW/m²), THR values were comparable between orientations. Yet, at higher fluxes (40 – 50 kW/m²), vertical samples exhibited slightly greater total energy release. For instance, at 50 kW/m², vertical samples produced up to 215,7 kJ, compared to 188.8 kJ in the horizontal orientation.

  Cable B displayed similar behaviour to Cable A, with THR increasing as heat flux rose, indicating more complete combustion with higher energy input. However, no significant differences were observed among the 40, 45, and 50 kW/m² tests. At 25 kW/m², horizontal THR values ranged from 196.4 to 288.8 kJ, while vertical samples released up to 271.6 kJ. At 50 kW/m², these values peaked at 346.9 kJ for horizontal and 343.8 kJ for vertical samples.

  Vertical samples generally demonstrated greater THR, particularly at higher flux levels, suggesting improved combustion efficiency, likely driven by enhanced oxygen interaction and availability.

  The ignition temperature (T_{ign}) is determined using the ignition time (t_{ign}) and ambient temperature (T_0] following the Quintiere's procedure [13]. This method relies on experimental measurements of the minimum heat flux required for ignition under steady-state conditions. It assumes that heat transfer involves both convective and radiative components, leading to the following Equation (1):

  $$\dot{q}''_{min} = 0{,}015\ (T_{ign} - T_0) + \sigma(T_{ign}^4 - T_0^4) \qquad (1).$$

  And for h_{eff}, the procedure employs the relation of Equation (2):

  $$\dot{q}''_{min} = h_{eff}\ (T_{ign} - T_0) \qquad (2).$$

  In this method, the apparent thermal inertia (ρkc), which characterizes a material's resistance to temperature change when exposed to an external heat source, can also be calculated thanks to Equation (3):

$$\rho kc = {}^{4}/_{\pi} \cdot \left({}^{h_{eff}}/_{b}\right)^2 \quad (3),$$

where “b” is the slope obtained by plotting experimental t_{ign} against heat flux data. This procedure assumes that all materials behave as thermally thick. The ignition temperatures for the cables, based on their orientation, are provided in Table 8.

Table 8 Ignition temperature and apparent thermal inertia for cables

	Cable A		Cable B	
	Horizontal	**Vertical**	**Horizontal**	**Vertical**
Ignition temperature (T_{ign}) [°C]	401	401	424	424
Apparent thermal inertia (ρkc) [$kJ^2/m^4 \cdot s \cdot K^2$]	2.230	1.169	4.010	3.067

The CHF for both orientations in each cable was similar, indicating comparable ignition temperatures. However, sample orientation had a greater influence on the calculation of apparent thermal inertia. Higher values were obtained for samples in the horizontal position, suggesting that heat transfer to the sample occurs more slowly compared to the vertical orientation.

Finally, the propagation tests indicates as it could be expected, as oxygen concentration increased to 35 % and 40 %, peak HRR values increased substantially, and combustion occurred more rapidly and intensely. The curves also became sharper, indicating more aggressive burning behavior and faster combustion processes under oxygen-enriched conditions. However, for cable A the difference in HRR behavior between 35 % and 40 % oxygen was relatively minor, suggesting that beyond 35 %, the influence of additional oxygen on the combustion intensity becomes less significant for this cable. In contrary, for cable B the increase to 35 % and then 40 % resulted in a marked escalation of peak HRR values and THR. This indicates a greater sensitivity of Cable B to oxygen enrichment, with a more appreciable effect observed between 35 % and 40 % O_2 than in Cable A.

The FPI [11], [12], is a parameter used to assess a material's propensity to support fire spread. In simpler terms, a higher FPI value indicates a greater tendency for the material to propagate fire, while a lower FPI suggests better resistance to fire spread. It is calculated with the data of propagation tests at 40 % of O_2 and the TRP value calculated form combustion tests with samples in horizontal position as Equation 4 indicates:

$$PFI = 750 \cdot \left({}^{\dot{Q}_{chem}}/_{W}\right)^{1/3} \cdot \left({}^{1}/_{TPR}\right) \quad (4).$$

Table 9 presents the calculated values of the Fire Propagation Index (FPI) for both cable types.

Table 9 FPI for fire propagation tests

FPI	Cable A		Cable B	
	Horizontal	**Vertical**	**Horizontal**	**Vertical**
Test1 – Test2	7.41 – 7.37	8.77 – 8.73	6.05 – 6.09	7.37 – 7.36

These values are consistent with the previously calculated properties, indicating that a vertical position facilitates combustion.

The results from the tests conducted in the FPA apparatus underscore the critical influence of cable orientation on fire behaviour. While both the CHF and the ignition temperatures remain comparable between horizontal and vertical configurations, the vertical orientation distinctly enhances the rate and magnitude of energy release. However, the TRP and the FPI demonstrate clear sensitivity to the vertical configuration.

Additionally, a comparison between Cable A and Cable B reveals that, despite similar ignition temperatures, Cable A tends to exhibit lower TRP and apparent thermal inertia values, particularly in the vertical setup, indicating a more hazardous fire profile. The FPI values further corroborate this, as Cable A consistently presents a higher FPI than Cable B.

These findings indicate that the vertical orientation of the samples significantly increases fire risk and underscore the importance of considering cable orientation in fire safety evaluations, particularly regarding the dynamics of energy release once ignition occurs.

ACKNOWLEDGEMENTS

The authors would like to thank the project "Gemelos digitales para el diseño y desarrollo de nuevos cables empleados en sectores / infraestructuras críticas con mejores prestaciones frente al fuego-VULCABLE" (CPP2022-010025 funded by MICIU / AEI / 10.13039 / 501100011033 and UE Next Generation EU/PRTR]" and "Análisis de modelos numéricos y experimentales para la investigación de incendios en centrales nucleares- FIRENUC, and "Validación, calibración y aplicación de modelos de propagación de incendios en escenarios reales de centrales nucleares-NUCLEVS".

REFERENCES

[1] European Union (EU): Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC, Brussels, Belgium 2011, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011R0305.

[2] European Standards: EN 50399:2022 - Common test methods for cables under fire conditions - Heat release and smoke production measurement on cables during flame spread test - Test apparatus, procedures, results, 2022.

[3] European Standards: EN 13501-6:2018. Fire classification of construction products and building elements - Part 6: Classification using data from reaction to fire tests on power, control and communication cables. 2018.

[4] Hehnen, T., L. Arnold, and S. La Mendola: Numerical Fire Spread Simulation Based on Material Pyrolysis – An Application to the CHRISTIFIRE Phase 1 Horizontal Cable Tray Tests, Fire, 3(3), 33, MDPI 2020, https://www.mdpi.com/2571-6255/3/3/33.

[5] European Commission (EC): Fire Performance of Electric Cables – New Test Methods and Measurement Techniques (FIPEC), Final report of the European Commission SMT programme sponsored research project SMT4-CT96-2059, Brussels, Belgium, 2000: https://cordis.europa.eu/project/id/SMT4962059.

[6] Khan, M. M., R. G. Bill Jr, and R. L. Alpert: Screening of plenum cables using a small-scale fire test protocol, Fire and Materials Volume 30, Issue 1, pp. 65 - 76, August 2005, https://onlinelibrary.wiley.com/doi/10.1002/fam.899.

[7] Wang, Z., and J. Wang: An experimental study on the fire characteristics of new and aged building wires using a cone calorimeter, Journal of Thermal Analysis and Calorimetry, 135(3) :1-8, (6), pp. 3115 - 3122, August 2018,
DOI: 10.1007/s10973-018-7626-8.

[8] Meinier, R., et al.: Fire behavior of halogen-free flame retardant electrical cables with the cone calorimeter, Journal of Hazardous Materials 342, pp. 306 - 316, August 2017, DOI: 10.1016/j.jhazmat.2017.08.027.

[9] Martinka, J., et al.: Assessing the fire risk of electrical cables using a cone calorimeter, Journal of Thermal Analysis and Calorimetry, 135(6), pp. 3069 - 3083, July 2018,
DOI: 10.1007/s10973-018-7556-5.

[10] Magalie, C., et al.: Fire behaviour of electrical cables in cone calorimeter: Influence of cables structure and layout, Fire Safety Journal, 99, pp. 12 - 21, July 2018,
DOI: 10.1016/j.firesaf.2018.05.001.

[11] International Organization for Standardization (ISO): ISO 12136:2011 Reaction to fire tests – Measurement of material properties using a fire propagation apparatus, Edition 1, 2011.

[12] ASTM International: ASTM E2058 - 19: Standard Test Methods for Measurement of Material Flammability Using a Fire Propagation Apparatus (FPA), 2019.

[13] Babrauskas, V.: Ignition Handbook: Principles and Applications to Fire Safety Engineering, Fire Investigation, Risk Management and Forensic Science, Fire Science Publishers, ISBN: 978-09728111-3-2; 2014,
https://www.researchgate.net/publication/288833461_Ignition_Handbook.

Experimental Investigation of the Combustion and Spread Characteristics of Cable Fires in a Trough Box Cable Tray: Full-Scale Fire Experiments

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ABSTRACT

Cable fires in trough box cable trays are typical fire scenarios for fire hazard analysis (FHA) in nuclear power plants (NPPs). To better understand the characteristics of cable fires in trough box cable trays, full-scale experiments have been conducted using trays with different bottom types and cable filling rates.

The cable filling rate significantly influenced the extent of flame spread within the trough box cable tray. At a filling rate of 8 %, the flame could spread up to 1.5 m along the tray. When the filling rate increased to 30 %, the denser cable arrangement reduced the available air, and no flame spread was observed. Furthermore, when the tray bottom was replaced by only metal crossbeams, allowing more air exposure to the cable layer, no flame spread occurred either. These findings suggest that the bottom type of the trough box cable tray has only a limited effect on the flame propagation.

Given the significant differences in combustion and flame spread between trough-type and ladder-type cable trays, the findings suggest that engineers may reconsider current fire analysis practices for trough-type trays.

INTRODUCTION

Currently, in fire protection design and safety analysis for NPPs, it is generally assumed that trough box cable trays and cable ladders provide similar combustion and flame spread characteristics in fire scenarios [1].

Most existing studies on cable fires focus on ladder-type trays, while research specific to trough box cable tray fires remains limited, and no dedicated publications on this topic have been identified. Existing studies suggest that higher cable filling rates in ladder-type trays lead to more complete combustion, thereby increasing the fire risk [2]. Unlike ladder trays, trough box cable trays are enclosed with a metal cover on top and a solid or perforated steel plate at the bottom. This enclosed structure may shield the cables and result in different combustion and spread characteristics compared to exposed ladder-type trays.

To explore the combustion and flame spread behaviour of cables in trough box trays, four sets of full-scale fire experiments were conducted. The first two sets used trays with solid bottoms and cable filling rates of 8 % and 30 %, respectively, while the latter two used open-bottom trays with filling rates of 30 % and 20 %. These tests aim to provide a reference for the fire protection design in NPPs.

EXPERIMENTAL FACILITY

A series of experiments on the combustion behaviour of trough box cable trays was conducted using the full-scale comprehensive experimental platform for nuclear power plant fires. As shown in Figure 1, the platform comprises five experimental rooms, covering a total floor area of approximately 300 m². It is designed for conducting experiments on fire spread in both horizontal and vertical cable configurations. The platform includes multiple horizontal and vertical compartments, shaft structures, and long corridors - features commonly found in building interiors. This design facilitates a wide range of indoor fire safety experiments. Each room is equipped with both water spray and water mist fire suppression systems, as well as air inlets and outlets connected to a mechanical ventilation system for an effective environmental control. Experimental rooms 1, 2, 3, and 5 each have dimensions of 6.0 m x 5.0 m x 4.0 m. Room 4 is a corridor space with a volume of 15.0 m x 2.5 m x 5.0 m. Rooms 3 and 5 are vertically connected and separated by a steel mesh. A shaft structure, measuring 1.8 m x 1.0 m x 8.2 m, runs between these two rooms. The experiments discussed in this study were conducted in Room 2.

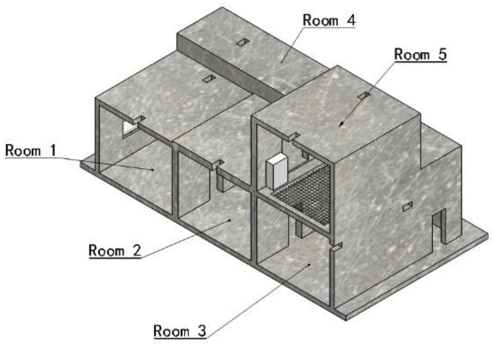

Figure 1 Full-scale comprehensive experimental platform for NPP fires

The width of the metal trough box cable tray is 0,3 m, with a non-ventilated metal plate at the bottom, and the material of the cable tray is galvanized iron. Single-core aluminium core PVC cables with a cable diameter of about 0.01 m were selected for the experiments. The square burner has dimensions of 0.3 m x 0.3 m x 0.1 m. Propane is supplied to the burner through a control pipeline, and the burner is equipped with a sensing needle and an ignition needle to control the combustion time.

The length of both the trough box cable tray is 3.50 m. The burner is installed directly below the centre of the trough box cable tray, maintaining a distance of 0.15 m from the cable tray. This is illustrated in Figure 2. On the uppermost part of the cable tray, a total of nine thermocouples are installed. The arrangement sequence and spacing between the thermocouples are detailed in Figure 3. The thermocouples used for the experiment are K-type thermocouples, with a temperature measurement range of 0 to 1300 °C and a measurement accuracy of ± 1.5 °C. This includes both armoured and unarmoured thermocouples. The tree thermocouple is a K-type armoured thermocouple with a diameter of 0.02 m. The cable surface thermocouple is a GG-K-30 thermocouple, with a measurement point diameter of about 0.01 m.

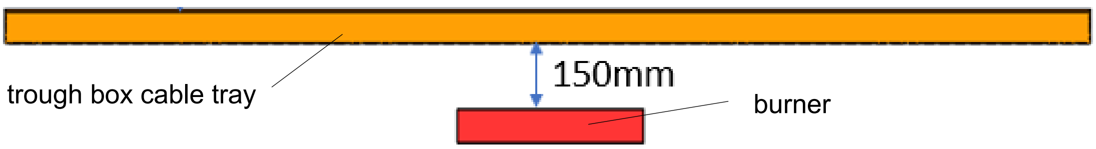

Figure 2 Trough box cable tray and burner arrangement

The detailed configuration of the fire experiment is listed in Table 1.

Table 1 Trough box cable tray experiment configuration

Series No.	Width [mm]	Filling Rate	Solid Bottom	Fire Source Power [kW]	Ignition Duration [s]
1	300	8 %	yes	70	600
2	300	30 %	yes	28	2414
3	300	30 %	no	28	2400
4	300	20 %	no	28	1800

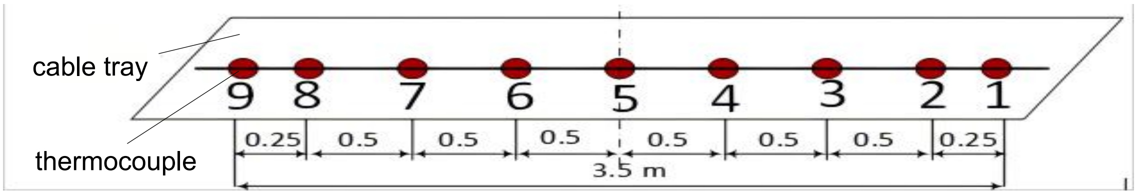

Figure 3 Thermocouple arrangement

EXPERIMENTAL RESULTS

Upon completion of the four experiments, only the first set of experiments exhibited cable combustion, with a flame spread distance of approximately 1.5 m, whereas no combustion was observed in the other three sets of experiments. In the following, more details are presented.

Results of the First Set of Experiments

Photos Related to the Experiments

Photos taken before and after the experiment are shown in Figure 4 to Figure 7.

Figure 4 illustrates the configuration of the cable tray at an 8 % fill rate, where the interior of the trough-type cable tray appears largely unoccupied, providing ample internal space.

Figure 4 Photo of the trough box cable tray before the experiment

Figure 5 shows the post-test condition of the cables, indicating that most of the cable material within the trough box tray was consumed during combustion.

Figure 5 Photo of the trough box cable tray after the experiment

Figure 6 reveals that the insulation layers were almost completely destroyed, with the aluminum conductors exposed as a result of intense burning,

Figure 6 Photos of the trough box cable tray after the experiment

Figure 7 highlights extensive thermal degradation of the cable insulation on both sides of the burner, with the material nearly reduced to ash, confirming the severity and completeness of localized combustion.

Figure 7 Photo of the trough box cable tray after the experiment

Discussion

Following the turn-off of the burner at 600 s after ignition, continued burning inside the trough box cable tray was observed, as reflected by the temperature evolution shown in Figure 8. Thermocouples 2 and 8 recorded two distinct temperature peaks, with the second peak is attributed to the complete consumption of the primary cable insulation and the subsequent ignition of neighbouring cables. This behaviour demonstrates that flame spread within the trough box was rapid and that the combustion process was extensive and vigorous.

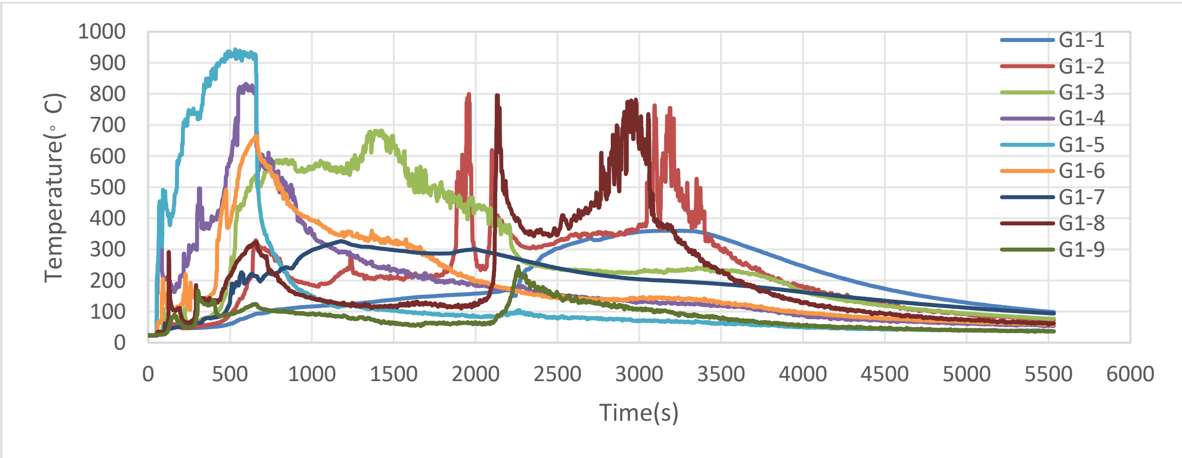

Figure 8 Cable fire temperature curves of trough box cable tray

The prevailing view holds that when the temperature measured by a thermocouple reaches 500 °C, the cable starts to burn [3].

Analysing Figure 8, it was found that after the burner was turned off the thermocouples 2, 3, 4, 5, 6, and 8 recorded temperatures exceeding 500 °C. This indicates a fire spread outward along the cable in both directions from the burner at the centre, with a total propagation distance of approximately 1.5 m.

Based on the data recorded by thermocouple 5, located directly above the burner, the calculated flame spread rates were as follows:

- from thermocouple 5 to 4: 1.69 mm/s,
- from thermocouple 4 to 3: 3.25 mm/s,
- from thermocouple 3 to 2: 0.40 mm/s,

– from thermocouple 5 to 6: 1.35 mm/s, and
– from thermocouple 6 to 8: 0.63 mm/s.

Thermocouple 7 did not register temperatures exceeding 500 °C and was therefore excluded from the flame spread velocity analysis.

These variations in spread velocity suggest that the fire developed in distinct stages. This staged spread behaviour aligns well with the multi-peak trend observed in the fire temperature curves, further confirming the complexity of the combustion process within the trough box cable tray.

Results of the Other Three Sets of Experiments

Photos Before and After the Experiment

The photos taken before the three sets of experiments are shown in Figure 9.

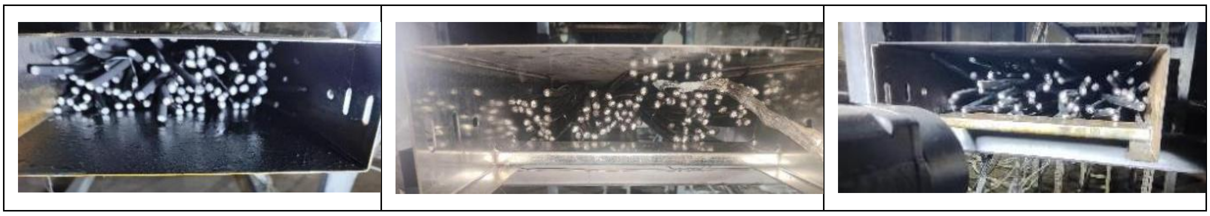

Figure 9 Photos taken before the three sets of experiments

Figure 10 shows the post-test condition of the cables. While minimal flame spread was observed in the second and third experiment, the fourth experiment provided a significantly greater burning and cable degradation across a wider section of the tray.

Figure 10 Photos taken after the three sets of experiments

Discussion

The cable tray filling rate of the second and third groups of experiments reached 30 %, but no metal plate was installed at the bottom of the cable tray in the third group of experiments. Nevertheless, from the comparison of the fire temperature curves of the two sets of experiments, the difference is not significant. Specifically, the maximum temperature recorded by the thermocouple 5 above the burner was 219.7 ℃ and 270 ℃. The relevant fire temperature curves are detailed in Figure 11 and Figure 12.

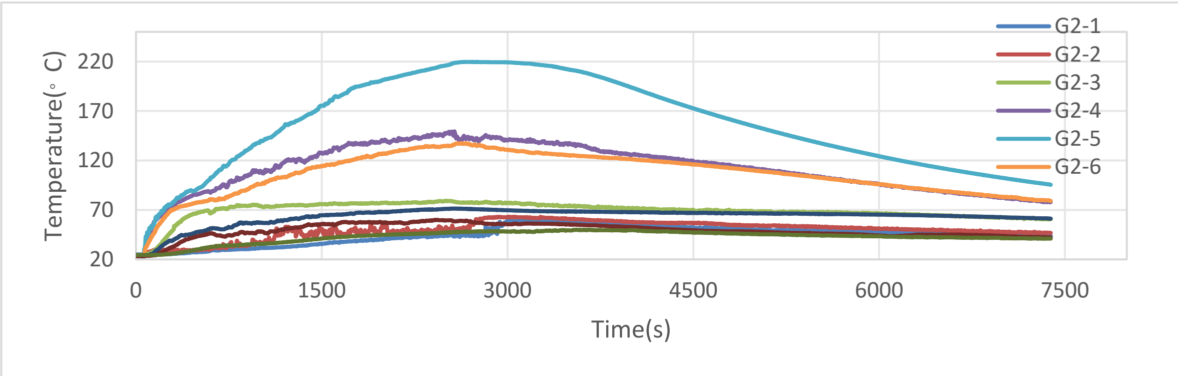

Figure 11 Cable fire temperature curves of the second set of experiments

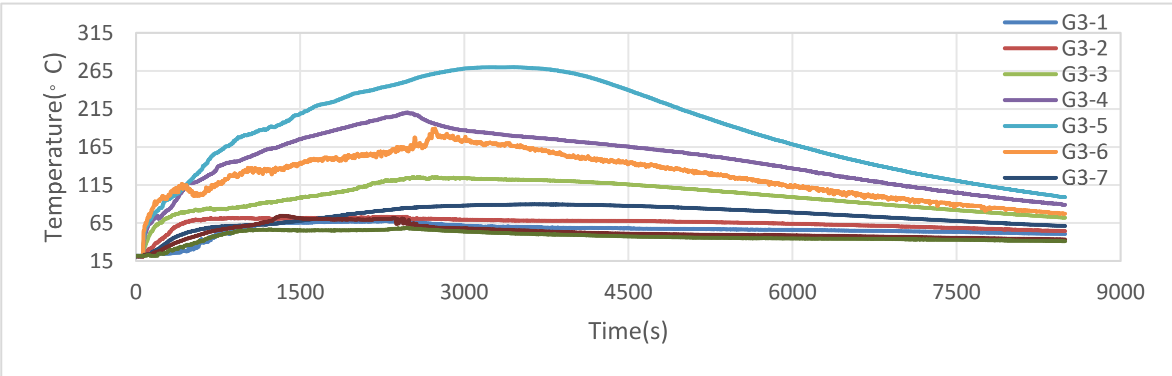

Figure 12 Cable fire temperature curves of the third set of experiments

In the fourth set of experiments, the cable tray filling rate reached 20%, and no metal plate was installed at the bottom of the cable tray. Compared with the second and third experiments, the fire phenomenon was more intense, and the measured maximum temperature was 864.4°C. However, when the burner was turned off, the cable fire did not spread. The fire temperature curves are detailed in Figure 13.

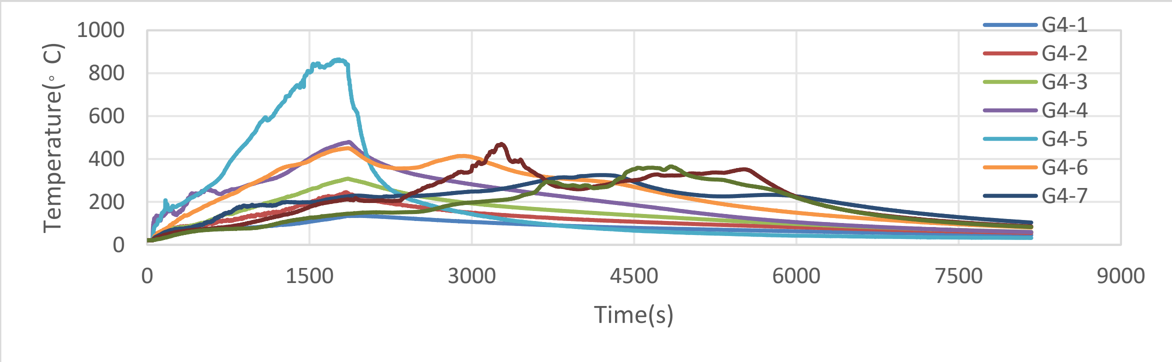

Figure 13 Cable fire temperature curves of the fourth set of experiments

The fire temperature curves, and the visual observations indicate that in high cable filling scenarios, the limited internal volume of the trough box cable tray hindered air exchange. Consequently, the initial ignition rapidly consumed the available oxygen, and the insufficient ventilation prevented continued combustion after the external heat source was removed.

CONCLUSION

The objective of this study was to investigate how different cable filling rates and bottom configurations of trough box cable trays influence fire behaviour, specifically focusing on cable combustion and flame spread characteristics.

In the first test, where the cable filling rate was 8%, the fire was observed to spread approximately 1.5 m along the tray. However, in the subsequent three tests with higher filling rates no flame spread occurred. The results indicate that, in trough box cable trays higher cable filling rates inhibit the flame spread due to the reduced air availability, whereas lower filling rates allow for a faster and more extensive burning.

Furthermore, replacing the tray bottom with a perforated metal plate had minimal impact on the combustion and flame spread behaviour of the cables. This suggests that ventilation limitations imposed by the tray geometry play a more critical role than bottom structural variations.

Notably, this behaviour contrasts sharply with that of traditional ladder-type cable trays, where increased filling rates are generally associated with enhanced fire growth and propagation due to the abundance of combustible material and better ventilation. In current fire protection design and analysis practices for NPPs, trough box and ladder-type cable trays are often assumed to share similar fire risk characteristics. However, the findings of this study challenge that assumption, providing valuable insights for fire safety engineers and analysts engaged in nuclear facility design and risk assessment.

ACKNOWLEDGEMENTS

The completion of this research and experimental work would not have been possible without the support and assistance from various parties, for which I am deeply grateful. First and foremost, I would like to express my sincerest gratitude to Dr. Huang Xianjia for his meticulous guidance and valuable advice on experimental design, data analysis, and paper writing. Dr. Huang's rigorous academic attitude and profound professional knowledge have laid a solid foundation for this research. Additionally, I would like to thank the Guangzhou Industrial Research Institute Co., Ltd. for providing experimental equipment and technical support, with special thanks to Mr. Xing Zhaoliang, Mr. Zhao Chunyang and Mr. Li Lei for their professional assistance in experimental operations and instrument adjustments. Moreover, the financial support from China Nuclear Power Engineering Co., Ltd. was indispensable, providing crucial guarantees for the smooth progress of the experiments. Lastly, I would like to extend my deepest thanks to all individuals and institutions that have shown concern and support for this research.

REFERENCES

[1] AFCEN: RCC-F Design and Construction Rules for Fire Protection of PWR Nuclear Plants, 2020, https://www.afcen.com/en/rcc-f/271-rcc-f-2020-9791095971481.

[2] McGrattan, K. B., and S. D. Bareham: Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 2: Vertical Shafts and Corridors, NUREG/CR-7010, Vol. 2, prepared for United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research, Washington, DC, USA, December 2013, https://www.nrc.gov/docs/ML1334/ML13346A045.pdf.

[3] Séguillon, J., H. Prétrel, and. S. Suard: Experimental study of a travelling fire along a cable tray assembly in a mechanically ventilated enclosure, Fire Safety Journal, Volume 141 (1):104016, December 2023, https://doi.org/10.1016/j.firesaf.2023.104016

Experimental Investigations on the Ignition Behaviour of Oil Used in Nuclear Power Plants

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ABSTRACT

A test campaign was carried out on the IGNIS scale 1 fire safety platform at EDF (*É*lectricité *d*e *F*rance) to investigate ignition scenarios involving oil, to better account for them in fire risk assessment studies. In the frame of this campaign, a heated 50 cm inner diameter stainless steel burner was set inside a 712 m^3 mechanically ventilated facility. This burner was filled with an oil that is used in the French nuclear power plants (NPPs). Various ignition scenarios were implemented to investigate the effects of the oil preheating temperature and of burning droplets dripping on an oil slick. Measurements included oil temperature, flame temperature profile, mass loss rate (MLR), heat release rate (HRR), pressure and temperature profile inside the room, ventilation flow rates and heat fluxes. These tests showed that the oil needs to be heated to at least 200 °C in order to burn and that the preheating temperature does not affect the HRR plateau. No ignition was observed during the oil dripping test. These observations could be strengthened by further tests including dripping flow rate variation.

INTRODUCTION

Pool fires are among the most critical fire scenarios in NPPs as they involve large HRRs and can reach the maximum power in a few seconds. In the case of the reactor building, the main liquid fuel is the oil stored inside the primary coolant pump, and events involving leaks on hot pipes followed by localized ignition were reported in the past. This scenario, amongst others, is treated in the safety demonstration. Another scenario involves the ignition of an oil slick that would be located on the ground. This scenario is treated with no consideration of the oil ignition resistance, potentially resulting in conservative results.

The aim of this work was therefore to study the ignition and burning behaviour of the Mobil DTE Medium oil which is used in French NPPs to better account for oil fire scenarios. This study consisted in an experimental campaign involving seven experiments designed and carried out at the EDF Lab Chatou. Six of these experiments consisted in investigating the effect of preheating on the ignition and burning behaviour of the fuel. The last test was more complex and consisted in studying a scenario in burning oil from a leak at a pump dropping on an oil slick on the ground. Table 1 sums up the test matrix of the campaign carried out in the IGNIS platform at EDF R&D.

Table 1 Test matrix of the campaign

Test	Conditions
CFL-01	0.2 m^2 oil surface preheated to 80 °C, 5 min aggression by an 8 kW flame
CFL-02	0.2 m^2 oil surface preheated to 120 °C, 5 min aggression by an 8 kW flame
CFL-03	0.2 m^2 oil surface preheated to 150 °C, 5 min aggression by an 8 kW flame
CFL-04	0.2 m^2 oil surface preheated to 200° C, 5 min aggression by an 8 kW flame
CFL-05	0.2 m^2 oil surface preheated to 250 °C, 5 min aggression by an 8 kW flame
CFL-06	0.2 m^2 oil surface preheated to 80 °C, 15 min aggression by an 8 kW flame
CFL-07	Burning oil spilling on a preheated oil slick

EXPERIMENTAL SETUP

The ME1 Facility of the IGNIS Platform

IGNIS is a platform dedicated to real scale fire tests built in Chatou (France) [1]. It includes four complementary configurations, from open atmosphere to mechanically ventilated compartments (cf. Figure 1). The experimental work described here was performed in the ME1 facility, which is a mechanically ventilated 712 m^3 concrete compartment. This facility is 12 m long, 8.5 m wide, 6 m high and includes a 10 m high part on a 5 m x5 m section. The air renewal rate was set to 10 vol/h, equally split between the 13 ducts of the facility which means a flow rate of ≈ 550 m^3/h per outlet and inlet. This high renewal rate was chosen to avoid under-ventilated conditions.

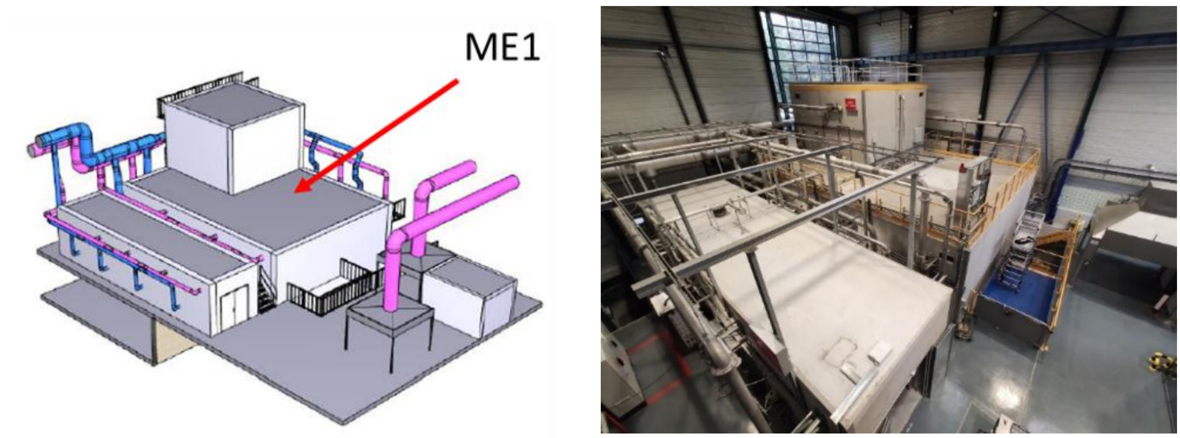

Figure 1 The ME1 facility on the IGNIS platform

Burner Setups

Two setups were installed inside the ME1 facility: one for the preheating temperature test and another one for the dripping test. Both were installed in the middle of the ME1 facility to maximize the distance between the flame and the air inlets that could induce flow perturbations.

Preheating Temperature Tests

The burner configuration used for these tests is illustrated by Figure 2. It consists of a flat bottom aluminium 50 cm inner diameter burner which is placed on a heating plate. This plate can be controlled to heat the burner to temperatures ranging from room temperature up to 300 °C. Both systems are set on a Mettler Toledo industrial scale used to monitor the MLR during the tests. The burner if filled with oil, and the ignition is provided by a remotely controlled 8 kW propane gas burner. The heating plate remains turned on during the whole test duration.

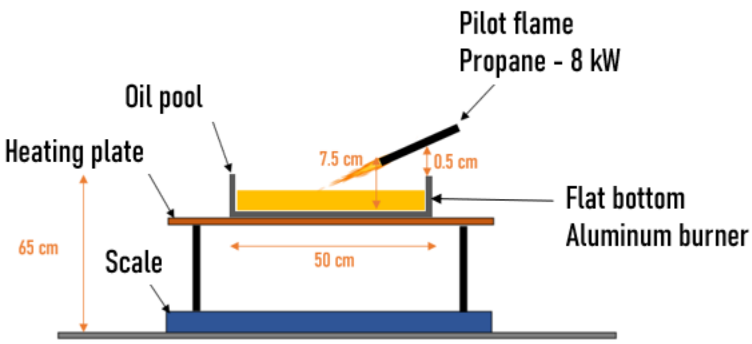

Figure 2 Burner setup used for the preheating tests

Leaking Test

The burner configuration used for these tests is illustrated by Figure 3. For this test, an oil pool is maintained at 80 °C, and burning droplets are spilled on it. A 1 cm deep target pool is therefore placed in the same aluminium burner used for the temperature effect tests and maintained at a temperature of 80 °C using an automatic heating plate. The plate was powered during the whole test, but only turned on if the temperature of the pool decreased and reached a temperature below the order. A specific device to produce a burning spill was developed for this study. Oil was pumped from a tank into a top opened buffer tank at a steady flowrate. This buffer tank was preheated at 200 °C, and an 8 kW burner was used to ignite the oil surface on top of the tank. Both systems remained turned on during the whole test in order to maintain the ignition. A spilling ramp was then connected to the top part of the tank, enabling the burning oil to flow towards the target oil pool.

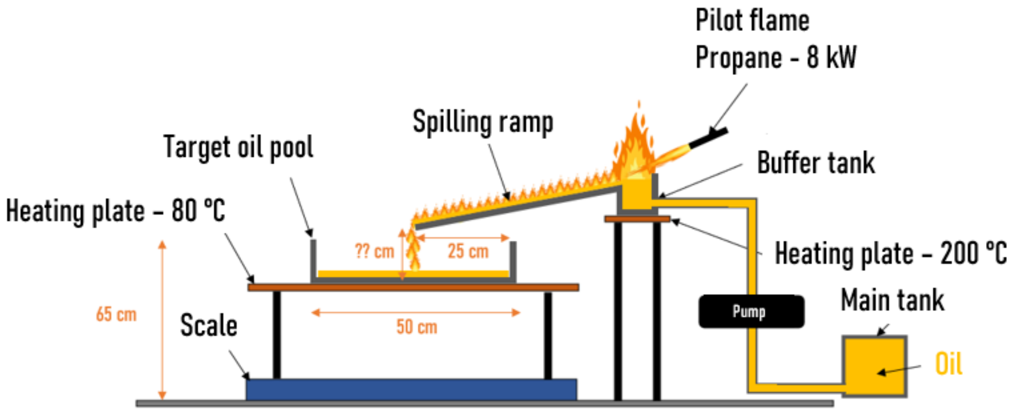

Figure 3 Burner setup used for the leaking tests

Instrumentation

The whole instrumentation configuration is illustrated by Figure 4 which is a top view of the facility.

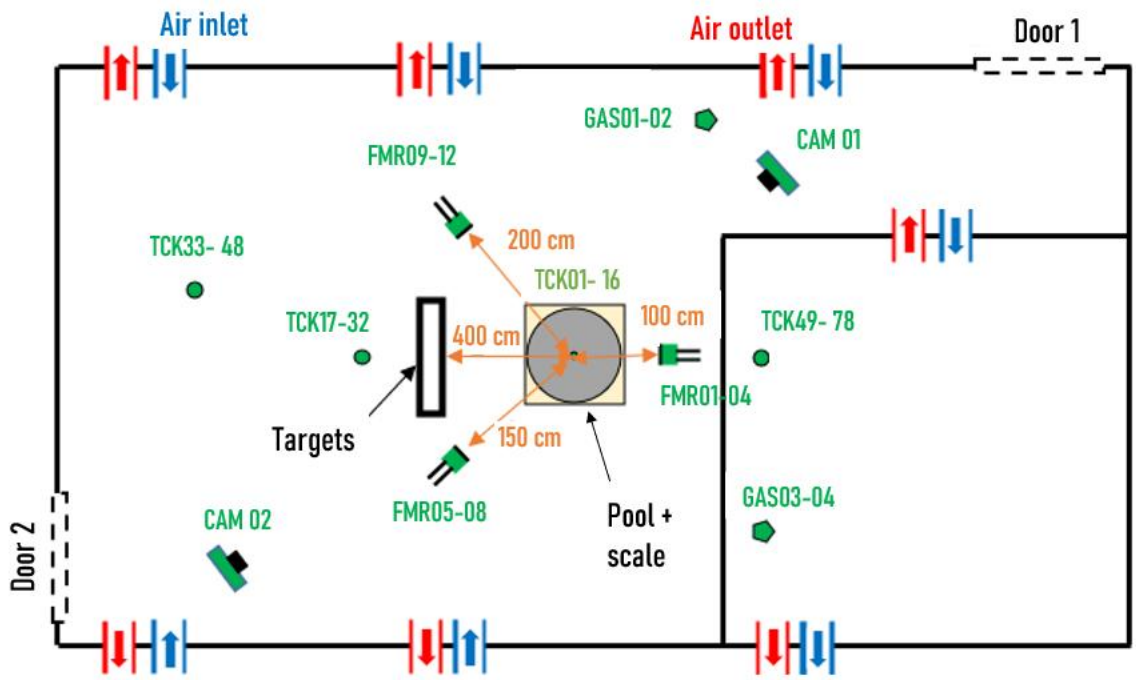

Figure 4 Instrumentation location inside the ME1 facility (top view scheme)

The temperature inside the facility is monitored by 72 1 mm Inconel sheathed thermocouples installed on four measurement trees including one focusing on the vertical temperature profile inside the flame. The distance between the thermocouples is Δz = 35 cm.

Twelve total heat flux water cooled gauges are positioned on three brackets at heights of 50, 100, 150 and 200 cm and at distances of 100, 150 and 200 cm from the flame centerline to measure the heat flux emitted by the flame.

Gas measurements include O_2, CO, CO_2 and total unburned gases concentrations at four heights inside the facility. Another measurement point is located inside the extraction line of the facility. The measurements are used to calculate the HRR using CO_2 calorimetry as described by Prétrel et al. [2].

For each air inlet (13) and outlet (13), gas temperature and flowrate are measured continuously during the test, and two pressure sensors are used to monitor the pressure inside the facility.

Targets equipped with total heat flux meters are also installed 4 m away from the flame centerline at z = 100 cm and z = 150 cm. They consist of a 10 cm x 10 cm PVC (*p*oly*v*inyl *c*hloride), PE (*p*oly*e*thylene) and steel samples set on an insulated board to provide adiabatic conditions. These targets are illustrated by Figure 5.

Finaly, two HD (*h*igh *d*ensity) cameras are used to observe and record the test at 20 fps, and the MLR is recorded through a 0 – 150 kg Mettler Toledo industrial scale.

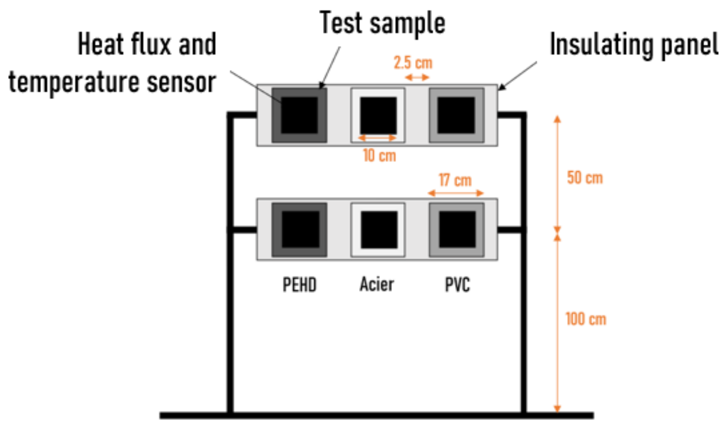

Figure 5 Configuration of the targets

RESULTS

Preheating Temperature

In the following, the studied global temperature behaviour as well as the HRR and the MLR are described.

Global Temperature Behaviour

Table 2 summarises the results of this part of the study. It was found that the oil needs to reach a threshold temperature of 200 °C to ignite. This situation can be reached either if the preheating temperature is high or if the igniter provides enough energy to the oil surface.

Table 2 Synthesis of the results for the preheating tests

Test		Fuel	Pilot Flame	Ignition
CFL-01		5 cm / 80 °C	8 kW – 5 min	no
CFL-02		5 cm / 120 °C	8 kW – 5 min	no
CFL-03		5 cm / 150 °C	8 kW – 5 min	yes
CFL-04		5 cm / 200 °C	8 kW – 5 min	yes
CFL-05		5 cm / 250 °C	8 kW – 5 min	yes
CFL-06		5 cm / 80 °C	8 kW – 15 min	no

Figure 6 illustrates the case of the CFL-03 test (preheating temperature of 150 °C), for which ignition is not instantaneous. In that case, the pilot flame hits the fuel surface for almost 200 s with no ignition. After this period, the local temperature is high enough to initiate combustion, and the whole oil surface ignites. The behaviour observed is then similar to other pool fires reported in the literature [3] to [6]. The whole oil volume is consumed for all the tests for which ignition was observed.

Figure 6 Development over time of the flame for one of the tests

Heat Release Rate and Mass Loss Rate

Figure 7 shows the development of the HRR and the oil MLR over time for those tests for which ignition was observed. For tests with preheating of 200 °C or more, ignition is instantaneous upon the appearance of the pilot flame. The power then increases very quickly and reaches a peak of 300 kW before gradually decreasing to stabilize at approximately 125 kW. This plateau value is reached for both preheating temperatures.

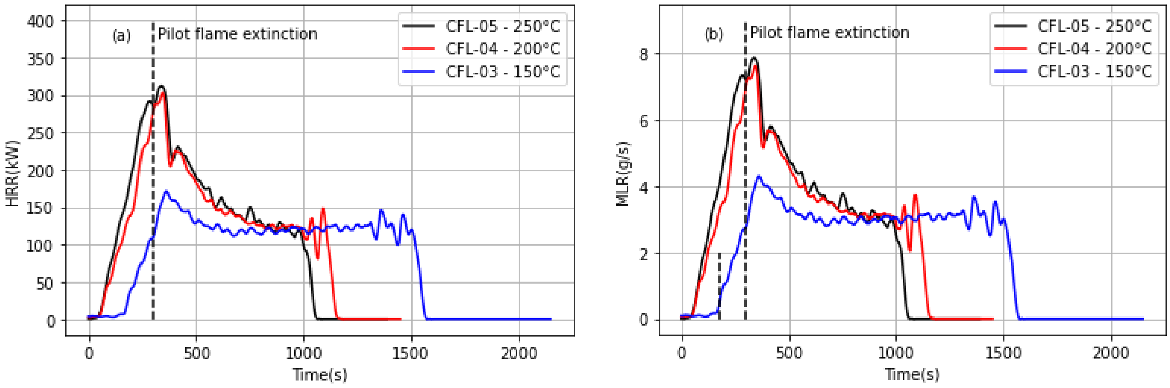

Figure 7 HRR (left) and MLR (right) development over time for the tests for which ignition occurred

In the case of preheating to 150 °C, ignition is observed 3 min after the pilot flame has been ignited. This period is necessary for the pilot flame to heat up the oil to a temperature close to 200 °C. The HRR peaks at 175 kW, then gradually stabilizes towards the same plateau as for the other two tests (125 kW). The significant power peak observed at ignition can be explained by preheating, which is not instantaneous and gradually generates an excess of fuel vapours which produces power once ignited. Once these vapours are consumed, an equilibrium is gradually reached. This hypothesis is supported by the peak observed for the test with less preheated oil (150°C) for which the peak at ignition is the smallest.

Temperature

Figure 8 illustrates (a) the average temperature profile in the flame and (b) in the test facility during the steady state of the test CFL-03 (oil) and data from another test with another fuel (diesel fuel) and a similar HRR output. The profiles are very similar for both fuels, which is consistent with the HRR of the two sources. The temperature increase in the room is moderate and the formation of two zones is observed: a first one for which the temperature increases slowly and linearly up to approximately z = 350 cm, followed by a second one for which a sudden increase in temperature is observed (for z from 350 to 600 cm). This temperature profile also shows that the test conditions are close to open atmosphere.

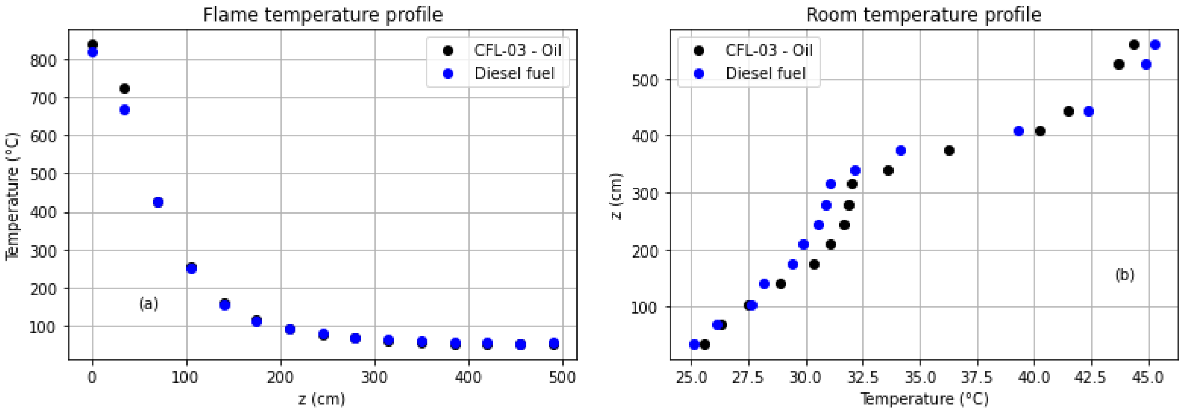

Figure 8 Temperature profile inside the flame(left) and temperature stratification inside the facility (right) during the steady state period of the CFL-03 test

Heat Fluxes and Targets

Figure 9 illustrates the development of the heat flux emitted by the source for three distances from the centre of the burner used in the CFL-03 test. At a distance of 1 m from the flame centre, the flux was homogeneous between z = 100 cm and z = 150 cm and weaker at z = 50 cm and z = 200 cm, which corresponds to altitudes slightly below the flame and above the flame respectively. For d = 150 cm, this trend faded away and the measured heat fluxes were homogeneous between z = 100 cm and 200 cm and lower at z = 50 cm. This homogeneity can be observed as well for d = 200 cm, except for z = 50 cm, for which no heat flux is measured. Overall, the maximum heat flux measured during the steady state period was close to 2.5 kW/m^2. This value is divided by 2 for every additional 50 cm distance from the flame.

Figure 10 illustrates the development over time of the total heat flux received by the targets located at z = 100 cm as well as that of their temperatures. The heat flux profiles follow closely the trend observed on the HRR profile, and the temperature gradually increases. The behaviour observed for PVC and HDPE (*h*igh-*d*ensity *p*oly*e*thylene) is very similar (same heat flux received), but PVC tends to heat slightly more. The heat flux received by the steel sample is a bit higher, which is coherent with the temperatures measured that are clearly lower than those of PVC and HDPE. These discrepancies are related to the samples' thermal properties.

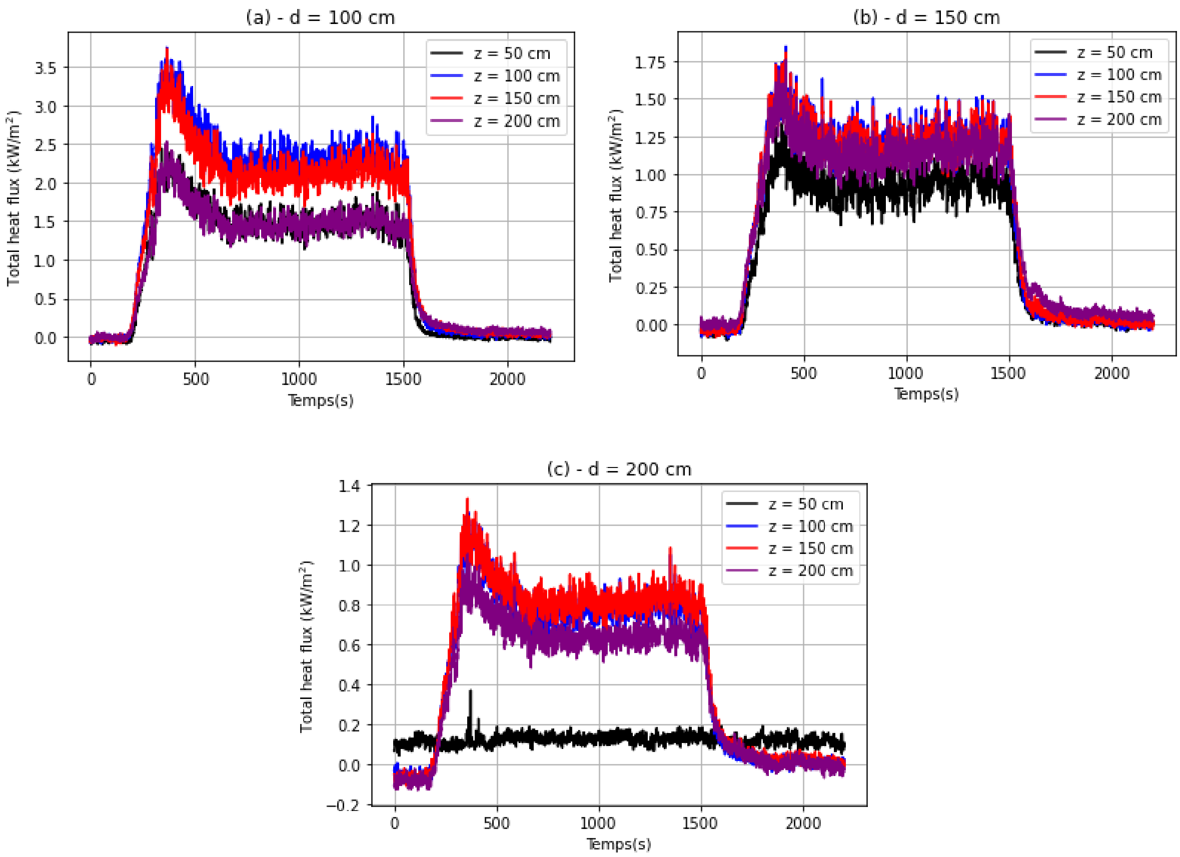

Figure 9 Development over time of the heat flux emitted by the flame measured at 100 cm (a), 150 cm (b), and 200 cm (c) of the flame centerline for the CFL-03 test

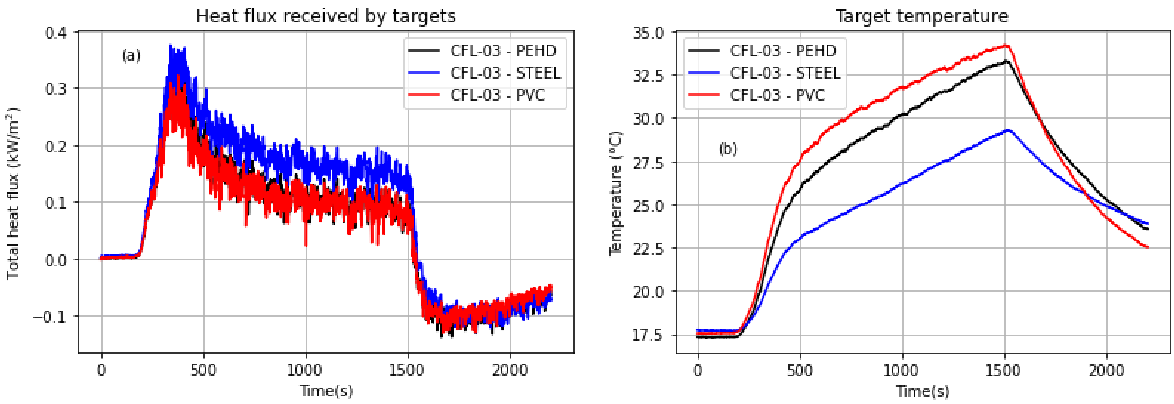

Figure 10 Development over time of the heat flux received by the targets (left) and of the targets´ temperatures (right)

Spilling Test

For this test, the burner and the buffer tank were first preheated to their respective temperatures (80 °C and 200 °C). Once the equilibrium was reached, the pump was started, and a constant oil flow was established in the burner. The pilot propane burner was then started to ignite the surface of the buffer tank and gradually ignite the flow. Once the flow channel was sufficiently hot, a thin flame developed along the entire path, travelled by the oil, and a flaming flow was established on the preheated layer in the burner. This flow state stabilized and was maintained for more than an hour (cf. Figure 11).

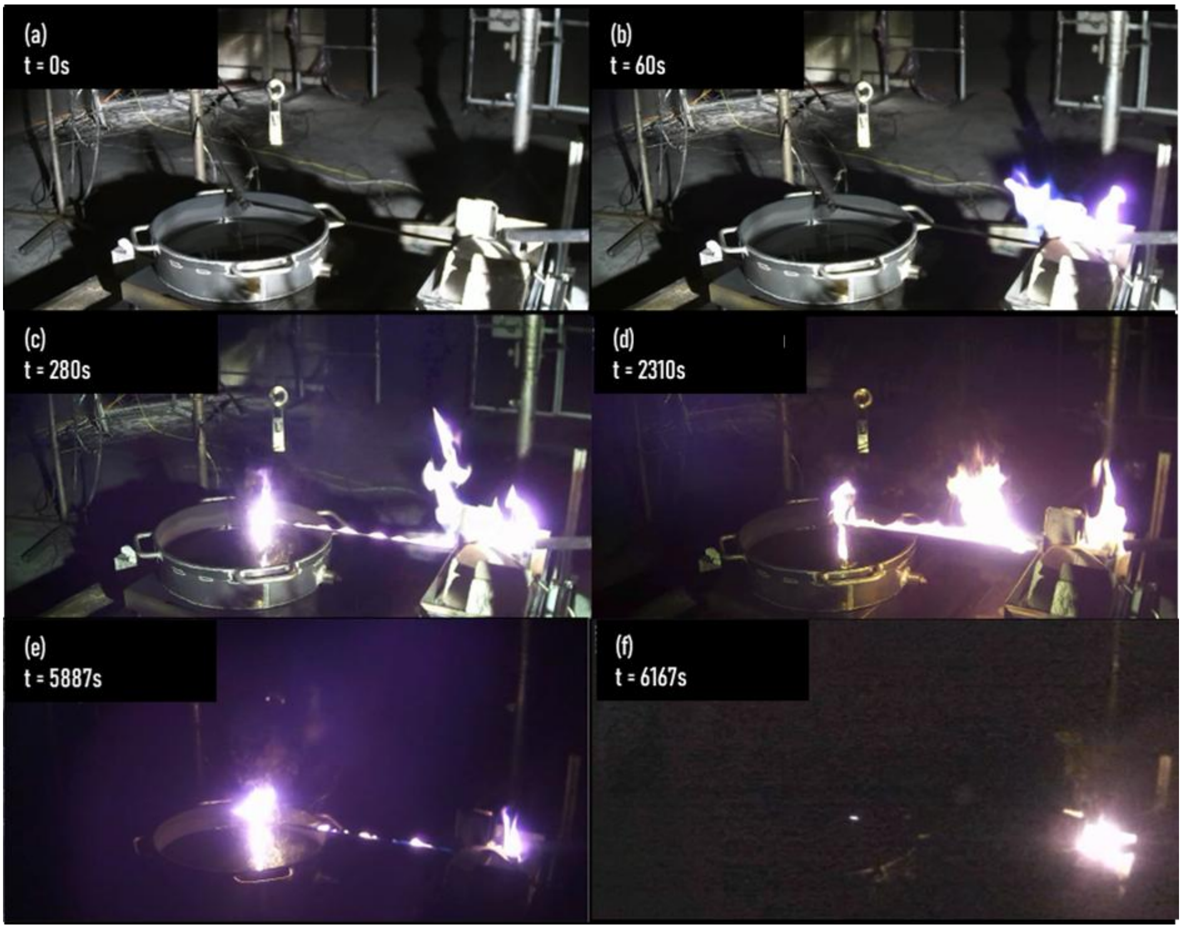

Figure 11 Behaviour of the burning oil for the spilling test at various points in times

The oil flow rate was arbitrarily set to an average value of 0.2 g/s for the test. The flow was maintained for more than 90 min, without ignition of the target oil pool. The final mass of oil in the burner was more than twice the initial fuel mass. The hot oil flow resulted in a temperature rise of the target pool, which stabilized at a temperature close to 110 °C at its centre and decreased at the end of the test. Part of this heating is explained by the temperature of the flowing oil (which is preheated to 200 °C) and not by the contribution of the flames. Figure 12 shows that the temperature is higher at the point where the flow drops (blue curve) closer to the edges of the burner (orange curve, halfway around the burner radius).

The profiles obtained show that under the given conditions (target pool heated and stored in a metal support rather than on a concrete support) ignition is not reached because the flow does not heat the liquid enough to reach a critical temperature of 200 °C. In a more realistic industrial environment, the pool would be placed on concrete at room temperature, potentially increasing the ignition resistance.

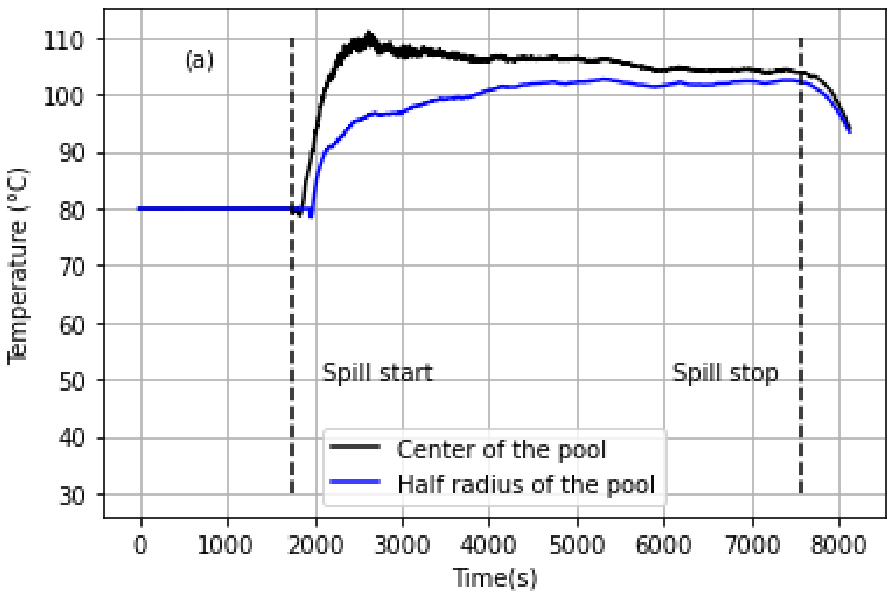

Figure 12 Development of the oil temperature inside the target pool over time

CONCLUSIONS

Seven tests were performed to investigate the ignition and burning behaviour of the oil used in the NPPs´ primary coolant pumps. The test campaign confirms the difficulty of igniting oil: in the case of a delayed ignition of a slick formed on the ground following a leak. Significant energy must be applied for a sufficient time period to reach a temperature of around 200 °C to consider ignition.

The test consisting of dripping a flaming liquid onto a slick on the ground was set to investigate a scenario in which an oil leak would ignite upon contact with hot piping (e.g., oil-impregnated insulation in contact with the piping) and flow onto an oil slick previously formed on the ground leading to ignition and to a new, larger scenario. The test campaign showed that a flaming flow was unable to ignite the oil slick on the ground, making this scenario unlikely.

The tests showed that the critical temperature to be reached for igniting the oil is 200 °C, which is coherent with the safety datasheet of the fuel. The initial HRR peak measured for the test for which ignition occurred was twice the HRR value observed during the steady state. The initial preheating temperature has no effect on the HRR at the steady state.

REFERENCES

[1] Thion, S., et al.: IGNIS: A New Experimental Platform Dedicated to Real Scale Fire Studies, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 26, 17th International Seminar on Fire Safety in Nuclear Power Plants and Installations, Westerburg Huy, Germany, October 24-26, 2022, GRS–705, ISBN 978-3-949088-96-4, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, November 2022, https://www.grs.de/publikationen/grs-705.

[2] Prétrel, H., W. Le Saux, and L. Audouin: Experimental determination of fire heat release rate with OC and CDG calorimetry for ventilated compartments fire scenario, Fire and Materials, Volume 38,Issue 4, pp. 474 - 506, June 2014, https://onlinelibrary.wiley.com/doi/10.1002/fam.2193.

[3] Mazurek da Silva, R., et al.: Experimental study of the thermal and burning characteristics of 15 cm pool fires fueled by heptane-toluene mixtures, International Journal of Thermal Sciences, Volume 193, 108454, November 2023, https://doi.org/10.1016/j.ijthermalsci.2023.108454.

[4] Klassen, M., and J. Gore: Structure and radiation properties of pool fires, NISTGCR-94-651, National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA,1994, https://archive.org/details/structureradiati9465klas..

[5] Weckman, E. J., and A. B. Strong: Experimental investigation of the turbulence structure of medium-scale methanol pool fires, Combustion and Flame, Volume 105, Issue 3, pp. 245 - 266, May 1996, https://www.sciencedirect.com/science/article/abs/pii/0010218095001034.

[6] Ditch, B. D., at al.: Pool fires – An empirical correlation, Combustion and Flame, Volume 160, Issue 12, pp. 2964 – 2974, December 2013, https://www.sciencedirect.com/science/article/abs/pii/S0010218013002459.

3.6 Topical Session on Fire Modelling

The last topical session of the seminar covered a total of six presentation, chaired by William Plumecocq (ASNR, France) and Walter Klein-Heßling (GRS, Germany) consisted of six presentation and was mainly devoted recent developments and applications of fire models.

The first presentation ‘Enhancing Early Design Safety – Integrating Fire Modelling to Mitigate Risks’ by Georgi Georgiev (newcleo, United Kingdom) emphasized the importance of incorporating fire modelling into the early stages of nuclear power plant design, particularly for newcleo’s lead-cooled fast reactor. Fire modelling supports identifying critical risks associated with the spatial distribution of combustibles and ignition sources, enabling proactive design adjustments that reduce hazards and avoid costly modifications in the late design stage. The methodology involves an iterative risk-informed design, where fire models are updated as design details evolve.

The approach uses room geometry data, fire type selection and heat release rate timelines to simulate scenarios via the RAVEN framework coupled with CFAST zone models. Key parameters such as hot gas layer temperature and height are analysed to identify rooms at risk of exceeding damage thresholds for equipment and cables. First results have shown that electrical cabinet fires and large oil spills pose the highest risks, while transient fires are less significant.

Recommendations include avoiding cable trays above electrical cabinets, enhancing fire detection and extinguishing systems, and implementing robust layout strategies to minimize fire propagation. Future iterations will refine the models with detailed ignition source data and explore advanced CFD simulations for complex geometries. This iterative risk-informed process ensures that fire safety is embedded in the design from the outset.

In the second presentation of this session Ramprasad Sampath from Centroid Lab (USA) introduced the software platform FRI3D, designed to integrate zone models (e.g., CFAST) and computational fluid dynamics (CFD) models (e.g., FDS) within a unified 3D environment for fire risk assessment of Small Modular Reactors (SMRs). Traditional fire modelling workflows are fragmented and resource-intensive; FRI3D addresses these challenges by combining CAD/BIM data, PSA logic and fire simulation tools into a single interface, enabling automated scenario generation and visualization. FRI3D’s architecture allows flexible switching between zone-based and CFD-based simulations, providing scalability for both quick screening and high-fidelity analysis. Visualization enhances model validation and decision-making.

The platform's application to SMRs is particularly valuable due to their compact designs and unique hazards, such as sodium fires. FRI3D can incorporate heat release rate data from advanced codes such as MELCOR and SAFIRE to simulate sodium spray and pool fire scenarios, supporting risk-informed design and fire protection strategies.

In the third presentation of the session, Walter Klein-Heßling (GRS, Germany) discussed validation and application of the COCOSYS (*Co*ntainment *Co*de *Sys*tem) cable fire model to large-scale experiments involving long cable trays. The lumped parameter code COCOSYS uses an extended FLASHCAT approach to simulate cable pyrolysis and flame propagation under confined and ventilated conditions. Previous validations focused on short trays (≈ 2.5 m), but recent tests with 6 m trays revealed the need for parameter adjustments. Key modifications included reducing horizontal flame propagation velocity, adjusting material density, and refining mass loss rate (profiles to better match experimental data. Comparisons of measured and simulated temperatures and heat release rates showed improved alignment, though discrepancies remain.

The study underscores the importance of continuous model refinement and anticipates further insights from the OECD/NEA FAIR experiments with even longer cables. Accurate fire modelling of cable trays is essential for assessing thermal loads and ensuring the safety of nuclear installations under complex fire scenarios.

The presentation entitled 'Development of a Simplified Semi-Empirical Model for Fire-Induced Electrical Cable Failure' by Koji Tasaka (CRIEPI NRRC, Japan) addressed the challenge of predicting fire-induced electrical cable failure in nuclear power plants. Traditional approaches rely on conservative screening criteria or lookup tables, which often lack precision. The authors therefore proposed a semi-empirical model based on experimental fragility tests and Arrhenius analysis to improve accuracy in estimating time-to-failure under fire conditions.

Fragility tests were conducted using a cone calorimeter to expose thermoplastic cables to varying heat flux levels. Two failure modes were monitored: hot shorts (conductor-to-conductor) and shorts to ground (conductor-to-tray). The results showed that higher heat flux accelerates thermal degradation, reducing the failure time significantly. The study also confirmed that conductor-to-conductor shorts occur faster than shorts to ground.

The fifth presentation of this session given by Laurent Vinçon (Framatome, France) covered the risks posed by unburned gases generated during under-ventilated fires in confined compartments of nuclear facilities. These gases can ignite later, causing smoke explosions or secondary fires, which must be considered in fire safety assessments. The study analysed the ability of the two-zone fire model CFAST to simulate unburned gas production, transport and combustion.

The authors observed that CFAST can model unburned gas accumulation and ignition at vents in horizontally connected rooms. However, in vertically connected compartments, the model failed to reproduce realistic combustion behaviour, as oxygen depletion prevented ignition despite expected conditions. This limitation highlights the constraints of zone models in complex geometries.

The findings suggest that while CFAST can handle basic scenarios, its predictive capability for unburned gas combustion in multi-compartment fires is limited. Future work will involve comparing these results with CFD models like FDS and validating them against experimental data from the OECD/NEA PRISME projects. This research underpins the need for improved modelling approaches to address re-ignition risks in nuclear fire safety.

The last presentation by William Plumecocq (ASNR, France) was devoted to the use of artificial intelligence (AI) techniques for improving cable tray fire modelling. Cable tray fires pose significant risks in nuclear power plants; however, modelling them accurately remains challenging due to numerous uncertain parameters. The presentation introduced an AI-driven expert system based on Bayesian networks to enhance fire modelling by inferring missing input data from experimental results. The system leverages a database of large-scale cable tray fire tests from the OECD/NEA PRISME and the U.S. NRC CHRISTIFIRE projects.

The expert system operates in diagnostic and prognostic modes, identifying influential parameters such as fuel mass fraction, ignition temperature and bench-scale heat release rate. By optimizing these inputs, simulations using the ASNR SYLVIA code achieved markedly improved agreement with experimental data compared to default parameter values.

Beyond improving accuracy, the AI approach helps distinguish discrepancies caused by data uncertainty from those due to model limitations. It also guides future experimental campaigns by pinpointing critical parameters. The study concludes that symbolic AI offers a transparent, interpretable method for refining fire models, bridging gaps between experimental data and simulation, and strengthening fire safety assessments of nuclear installations.

All six contributions of this seminar session are provided hereafter.

Enhancing Early Design Safety: Integrating Fire Modelling to Mitigate Risks

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ABSTRACT

This paper explores the critical role of fire modelling in the early stages of design development, providing valuable insights that can significantly influence safety outcomes. By developing a wide range of models, we address various uncertainties related to fire severity, spatial characteristics of buildings, and the nature of potential targets. These models enable a nuanced understanding of fire dynamics and risk factors. As a result, a set of recommendations aimed at minimising fire risk is proposed. These recommendations focus on the strategic placement of fuel and ignition sources, the selection of permissible combustible materials, and the regulation of activities within the building. Our findings underpin the importance of integrating fire modelling into the design process to enhance safety and mitigate fire related hazards effectively.

INTRODUCTION

Newcleo's Lead-cooled Fast Reactor (LFR) technology represents a significant advancement in nuclear energy, designed to enhance efficiency, safety, and flexibility. The LFR design incorporates numerous safety features, including robust containment structures, passive cooling systems, and a modular construction approach that minimizes installation-related risks. This paper focuses on the fire safety considerations in Newcleo's LFR technology, analysing the specific design elements and protocols that safeguard the reactor from fire-induced disruptions. By leveraging detailed layout information and adhering to modern industry standards, the paper presents an approach to optimization of the buildings and plant layout design. Fire risk management is critical in the design and operation of nuclear power plants (NPPs) due to the potential for significant safety hazards and costly operational interruptions. The integration of fire safety measures is paramount, as even small fires can have severe consequences, including physical damage, environmental impact, personnel and public health risks and reactor shutdowns. The spatial distribution of ignition sources and combustible materials within a nuclear facility directly affects fire risk levels. Understanding this distribution can enable more robust fire and the development of effective mitigation strategies.

This study aims to address the key question: How does the spatial distribution of ignition sources and combustible materials affect fire risk in a NPP? To achieve this, the study focuses on a method to iteratively re-assess the risk of fires with the progress of the design and to implement further details at each iteration while processing the resulting data to provide actionable information to the design team. The objectives are to enhance the safety and reliability of NPP designs by incorporating comprehensive fire risk analysis into their planning and construction phases.

It is acknowledged that the process of risk-informing the plant layout design is iterative in nature. Therefore, the study presented here below only reflects the development of the methodology and running the first iteration of the fire model calculations.

PLANT LAYOUT DESIGN RISKS

In the process of a NPP layout design, the location and quantity of combustible materials and components pose significant risks to the overall fire safety. Improper placement of these materials can lead to increased fire hazards or potentially affecting nuclear safety. Addressing any of these risks at a later stage of the design to comply with fire protection requirements can add to both – the cost and the time for completing the design. For instance, flammable substances and equipment such as oils, gases, and electrical components, if not strategically located, can exacerbate the potential for fire growth and propagation. Detailed fire models developed at an early design stage can help identify and mitigate these risks by simulating various fire scenarios and optimizing the layout to minimize fire hazards. This proactive approach ensures that fire safety measures are integrated into the design at an early stage, reducing the likelihood of fire incidents and avoiding expensive modifications later on.

FIRE MODELLING APPROACH

To perform fire modelling work in support of layout design, a methodological approach is outlined as follows:

1. **Compilation of room list**s**:** A list of all rooms in the building is first compiled from the layout design [1]. This compilation involves a detailed inventory of all existing rooms as far as the design maturity allows. This list is crucial as it forms the backbone for the subsequent fire modelling process.
2. **Acquisition of room geometry data:** The dimensions of each room are then systematically obtained. This step involves querying the layout database [1] for the room's length, width, and height or calculating them form the available information. These dimensions are essential for accurately simulating the heat distribution and gas layer behaviour within the rooms. In future iterations this step will also include other geometry characteristics such as doors and vents size and locations.
3. **Selection of the fire type:** Based on the description of each room, the correct fire type is selected. The selection is informed based on the presence of specific combustibles and potential ignition sources within each room. This information is taken from the fire load inventory. Common fire types include electrical fires, liquid spill fires and storage material fires. This step ensures that the simulations accurately reflect the most likely scenarios associated with each room. For the initial iterations this step relies on the analyst judgement as no detailed information is expected to be available in the initial phases of the design.
4. **Generation of the heat release rate (HRR) timeline:** For each selected fire type, a typical HRR timeline is generated. This timeline includes the initial fire growth, peak HRR, and decay phases of the fire. The HRR values and durations are derived from empirical data

and validated models to ensure accuracy and reliability of the simulations. The documents used as main fire data sources are NUREG-6850 [2], NUREG-1934 [3].

5. **Running of fire models:** Utilising the Risk Analysis Virtual Environment (RAVEN) [4] framework, a fire model is run for each fire type and for each selected room. The RAVEN framework is a powerful simulation tool capable of adjusting the exiting fire model to the dimensions of each room and running the simulations with the selected modelling software, including the initial collection and processing of the results. This step employs the previously generated HRR timelines and room dimensions to simulate the fire scenario for each room.
6. **Calculation output collection:** From each calculated fire model, the maximum hot gas layer (HGL) temperature and minimum layer height are collected systematically. These parameters are critical indicators of the severity of fire conditions and are used to assess the impact of the fire on the room environment.
7. **Identification of critical conditions:** The results are then analysed comprehensively to identify which rooms will reach critical conditions. A critical condition is typically defined by thresholds such as excessive HGL temperatures and low layer heights that exceed safe operational limits. These limits are usually defined based on the comparison of the gas temperatures to the damage criteria for cables and sensitive equipment with the layer hight used to judge if the hot gases decrease to a level sufficiently low to cause any equipment damage. This analysis aids in identifying the most vulnerable areas within the building, thereby guiding mitigation strategies and design improvements.
8. **Reporting findings:** The findings from the fire modelling process are reported to the relevant design teams such as layout design team, electric design team, instrumentation and control (I&C) design team, etc. This report includes detailed scenarios, critical conditions identified and recommendations for layout modifications to mitigate fire risks. The reporting step ensures that the relevant design teams have accurate and actionable information to enhance the overall safety and robustness of the building layout.

This process is repeated iteratively, accounting for any changes in the layout design and incorporating additional information that may become available during the design phase. This iterative approach ensures that the fire modelling is consistently updated to reflect the most current building design and equipment layout, providing a reliable basis for safety and design improvements.

REVIEW AND SELECTION OF FIRE IMPACTS AND APPLICABLE FIRE MODELS

To enhance the layout design team's capacity to effectively address fire hazards, thorough research was conducted on potential fire impact mechanisms. These mechanisms include:

- **Fire plume:** A rising column of hot gases and smoke that can influence the temperature and conditions at the higher levels of a building, affecting the ventilation system and air quality, and potentially spreading smoke to adjacent rooms.
- **Radiated heat:** Infrared radiation emitted by a fire that can damage nearby structures and equipment and increase the surrounding temperatures.
- **HGL:** A layer of hot gases accumulating in the higher parts of the room and decreasing with the fire growth, capable of inducing secondary fires in case of propagation to combustible materials.

- **Smoke spread:** Rapidly filling a space and reducing visibility, leading to respiratory issues and potential electrical problems in NPPs due to soot deposition on components.

At the design early stage, it was found not to be possible to assess the effects of the fire plume, radiated heat and the smoke spread. Therefore, for the first iteration of the study the HGL temperature and height are considered to be the key fire parameters. Three types of models are currently widely applied within nuclear industry: algebraic models, zone models and CFD (*c*omputational *f*luid *d*ynamics) codes:

Algebraic models: Those are equations found in literature which can be implemented into spreadsheets such as the NRC's Fire Dynamics Tools (FDTs) [6]. Algebraic models provide an approximation of the analysis. They are mainly used as a first approach because they do not need a lot of calculations or input variables. However, the approach is only used to give an overview of the results, and more in-depth calculations need to be performed in order to establish a reliable fire model.

Zone models: Zone models consist of dividing the space between volumes and zones. The two zones inside a room are a colder lower layer and the HGL. The modelling is such that each zone is homogeneous and uniform (i.e., temperature, smoke concentration, etc.). Each parameter is calculated by applying the ideal gas law. Zone models are often used to determine the HGL temperature of single volumes or a group of interconnected volumes. Nevertheless, it could be complicated to simulate rooms with complex geometries by a "zone" approach that led to a uniform HGL. The zone models CFAST (*C*onsolidated *F*ire Growth *a*nd *S*moke Transport) developed by the National Institute of Standards and Technology (NIST) [5] and MAGIC developed by Électricité de France (EDF) (as mentioned in [3]) are the two main zone models applied within nuclear industry.

CFD codes: CFD models are used to analyse fire variables in complex geometries where zone models fall short. They involve a preprocessor, solver and postprocessor and work by solving conservation equations across a grid of cells. CFD models offer higher spatial accuracy than zone models, making them ideal for large or complex spaces. However, they are time-consuming and computationally intensive. They are particularly useful when precise spatial resolution, large compartments or complex geometries are involved.

The zone model CFAST has been chosen as fire modelling tool for this work, primarily because of its relative simplicity in model setup and its ability to perform fast-running calculations. It has been validated against experimental data, ensuring its reliability in various fire scenarios. Additionally, CFAST allows for an easy setup of multiple runs and efficient collection and processing of results, making it a practical choice for this project's purpose. However, it has some known limitations, such as limited precision compared to CFD models and a tendency to overpredict the HGL temperature. Despite these drawbacks, the uncertainties associated with CFAST are well understood, allowing users to account for them in their analyses.

In the fire modelling process, key parameters are categorized into input and calculated parameters. Input parameters encompass variables such as the HRR, ambient temperature, fuel quantity, rate of fire growth and the initial oxygen concentration, which are essential initial conditions. Calculated parameters, derived from established models, include the HGL thickness, smoke height, heat flux, target surface and surrounding gas temperature, oxygen concentration change with time and the associated uncertainties. These calculated parameters are critical for accurately predicting fire behaviour and its impact on the surrounding environment.

CFAST was included in the fire modelling tools validation programme published in NUREG-1824 [7]. As part of that programme, a set of validation limits was established, and the use of CFAST beyond these ranges will need further justification. As the design details of Newcleo's 30-Megawatt Lead-cooled Fast Reactor (LFR – 30) become available in future iterations, the fire models calculated by CFAST will be re-evaluated against these validation limits to ensure that the predictions remain within acceptable bounds of accuracy.

FIRE CHARACTERISATION

While the first iteration of the study is being performed at a very early design stage, it is not possible to precisely define the nature of all possible ignition sources. Therefore, one of three fire types – electric fires, lubrication oil spill fires and transient fires – is selected for each room based on the initial room information. This approach is believed to create a bounding case for each room in our current layout design.

A series of three detailed simulations was performed to model electrical fires in different cabinet configurations. The first scenario involved a single electrical cabinet, providing a baseline for fire behaviour and spread within a typical electrical room. The second simulation focused on a slightly more complex setup, featuring one central cabinet flanked by two additional cabinets on each side, which allowed for the assessment of how adjacent structures affected the fire dynamics and heat transfer. The third and most comprehensive configuration included three cabinets in a row with a cable tray positioned above them. This setup was designed to investigate the impact of elevated fuel sources (cable trays) on the fire intensity and the potential for three-dimensional fire propagation. It is recognised that the selected fire configurations are strongly conservative; however, for the initial iteration of the process they were found suitable for the purpose of identifying the high-risk rooms.

Additionally, two oil fire simulations were conducted to further analyse fire behaviour in the rooms identified as expected to contain any equipment that might contain certain quantity of lubrication oil. The first oil fire simulation involved a small spill of 1 l, while the second scenario included a larger spill of 5 l. These simulations provided insights into how different volumes of spilled oil impact fire intensity, spread, and the overall thermal environment. The results from these simulations will help in optimising fire safety measures and mitigation strategies for both electrical and oil-related fire risks in industrial environments.

Transient stored materials fire (further referred to as “transient fire”) has a behaviour that was also studied according to the data given in NUREG/CR-6850 [2]. While newer data are available, adherence to this reference was chosen for consistency to ensure that the analyses align with established standards and best practices. The results from these simulations will help optimizing fire safety means and mitigation strategies for electrical, oil-related and transient fires.

While CFAST has a proven capability to model oxygen limited fires, the approach selected for the first iteration of this study is not to limit the oxygen supply to the fire in order to build a bounding fire model.

The detailed characteristics of the selected fires are presented below.

Electrical Cabinet Fire

In accordance with the methodology outlined in NUREG/CR-6850 [2], the HRR for a single electrical cabinet was calculated. The analysis indicates a peak HRR of 702 kW, with the time to reach the peak HRR being 12 min. Following the peak, the HRR sustains at this maximum level for a steady-burn period of 8 min. Post-peak, the HRR is assumed to decay linearly over a 20 min period. The equation describing the time growth to peak HRR can be written as follows:

$$\dot{Q}(t) = Min\left(\dot{Q}_{peak}; \dot{Q}_{peak} * \left(\frac{t}{\tau}\right)^2\right) \quad (1),$$

where τ is the time to reach the peak HRR, $\dot{Q}_{peak}$ is the peak HRR, and t is the time.

Figure 1 shows the growth, the steady burn and the decay as described previously.

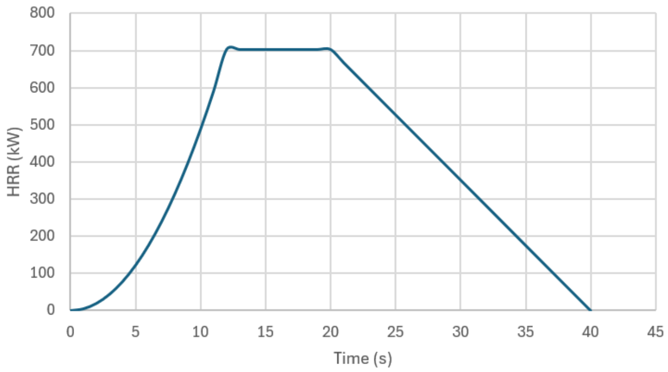

Figure 1 HRR development over time for a single electrical cabinet fire

Table 1 below shows the HRR profiles applied in the calculations for the three electric fire configurations applied for simulating fires in electrical equipment rooms.

Table 1 HRR for different electrical fires

Single Electrical Cabinet		Three Electrical Cabinets		Electrical Cabinets and Cable Trays	
Time [sec]	**HRR [kW]**	**Time [sec]**	**HRR [kW]**	**Time [sec]**	**HRR [kW]**
0	0	0	0	0	0
60	60	300	122	120	79
240	240	660	600	240	212
480	480	900	946	420	513
660	660	1140	1492	660	1057
720	702	1320	2036	1020	1836
1200	702	1620	1860	1140	2184
1440	562	1800	1755	1200	2375
2400	0	2400	702	2400	1395
3000	0	3000	0	3000	693

Oil Fire

Concerning oil fires, Section G from NUREG/CR-6850 [2] was used stating that for a less than 95 l spill, the depth is 0.71 mm. It is assumed that the peak HRR is instantly reached because of the fast reaction of an oil fire. The peak HRR is calculated following this equation:

$$\dot{Q} = \Delta H_C \dot{m}'' A \quad (2),$$

where:

$\dot{Q}$ = HRR of the fire [kW]

DHc = heat of combustion (HOC) [kJ/kg]

$\dot{m}$” = specific burning rate [kg/sec. m^2]

A = area [m^2]

The typical HRR profiles for 1 l and 5 l oil spill fires are shown in Table 2 below.

Table 2 HRR for oil spill fires

1 l Oil Spill Fire		5 l Oil Spill Fire	
Time [sec]	**HRR [kW]**	**Time [sec]**	**HRR [kW]**
	0	0	0
1	1957	1	9785
40	1957	975	9785
41	0	976	0

Due to the highly flammable nature of the oil, it was considered that once the fire started, the peak HRR was immediately achieved, with no time of growth. This means that the combustion process for this type of oil is extremely rapid and intense, leading to an instantaneous release of heat at the maximum possible rate as soon as ignition occurs. The area of the spill was calculated by dividing the volume by the depth of the spill.

Transient Fire: Transient fires are stochastic events that can be initiated through various mechanisms and occur in different rooms. These fires are complex to predict due to their dependence on numerous parameters, including ignition sources, fuel types, and room configurations. Transient fires are challenging to predict due to the numerous variables involved, many of which may be unknown. The time to growth, steady burn and decay phases are three critical variables that depend on various parameters, including the HRR, the combustion rate, and the mass of the combustible materials. It has been decided to use the NUREG-1934 [3] example where a fire occurs in a garage bin inside a cable spreading room (CSR). This scenario seems relevant to see what impact a transient fire can have on safe shutdown cables. The parameters characterising the growth of a transient fire used in the models presented below are shown in Table 3.

Table 3 Parameters for Transient Fire

Parameter	Value
Peak HRR	317 kW
Time to reach the peak HRR	480 s

Parameter	Value
Steady burn	320 s
Total burning time	800 s
Heat of combustion (HOC)	30 400 kJ/kg

RAVEN – CFAST SETUP

RAVEN [4] was utilized in combination with CFAST to enhance the efficiency of the fire modelling process. Among its wide range of capabilities, RAVEN allows for the variation of multiple parameters over a specified range, such as the HRR and room dimensions, without the need for manual input of configurations into CFAST. This capability significantly reduces the analytical effort and minimizes the potential for human error associated with manual input.

In essence, RAVEN automates the simulation system for selected parameters, enabling a systematic and efficient exploration of various scenarios. This automation facilitates the generation of comprehensive data sets that are used to analyse the fire behaviour under different conditions. The workflow within RAVEN framework is a relatively simple and streamlined. It consists of the preparation of the initial set of parameters to be varied for the set of CFAST runs, the preparation of a CFAST template input (the .in text file) and a process control file written in XML. With these inputs RAVEN runs the CFAST simulations autonomously and extracts the key parameters of interest in a simple CSV format as shown in the flowchart in Figure 2 below.

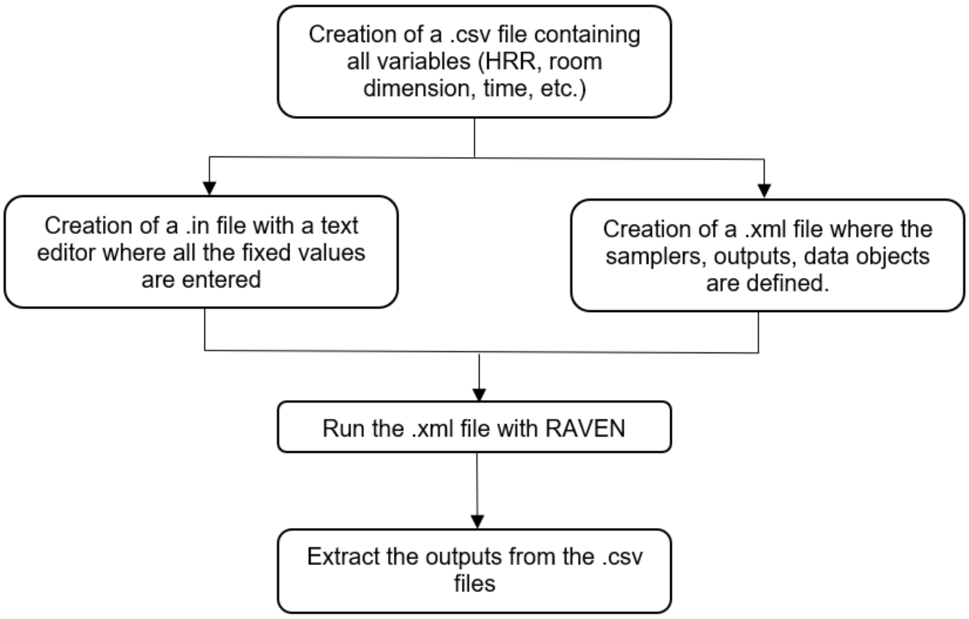

Figure 2 Diagram explaining the utilisation of RAVEN

DISCUSSION OF THE RESULTS

The results from the CFAST calculations have been sorted by RAVEN in order to identify the maximum temperature and the minimum height of the HGL during fire scenarios within various sized compartments. For each compartment examined, the highest temperature recorded in the HGL as well as the minimal height of this layer have been identified over the entire duration of the fire. This approach allows for a better understanding of the worst-case conditions, which is important for optimizing fire safety and fire prevention arrangements. The damage criterion for the purposes of this iteration of the study is taken as the thermoset cable damage temperature as defined in [2]. A summary of the results grouped by fire type is presented in the table below. Moreover, for each scenario studied graphs have been plotted, one for the temperature and another for the height of the HGL.

Table 4 shows that the number of ignited electrical cabinets directly correlates with the likelihood of exceeding the damage criterion. Transitioning from a single cabinet to three cabinets significantly increases the risk. The presence of a cable tray above the cabinets further increases the fire load, thereby increasing the probability of reaching the damage threshold. Furthermore, for an oil fire, increasing the spill led to a significant change in the temperatures and layer height reached. According to the study, fires with the most significant impact occur in rooms with numerous electrical control panels or large oil spills. For the purposes of this study a 'large oil spill' refers to a fire originating from a spill of 5 l of oil. However, it should be noted that 5 l may not be significant for rooms of larger size.

Table 4 Summary of initial results

Type of Fire		Number of Rooms Modelled	Number of Rooms with HGL Temperature Exceeding Damage Criterion	Minimum-Maximum Layer Height [m]
Electrical cabinet fire	Single electrical cabinet	49	8	0.41 – 0.63
	Three electrical cabinets	49	45	0.42 – 0.61
	Three electrical cabinets and cable tray	49	46	0.42 – 0.58
Oil fire	1 l oil spill	29	3	0.22 – 12.7
	5 l oil spill	29	24	0.02 – 0.33
Transient Fire		202	0	0.25 – 1.87

The layer height for the small oil spill fire exhibits a broader range compared to the larger fire. This discrepancy can be attributed to the dimensions of the room in which the maximum values were observed.

One particular room has been identified as an outlier with a floor area of 600 m² and a height of approximately 17 m. Due to the significant volume of the room it exceeds the validation range of CFAST and will need a more detailed fire simulation during the next iteration cycle in order to bring the results into the range of validity.

The figures shown below present the results in a more visual way and allow for a more comprehensive understanding of the spread of fire damage given the rooms dimensions.

For the first two electrical fires (cf. Figure 3 and Figure 4), the damage criterion was set at 330 °C. To be able to see it correctly in the graph, each time the maximum temperature reached a higher temperature than 330 °C, the markers were coloured in red. With a few exceptions, the single electrical cabinet fire maximum temperature in the HGL is always below 330 °C. Nevertheless, when two additional electrical cabinets are placed on each side of an existing cabinet, the resulting increase in localized heat generation significantly increases the overall temperature in the area as illustrated in Figure 4.

For scenarios where the combustibles configuration includes cable trays above the electrical cabinets (cf. Figure 4), the cable tray ignition criterion was set at 500 °C. One observation was that the smaller rooms tend to reach extremely high temperatures. A particularly important factor in these fire models is the distance between the top of the electrical cabinet and the bottom of the cable tray stack as this distance defined the time delay before the onset of the secondary fire.

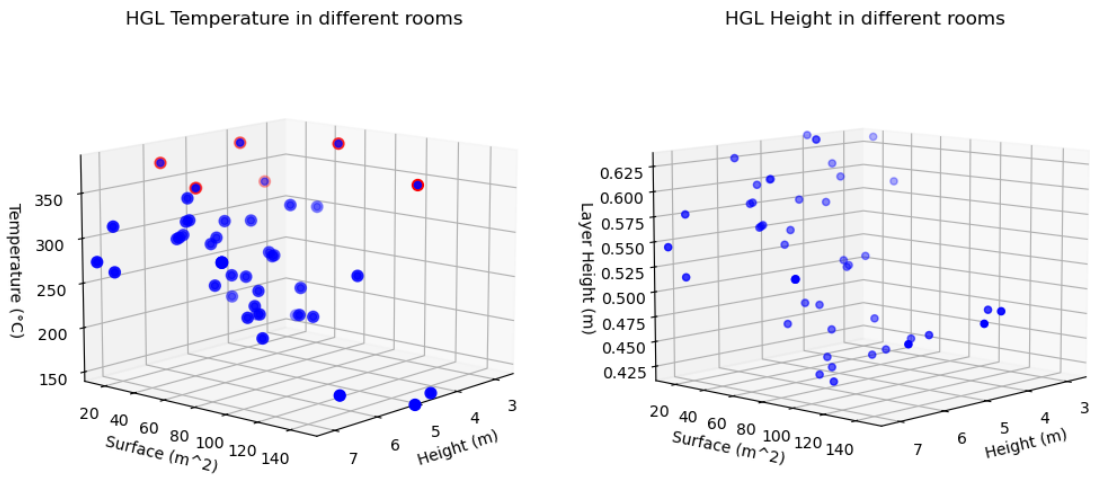

Figure 3 Temperature and height of the HGL as function of room dimensions during a fire in one electrical cabinet

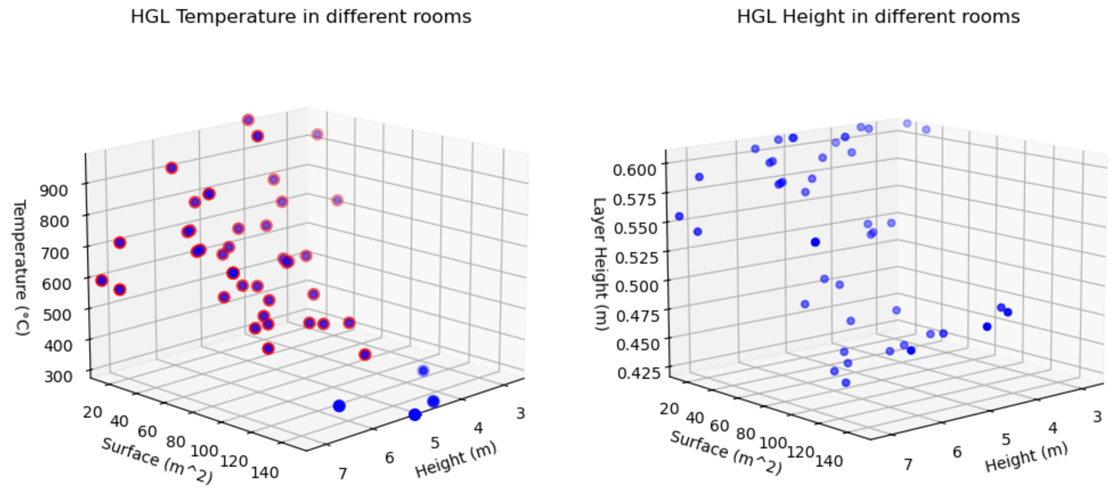

Figure 4 Temperature and height of the HGL as a function of room dimensions during a fire in an electrical cabinet propagating to both sides

Figure 5 and Figure 6 represent two different oil spill fires. As demonstrated in Figure 5, the damage criterion of 330°C is almost never reached while in Figure 6 it is reached for almost all of the room's dimensions.

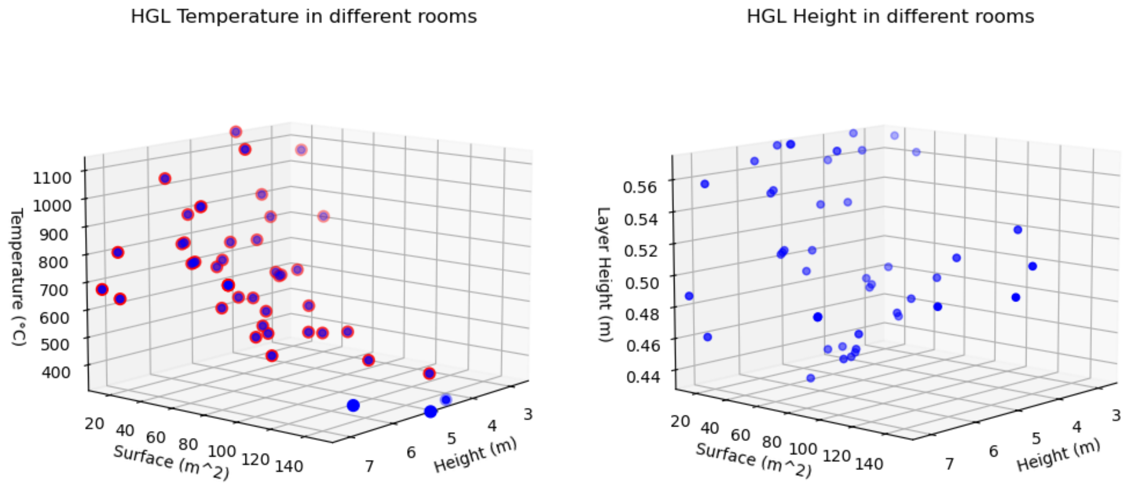

Figure 5 Temperature and height of the HGL as a function of room dimensions during a fire with three electrical cabinets and a cable tray on top

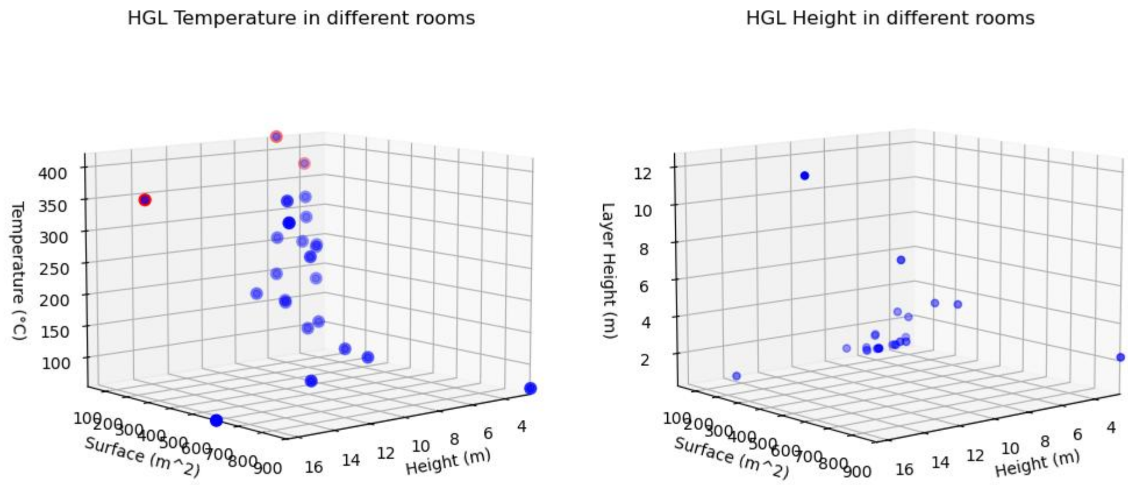

Figure 6 Temperature and height of the HGL as a function of room dimensions during a 1 l oil spill fire

It is important to note that CFAST was not able to run the simulations for all the room's dimensions for an oil spill fire larger than 5 l because of the large amount of energy released. The results from the large oil spill fire models are illustrated in Figure 7. It should be noted that only a very limited number of simulations resulted in HGL peak temperature below the selected cable damage criterion.

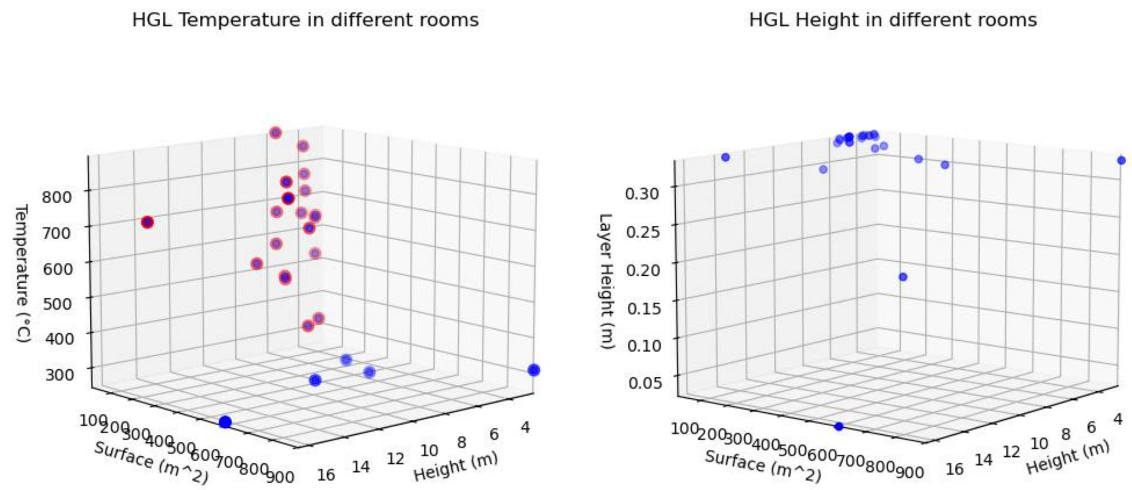

Figure 7 Temperature and height of the HGL as a function of room dimensions during a 5 l oil spill fire

In contrast to the above, in the transient fire simulations, as presented in Figure 8, the maximal HGL temperature did not exceed the damage criterion of 330 °C.

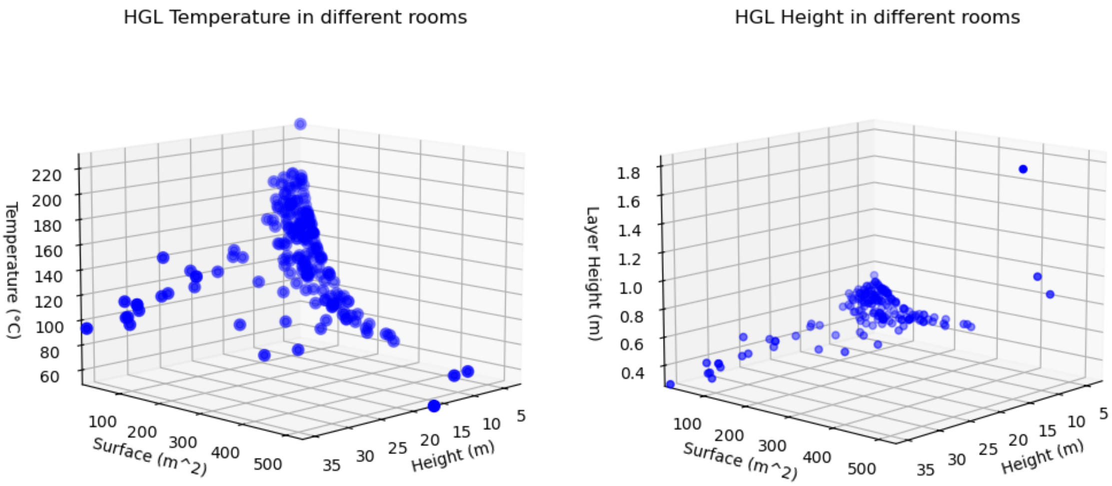

Figure 8 Temperature and height of the HGL as a function of room dimensions for a transient fire

CONCLUSIONS

The method presented for risk-informing the layout design through early-stage fire modelling has been demonstrated to be both practical and efficient. This method allows for effort-efficient iterations with each iteration incorporating an increasing level of detail. It enables a quick screening of rooms that present a low fire risk, thereby shifting the focus to those rooms with higher risk significance.

In general, the results indicate that transient fires present a relatively low risk compared to electrical and oil spill fires. The findings allow for narrowing down the electrical rooms where fire could be a high risk contributor, thus focusing the design effort on fire prevention and protection means. Additionally, the results show that small oil leakage fires are generally manageable, but appropriate measures must be taken to prevent large oil spills.

For the layout design team, it is crucial to implement enhanced fire protection features in rooms with multiple electrical cabinets. Installing cable trays directly above electrical cabinets should be avoided to reduce the fire load and mitigate risks. Additional safety measures should include enhanced fire detection and suppression systems in these rooms. Regular inspections and maintenance of electrical installations are essential to prevent potential ignition sources.

These conclusions support the effectiveness of the method in identifying and addressing critical fire risks, thereby enhancing the overall safety and robustness of the layout design.

FUTURE WORK

Future iteration cycles of this study will involve a more in-depth exploration of the room characteristics, materials and internal layout to enhance the accuracy of fire modelling in the frame of safety assessments. By gathering detailed information on ignition sources and potential targets, it will be possible to incorporate these parameters into simulations using a comprehensive range of peak HRR values. This will enable the development of more precise damage probability distributions and allow for a determination of the time window during which fire suppression teams can successfully intervene. These advancements are expected to significantly improve the understanding of fire dynamics in complex environments and contribute to implement more effective fire safety means.

REFERENCES

[1] Newcleo: LFR-AS-30 Nuclear Island Layout, Lyon, France, January 2025 (internal Newcleo document).

[2] United States Nuclear Regulatory Commission (U.S. NRC) / Electric Power Research Institute (EPRI): EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Plant Facilities Volume 2: Detailed Methodology, Final Report, NUREG/CR-6850, EPRI 1011989, Washington, DC, USA, September 2005, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/v2/cr6850v2.pdf.

[3] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research (RES) / Electric Power Research Institute (EPRI): Nuclear Power Plant Fire Modeling Analysis Guidelines (NPP FIRE MAG) – Final Report, NUREG-1934, EPRI 1023259, Washington, DC, USA, November 2012, https://www.nrc.gov/docs/ML1231/ML12314A165.pdf.

[4] Idaho National Laboratory (INL): Risk Analysis Virtual Environment (RAVEN), Idaho Falls, ID, USA, last access: February 2025, https://inl.gov/raven/.

[5] National Institute of Standards and Technology (NIST): Consolidated Model of Fire and Smoke Transport (CFAST v.7.7.4), Gaithersburg, MD, USA, last accessed February 2025 https://pages.nist.gov/cfast/index.html

[6] United States Nuclear Regulatory Commission (U.S. NRC): Fire Dynamics Tools (FDTs) – Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program, Final report, NUREG-1805, Washington, DC, USA, 2013, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/index.html.

[7] United States Nuclear Regulatory Commission (U.S. NRC), Office of Nuclear Regulatory Research (RES), Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications Volume 5: Consolidated Fire Growth and Smoke Transport Model (CFAST), NUREG-1824, Volume 5), Final Report, NUREG-1824, EPRI 1011999, Washington, DC, USA, https://www.nrc.gov/docs/ML0717/ML071730527.pdf.

A Unified 3D Framework for Zone models and Computational Fluid Dynamics Models for Fire Risk Assessment in Small Modular Reactors

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ABSTRACT

Plant internal fires pose a risk in nuclear power plants (NPPs), making fire probabilistic risk assessment (PRA/PSA[1]) essential for informed decision-making by operators and regulators. Originally developed under the light Water Reactor Sustainability (LWRS) Program, the fire risk investigation in 3D (FRI3D) software has evolved to support fire risk assessment and design for small modular reactors (SMRs).

Advanced fire modelling in nuclear plants relies on tools such as zone models (CFAST) [1] and computational fluid dynamics (CFD) models like the Fire Dynamics Simulator (FDS) [2], often coupled with codes for cable failure analysis based on Nuclear Regulatory Commission Reports (NUREG-2178 [3], NUREG/CR-6931 [4] and NUREG/CR-7010 [5]). However, transitioning between models, updating scenarios, and incorporating regulatory changes – such as revised heat release rates (HRRs) and incorporating guidelines on e.g. high energy arcing faults (HEAFs), can be resource-intensive, requiring substantial effort and cost across multiple platforms.

This paper presents the underlying FRI3D framework, which integrates plant model databases, computer aided design (CAD) models, and building information models (BIM) into a unified 3D environment. By seamlessly incorporating fire modelling tools, the outlined framework enables rapid, accurate visualizations of fire scenarios based on simulation results, while allowing users to choose between zone models and CFD based approaches. A case study of a SMR room illustrates its capabilities.

Additionally, this paper highlights key insights that enhance fire modelling for Small Modular Reactors (SMRs), aiding design decisions and PSA while serving as a digital twin for fire risk and hazard analysis.

INTRODUCTION AND BACKGROUND

Fire Risk Investigation in 3D (FRI3D) [6] is a software that implements industry approved methods to simplify and automate many tasks required for NPP fire modelling. To that extent,

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[1] It should be noted that probabilistic risk assessment (PRA) and probabilistic safety assessment are used interchangeably in this paper.

FRI3D was designed with the ability to couple the most commonly used tools and methods used by the NPP industry such as RiskSpectrum Inc.'s (RS) RiskSpectrum® PSA (RSPSA) software [7], Electric Power Research Institute (EPRI)'s software CAFTA [8] as well as the United States Department of Energy's Software SAPHIRE [9]. CAFTA, SAPHIRE and RiskSpectrum® PSA are used to construct and calculate NPP risk models, typically for regulatory use. FRI3D automates the Fire PSA process to create and calculate its scenarios and output its analysis to the appropriate PSA software. The main focus of this paper is to highlight the flexible design of the FRI3D Software to render itself to be used in zone models as well as Computational Fluid Dynamics Models as well as its applicability in making design decisions for SMRs. as well as to provide a system to enable the transition to a PSA workflow.

FRI3D INTERFACE AND FEATURES

FRI3D provides a graphical user interface that includes CAD based modelling tool to view different compartments and associated scenarios, then assign or modify the spatial information in the center 3D area. By combining 3D visualization directly with the PSA data and fire calculations, FRI3D provides a single interface for developing and analysing fire models, while automating many steps. Figure 1 shows the User Interface (GUI) which has five primary areas:

- Compartment/Scenario Editor (top left) – displays all the items in the current compartment/scenario;
- Properties Editor (bottom left) – shows the properties for the selected item and allows the user to edit;
- 3D View (center) – allows for modelling and viewing the spatial relationships, along with fire simulation results;
- Fire Logic View (right side) – shows the logical mapping of raceways, cables, components, and PSA basic events;
- Timeline – displays the timing results from fire simulation and failure calculations (i.e., when items fail).

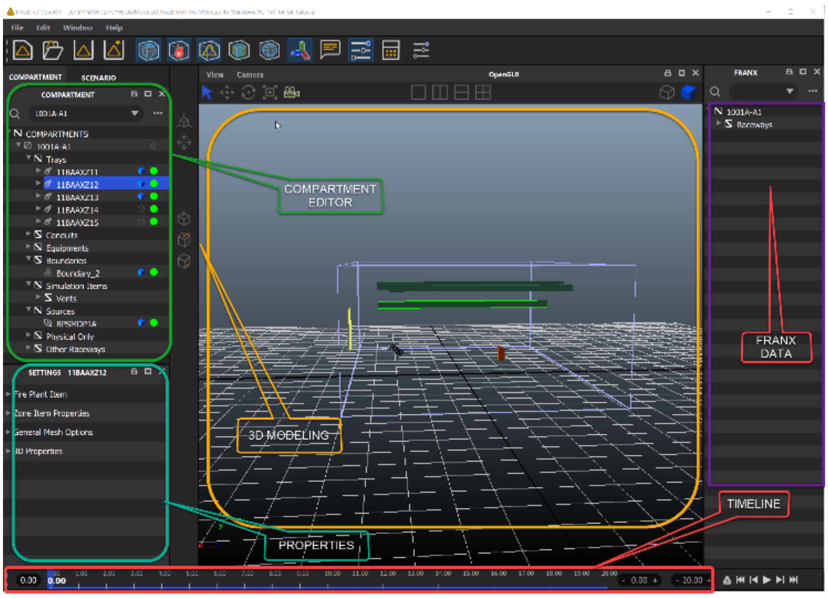

Figure 1 FRI3D user interface

Fire scenarios can be created manually or preferably automatically by running a fire simulation using FRI3D. The automations eliminate the need for the various stages of hand calculations and manually assigned failed components and is thus less error prone. The following steps are used to auto-generate a scenario:

1. Construct fire models from FRI3D's model with 3D data and properties.
2. Simulate fire using specified HRRs.
3. Determine if there are any secondary combustibles after an initial fire simulation, results, use the FLASH-CAT Method [5], generate a new HRR and go back to step 2.
4. Use simulation results t3o determine additional cable failures using the Thermally Induced Electrical Failure THIEF method [4] if cable data exists. If cable data do not exist, use the heat soak method [4]. Also, use simulation data to determine direct component failures for the compartment.
5. Use the fire logic mapping to determine subsequent components that failed due to cable failures.
6. Save failures, timing, and other data as a scenario for the compartment.

Scenarios generated can then be evaluated or modified by the user and sent to the PSA model for a conditional core damage frequency and other PSA calculations.

FRI3D METHODOLOGY AND VISUALIZATIONS

The progression of temperatures on the various components which take part in the simulation is also displayed. As the user adjusts the time, the temperatures of each component, shown by the colour, adjusts according to the heat scale, as shown in Figure 2.

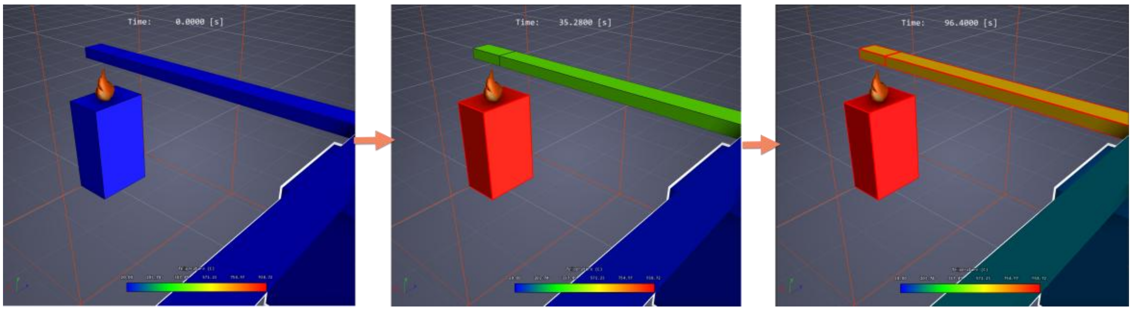

Figure 2 Progression of component temperature

There are many benefits to visualizing the fire simulation results in FRI3D. A key one is being able to see the fire progression and qualitatively verify that it is as expected. Errors in the model such as venting issues or other incorrect simulation parameters can often be identified. By showing component failures and temperatures over time, the modeler can visualize and identify key items to add shielding or other simple modifications that could eliminate large risk contributions. Additionally, when making plant modifications, the user can easily determine good locations for equipment and cables.

FRI3D COST BENEFIT ANALYSIS

In collaboration with the United States pressurized-water reactor owners group (PWROG) and Engineering Planning and Management, Inc. (EPM), FRI3D was used for a plant modification that was upgrading and moving plant equipment [10]. The following sections outline the work performed highlighting the time and cost benefits by using FRI3D for Fire Analysis in comparison with the existing methods used for Fire modelling.

Model Setup

As part of the evaluation, EPM performed an impact review of the plant modification as they typically would for the facility. In this modification, a newer version of oil containing equipment would be replaced and moved. The new equipment had a different volume of oil and were closer to the fire zone boundary.

It was determined to model eight different fire scenarios associated with the two pieces of equipment being moved. The main analysis was to evaluate design options to limit the maximum 100 % oil spill size from affecting PSA target items beyond the originating fire zone. There were three options to minimize the effect of the 100 % oil spill: using curbing in the new area, incorporating an oil confinement system around the equipment, or crediting the existing plant drains near the equipment to limit the spill area. Using these calculations, EPM was able to risk-inform the decision process and present the options to the plant operators, who then selected using the floor drains.

NRC's Fire Dynamics Tools (FDTs) [11] provides a model for the zone of influence (ZOI) for a fire. The ZOI model provides conservative estimations for the properties of the fire given the user inputs.

For evaluating results, it was determined to use the more detailed CFAST [1] based zone model to run simulations using FRI3D vs EPM's model which used FDTs to determine the failures. Figure 3 depicts the compartment in FRI3D.

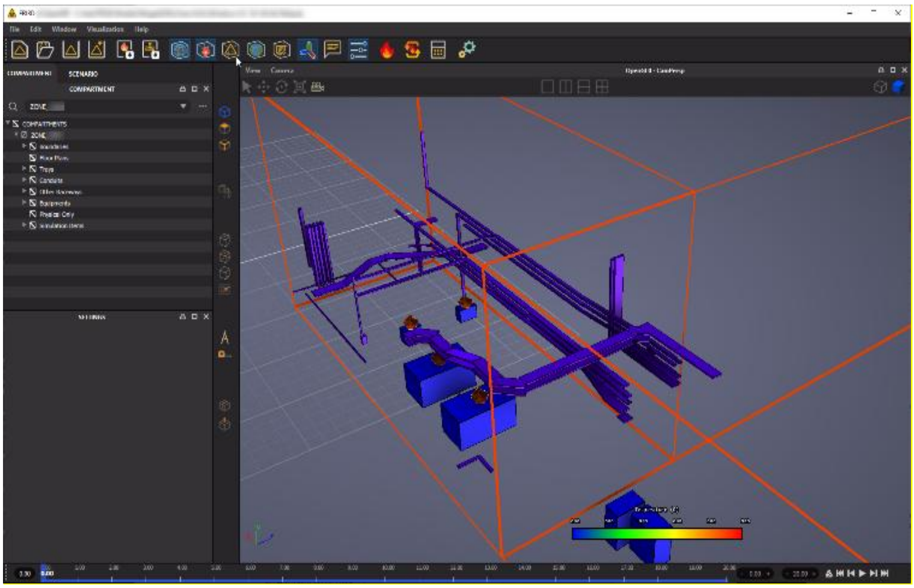

Figure 3 Plant compartment model

Plant Data Import

The FRANX [12] database file and format was developed and is used by EPRI for external hazards modelling in their CAFTA risk analysis software and was used to import the fire scenarios, compartments and mappings from cables to raceways to components and its associated basic events FRI3D's flexible design enabled the import of existing fire model data and scenarios from the FRANX database format in this case.

In addition, plants may have their internal database comprising of various cable routes, location of equipment etc which may or may not be PSA relevant. This particular study involved the modelling of compartment boundaries and then the targets (cable raceways and components) in 3D using the FRI3D interface. FRI3D's interface provided a set of tools to ease raceway modelling. There were approximately 100 raceways for the test case compartment. Select raceways were excluded based on difficulty identifying the raceway in drawings and insignificant mapping to PSA equipment.

The last step was to add the fire sources for the new equipment and running the fire simulation. Due to the prebuilt database of all the potential fires affecting a plant in FRI3D, this process of creating the fire properties associated with the source was greatly simplified.

Simulation and Results

The following Table 1 provides estimations of time comparisons for using FRI3D vs. current analysis methods using provided average estimates and extrapolating time from the pilot test results. Detailed breakdowns of the steps involved in the comparison is included in [10].

The table depicts the generalized time comparison for plant modifications between traditional methods and FRI3D based on three criteria outlined in the last three columns.

Table 1 Simulation results

FRI3D [h]	Traditional [h]	No. of New Sources	No. of Raceways	Existing FRI3D Compartment
19	32	8	100	false
2	32	8	100	true
11	32	8	50	false
2	32	8	50	true
7	8	2	25	false
0.5	8	2	25	true

In this table the last column indicates whether it is the first time a model was built in FRI3D. Once the plant completes the import of their existing fire model/data into FRI3D, it is available for plant modification analysis. No further modeling is needed in 3D until a scenario needs that compartment. The components in the compartment can be built incrementally and not all at once. depending on the scenario.

To summarize, the results showed that building a first-time model in FRI3D, the first plant modification in a compartment takes approximately the same time as current analysis methods, as shown in Table 1. However, if it is a new compartment to be analyzed or a modification with many scenarios, FRI3D is significantly faster to use. Subsequently, after a compartment has been modeled, it will only take a few hours for the analysis turn-around time as indicated by the results.

FRI3D ARCHITECTURE FOR ZONE MODELS AND 3D CFD MODELS

FRI3D's architecture consists of two main parts: the application programming interface (API) backend with the logical fire model, and the graphical program interface with a 3D visualization front end. This combination allows users to develop and see spatial relationships, along with existing fire models. The API presents all the developers with access to the database as well as enables simulation runs with either the zone model or the 3D CFD model. In either of these cases the input model is passed on as part of the data pertaining to the API for the backend to discretize this model appropriately to present it to either the zone model or the CFD model. The backend is therefore suitable for a choice of presenting any frontend application developer a choice in developing their appropriate interface. However, FRI3D is bundled along with a desktop frontend interface with a 3D modelling toolkit to enable the user to build a fire model from scratch.

FRI3D's frontend and backend architecture enables simulation by a zone model (CFAST) as well a fully 3D CFD model based on FDS The data which is needed for each of these models are generated from the specified 3D information given to FRI3D. After a simulation, for a two-zone model, the lower gas layer and the upper gas layer temperatures are retrieved, and the appropriate visualization is enabled in 3D visualization window as soon as the simulation completes Figure 4. In the case of a fully 3D computational fluid dynamics model such as FDS, the data resulting from the simulation is more complex since it is a time series value of values determined throughout the discretized computational domain. The data resulting from these simulations are communicated to the frontend by means of API calls. FRI3D's architecture is flexible to incorporate data retrieval and mesh generation for each of these computational models. In addition, in order to determine the failures of various equipment involved in the simulation, the target location placement is determined by the closest distance to the source and the target temperature is selected corresponding to whether it's a zone model or a 3D computational fluid dynamics model. The following sections dive a bit deeper into these determinations.

When the CFAST model is built, each condition described above is verified against the acceptable ratios. Any result outside the accepted level is saved in FRI3D's database as an issue. The example case violates each issue and has been added as a unit test in FRI3D's testing architecture.

Zone Model Based Simulation in FRI3D Using CFAST

CFAST [1] is a traditional two-zone model assuming evident stratification of the hot gas layer and cold gas layer, and each layer is assumed to be uniform in temperature, vertical elevation, and chemical composition.

The 3D Data from FRI3D is used to construct a model which is feasible for simulation by CFAST. Since CFAST is a zone model, this data comprises of compartment dimensions and equipment location, its size and material properties. These property values for items are copied and assigned to the equivalent properties in CFAST. In case of properties which are lacking, FRI3D tries to simplify the requirements from the user by providing conservative default values as described in [6]. Figure 4 depicts a general CFAST simulation run with a model setup by FRI3D.

After CFAST simulates the fire, the surface temperature and incident flux for all the components are read from the cfast_devices.csv results file, columns TRGSURT, and TRGFLXI respectively. These results are used to determine cable and component failures and the FLASH-CAT calculations for secondary combustibles. These results are enabled to be retrieved via API calls. Figure 4 depicts the algorithm on the left, and the results on the right for a CFAST simulation.

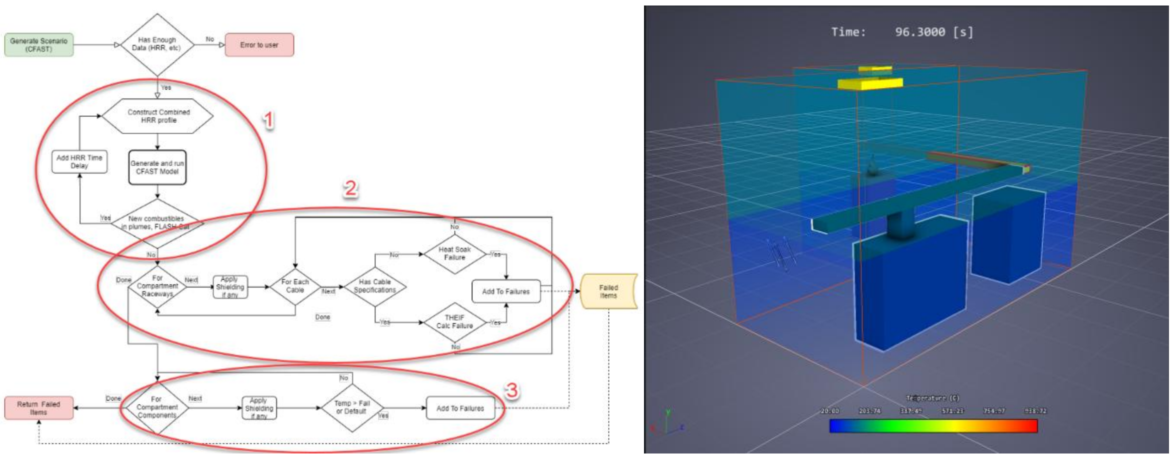

Figure 4 Flow diagram showing the process for auto-generating failed items for a scenario using CFAST

3D CFD Based Simulation in FRI3D Using FDS

FDS [2] is a CFD model of fire-driven fluid flow. The FDS software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flow with an emphasis on smoke and heat transport from fires. For FDS data to be output by FRI3D, a full 3D representation of all necessary boundaries and all equipment/cables/raceways in the compartment to be simulated are needed. For the computational domain, the FRI3D backend reads the 3D information provided by the front end with regards to the bounds of the simulation and generates directives like the following:

&MESH XB=0,2,0,4,0,2.5, IJK=32,32,32/

With regard to equipment/raceways and compartment geometry, FDS requires that these be specified with respect to specific obstacle directives and be provided with the bounding box. Since a FRI3D model consists of items contained inside a compartment, made up of many geometrical entities modelled by the user or imported from other 3D data, the front end decomposes the boundary elements in FRI3D to set of obstacle elements for FDS. A set of computational geometry operations are done to consolidate all the boundary meshes, and then a determination is made from the outer boundaries based on orientation to indicate the outer walls/ceiling and floor so as to differentiate them. The backend code then computes a list of axis-aligned bounding boxes and generates appropriate OBST calls. The wall thickness is specified as part of the material properties of the walls are saved as part of the model and used to generate the thickness of the boundary walls.

Similarly, computational geometric operations are performed on the input geometry given to the backend, of the appropriate entries tagged as doors/windows and other forced ventilations to generate VENT directives to FDS. VENTS in FDS are considered boundary flow conditions and sources are also considered as VENTS for FDS.

For sources, the user specified dimensions of the source geometry along with the equipment/item which initiates the fire are used to generate the appropriate FDS directives to specify the boundary condition. The HRRs of the source are specified in the interface.

In CFAST, each object/obstacle is specified by one material line. However, in FDS, this is done in two parts. The first one specifies the material properties (MATL), and the second one specifies the surface or boundary properties (SURF). The thermal and burning properties of each material are specified via the MATL group. Then materials are invoked by the SURF group to define boundary conditions for solids. For more information about FDS specific directives, please refer to [2].

After an FDS simulation, FRI3D reads the comma-separated temperature or flux values found in the device csv file. This file stores the historical temperature or flux values of the devices declared in the FDS input file. The temperature profile of the domain is stored in a volumetric grid and FRI3D reads this information supplied to it from the backend in order to visualize for the user Figure 5.

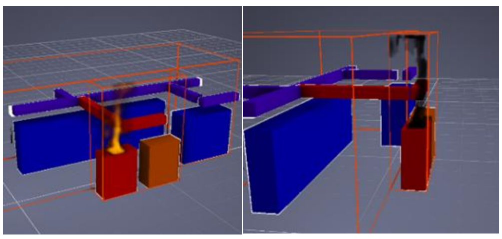

Figure 5 FDS results visualization in FRI3D

FRI3D CONSIDERATIONS FOR SMALL MODULAR REACTORS

Recent trends in the nuclear energy sector show growing momentum toward the development and deployment of Small Modular Reactors (SMRs). FRI3D supports this evolution by enabling detailed fire modeling with specific consideration to the unique design characteristics of SMRs.

CAD Models

Given the innovative and evolving nature of SMR designs, there is an increasing reliance on advanced CAD tools and modelling environments. These tools support efficient design iteration, digital verification against regulatory requirements, and early-stage assessment of fabrication and assembly constraints. In parallel, the adoption of BIM has introduced the capability to create comprehensive 3D models that serve as digital twins, supporting design, construction, operations, and maintenance activities.

A key enabler of interoperability within BIM workflows is the use of industry foundation classes (IFC), an open, vendor-neutral data standard maintained by buildingSMART. IFC facilitates consistent exchange of building and infrastructure data across disciplines, which is essential in nuclear projects where systems are developed and reviewed by a wide range of stakeholders. Most modern CAD platforms, including Revit, Navisworks, and CATIA, support IFC export. Figure 6 (left) depicts the turbine room of an SMR imported in FRI3D as CAD, Figure 6 (right) depicts the layout of the plant with the reactor room.

FRI3D enables seamless integration of these models into fire analysis workflows through its ability to import and interpret IFC data. Component tags and classifications embedded in the IFC allow FRI3D to automatically recognize and categorize architectural elements such as walls, doors, and windows. This enhances simulation fidelity by allowing zone model and CFD based outputs to treat such components appropriately, for instance, treating a door as a potential ventilation boundary or a window as a heat flux-loss interface.

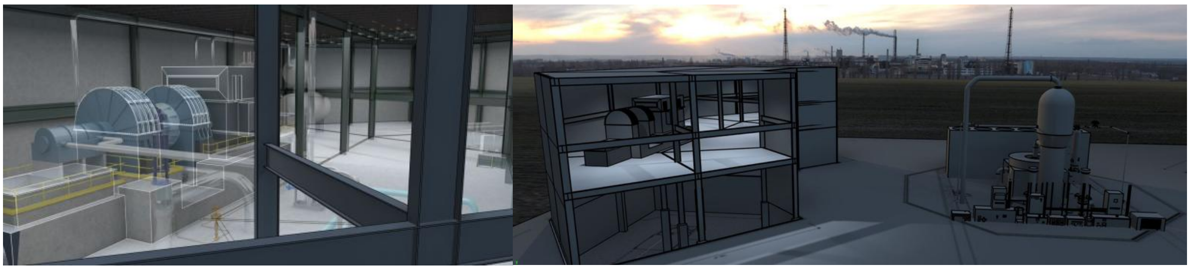

Figure 6 CAD model of a SMR in FRI3D

Design Decisions / Modifications

FRI3D plays a critical role in informing design decisions during the layout and development of SMRs by enabling early-stage fire hazard analysis. Using IFC-integrated models, designers can simulate a wide range of fire scenarios under varying operational conditions and component arrangements. For example, analyses can be performed to assess the impact of placing electrical cabinets, cable trays, or ventilation ducts near potential ignition sources. Multiple simulations can be run in parallel, each varying the location or configuration of key components, enabling comparative risk assessments to be generated.

These simulation outputs help quantify risk profiles, identify high-consequence zones, and guide design teams toward configurations that minimize fire propagation pathways and improve compartmentalization. Moreover, the ability to iteratively test design changes using actual model geometry ensures that fire safety considerations are integrated into the SMR development process from the outset, rather than being retrofitted later in response to compliance reviews.

This proactive, simulation-based approach supports not only safety case development but also cost optimization by reducing the need for conservative overdesign and allowing targeted placement of passive and active fire protection systems. In summary, FRI3D enhances the decision-making process by transforming fire modelling into a practical design tool, fully aligned with modern digital engineering practices for SMRs.

Alternate Fire Considerations

Several advanced SMR designs under development employ liquid sodium as a primary coolant. While sodium offers significant thermal advantages – such as high thermal conductivity and favourable heat transfer characteristics at low system pressures – it also presents unique fire safety concerns. Sodium is highly reactive with both, air and water, and may ignite spontaneously upon exposure to ambient atmosphere. These characteristics introduce non-conventional fire scenarios that require specialized analysis tools and methodologies beyond standard hydrocarbon-based fire models.

Sodium fire scenarios are generally categorized into two classes: pool fires and spray fires. Pool fires involve burning of stationary sodium collected on a surface and typically evolve more slowly. In contrast, sodium spray fires – resulting from pressurized leaks, flange failures, or rupture of sodium-carrying piping – can lead to instantaneous combustion of atomized sodium droplets upon contact with air. These events are violent, highly exothermic, and often quasi-explosive in confined or semi-confined environments.

Sodium spray combustion rapidly consumes oxygen, generates high thermal fluxes, and produces corrosive and radioactive aerosols if sodium has interacted with activated surfaces. The explosive nature of these fires stems from the rapid expansion of hot gases and pressure rise in confined spaces – posing threats to structural integrity, safety-critical components, and habitability zones.

MELCOR [13] is a computer code developed by Sandia National Laboratories. Its primary purpose was to provide an integrated, engineering-level simulation of the progression of severe accidents in nuclear power plants.

To model sodium phenomena, the MELCOR system code has been extended with sodium-specific models under its sodium fast reactor (SFR) capability set [14]. MELCOR includes detailed physics for spray jet breakup, droplet combustion, aerosol formation, and confinement pressurization, enabling it to represent the transient dynamics and mechanical loading associated with sodium spray fires and has been validated by recent studies [15]. It also accounts for structural heat feedback, oxygen consumption, and combustion product transport, making it suitable for evaluating both localized and system-wide consequences.

For pool fire scenarios or bounding estimates of HRRs, the legacy SOFIRE [16] code remains applicable. SOFIRE provides conservative estimates of energy release and oxygen depletion, which can be used in simplified analyses or for input into broader fire modelling environments.

FRI3D currently can support the output of HRRs output from SOFIRE and simulate the equipment failures resulting from sodium leaks. However, a more comprehensive treatment of modelling spray phenomenon using MELCOR is planned for the future.

The FRI3D fire platform can complement MELCOR by enabling geometry-resolved fire simulations based on CAD models. This allows realistic modelling of sodium spray fire scenarios within the as-designed layout of an SMR, including:

- integration of MELCOR-derived HRR and aerosol source terms,
- simulation of ventilation-dependent pressure rise and thermal propagation,
- assessment of door blowout, duct damage, and barrier failure risks, and
- placement of sensors, dampers, and passive fire barriers in high-risk zones.

Forthcoming work for FRI3D's development is to incorporate the impact of quasi-explosive fire scenarios on nearby equipment, support deterministic and probabilistic risk analyses, and validate the adequacy of fire protection systems, such as fast-acting sodium leak detection, inerting systems, and pressure relief strategies.

CONCLUSION

The FRI3D platform provides an advanced environment for conducting detailed fire modelling and analysis in support of Fire PSA and Fire Hazard Analysis (FHA). Its architecture enables integration of both zone models (e.g., CFAST) and CFD models to simulate a wide range of fire scenarios across nuclear facilities. This dual-modelling approach allows for scalable fidelity—supporting rapid assessments using zone models as well as high-resolution analyses for critical areas using CFD.

Its automated scenario generation, support for 3D geometry, and enhanced visualization tools – such as item temperature tracking and failure timelines – enable efficient development and analysis of complex fire scenarios.

This capability is especially valuable for SMRs, which often feature compact, integrated designs and the use of non-traditional coolants such as liquid sodium. While FRI3D does not simulate combustion chemistry or blast dynamics, it can incorporate time-dependent HRRs derived from detailed codes like MELCOR or SOFIRE, enabling realistic simulation of the thermal and smoke transport effects from sodium fire scenarios.

By streamlining scenario development and enabling informed scenario binning, FRI3D enhances the accuracy, efficiency, and cost-effectiveness of fire modelling for advanced reactor designs – supporting credible, risk-informed safety evaluations.

REFERENCES

[1] National Institute of Standards and Technology (NIST): CFAST, Fire Growth and Smoke Transport Modeling, Engineering Laboratory Fire Research Division, Gaithersburg, MD, USA, updated October 16, 2019, https://www.nist.gov/el/fire-research-division-73300/cfast-fire-growth-and-smoke-transport-modeling

[2] National Institute of Standards and Technology (NIST): FDS-SMV: Fire Dynamics Simulator (FDS) and Smokeview (SMV), Gaithersburg, MD, USA, accessed September 2022, https://pages.nist.gov/fds-smv/.

[3] Salley, M. H., and A. Lindeman: Refining and Characterizing Heat Release Rates from Electrical Enclosures During Fire, Volume 2: Fire Modeling Guidance for Electrical Cabinets, Electric Motors, Indoor Dry Transformers, and the Main Control Board, NUREG-2178, Volume 2, and EPRI 3002016052, United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research, https://www.nrc.gov/docs/ML2016/ML20168A655.pdf.

[4] McGrattan, K. B.: Cable Response to Live Fire (CAROLFIRE) Volume 3: Thermally-Induced Electrical Failure (THIEF) Model, NUREG/CR-6931, Volume 3 and NISTIR 7472, United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research, Washington, DC, USA, and National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, April 2008, https://www.nrc.gov/docs/ML0811/ML081190261.pdf.

[5] McGrattan, K., et al.: Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 1: Horizontal Trays, NUREG/CR-7010, Volume 1, United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research, Washington, DC, USA, July 2012, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7010/v1/index.html.

[6] Sampath, S. Prescott, and R. Christian: Fire Modelling Automation and Visualization in the Context of Fire Probabilistic Risk Analysis for Nuclear Plants, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 26, 17th International Seminar on Fire Safety in Nuclear Power Plants and Installations, Westerburg Huy, Germany, October 24-26, 2022, GRS–705, ISBN 978-3-949088-96-4, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, November 2022, https://www.grs.de/de/aktuelles/publikationen/grs-705.

[7] Lloyd´s Register (LR): RiskSpectrum®: Risk and Reliability Software, Sundbyberg, Sweden, 2025, https://www.lr.org/en/riskspectrum/.

[8] Electric Power Research Institute (EPRI: Computer Aided Fault Tree Analysis System (CAFTA), Version 6.0b, software, Product ID 3002004316, Palo Alto, CA, USA, August 26, 2014, https://www.epri.com/research/products/000000003002004316.

[9] Idaho National Laboratory (INL): SAPHIRE – Risk and Reliability Assessment Tools for the 21st Century, Idaho Falls, ID, USA, 2022, https://saphire.inl.gov/.

[10] Prescott, S., M. Schairer, and R. Sampath: A pilot study of using Fire Risk Investigation in 3D (FRI3D) software for performing fire analysis of plant modifications, Canadian Nuclear Society (CNS), p. 26, Ottawa, ONT. Canada, 2023.

[11] Stroup, D., G. Taylor, and G. Hausman: Fire Dynamics Tools (FDTs) Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program, NUREG-1805, Supplement 1, Vol. 1, United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research, Washington, DC, USA, Office, Washington, DC, USA, December 2004, https://www.nrc.gov/docs/ML1321/ML13211A097.pdf.

[12] Electric Power Research Institute (EPRI): FRANX v4.3, software, Product ID 3002002729, Palo Alto, CA, USA, November 6, 2015, https://www.epri.com/research/products/3002000098.

[13] Gauntt, R. O., et al: MECOR Computer Code Manuals, Volume 1: Primer and User's Guide, Version 1.8.5, NUREG/CR-6119, Volume 1, Revision 2, United States Nuclear Regulatory Commission (U.S. NRC), Washington, DC, USA, December 2000, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6119/v1/index.html.

[14] Louie, D. L., L. H. Humphries, and M¨R. Denman: Containment Sodium Chemistry Models in MELCOR, SAND2017-3798J, Sandia National Laboratories (SNL), Albuquerque, NM, USA, 2017, https://www.osti.gov/servlets/purl/1429762.

[15] Louie, D. L., and M. A. Aoyagi: Sodium Fire Collaborative Study Progress (CNWG) Fiscal Year 2022), SAND2022-14235, Sandia National Laboratories (SNL), Albuquerque, NM, USA, October 2022, doi: 10.2172/1892376.

[16] Beiriger, P, et al.: SOFIRE II Report, Canoga Park, CA, USA,1973.

Application of the COCOSYS Cable Fire Model to Long Cable Tray Fire Experiments in the DIVA and SATURNE Facilities

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ABSTRACT

Fire simulations and analytical validation approaches are relevant, in particular with respect to fire safety assessment of operating nuclear power plants (NPPs). For providing an added value to the regulatory authorities and the technical safety experts authorized by them suitability and applicability of the analytical tools such as fire simulation codes applied need be known and demonstrated.

The COCOSYS (*Co*ntainment *Co*de *Sys*tem) code as part of the AC^2 code package developed by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH contains i.e. models for simulating cable fires as well as liquid fuel fires. The cable fire model is based on an extended FLASHCAT model, using a flexible mass loss rate (MLR) profile to consider composite materials to regard the increase of heat of combustion in the later phase of the fire and to consider under-ventilated conditions.

The validation conducted so far using experiments with a cable length of about 2.5 m in horizontal direction. This paper presents COCOSYS applications to the PRISME 3 CFP-D41 experiment using a cable length of 6 m. The application on this long cable tray experiment shows the need to readjust the cable specific input data, caused by a too high assumed propagation velocity. As a consequence, previous validations have been repeated.

As expected, fires of vertically routed cables show a much higher propagation velocity caused by preheating of cables by the flame. In preparation of the COCOSYS application to long vertical cale fire experiments in the DIVA facility in the frame of the international FAIR (*F*ire Risk *A*ssessment through *I*nnovative *R*esearch) Project by the OECD Nuclear Energy Agency (NEA), open calculations on open vertical cable fire experiments in the SATURNE facility using ALSECURE® cables have been conducted with COCOSYS.

In general, new insights are expected from the cable fire experiments in the FAIR Project with long horizontal and vertical cable trays under different conditions, because so-called edge effects at the beginning and end of the cable trays are reduced compared to previous experiments.

INTRODUCTION

Fires can jeopardize the safety of a NPP. Significant effort is therefore spent on the enhancement of fire simulation tools. Nowadays, these tools are becoming increasingly important, particularly with regard to the assessment of the fire safety of operating nuclear installations. For providing an added value to the regulatory authorities and the technical safety experts authorized by them suitability and applicability of the analytical tools such as fire simulation codes applied need be known and demonstrated. COCOSYS has already been validated against many fire experiments, particularly those from the OECD/NEA PRISME (French: *Pr*opagation d'un *i*ncendie pour des *s*cenarios *m*ulti-locaux *é*lémentaires) Project.

Main objective of the international PRISME Project [1] launched by the OECD/NEA was to study amongst others the effects of under-ventilated and confined conditions on cable fires and the propagation of heat and soot in a multi-compartment configuration. The OECD/NEA FAIR Project [2] as follow-on of PRISME is concerned with fire propagation along horizontal and vertical cable trays with a focus on the effects of long length cables and cable ageing, fires in confined and mechanically ventilated compartments with a focus on the effects of hot and vitiated environments on the combustion and the re-inflammation of unburned material, and multi-source and multi-compartment complex scenarios with a focus on fire propagation between discrete sources and smoke propagation in complex room configurations.

A crucial point for simulation of fires in a confined compartment is the estimation of the pyrolysis rate (i. e. the rate of vaporized fuel mass) respectively the burning rate and its development over time. For computer code validation against available experimental data, the experimentally obtained pyrolysis rate is usually entered into the code as user input. The situation is different particularly for blind pre-test calculations or real applications. In this context, it is important to predict pyrolysis rates. Regarding the wide range of uncertainty due to the complexity of the processes taking place during combustion, at least a prediction of the fire development and thermal loads on items important to safety within some uncertainty boundaries is desired.

The implemented so-called simple cable fire model in COCOSYS [3], [4] has been improved, using now an extended FLASHCAT approach [5]. It has been validated against several selected OECD/NEA PRISME 2 and PRISME 3 experiments using different cable types. One main objective is to use the same set of input parameters just depending on the properties of the cable insulation materials used. This validation so far was conducted against experiments all with a cable length of about 2.5 m in horizontal direction.

To further extend the validation of the COCOSYS cable fire model the experiment PRS3-CFP-D41 using 6 m long horizontal cable trays in the corridor of the DIVA facility and an open cable fire experiment using 3 m long vertical cable trays with ALSECURE®[1] cables inside the SATURNE facility have been simulated. DIVA and SATURNE are part of the French ASNR's GALAXIE experimental platform.

After a short introduction of the COCOSYS fire model, the new results and consequentially further improved input are presented.

OUTLINE OF THE CABLE FIRE MODEL IN COCOSYS

COCOSYS 3.0, as part of the GRS AC^2 code package [7], is a system code for the simulation of phenomena in containments and/or further buildings, mainly of light water reactors (LWR) from normal operation up to severe accident conditions with fission product (FP) releases. The fire models are implemented in the THY (*t*hermal *hy*draulics) module applying a lumped parameter (LP) approach for the nodalisation of containment compartments. COCOSYS simulates energy and mass flows in buildings based on a network of interconnected control

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[1] ALSECURE 0.6/1 kV 3G2.5 power cable, halogen-free 0.6/1 kV rigid cables, fire retardant; the outer sheath is composed of: PE, PVA, $CaCO_3$, $Al_2Si_2O_5(OH)$ [6].

volumes or "zones". Different from CFD (*c*omputational *fl*uid *d*ynamics) codes, a momentum balance is not considered.

In the COCOSYS cable fire model [4] each cable tray is represented and segmented according to the nodalisation (grid of control volumes) in the input file (cf. Figure 1). To be able to simulate an increasing effective heat of combustion the new model uses several (here two) different cable materials *k*. This allows to apply different values for the heat of combustion and different chemical compositions. The extended model based on a FLASHCAT approach assumes a user provided specific local MLR history profile $r_k(t)$ [1/s] for each material k, comparing to the trapezoid characteristic of the heat loss rate in the original FLASHCAT model.

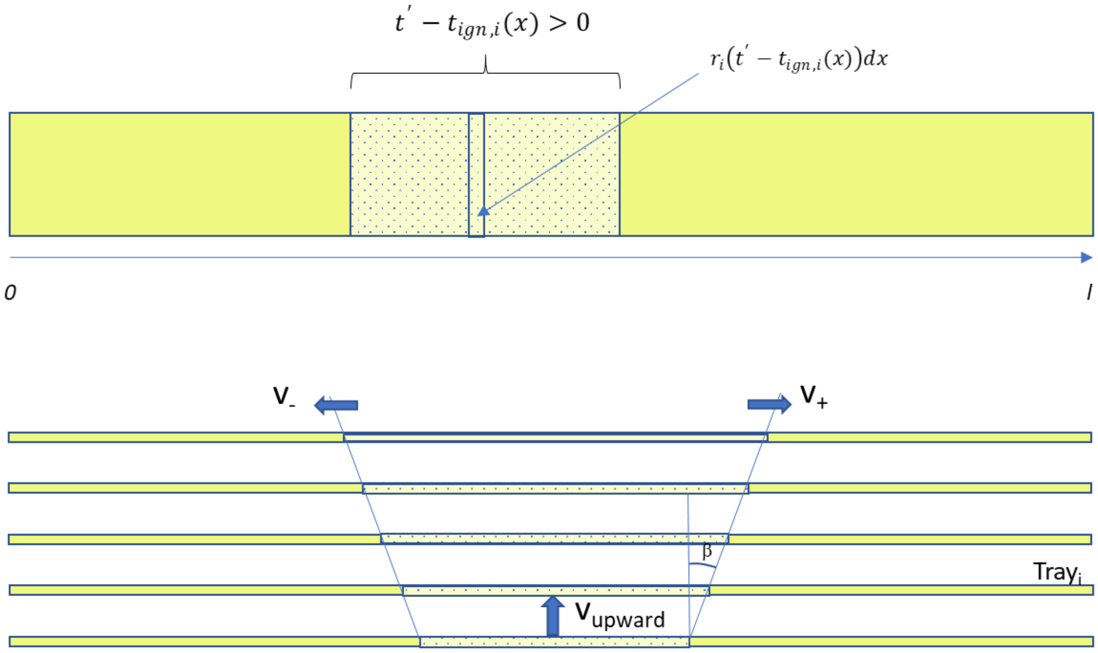


Figure 1 Concept of the extended simple cable pyrolysis model in COCOSYS

The flame propagation (point of ignition) maybe be asymmetric, and the propagation velocity maybe be different for both directions (e.g., downward, and upward flame propagation). Then, the resulting equation is as follows:

$$R_i(t) = b\, f(c_{O_2}) \sum_k D_k \int_0^l r_k \left(t' - t_{ign,i}(x)\right) dx \qquad (1)$$

with the user-defined and time dependent mass loss profiles r_k [1/s] for each material. These profiles have to be normalized, so that $\int r_k dt = 1$. Other variables are the width *b* and length *l* of the tray, and the cable mass density D_k [kg/m²] of the material *k* without the residual mass fraction. The time of ignition at location *x* considers two different propagation velocities v_+ and v_-.

$$t_{ign,i} = t_{ign,i,0} + \begin{cases} \frac{x_{l,0} - x}{v_-} & x < x_{l,0} \\ 0 & x_{l,0} \le x \le x_{r,0} \\ \frac{x - x_{r,0}}{v_+} & x > x_{r,0} \end{cases} \qquad (2)$$

In case of a vertical cable tray, these velocities v_+ and v_- correspond to upward and downward flame propagation velocity respectively. To consider the dependency on the oxygen concentration c_{O_2} it is assumed that a reduced amount of oxygen will lead to a slowdown of burning process and resulting in a somehow time delay *t'*

$$t' = \int_0^t f(c_{O_2}) \quad (3)$$

This time *t'* is used as argument of r_k in equation (1).

VALIDATION OF THE NEW MODEL AGAINST THE PRS3-CFP-D41 EXPERIMENT

Within the OECD/NEA PRISME 3 Project confined fire tests with long cable trays have been conducted [8]. The main objectives of these tests were to characterize a quasi-steady flame propagation on cable trays and a maximum fire HRR. The fire source consisted of three cable trays of 6 m length, located in the corridor L0 of the DIVA facility, adjacent to the three rooms L1 to L3. The admission flow rate in each room was set to 1,500 m^3/h. The exhaust flow rate was set to 3,000 m^3/h in the corridor and 1,500 m^3/h in the room L3 (cf. Figure 2).

The fire source consists of a set of three horizontal ladder type trays of 6 m length and 0.45 m width. The vertical distance between trays is set to 30 cm. The three trays are filled with 32 samples of cables with a total mass of cable of about 400 kg. The electrical cable type used contains a halogen-free flame retardant (HFFR). Its characteristics are 20 mm in diameter, 0.70 kg/m of load and 12 x 1.5 mm^2 conductors. The supplier reference is NU-SHX (ST) HX 1 kV (GDF-SUEZ).

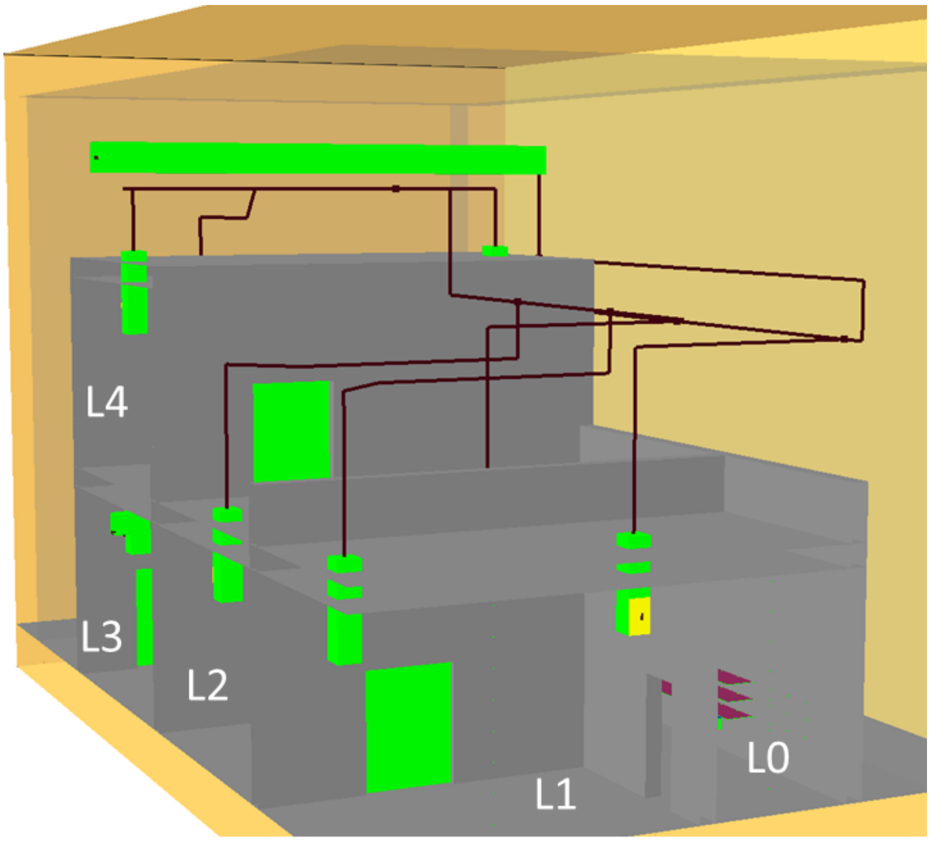


Figure 2 Room configuration of the DIVA facility

First COCOSYS applications on this model show a much to fast flame propagation. Therefore, it was necessary to reassess already conducted simulations of PRISME experiments using the same cable material (cf. Table 1).

The cable insulation used in the 2.5 m and 6 m experiments are not exactly the same. Therefore, the material density has been increased to 38.82 kg/m^2 for the PRS3-CFP-D41 experiment. Regarding the residual mass, there is no model available in COCOSYS. So, this input value must be adjusted for each experiment. The fraction of mass with higher heat of combustion of 45 MJ/kg has been reduced to 15 %, and the heat of combustion of the first material has been increased to 28 MJ/kg. The reduction of horizontal flame propagation was most important. This value has been reduced from 3 mm/s to 0.5 mm/s.

Table 1 Modified cable input data compared to [3], [4]

Property	Previous	New
Material density [kg/m^2]	28.33	28.33 / 38.82
Residual mass fraction	0.36 to 0.43	0.37 to 0.51
2nd mass fraction	0.38	0.15
Heat of combustion [MJ/kg]	20 / 45	28 / 45
Horizontal propagation velocity [mm/s]	3.0	0.5

In addition, the MLR history profile $r_k(t)$ has been adjusted. The new profile (cf. Figure 3) uses now a quadratic increase and a linear decrease.

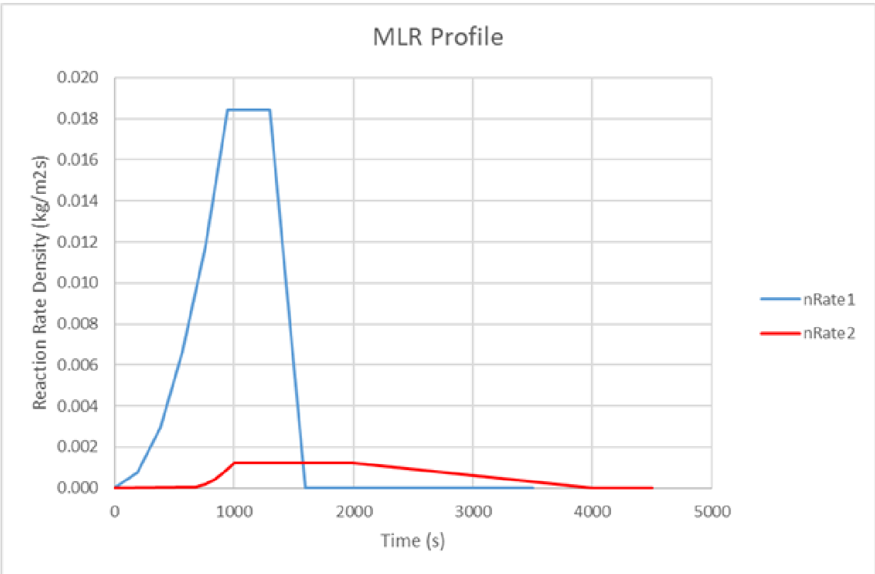


Figure 3 MLR profile $r_k(t)$ used

In Figure 4 the measured and simulated cable surface temperatures are compared. As for other experiments, COCOSYS underestimates the surface temperatures, however the time characteristic of temperature peaks is quite similar, indicating the correct flame propagation velocity.

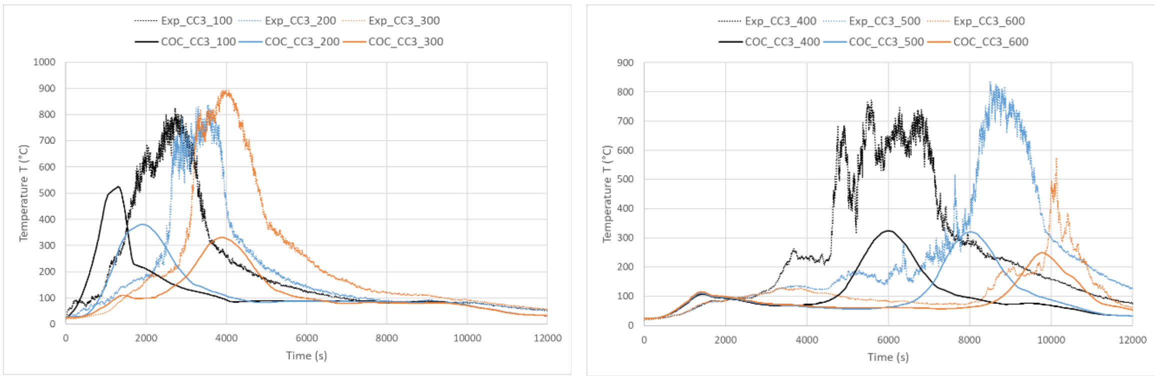


Figure 4 Comparisons of cable surface temperatures along the cable tray (left: 1 to 3 m, right: 4 to 6 m) in the PRS3-CFP-D41 test

A comparison of the temperature stratification at the north-west side of corridor is shown in Figure 5. In the COCOSYS calculation the temperatures at 3 and 3.8 m are quite similar, where in the experiment a stratification can be observed. In the initial phase the temperatures are overestimated. This is caused by a too high initial MLR (cf. Figure 6). This experiment did not show a clear steady-state phase. New insights are expected from the intended OECD/NEA FAIR experiments using cables with a length of 9 m.

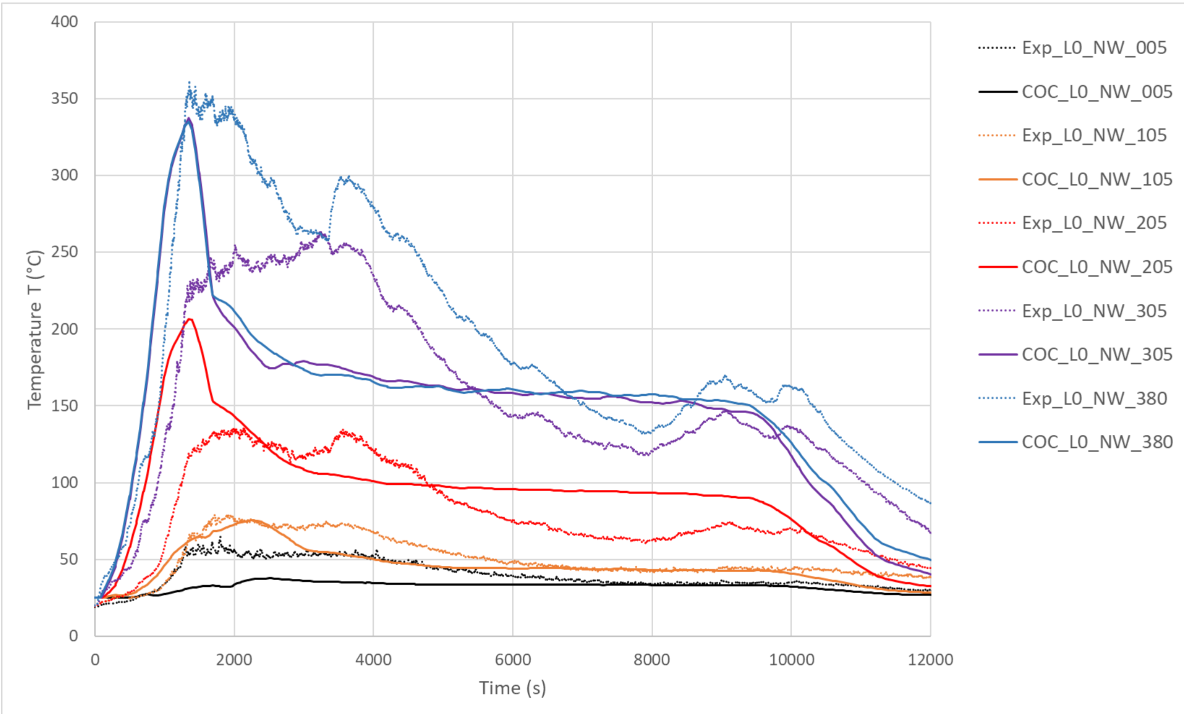


Figure 5 Comparison of atmospheric temperatures at different elevations in the north-west part of corridor (at the side of the burner) of the PRS3-CFP-D41 test

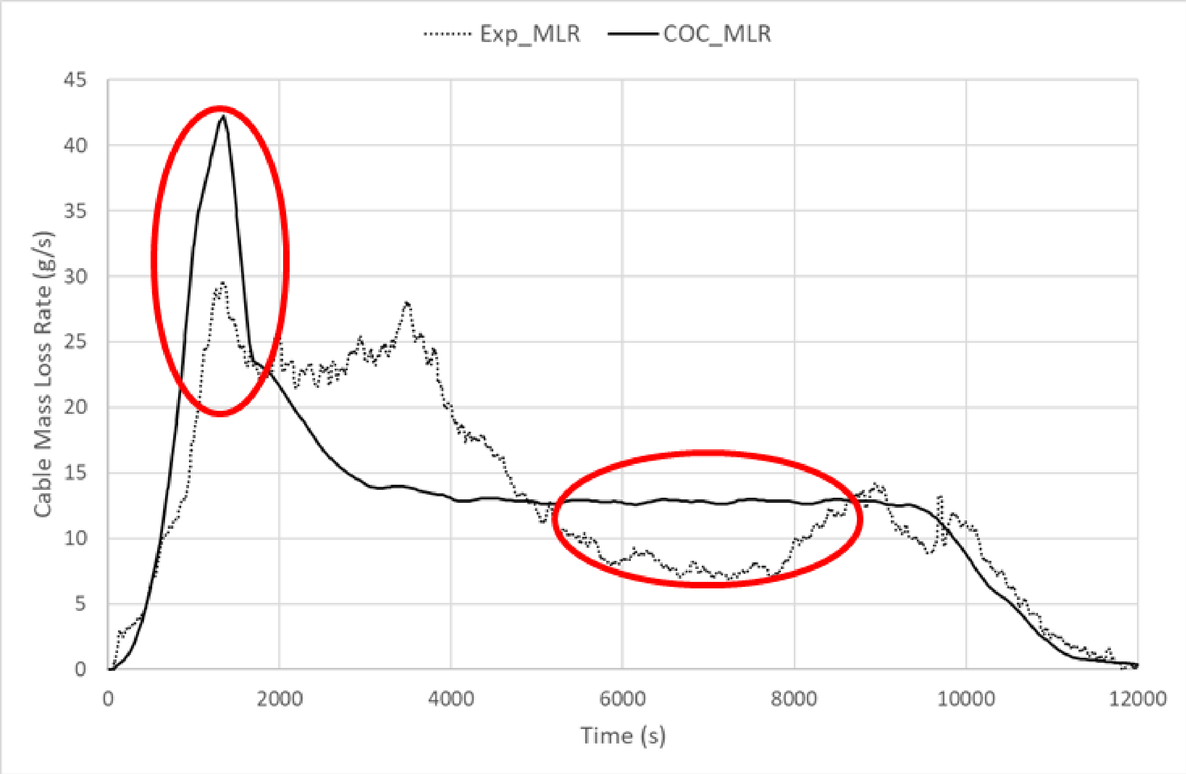


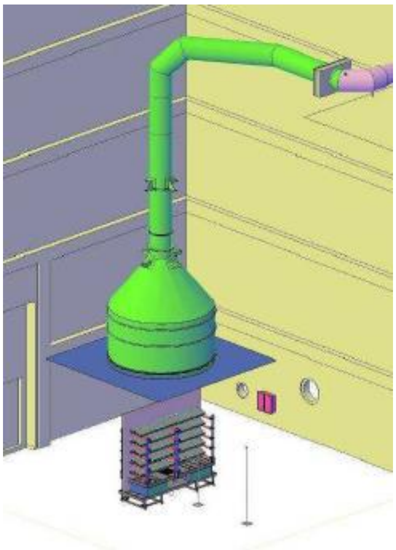
Figure 6 Comparison of experimental and simulated MLR in the PRS3-CFP-D41 test

REPETITION OF THE VALIDATION AGAINST PRISME 2 EXPERIMENTS

The cable input data has been adjusted; therefore, previously conducted validation calculations need to be repeated. These cables have been used, e.g., in the PRS2-CFSS-2 support experiment in open atmosphere and in the PRS2-CFS-4 experiment [9] conducted in the DIVA facility. Experiments under open atmospheric conditions are conducted in the SATURNE facility, the confined test in the DIVA facility in a two-room configuration with an open door in-between [10].

A large-scale calorimeter was installed in the 2,000 m³ SATURNE enclosure (10 m long, 10 m wide and 20 m high, cf. Figure 7). The hood with a diameter of 3 m was connected to an exhaust duct linked to a ventilation network. The initial flowrate at the outlet duct was about 20,000 m³/h. The exhaust duct collects the entire combustion products. Openings in the upper part of the fire compartment allow fresh air to flow in.

The main objective of the PRS2-CFS tests was to investigate the fire spreading over five horizontal cable trays in a confined geometry. The two rooms used were connected by an open doorway and ventilated by a fan system. The inlet of the fan system was in the fire compartment and the outlet in the adjacent room (cf. Figure 8).



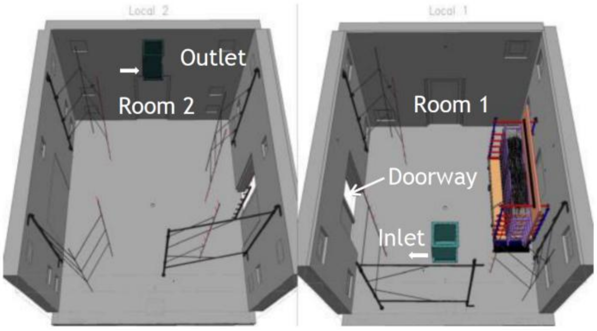
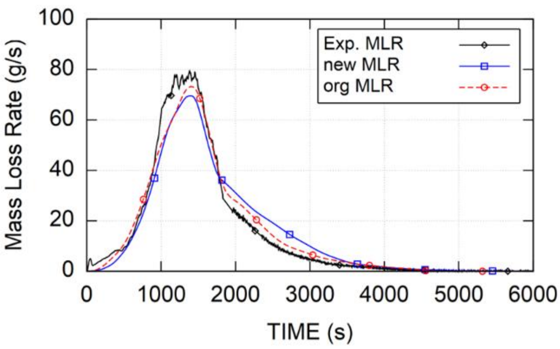


Figure 7	SATURNE experimental facility scheme including five cable trays, device, hood and exhaust duct [11]	**Figure 8**	Top view on the rooms of the DIVA facility used for the PRS2-CFS tests [12]

Figure 9 provides the comparisons of the total MLR and HRR for the PRS-CFSS-2 experiment. Experimental data are presented in black, COCOSYS results using previous input data are presented in red curves and the new COCOSYS results in blue. The quality of the simulation is quite similar.



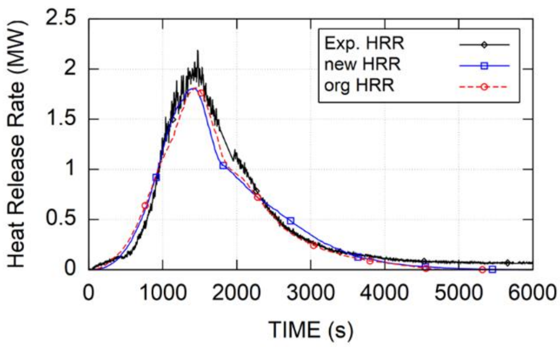


Figure 9 Comparisons of the MLRs and the HRRs in the PRS2-CFSS-2 test – left side: MLR, right side: HRR (experiment: black curve; new input: blue curve; previous input: red dashed curve)

In a similar way the results regarding the PRS2-CFS-4 experiment are presented (cf. Figure 10). Again, the quality of the results is quite similar.

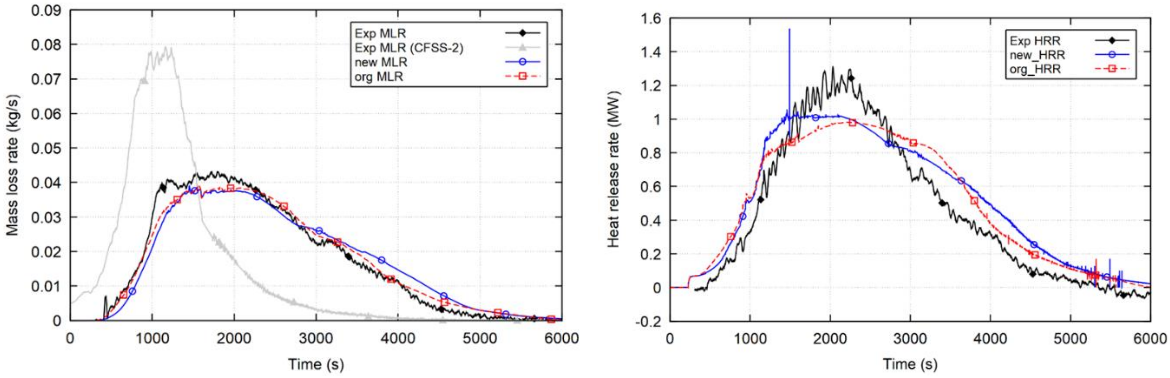


Figure 10 Comparison of the MLRs and HRRs in the PRS2-CFS-4 test – left side: MLR, right side: HRR (experiment: black curve; new input: blue curve; previous input: red dashed curve)

VALIDATION AGAINST A VERTICAL CABLE FIRE

Large-scale tests of the FAIR experimental campaign are proposed to address the full characterization of fire propagation over long horizontal and vertical cable trays in mechanically ventilated confined compartments. In parallel to the OECD/NEA experimental FAIR Project, several so-called Analytical Working Groups (AWGs) have been installed. Within one of these groups, blind and open fire simulation calculations on long cable tray experiments will be carried out. To support the blind calculations on fire experiments with long vertical cable trays (LVCT) it was agreed to perform open calculations on an available vertical cable tray fire experiment [6] in the SATURNE facility using ALSECURE® HFFR type cables. In the following, COCOSYS results are presented.

The geometric configuration around the vertical cable is shown in Figure 11 (left side). As is usual in the COCOSYS calculation, plum-shaped zone volumes are used (centre figure). This is necessary to ensure an inflow of fresh air into the zone volumes in which the reaction takes place. Consequently, the upper zone volumes are larger leading to an averaging of gas temperatures and lower cable surface temperatures. In the real experiment, the flames are connected directly to the cables.

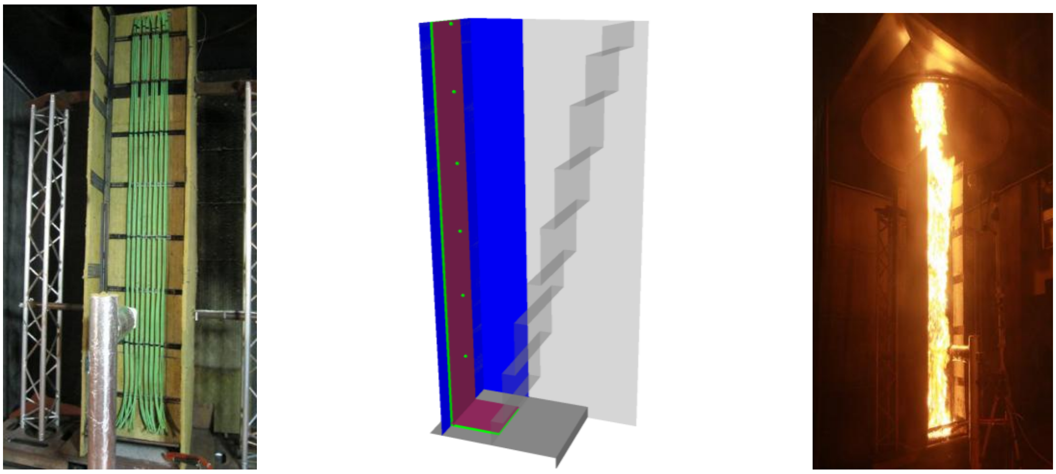


Figure 11 Geometrical configuration of ALSECURE® vertical cable fire experiment [6]

Comparisons of the experimental measurements and the COCOSYS simulations results are presented in Figure 12 and Figure 13. It should be pointed out, that the cable input data have been adjusted to this experiment. The increase of the HRR and the MLR corresponds reasonably to the experiment. However, using a FLASHCAT approach the decrease of the HRR (and the MLR) in COCOSYS is much smoother compared to the experimental data.

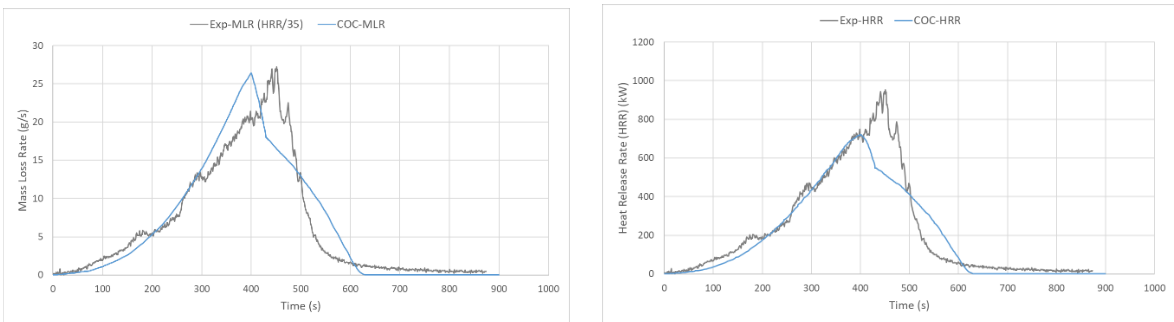


Figure 12 Comparisons of the experimental and simulated MLRs and HRRs in the vertical test – left side: MLR, right side: HRR (the experimental MLR has been derived from the HRR, assuming 35 MJ/kg)

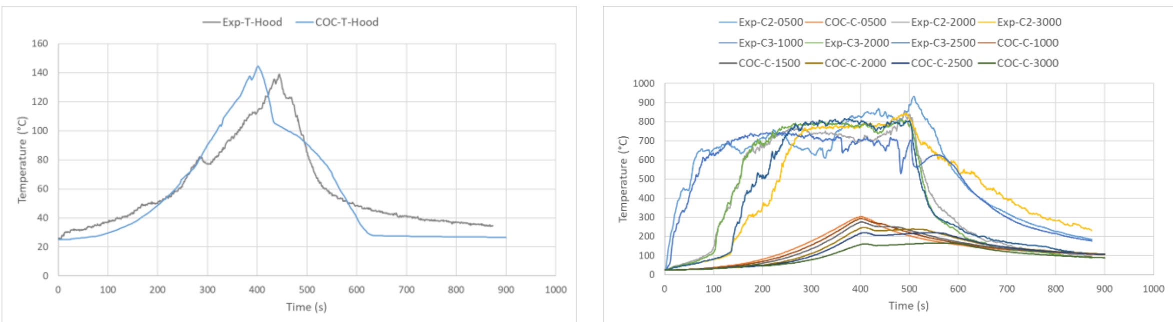


Figure 13 Temperature inside the hood (left) and cable surface temperatures (right) in the vertical cable test

On the left side in Figure 13, a comparison of the experimental and simulated gas temperature inside the hood is provided showing a similar characteristic in the phase of increasing temperatures. Here again, the decrease of measured and calculated temperatures looks somewhat different.

As already explained above, the calculated cable surface temperatures are much too low. Further improvements of the COCOSYS modelling are necessary.

CONCLUSIONS

The COCOSYS application to the cable fire experiment PRS3-CFP-D41 with 6 m long cables revealed the necessity to readjust the input parameters. Especially the previously used flame propagation velocity was too high. The comparison of calculated and measured MLR still shows some deviations (cf. Figure 6). The initial MLR is too high and during the steady-state phase still some deviations could be observed. New findings from the FAIR experiments with 9 m long cables are expected.

Regarding the application to vertical cable tray experiments the calculated cable surface temperatures are too low. Here some modelling improvements are needed. Again, new insights are expected on the intended FAIR experiments with 6 m long vertical cables.

ACKNOWLEDGEMENTS

The author wants to acknowledge the support by the experts from ASNR and all members from the Analytical Working Groups of the PRISME and FAIR Projects.

The activity presented in this paper has been funded by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) within the project 4722R01410.

The participation of Germany in the OECD/NEA PRISME and FAIR Projects has been granted by the German Federal Ministry for Economics and Energy (BMWi) and is now granted by the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV).

REFERENCES

[1] Suard, S., P. Zavaleta, and H. Prétrel: Overview of the OECD PRISME 3 Project, Fire Safety and Emergency Preparedness for the Nuclear Industry, Presentation at the at FSEP 2019 – 3ed Conference on Fire Safety and Emergency Preparedness, Ottawa, ONT, Canada, October 28-30, 2019.

[2] OECD Nuclear Energy Agency (NEA): Fire Risk Assessment through Innovative Research (FAIR) Project, Paris, France, https://www.oecd-nea.org/jcms/pl_84289/fire-risk-assessment-through-innovative-research-fair-project.

[3] Klein-Heßling, W.: Implementation of an Extended FLASHCAT Model, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 26, 17th International Seminar on Fire Safety in Nuclear Power Plants and Installations, October 24-25, 2022, Westerburg, Huy, Germany, GRS-705, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, November 2022, https://www.grs.de/de/aktuelles/publikationen/grs-705.

[4] Klein-Heßling, W.: Validation of the extended COCOSYS cable fire model based on a generic FLASH-CAT approach, Fire Safety Journal, Volume 142, Elsevier, October 2023, https://doi.org/10.1016/j.firesaf.2023.104042.

[5] McGrattan, K., et al.: Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE), Phase 1: Horizontal Trays, NUREG/CR-7010, Vol. 1, prepared for U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research, Washington, DC, USA, July 2012, https://www.nrc.gov/docs/ML1221/ML12213A056.pdf.

[6] Passalacqua, R., et al.: Experimental characterisation of ITER electric cables in postulated fire scenarios, Fusion Engineering and Design 88 (9-10), pp. 2650 - 2654, Elsevier, October 2013, https://doi.org/10.1016/j.fusengdes.2013.01.026.

[7] Wielenberg, A., et al.: Recent improvements in the system code package AC²-2019 for the safety analysis of nuclear reactors, Nuclear Engineering and Design, Volume 354 (2019) 110211, Elsevier, August 2019, https://doi.org/10.1016/j.nucengdes.2019.110211.

[8] Séguillon, J., H. Prétrel, and. S. Suard: Experimental study of a travelling fire along a cable tray assembly in a mechanically ventilated enclosure, Fire Safety Journal, Volume 141 (1):104016, December 2023, https://doi.org/10.1016/j.firesaf.2023.104016.

[9] Zavaleta, P., and L. Audouin: Cable tray fire tests in a confined and mechanically ventilated facility, Fire and Materials, Volume 42(12), pp. 28 - 43, July 2017, https://doi.org/10.1002/fam.2454.

[10] Prétrel, H., P. Zavaleta, and S. Suard: Experimental study on the effect of the mechanical ventilation on cable tray fires in compartments, Fire Safety Journal, Volume 138, 103792, ISSN 0379-7112, Elsevier, July 2023, https://doi.org/10.1016/j.firesaf.2023.103792.

[11] Zavaleta, P., R. Hanouzet, and T. Beji.: Improved Assessment of Fire Spread over Horizontal Cable Trays Supported by Video Fire Analysis, Fire Technology 55 (5), pp. 233–255, November 2018, https://doi.org/10.1007/s10694-018-0788-x.

[12] Plumecocq, W., et al.: Common OECD/NEA FIRE and PRISME Cable Benchmark Exercise, Fire Safety Journal, Volume 139 (Issue 1):103815, Elsevier, June 2023, https://doi.org/10.1016/j.firesaf.2023.103815.

Development of a Simplified Semi-Empirical Model for Fire-Induced Electrical Cable Failure

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ABSTRACT

In implementing practical fire probabilistic risk assessment (PRA) for nuclear power plants (NPPs), several fire scenarios need to analyze more realistic fire consequences near targets typically considered in Fire PRA such as heat flux to targets from a flame, smoke gas layer or surrounding. In general, electrical cables are mainly addressed as the targets, and a fire simulation code is applied in the above analysis. The Nuclear Risk Research Center (NRRC) of the Central Research Institute of the Electric Power Industry (CRIEPI) has continuously improved the two-layer zone model named BRI2-CRIEPI to allow the analysis of compartment fire behaviour of NPPs. In recent developments, sub-models on the radiative heat flux from fire consequences and the time to failure on electrical cables have been incorporated in BRI2-CRIEPI.

This paper presents the results of cable fragility tests to determine the time of fire-induced electrical cable failure. The fragility tests were performed using a cone calorimeter test apparatus. The test parameters were assumed to be a type of cable insulation material, incident heat flux, failure mode of electrical cables. In addition, the insulation resistance of the cable was monitored to determine the time to failure in the tests. Based on the test results, a simplified semi-empirical model was developed to estimate fire-induced electrical cable failure. The case study was demonstrated to compare with the previous approach based on NUREG/CR-6850 and the proposed model was also presented. The proposed model found the potential to define a time to failure considering practical cable fragilities and fire consequences such as heat flux and temperature to the electrical cables.

INTRODUCTION

In detailed fire modelling within Fire PRA for nuclear installations, the Fire PRA analyst defines fire scenarios including the fire ignition source, the component in the near vicinity of the fire source as target and information related to the size, layout and ventilation rate for each compartment. As a practical manner, electrical components such as electrical cables and electronics are generally addressed as ignition and damage targets.

The well-known screening criteria or exposure thresholds for ignition and damage of components have been provided by NUREG/CR-6850 [1] which is also referred to in the NRRC Fire PRA guide for the Japanese utilities [2]. The screening criteria as a function of temperature and heat flux have been defined as 205 °C and 6 kW/m^2 for thermoplastic (TP) cables, 330 °C and 11 kW/m^2 for thermoset (TS) cables and 65 °C and 3 kW/m^2 for electronics (solid state control components). Regarding electrical cables, based on either TP or TS cable types, Tsuchino et al. [3] have concluded the screening criteria seems to be applicable for Japanese cables. In addition, they have summarized the relationship between cable temperature and the insulation resistance can be expressed by an Arrhenius plot. The other methods for assessing the damage potential of electrical cables are also presented in NUREG/CR-6850 [1], Supplement 1 to NUREG-1805 [4], NUREG-2178, Volume2 [5], etc.

A new approach named "heat soak method" has been particularly provided by NUREG-2178, Volume 2 [5] and seems to be applicable to reduce conservatism of the previous cable damage modelling approaches such as use of an exposure threshold and use of a lookup table for time-to-failure as a function of constant exposure. According to the heat soak method, the damage integral value ω [-] caused by the fire consequence is expressed by Equation 1. *R(t)* is the damage rate [min^{-1}] at the time *t* as a function of the heat flux range or temperature range that is defined as being inverse of the time to failure [min] listed in the tables of Appendix H of NUREG/CR-6850 [1]. In this method, the time to electrical cable failure would then determine with ω of 1 or greater than 1. However, *R*(t) is not clear to be applicable or not to Japanese cables even though a similar method has been incorporated in BRI2-CRIEPI [6].

$$\omega = \int_0^t R(t)dt \qquad (1).$$

For determining the damage rate from time to failure, this paper presents the progress and results obtained in the small-scale tests focusing on cable fragility and discussions on a modelling approach based on experimental data. The objective of this study is to document a first report on the insights and conclusions that NRRC of CRIEPI developed related to cable fragility.

CABLE FRAGILITY TEST

In order to establish a damage rate due to a fire environment, the fragility of the targets exposed by heat flux and hot gas must be determined. The heat flux and gas temperature with a fire duration time is considerably. Because of this, evaluation of two failure modes was considered to evaluate the fragility of cables exposed to a fire. In other words, hot shorts and shorts to the ground were addressed.

Test Conditions

The fragility tests using the cone calorimeter were performed at the NRRC of CRIEPI in Abiko, Chiba. The cone calorimeter can generate constant radiative heat flux reaching a maximum of 100 kW/m^2 on a spot roughly 10 cm in diameter. In this study, representative samples of TP cables were tested at four different heat fluxes (from 9 kW/m^2 to 25 kW/m^2) to determine the time to failure of cables. The cable samples were cut into 40 cm and placed on top of the cable tray made from steel. The materials of cable insulation and cable jacket were polyvinyl chloride, and the flame retardant grade was qualified by IEEE383 [7]. The number of conductors was three and the size was 1.25 mm^2. The outer diameter of cable was around 10 mm. For determining time to failure of cables, the loss of insulation resistance between the conductor-conductor or the conductor-tray was monitored by a super megohm meter. A thermal image camera was applied to measure the surface temperature of cable samples sprayed with the black body paint; the emissivity was 0.94. Figure 1 shows the overview of the cable fragility test configuration. The gap between the bottom of the cone heater and the surface of the cable samples was set to 25 mm. Figure 2 illustrates the overviews of measurement system on the isolation resistance of cables. The measurement points of the isolation resistance were connected to each conductor inside the cable sample or conductors and cable tray depending on the failure mode during the tests.

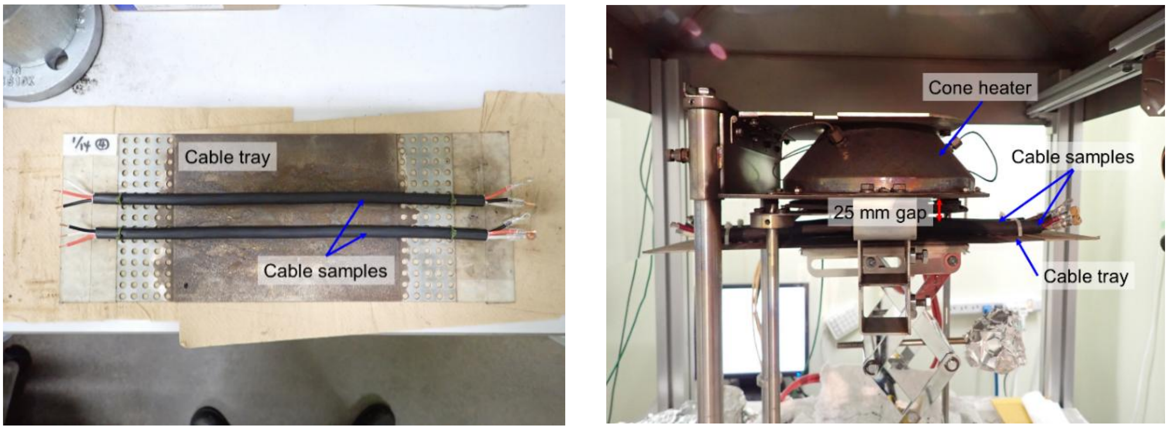

Figure 1 Overview of cable fragility test configuration

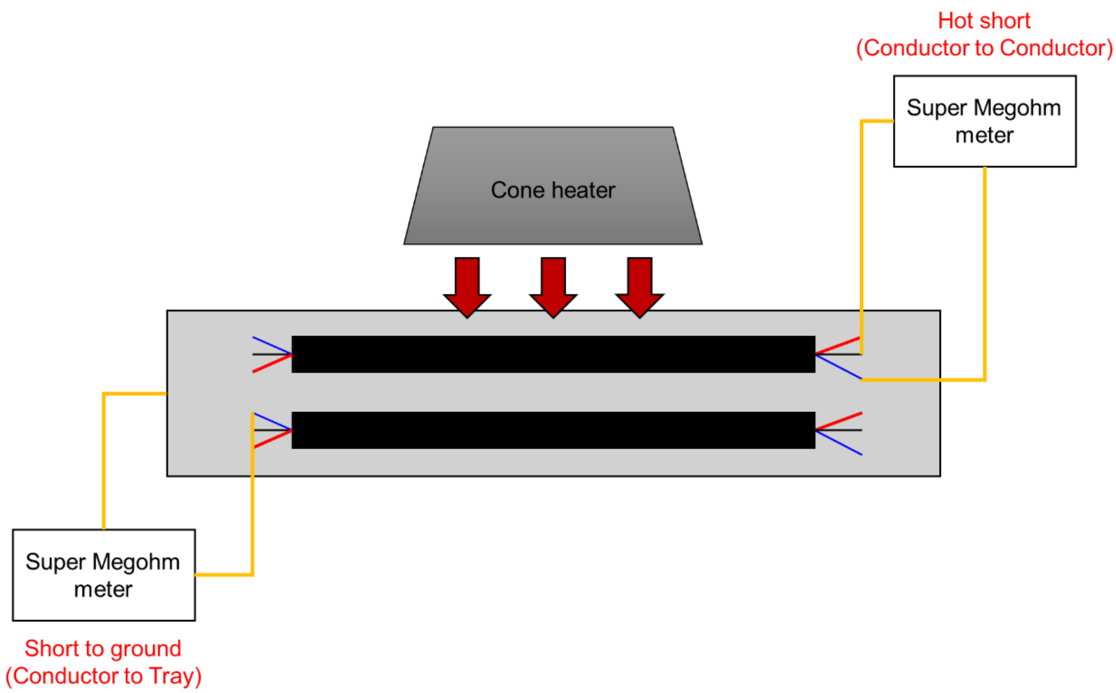

Figure 2 Overview of the measurement system for the isolation resistance of cables

Test Results

Figure 3 shows an example of the time history of cable insulation resistance during the fragility tests. As shown in Figure 3, the isolation resistance dramatically decreases when either a hot short (conductor-to-conductor) or a short to ground (conductor-to-tray) occur as failure modes.

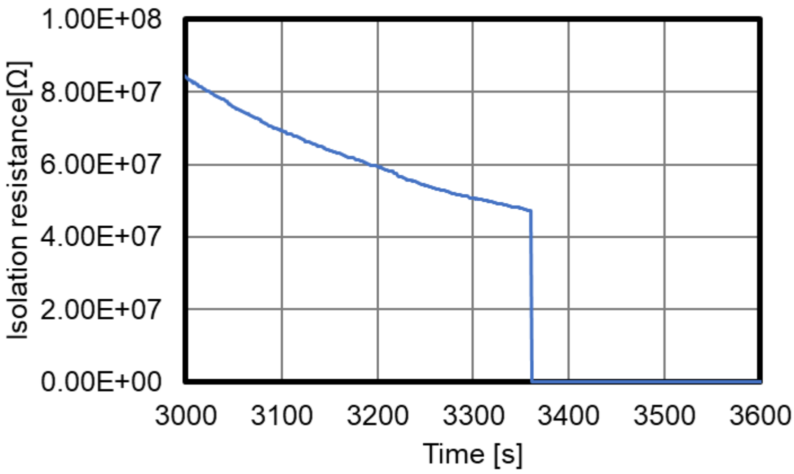

Figure 3 Example of the time history of the cable insulation resistance

Figure 4 summarizes the experimental data focus on the time to the failure temperature relationship (see Figure 4a) and the time to failure heat flux relationship (see Figure 4b), respectively. For TP cables, the failure mode of conductor-to-conductor shorts tend to have shorter failure times than conductor-to-tray shorts. In addition, the general trend of the experimental data finds that the more severe heat flux or temperature exposed, the more accelerated the thermal degradation of the cable materials and the shorter the failure time. Figure 5 shows the photo of cables after the tests. Depending on the exposure conditions, TP cable material was in different states of deterioration.

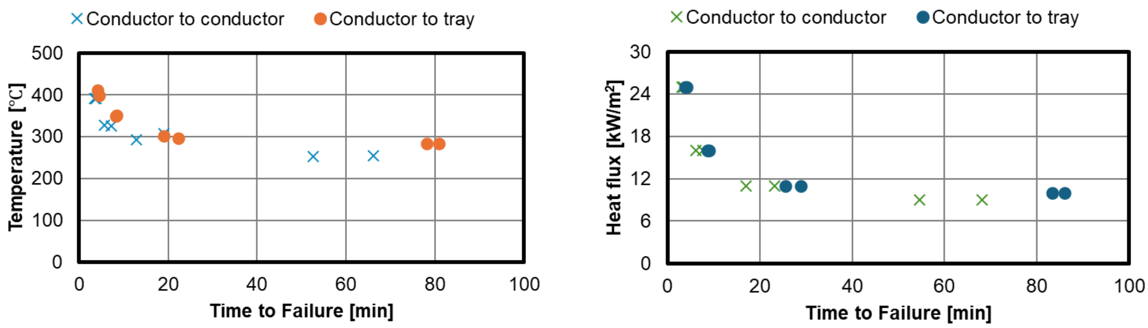

Figure 4 Summarization of experimental data fucus on the time to failure of cables – left: failure temperature relationship (a), right: failure heat flux relationship (b)

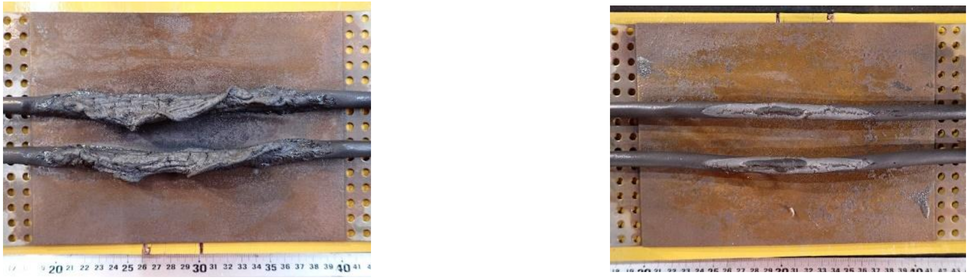

Figure 5 Comparison of the cables after the fragility test – left: 25 kW/m^2, right: 9 kW/m^2

DATA ANALYSIS AND DISCUSSION

To develop a simplified semi-empirical model for fire-induced electrical cable failure, an Arrhenius plot analysis is performed using the data obtained from the fragility tests. The basic model is expressed as Equation 2 [8].

Figure 6 shows the analysis results with Arrhenius plots. According to the data plots related to the failure mode of conductor-to-conductor shorts, the coefficients of determination exceed 0.9 and each linear approximation is in good agreement. Therefore, reorganizing Equations 2 and 3 with respect to time, Equations 4 and 5 are obtained. The inverse of these equations can be applicable for the damage rate used in estimating time to failure of cables subjected to a fire.

Here t_e is a life span, ΔE is an activated energy of apparent thermal degradation, *R* is the gas constant, *T* is the absolute temperature, and *a* and *b* are the numbers of constant. For the analysis on failure time-heat flux relationship, using the equation relating *T* and the heat flux $\dot{q}''$ ($T \propto \sqrt[4]{\dot{q}''}$), Equation 2 can be transformed into Equation 3.

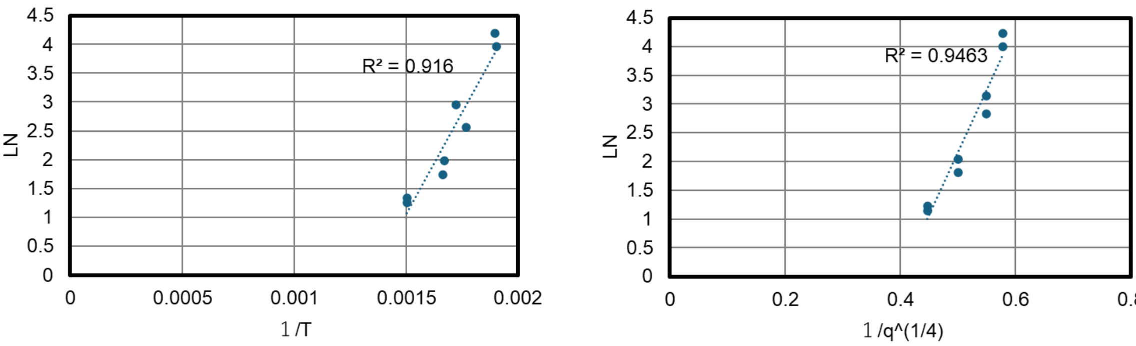

Figure 6 Arrhenius plot analysis results using the data obtained by this fragility tests – left: plot of exposure temperature vs. failure time (a), right: plot of exposure heat flux vs. failure time

$$log t_e = \frac{\Delta E}{RT} + b = \frac{a}{T} + b \quad (2).$$

$$log t_e = \frac{a}{\sqrt[4]{\dot{q}''}} + b \quad (3).$$

$$t_e = exp\left(\frac{a}{T} + b\right) \quad (4),$$

$$t_e = exp\left(\frac{a}{\sqrt[4]{\dot{q}''}} + b\right) \quad (5).$$

To discuss the applicability of the damage rate based on the above Arrhenius model, a constant heat flux exposure of 9 kW/m^2 is used to demonstrate the failure time evaluation. Figure 7 shows the estimation result of cable failure time with the heat soak method based on the Arrhenius model. In the experiment, cable failure occurred 3330 seconds from the start of the heat exposure; however, the evaluation using the conventional heat soak method based on the Appendix H of NUREG/CR-6850 [1] showed a large discrepancy. The Arrhenius model evaluation provides a prediction closer to the experimental results than the conventional method, suggesting that it can be applied to the evaluation of the failure time induced by fire. However, continuous accumulation and analysis of data is essential to establish an evaluation method for the damage rate using the Arrhenius model because of the wide variety of actual cable sheath materials, sizes, and internal structures. Subsequent testing and data analysis from this study is ongoing and will be reported at another time.

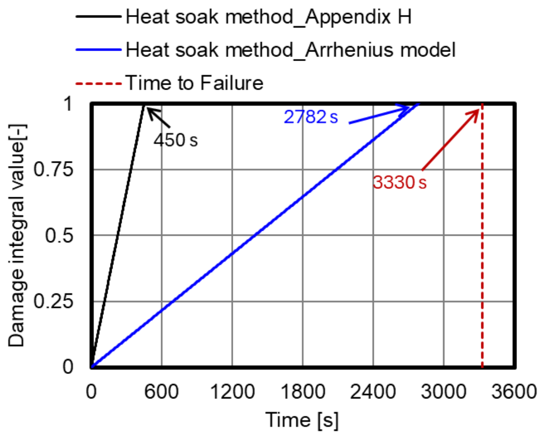

Figure 7 Estimation results of the cable failure time using the heat soak method

CONCLUSIONS

Test results for developing a simplified semi-empirical model to determine the damage rate of electrical cables subjected to fire consequences have been presented. The Arrhenius modelling approach has the potential to define a time to failure in real fire scenarios for nuclear power plants.

ACKNOWLEDGEMENTS

This research project was conducted as a joint project of nuclear power plant owners in Japan (Leader: Tokyo Electric Power Company (EPC) Holdings, Participants: Hokkaido EPC, Tohoku EPC, Hokuriku EPC, Chubu EPC, Kansai EPC, Chugoku EPC, Shikoku EPC, Kyushu EPC, Electric Power Development Company and the Japan Atomic Power Company).

REFERENCES

[1] United States Nuclear Regulatory Commission (U.S. NRC) / Electric Power Research Institute (EPRI): EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Plant Facilities, Final Report, Appendix H, NUREG/CR-6850 Volume 2, EPRI 1011989, Washington, DC, USA, 2005, https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6850/v2/index.html.

[2] Uchida, T., et al.: Development of Fire PRA Guide for Japanese Nuclear Power Plants, CRIEPI Report O20001, June 2020 (in Japanese and English), https://criepi.denken.or.jp/hokokusho/pb/reportDownload?reportNoUkCode=O20001&tenpuTypeCode=30&seqNo=1&reportId=8988.

[3] Tsuchino, S., and A. Matsuda: Damage Assessment in Case of Cable Fire in Nuclear Facilities Considering Damage Criteria for Each Material Type, Transactions of the Atomic Energy Society of Japan,Journal of Nuclear Science and Technology, 19 (2020) 4, October 2020 (in Japanese), https://doi.org/10.3327/taesj.J19.021.

[4] U.S. Nuclear Regulatory Commission (U.S. NRC): Fire Dynamics Tools (FDTs) Quantitative Fire Hazard Analysis Methods for the U. S. Nuclear Regulatory Commission Fire Protection Inspection Program, NUREG-1805 Supplement 1, Washington, DC, USA, July 2013, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1805/s1/index.html.

[5] U.S. Nuclear Regulatory Commission (U.S. NRC): Refining and Characterizing Heat Release Rates from Electrical Enclosures During Fire (RACHELLE-FIRE) Vo Volume 2: Fire Modeling Guidance for Electrical Cabinets, Electric Motors, Indoor Dry Transformers, and the Main Control Board, NUREG-2178 Vol. 2, Washington, DC, USA, June 2020, https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr2178/v2/index.html.

[6] Shirai, K., et al.: Development of two-layer zone model BRI2-CRIEPI applicable to fire PRA for nuclear power plants, Fire Safety Journal, Volume 141 (1):103948, December 2023, https://doi.org/10.1016/j.firesaf.2023.103948.

[7] Institute of Electrical and Electronics Engineers (IEEE) Standards Association: IEEE-383-1974 Standard for Test of Class IE Electric Cables, Filed Splices and Connections for Nuclear Generation Stations, ISBN 1-55937-206-0, IEEE Standards Press, Piscataway, NJ, USA, 1974.

[8] Urabe, S.: Life prediction of solid electrical insulation materials and judgment of equipment deterioration, Journal of Materials Life Society, 13(1]), 23, 2001 (in Japanese).

CONSIDERATION OF UNBURNED GASES PRODUCTION AND COMBUSTION IN FIRE MODELLING TOOLS

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ABSTRACT

The production of unburned gases generated by incomplete combustion in under-ventilated conditions represents a significant risk of smoke explosion and fire spread by re-ignition of unburned gases. Self-ignition of unburned gases becomes possible if the gas mixture contains a sufficient amount of oxygen, if it is within its flammability range and if its temperature is higher than its self-ignition temperature. This phenomenon must be taken into account in nuclear fire safety demonstrations. Nevertheless, interest in this question is quite recent, and no methodology for considering the possible ignition of unburned gases has yet been completely developed.

The fire related literature does not present any tests carried out on this specific issue. Framatome has therefore taken stock of the consideration of unburned gases in fire simulation tools, starting with CFAST (Consolidated Fire and Smoke Transport) [1] – a zone model developed by the National Institute of Standards and Technology (NIST) in the United States of America. The CFAST (version 7) model can simulate the production of unburned gases and their transfer from one compartment to another, as well as their self-ignition at the compartment openings. Framatome assessed different simple configurations to verify the modelling of the combustion of unburned gases through diverse types of vents. Combustion at vertical openings such as doors seems to be correctly represented, while this is not the case for horizontal openings at the ceiling level. Subsequently, Framatome continued its research by investigating the possibilities offered by the computational fluid dynamics (CFD) type code FDS (Fire Dynamic Simulator) [2] also developed by the NIST.

INTRODUCTION

Nuclear facilities contain radioactive material. Therefore, they include confined and mechanically ventilated compartments. A fire developing in these types of compartments can result in an under-ventilated combustion regime, and unburned gases can accumulate due to incomplete combustion, can be transferred out of the compartment through the ventilation ducts or openings and thus spread the fire if they ignite again.

The risks associated with unburned gases are a known issue. Nevertheless, the ability of available fire simulation tools to model these risks needs to be studied.

In 2024, Framatome has chosen to study the ability of CFAST to adequately simulate these phenomena. The objective of the study was twofold. It consists of investigating and understanding how CFAST simulations model:

- the production of unburned gases in the event of an under-ventilated fire,

- the transport and combustion of these gases in the neighbouring compartments.

BRIEF OVERVIEW OF THE CFAST FIRE MODEL

CFAST is an open-source two-zone fire model provided by the NIST of the United States Department of Commerce. This model predicts the thermal environment caused by a fire within a compartmented structure. Each compartment is divided into an upper and lower gas layer (zone in the term zone fire model refers to the layers being modelled). The fire drives combustion products from the lower to the upper layer via the fire plume. The temperature within each layer is modelled to be uniform, and its development over time is described by a set of ordinary differential equations derived from the fundamental laws of mass and energy conservation. The transport of smoke and heat from zone to zone is determined by empirical correlations. Figure 1 provides schematic view of the two-zone modelling approach.

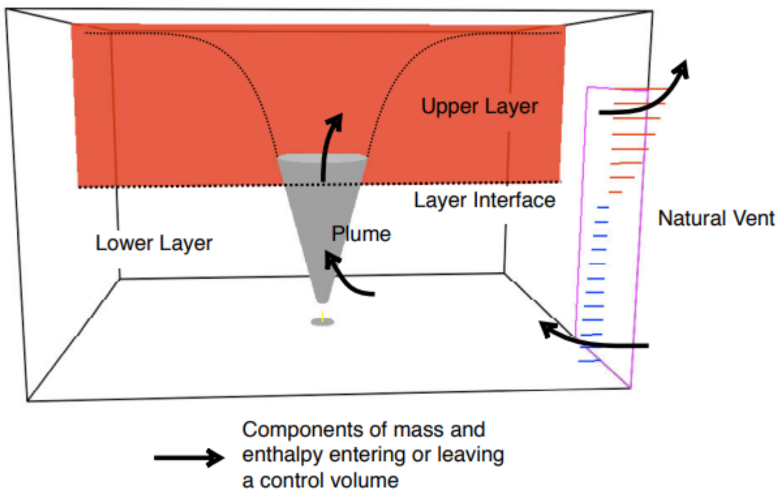


Figure 1 Schematic view of the control volumes in a two-layer zone model

The governing equations of CFAST concern the conservation of mass and energy within the lower and upper layers of connected compartments within a building. The momentum within any one zone is assumed to be zero. The momentum between zones in adjacent compartments is accounted for in terms of horizontal or vent flow equations (Bernoulli's law). Other features of CFAST include:

- Compartment geometry: CFAST is generally limited to fire scenarios where the compartment volumes are strongly stratified. The empirical correlations contained in CFAST were developed for relatively uncluttered, flat ceilings in compartments that can be characterized as "rooms" as opposed to corridors or vertical shafts. There are no hard limits on what types of compartments can or cannot be modelled in CFAST. The CFAST Validation Guide indicates the accuracy of its predictions for compartments of various aspect ratios.
- Heat release rate (HRR): CFAST does not predict fire growth at burning objects. The HRR is specified by the user for one or more fires. There is a simple sub-model to limit the heat release based on the oxygen available.
- Radiation from fires is modelled with a simple point source approximation. This limits the accuracy of the model within a few diameters of the fire. Calculation of radiative exchange between compartments is not modelled.

- Mechanical ventilation is modelled by specifying volumetric flow rates into or out of compartments. The overall HVAC (heating, ventilation, air conditioning) system is not modelled.
- Natural ventilation and leakage: The flow through vertical openings, such as doors and windows, is modelled using the Bernoulli equation for the pressure difference between two compartments. Horizontal openings, typically hatches, are treated with a single empirical correlation based on pressure and density differences between upper and lower compartments. The leakage is modelled by explicitly creating a small vertical or horizontal opening.

In case of incomplete combustion, any unburned fuel is tracked by the model and transported to the upper layer via entrainment in the fire plume or to other compartments through any user-specified vents. Unburned fuel may burn in the upper layer or at vents if sufficiently hot (if $T > 100\ K + T_{amb}$[1], $T_{amb} = 20\ °C$ by default) and if additional oxygen is available (if the oxygen concentration > Lower Oxygen Limit (LOL) which is a specified value, 15 % by default).

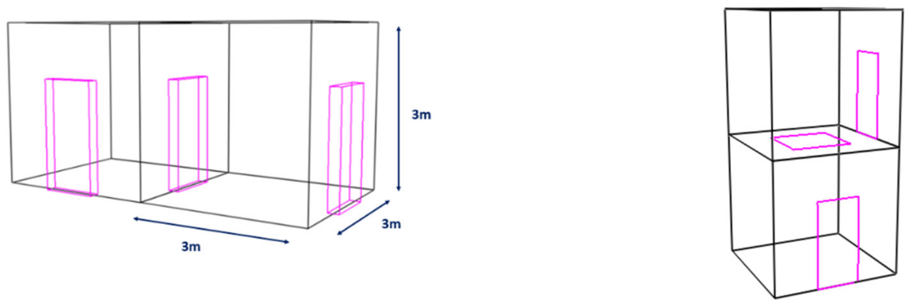
MODELLING OF UNBURNED GASES WITH CFAST VERSION 7

To reach the two objectives provided in the introduction, the work has been carried in a step-by-step approach.

First Step: Specification of Different Room Configurations to be Investigated

In the first approach, a single type of compartment of 27 m^3 (3 m x 3 m x 3 m) is specified, and two-compartment configurations have been studied as illustrated in Figure 2. Configuration 1 consists of two naturally ventilated compartments adjacent to each other on the same elevation connected by an open door and with open doors to the environment. Configuration 2 consists of two naturally ventilated compartments adjacent to each other in vertical direction connected by an open hatch and with open doors to the environment.

[1] Compared to the thesis of Mathis [3], the self-ignition temperature of 120 °C is low, but conservative.



Configuration 1 **Configuration 2**

Figure 2 Two-compartment configurations investigated, left: Configuration 1 horizontally connected compartments, right: Configuration 2 vertically connected compartments

Figure 3 presents the thermal properties of the concrete used to define walls, floor, and ceiling of the compartments specified in CFAST [1].

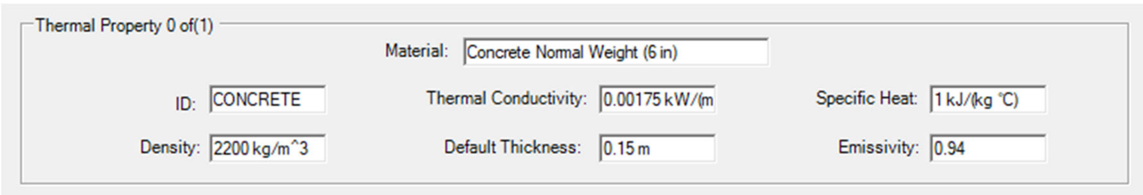


Figure 3 Thermal properties of the concrete (default value for concrete in CFAST)

Second Step: Set-up of a Theorical Fire Source

The second step is to define a sufficiently energetic fire so that it can be observed under-ventilated regime and thus obtain incomplete combustion. The following characteristics of fire, from [4] and corresponding to the combustion products for switchgear room cabinet and cable fire, are specified in CFAST [1]:

- Effective fuel formula: $C_2H_{3.5}Cl_{0.5}$ (combination of polyethylene and polyvinyl chloride (PVC)),
- Heat of combustion ΔH: 20,900 J/kg,
- CO_2 yield: 1.29 kg/kg,
- Soot yield: 0.136 kg/kg,
- CO yield: 0.147 kg/kg,
- Radiative fraction: 0.49.

The following data are used to specify the fire (as expected in open atmosphere) in CFAST:

- Peak HRR: 15,000 kW,
- Fire load: 20,000 MJ,
- Area: 5 m²,
- Height: 0 m,
- LOL: 10 %,
- Decreasing phase after the combustion of 70 % of the fire load [5],
- Growth coefficient α: 0.00293 kW/s² corresponding to a slow growth [6].

Figure 4 shows the HRR specified in CFAST called the expected HRR.

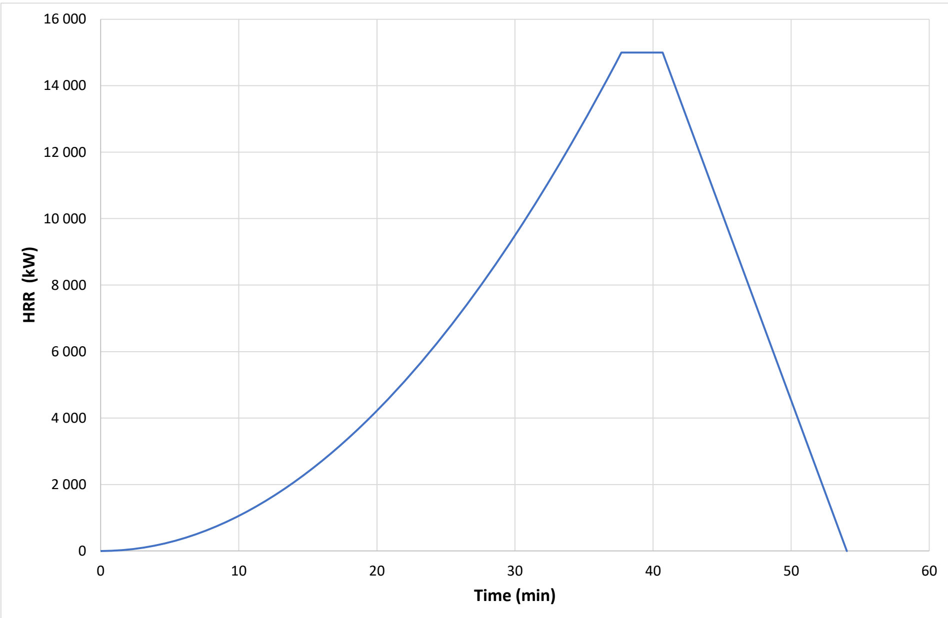


Figure 4 HRR of the fire test

As explained in the CFAST Technical Guide [1], CFAST does not include a pyrolysis model to predict, as opposed to specify, the growth and spread of the fire. Rather, the transient pyrolysis rates for each fire are prescribed by the user by defining the HRR. Using the specified HRR of the fire $\dot{Q}$, and a user-specified heat of combustion *ΔH*, the model calculates the pyrolysis rate of fuel, $\dot{m}_f$:

$$\dot{m}_f = \frac{\dot{Q}}{\Delta H} \quad (1).$$

Figure 5 illustrates the development of the pyrolysis rate over time.

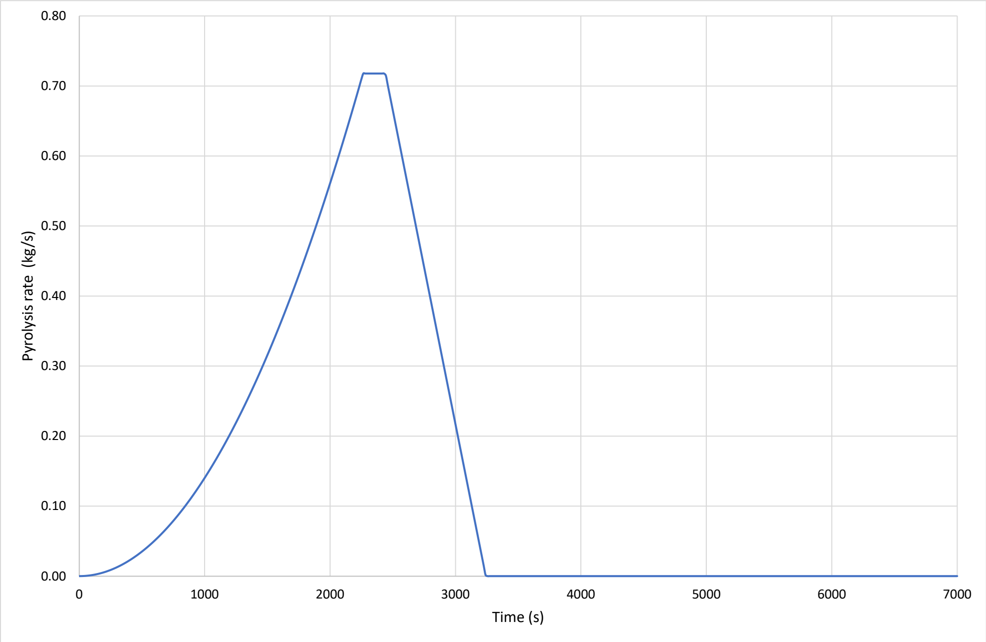


Figure 5 Pyrolysis rate of the fire test

Third Step: Checking the Combustion Regime in the Fire Compartment

Configuration 1 – Horizontally Adjacent Compartments

As shown in Figure 6, it has been observed that at 1470 s the HRR is limited and does not follow the HRR expected, thus confirming the transition to an under-ventilated regime:

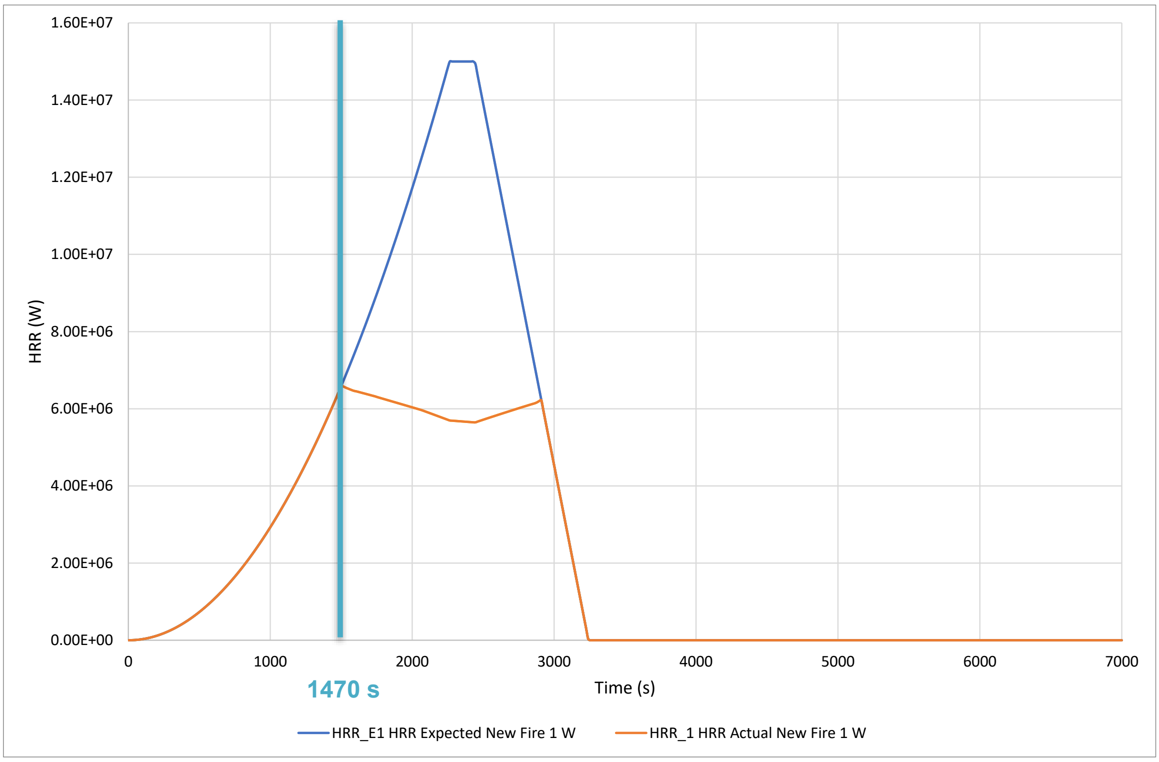


Figure 6 HRR – actual vs expected in Configuration 1 (horizontally adjacent compartments)

Indeed, at 1470 s the HRR is constrained by the availability of oxygen. As mentioned in the CFAST Technical Guide [1], it is assumed that the pyrolysis rate does not change[2]. However, only parts of the pyrolyzed fuel burns and the HRR becomes (cf. equation 2):

$$\dot{Q} = \min\left(\dot{m}_f \Delta H, \dot{m}_e Y_{O2} C_{LOL} \Delta H_{O2}\right) \quad (2),$$

with:

- $\dot{m}_f$: pyrolysis rate [kg/s],
- ΔH: heat of combustion [MJ],
- $\dot{m}_e$: entrainment rate [kg/s],
- Y_{O2}: mass fraction of oxygen,
- C_{LOL} (LOL): smoothing function ranging from 0 to 1,
- $$C_{\mathrm{LOL}} \approx \frac{\tanh\left(800(Y_{\mathrm{O_2}} - Y_{\mathrm{O_2},l}) - 4\right) + 1}{2} \quad (3),$$
- ΔH_{O2}: heat of combustion based on oxygen consumption (Thornton constant = 13,1 MJ/kgO_2 [5]).

---

2 As shown by Prétrel [7], the decrease in the oxygen concentration leads to a decrease in the pyrolysis rate. Therefore, CFAST overestimates the pyrolysis rate.

Configuration 2 – Vertically Adjacent Compartments

As shown in Figure 7, the under-ventilated regime is also reached in Configuration 2. Nevertheless, the HRR is constrained later than in the Configuration 1 because of the hatch which allows a higher plume entrainment rate $\dot{m}_e$.

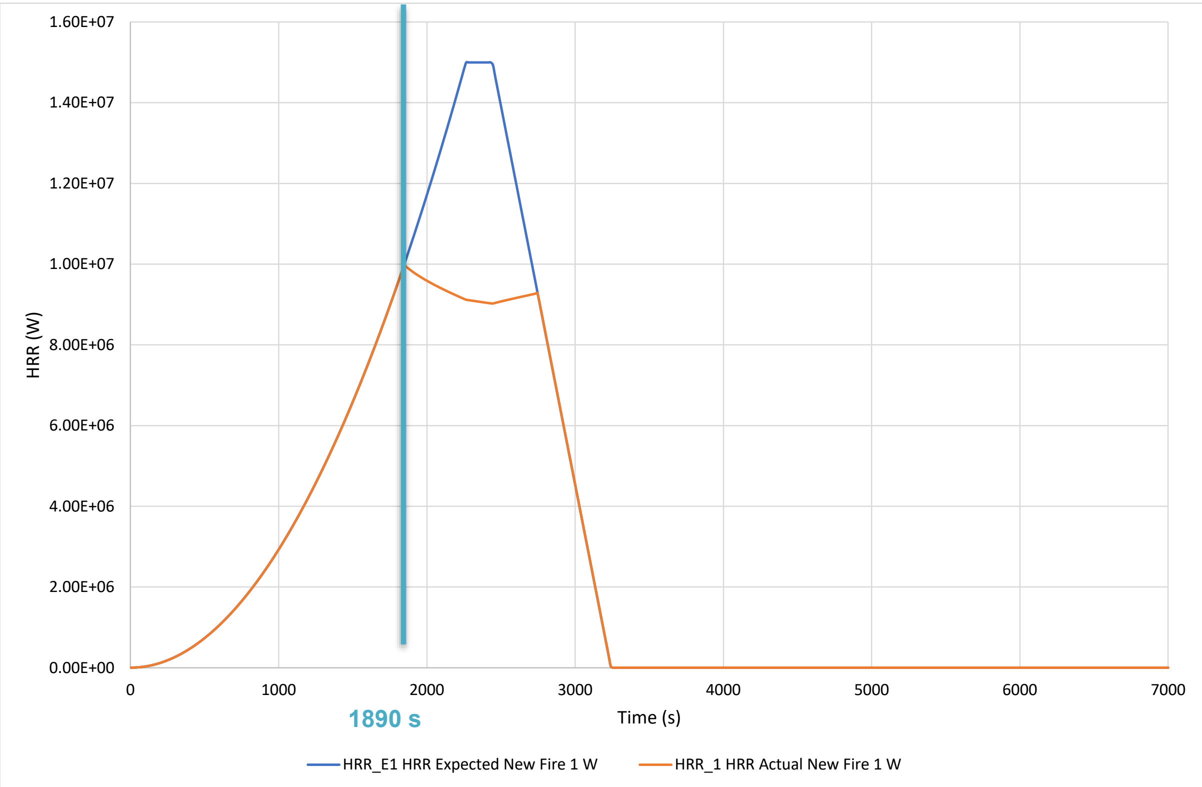


Figure 7 HRR – actual vs expected in Configuration 2 (vertically adjacent compartments)

Fourth Step: Checking the Transport and the Combustion of Unburned Gases in the Second Compartment

Configuration 1 – Horizontally Adjacent Compartments

As shown in Figure 8, a vent jet fire is observed in the second compartment, thus confirming the transport and the combustion of unburned gases in this compartment:

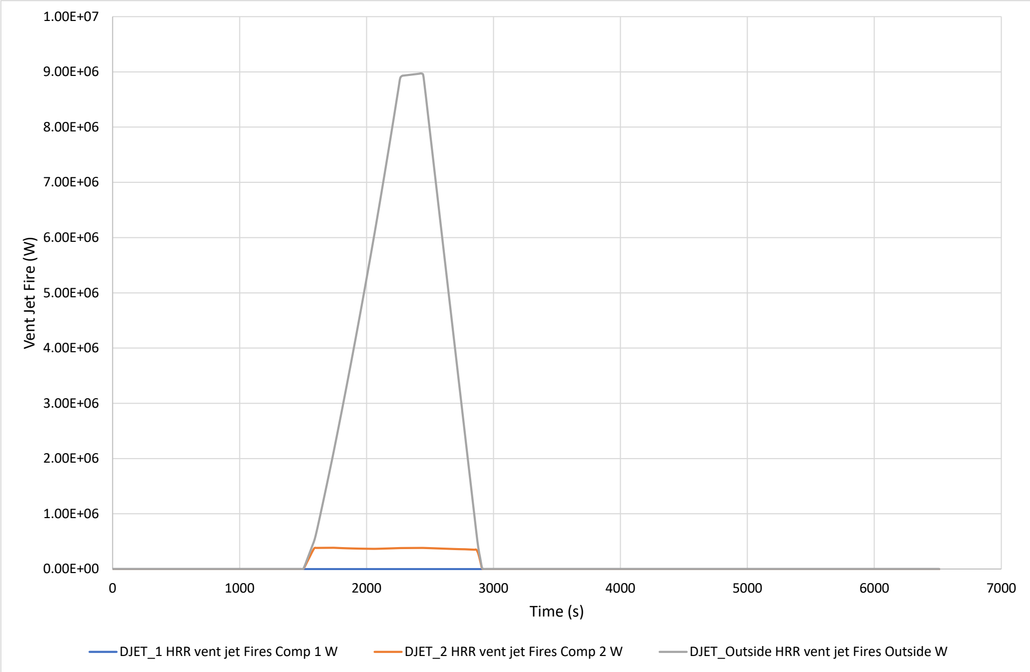


Figure 8 HRR vent jet fire in Configuration 1 (horizontally adjacent compartments)

Nevertheless, as shown in Figure 9, the oxygen concentration in the upper layer of the second compartment constrains the HRR, so it could be also observed that the unburned gases concentration in the second compartment raised at the same time (at 1470 s):

It has been verified that the area between the *HRR expected* and the *actual* curves in Figure 6 is equal to the areas under the *HRR vent jet fire compartment 2* and the *outside* curves. It allows to verify that all pyrolysis gases are burned at the level of the three doors. It has been observed that most of the unburned gases burn at the two doors level leading to the outside, i.e. to the environment.

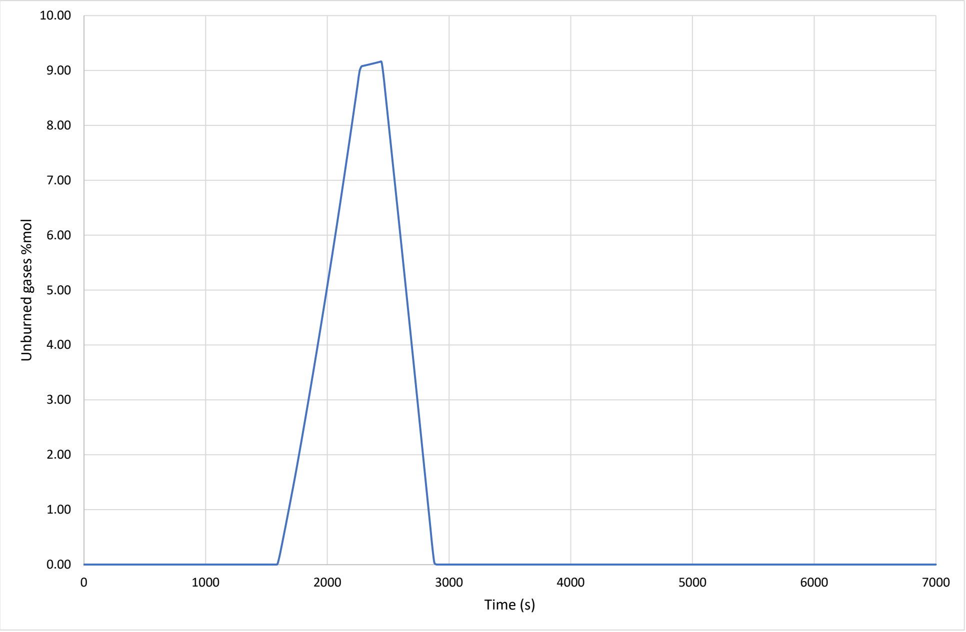


Figure 9 Unburned gases concentration in the second compartment in Configuration 1 (horizontally adjacent compartments)

Configuration 2 – Vertically Adjacent Compartments

As shown in Figure 10, no vent jet fire is observed in the second compartment:

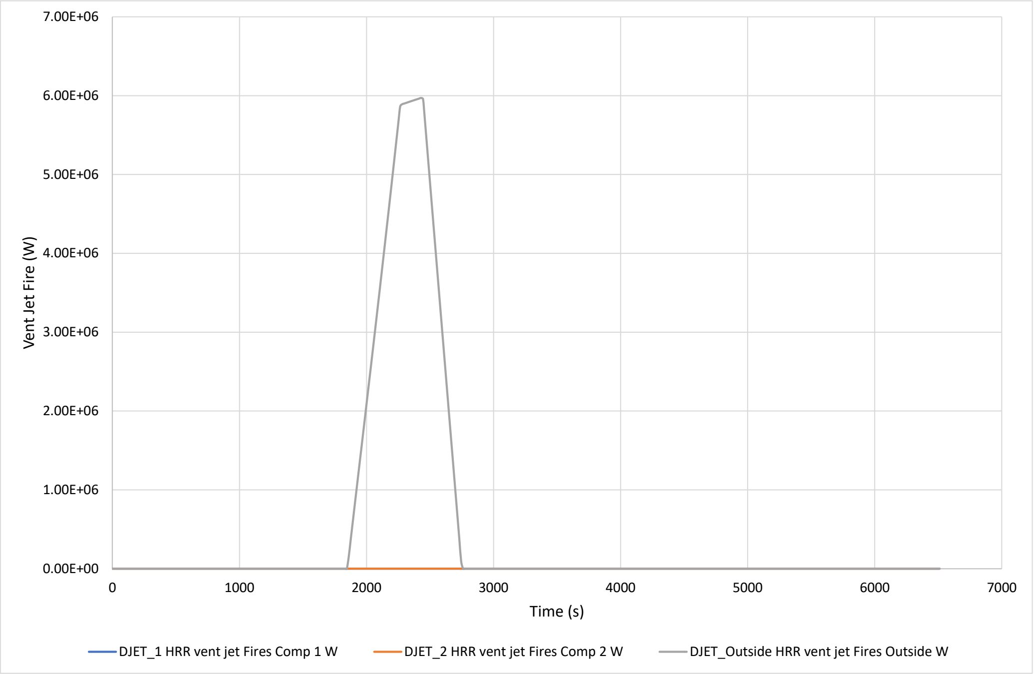


Figure 10 HRR vent jet fire in Configuration 2 (vertically adjacent compartments)

Indeed, as shown in Figure 11, the second compartment is reduced to a single layer very quickly until the fire is extinguished.

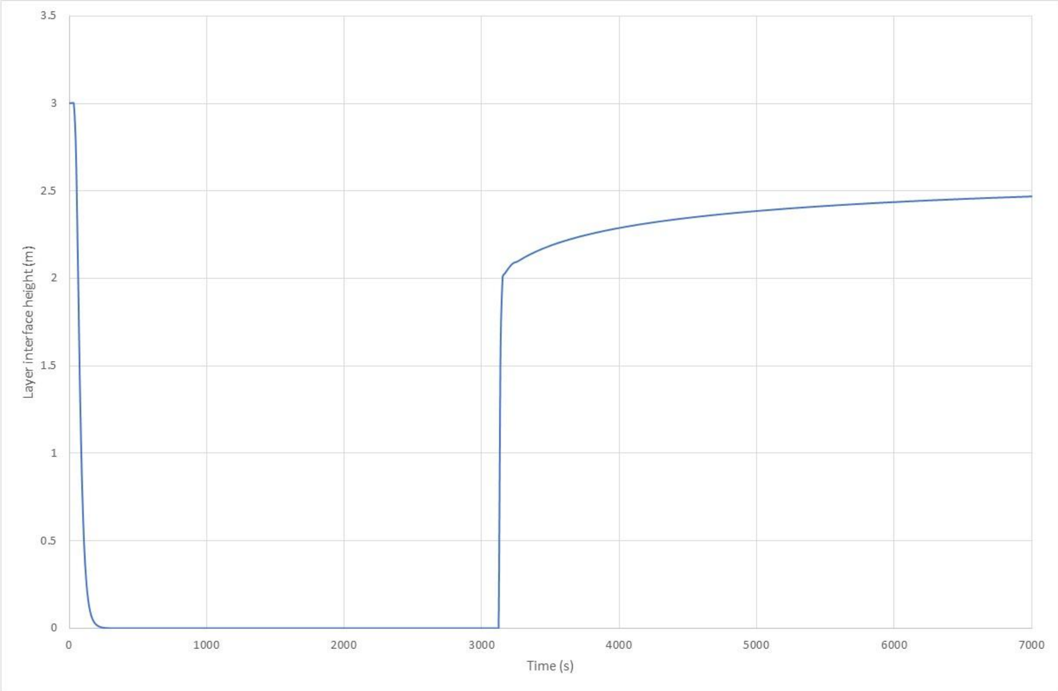


Figure 11 Layer interface height between upper and lower layers in Configuration 2 (vertically adjacent compartments)

As the oxygen concentration in the second compartment decrease under the LOL before 1890 s, unburned gases that are transferred to it cannot burn. They burn when they go through the door to the outside. These results are surprising and do not seem realistic because it is still expected that some of the unburned gases will be able to burn in the second compartment. It seems that CFAST cannot properly model these aspects in this configuration. It can also be noted that even though in our case the fire is just under the hatch, the flame height is limited to the height of the ceiling. This is also unrealistic, but these are limits of a two-zone fire model.

CONCLUSION AND NEXT STEPS

CFAST seems to be able to model unburned gases in an under-ventilated fire, their transport and combustion in an adjacent compartment. But in case of superposed compartments, modelling seems not realistic.

Work will be continued by comparing the results obtained with those of the FDS (Fire Dynamic Simulator) code.

Framatome will also use and compare this work with the results of PRISME 2 experiments carried out in the framework of an OECD project in the 2011-2016 which contain four experimental campaigns, including PRISME_2 Vertical Smoke Propagation (PR2-VSP) test series [8]. These test series investigate the smoke propagation through a horizontal opening connecting two compartments mechanically ventilated, the fire compartment being the lower one.

REFERENCES

[1] Peacock, R. D, et al.: CFAST – Consolidated Fire and Smoke Transport (Version 7) Volume 1: Technical Reference Guide, NIST Technical Note 1889v1, National Institute of Standards and Technology (NIST), Gaithersburg, MD, USA, October 2015, https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.1889v1.pdf.

[2] McGrattan, K., et al.: Fire Dynamics Simulator, Technical Reference Guide, Vol. 1: Mathematical Model, Sixth Edition, National Institute of Standards and Technology, Gaithersburg, MD, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, September 2013, https://github.com/firemodels/fds/releases/download/FDS6.10.1/FDS_Technical_Reference_Guide.pdf.

[3] Mathis, E.: Evaluation du risque d'inflammation de gaz imbrûlés au cours d'un incendie en milieu sous-ventilé. I NNT : 2016ESMA0012, SAE-ENSMA Ecole Nationale Supérieure de Mécanique et d'Aérotechnique, Poitiers, France, July 2016, https://www.researchgate.net/publication/310830909_Evaluation_du_risque_d'inflammation_de_gaz_imbrules_au_cours_d'un_incendie_en_milieu_sous-ventile.

[4] United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research (RES) / Electric Power Research Institute (EPRI): Nuclear Power Plant Fire Modeling Analysis Guidelines (NPP FIRE MAG) – Final Report, Table B-1. Products of combustion for switchgear room cabinet and cable fire, NUREG-1934, EPRI 1023259, Washington, DC, USA, November 2012, https://www.nrc.gov/docs/ML1231/ML12314A165.pdf.

[5] Norme réglementation NBN EN 1991-1-2-FR: NBN EN 1991-1-2: Eurocode 1 : Actions sur les structures - Partie 1-2: Actions générales - Actions sur les structures exposées au feu, 2003 (in French), https://www.buildwise.be/fr/normes-et-reglementations/chercher/nbn-en-1991-1-2-fr/.

[6] Hurley. M., and D. T. Gottuk (Eds.): SFPE Handbook of Fire Protection Engineering, Fifth Edition, Society of Fire Protection Engineers (SFPE), ISBN 10.1493925644 Springer, October 2015.

[7] Prétrel, H.: Mémoire d'habilitation à diriger des recherches, Contribution à l'étude de la dynamique des Incendies en milieu confine et mécaniquement ventilé, ISBN 978-2-9545237-6-7, IRSN/PSN-RES/SA2I/LEF, Laboratoire d'expérimentation des feu (LEF), Cadarache, France, 2018 (in French), https://www.irsn.fr/sites/default/files/documents/larecherche/publications-documentation/collection-ouvrages-irsn/HDR_Pretrel_web_nonimprimable.pdf.

[8] Audouin, L., H. Prétrel, and S. Vaux, Experimental and Numerical Study of Smoke Propagation Through a Vent Separating Two Mechanically Ventilated Rooms, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 23, 14th International Seminar on Fire Safety in Nuclear Power Plants and Installations, September 17-18, 2015, Salford, United Kingdom, GRS-A-3845, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, December 2015, http://www.grs.de/en/publications/grs-a-3845.

Use of an Artificial Intelligence Technique to Improve Cable Tray Fire Modelling

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ABSTRACT

Electrical cable trays are used in large quantities in nuclear power plants (NPPs). They are one of the main potential sources of fire. A malfunction of electrical equipment due to thermal stress for instance may lead to the loss of important safety functions of the NPP. Modelling such a fire source remains a complex issue due to the multitude of parameters involved in its definition, and existing models such as the FLASHCAT model still have limitations due to the lack of information on certain input data. This paper presents improvements in cable tray fire modelling by finding appropriate input data using an artificial intelligence (AI) technique. An AI-driven expert system was developed to assess missing data from a fire test database of 29 large-scale horizontal cable tray fire experiments in open atmosphere. The expert system quantifies the dependencies between input and output data, helps to identify influential parameters and to refine model inputs. It also guides modelling efforts by identifying areas for model improvement. In this way, the applicability of an expert system in obtaining reliable input data for simulation tools to simulate a real fire scenario that has already been performed is demonstrated. Cable tray fire simulation results obtained with AI contribution show improved accuracy compared to those obtained using default values for uncertain parameters.

INTRODUCTION

Electrical cable trays are used in large quantities in NPPs. They are one of the main potential sources of fire. A malfunction of the electrical equipment can result in a loss of important safety functions of the facility. Since the serious cable tray fire at the Browns Ferry NPP in 1975 [1] which resulted in a loss of the emergency core cooling system of the Unit 1, many efforts [2] to [4] have been made to enhance the prevention of such fires. As part of the CHRISTIFIRE program, McGrattan et al. [5], [6] conducted numerous cable tray fire tests at the National Institute of Standards and Technology (NIST) to quantify combustion characteristics in an open atmosphere for a wide range of cable tray configurations encountered in operating NPPs. Twenty-six horizontal cable tray tests without walls or ceilings, followed by ten corridor tests using horizontal cable trays located near the ceiling, were carried out.

As the study of cable tray fires in confined and mechanically ventilated compartments has been scarce up to date, the French Nuclear Safety and Radioprotection Authority (ASNR) conducted in the frame of the international project PRISME 2 ((French: *Pr*opagation d'un *i*n-cendie pour des *s*cenarios *m*ulti-locaux *é*lémentaires, Phase 2) [7] launched by the OECD Nuclear Energy Age (NEA) more than a dozen fire tests involving horizontal cable trays burning either under a calorimetric hood in an open atmosphere [8], [9] or inside a mechanically ventilated facility [10], [11].

Cable tray fire modelling remains a complex issue as highlighted by a recent cable benchmark exercise conducted for a realistic cable fire scenario in an electrical system of a NPP [12]. Given the multitude of parameters involved in the definition of such a fire source, no theory has yet been put forward on how to model all the aspects of the problem even for simple open atmosphere conditions. An empirical model referred to as FLASHCAT [5] (short for *fla*me *s*pread over *h*orizontal *ca*ble *t*rays) was developed by NIST for horizontal cable tray fires in open atmosphere. It is a relatively simple model for predicting the growth and spread of a fire within a vertical stack of horizontal cable trays. However, existing models such as the FLASHCAT model still have limitations due to the lack of information on certain input data.

To perform representative simulations, it is necessary to have available all the parameters involved in the specification of such a fire source. Unfortunately, in practice this is not the case, either because some parameters have not been measured, or because they are too difficult to measure. In this case, default values are used, leading to a deviation from experimental data. To overcome this difficulty, an AI technique can be used to better interpret the deviations between experimental and numerical results and try to reduce them. AI can be divided into two components: connectionist AI and symbolic AI. The first is characterized by machine learning and enables the development of models that cannot be formalized. To achieve good performances, these techniques require large databases. The latter aims to represent knowledge and formalize reasoning. It is easy to interpret.

In this paper, a method for using symbolic AI based on Bayesian networks is proposed, (1) to help exploit sparse experimental data corresponding to cable tray fire tests, (2) to distinguish the deviation attributable to imprecision in the data from that due to poor modelling, (3) to guide modelling work and identify the most relevant experimental measurements to be carried out.

GENERAL PRINCIPLE OF AN EXPERT SYSTEM

An expert system is an artificial intelligence tool capable of reasoning from observed data and generic knowledge, using an inference engine, as illustrated in Figure 1. Applied to cable tray fires, this tool provides a better understanding of the behaviour of a cable tray fire by dynamically combining the knowledge of the physical phenomena involved (knowledge base) with the knowledge specific to the experimental set-up (observation base). Information is propagated using an inference engine based on the Bayesian Belief Network (BBN) methodology [13]. As such, an expert system derives the most likely diagnosis or prognosis of a cable tray fire in negligible time.

The knowledge base gathers all the generic information from which the expert system will operate. This information is encoded by means of conditional probability tables (CPTs). In the case of the representation of simulation software by a Bayesian network, the generic information comes from a parametric study. The latter allows a set of study parameter values to be associated with the corresponding results for the responses of interest. The strength of the link between a response and its influential parameters is quantified by a CPT. In order to limit the size of the tables, the parameters and responses are discretized. Thus, each column of the CPT corresponds to a class of discretization of the response and each row to the histogram of the observed values of the response for a set of influential parameter values.

The inference engine is a set of algorithms for conveying information flows from the observation base through the knowledge base, both in the causal direction (prognostic mode) and in the reverse direction (diagnostic mode). The information relating to the state of a variable (parameter or response) is deduced from the crossing of the upstream and downstream information flows. For more details, please refer to [14].

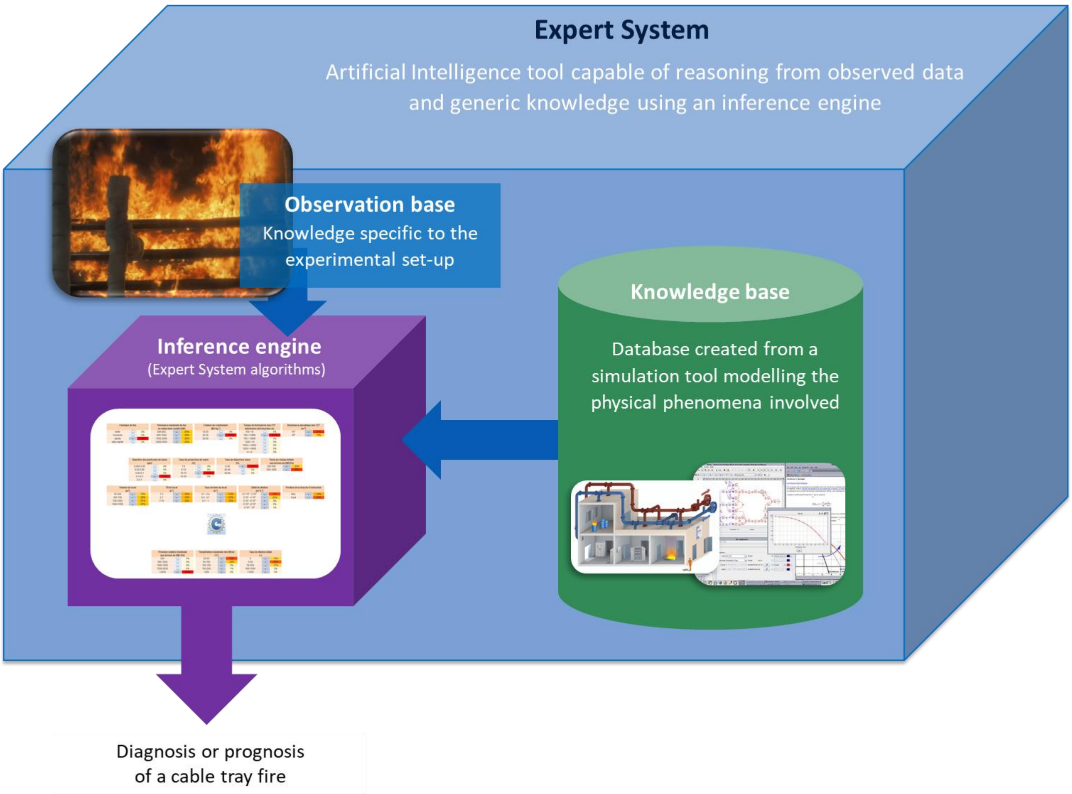

Figure 1 General principles of an expert system

EXPERIMENTAL DATA

The tests considered are large-scale experiments involving the combustion of horizontal cable trays in an open environment. They constitute the observation base of the expert system. The data have been obtained within two projects, the OECD/NEA PRISME Project steered by IRSN (which became the French Nuclear Safety and Radiation Protection Authority (ASNR) on January 1, 2025) and the CHRISTIFIRE project performed at NIST (outlined in publications and technical reports [5], [6], [8], [9], [14]). The fire consists of a set of cable trays positioned horizontally one above the other, on which unpowered electrical cables are laid to form the combustible material. The generic experimental procedure consists of igniting the fire in the centre of the lowest cable tray and following the combustion until it is extinguished. Measurements are taken to determine the development of the fire's heat release rate (HRR) over time. The parameters of the experiments (see Table 1) concern the physical properties of the cables (type, mass of cable per unit length), the dimensions of the cable trays (length, width, vertical distance between trays), the arrangement of the cables (loose or tight), the number of cables per tray, and finally the characteristics of the surrounding environment (presence of a side wall or ceiling).

The response of interest is the development of the HRR over time. This signal is similar for all tests, with a growth phase, a maximum and a decay phase. It is characterized by a set of three scalar quantities: the maximum HRR (HRR_{max}), the total heat released (THC), corresponding to the integral of the HRR, and the fire growth index (FGI), corresponding to the ratio between the maximum value of HRR and the time to reach it, as illustrated in Figure 2. The controlled parameters are the type of cable (thermoset or thermoplastic), the mass of fuel per unit length, the number of cable trays, the width and the length of the cable tray, the spacing between trays, the number of cables per cable tray, and the mass of cables per cable tray. The parameters to be calibrated in the absence of information are the mass fraction of the fuel, the thermal inertia of the cables, the bench-scale HRR per unit area, which is used in the prediction of the full-scale HRR, the ignition temperature of the cables, and the fire spread angle.

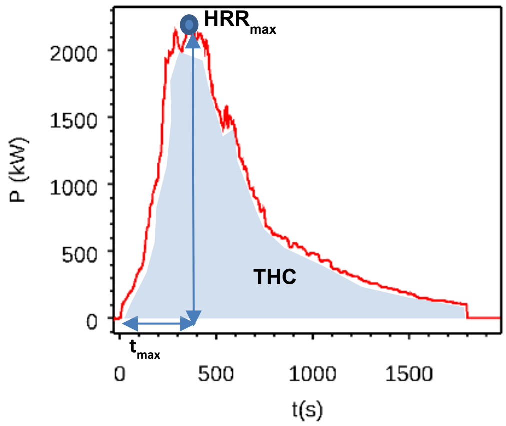

Figure 2 Characteristic development of the HRR over time for a horizontal cable tray fire in open atmosphere

Table 1 Test parameters

Institution	Name	Cable					Tray				Cable Arrangement		Environment	
		Type	Ref.	D	Mass		n	w	l	h	Number of Cables		Wall	Ceiling
				[mm]	[kg/m]	[kg]	[#]	[m]	[m]	[m]	[#/tray]			
IRSN	PR2_CFSS_1	TP	PVC_1	13.0	0.235	138	5	0.45	2.4	0.30	49	loose	yes	–
IRSN	PR2_CFSS_2	TS	HFFR_1	20.0	0.570	219	5	0.45	2.4	0.30	32	loose	yes	–
IRSN	PR2_CFSS_4	TP	PVC_2	14.5	0.320	169	5	0.45	2.4	0.30	44	loose	yes	–
IRSN	PR2_CORE_1	TP	PVC_3	28.0	2.000	504	5	0.45	2.4	0.30	21	loose	yes	–
IRSN	PR3_CFP_S0	TP	PVC_3a	28.0	1.750	441	5	0.45	2.4	0.30	21	loose	yes	–
IRSN	PR3_CFP_S1	TP	PVC_3a	28.0	1.750	441	5	0.45	2.4	0.30	21	Tight	yes	–
IRSN	PR3_CFP_S2	TP	PVC_3a	28.0	1.750	441	5	0.45	2.4	0.30	21	loose	-	–
IRSN	PRF_BCM_S1	TP	#900	16.0	0.382	205	2	0.90	2.4	0.45	112	loose	yes	–
IRSN	PRF_BCM_S2	TP	#900	16.0	0.382	205	2	0.9	2.4	0.45	112	loose	yes	–
NIST	CF_MT_2	TP	701	14.0	0.366	116	3	0.45	2.4	0.30	44	tight	-	–
NIST	CF_MT_8	TP	701	14.0	0.366	232	4	0.45	3.6	0.30	44	loose	-	–
NIST	CF_MT_9	TP	701	14.0	0.366	116	4	0.45	3.6	0.30	22	loose	-	–
NIST	CF_MT_16	TS	269	12.0	0.240	138	3	0.45	2.4	0.30	80/30/50	loose	-	–
NIST	CF_MT_7	TS	16	19.0	0.671	377	7	0.45	2.4/3.6	0.30	36	loose	-	–
NIST	CF_MT_17 *	TS	M		0.520	367	7	0.45	3.6	0.30	28	loose	-	–
NIST	CF_MT_18 *	TS	M		0.520	489	7	0.90	2.4	0.30	56	loose	-	–
NIST	CF_MT_20 *	TS	M		0.520	367	7	0.90	3.6	0.30	28	loose	-	–
NIST	CF_MT_22 *	TS	M		0.520	734	7	0.90	3.6	0.38	56	loose	-	–
NIST	CF_MT_23 *	TS	M		0.520	367	7	0.45	3.6	0.23	28	loose	-	–
NIST	CF_MT_24 *	TS	M		0.520	367	7	0.90	3.6	0.23	28	loose	-	–
NIST	CF_HW_1	TP	800	12.4	0.310	236	2	0.45	6.8	0.30	56	loose	yes	yes
NIST	CF_HW_2 *	TS	802/803	15.0	0.430	234	2	0.45	6.8	0.30	40	loose	yes	yes
NIST	CF_HW_3	TS	802	15.0	0.420	114	2	0.45	6.8	0.30	20	loose	yes	yes
NIST	CF_HW_4	TP	800	12.4	0.31	118	2	0.45	6.8	0.30	28	loose	yes	yes
NIST	CF_HW_6	TS	816	16.7	0.42	183	2	0.45	6.8	0.30	32	loose	yes	yes
NIST	CF_HW_7	TS	812	16.3	0.54	110	3	0.45	6.8	0.30	10	loose	yes	yes
NIST	CF_HW_8	TP	810	15.2	0.43	175	3	0.45	6.8	0.30	20	loose	yes	yes
NIST	CF_HW_9	TS	824	5.1	0.08	112	2	0.45	6.8	0.30	103	loose	yes	yes
NIST	CF_HW_10 *	TS	803/802	15.0	0.43	234	2	0.45	6.8	0.30	40	loose	yes	yes

* More than one type of cable
Cable type: TP = thermoplastic, TS = thermoset
Cable ref: Details are given in reference [1], [2], [3] and [4]; M means several types of cables

CABLE TRAY FIRE MODELLING

The knowledge base of the expert system is obtained from simulations performed with the SYLVIA code [16]. SYLVIA is a two-zone model developed by ASNR designed to predict the behaviours of mechanical/natural ventilation, fire growth, hot gas and smoke propagation, and airborne contamination transfer in confined and mechanically ventilated enclosures. It is used here to simulate a horizontal cable tray fire in an open atmosphere.

Model Assumptions

The cable tray fire model implemented in the SYLVIA software has been derived from the FLASH-CAT model [5], developed by NIST for horizontal cable tray fires in open atmosphere and adapted to confined fires.

Hypotheses used by the FLASH-CAT model suggest that the fire should propagate upward through the cable trays depending on an empirical timing sequence only based on the tray order in the stack model and assumes that, once ignited, the cables burn over a length that is greater than that of the tray below. The burning pattern has therefore an expanding V-shape as there is an increasing length of cable that initially ignite in case of fire propagates upwards and due to lateral propagation of the fire. As the mass of combustible material at the centre of the V is consumed a horizontal extinction front appears at the centre of the trays and the V-shape becomes an open wedge until the full length of cable is burned. A scheme of the modelling of the cables' burning surface area is shown in Figure 3.

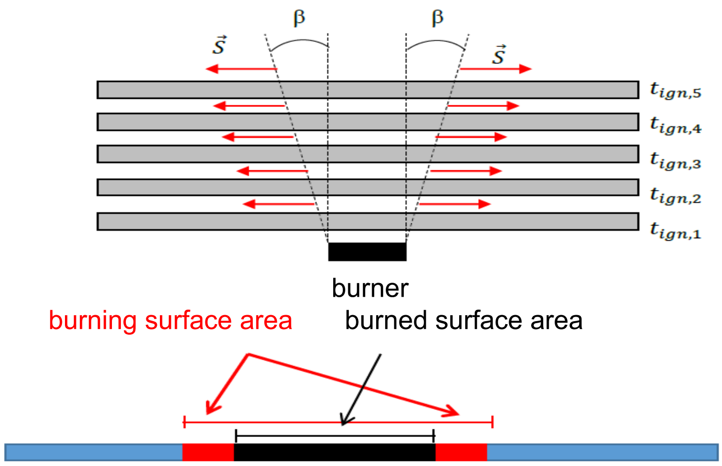

Figure 3 Scheme of the modelling of the burning surface area of cables

The SYLVIA modelling of horizontal cable tray fires differs from that of FLASH-CAT in terms of the upward spread of the fire in the cable tray stack and the flame spread velocity along the cables.

The empirical timing sequence applied in the FLASH-CAT approach for igniting cable trays does not consider the spacing between trays and the nature of the cables. Indeed, a PVC (*p*oly*v*inyl *c*hloride) cable will ignite more quickly than a HFFR (*h*alogen-*f*ree *f*lame-*r*etardant) cable. In SYLVIA, a thermally thick target, whose thickness corresponds to the thickness of the cables' sheath, is set at the supposed ignition zone of each cable tray. This target exchanges with the surrounding gas by convective and radiative heat transfers and by conductive heat transfer in its thickness (one-dimensional (1D) Fourier equation with an adiabatic internal face). The ignition of the cable tray is then operated on a temperature criterion, corresponding to the temperature of the mesh in contact with internal face of the target. Thus, the ignition time of cables is related to the cable properties, to the ambient conditions and to the incident heat fluxes.

The flame spread velocity along cables is a user input in FLASH-CAT because it is constant in open atmosphere. However, it varies from one cable tray to another. In a confined enclosure, the flame spread velocity along cables is no longer constant. This is due to the increase in temperature of the gas surrounding the cables, which tends to increase the flame spread velocity, while the decrease in oxygen content at the level of the cables tends to reduce this velocity, by reducing the heat flux transmitted by the flames to the surface of the cables. The flame spread velocity can be estimated by dividing the fuel distance heated by the flames by the time to ignition. In SYLVIA, the flame spread velocity is given by the Quintiere correlation [17] of the flame spread velocity in open atmosphere, based on a thermally-thick behaviour of the material, to which we apply a time dependence to the ambient gas temperature for confined fires and a correction factor (χ) to the incident heat flux from flames to the cable surface to take into account the decrease in heat flux with the oxygen depletion in the compartment:

$$v_b(t) = \frac{4\left(\dot{q}''_{f,\infty}\chi(O_2)\right)^2 \delta_c}{\pi(k\rho c_p)\left(T_{ig}-T_g(t)\right)^2} \quad (1),$$

where $\dot{q}''_{f,\infty}$ [W/m^2] is the incident heat flux from flames to the cable surface in open atmosphere, $\chi(O_2)$ [-] the oxygen limiting factor, δ_c [m] the heated fuel distance, $k\rho c_p$ [W^{2}s/m^{4}K^2] the thermal inertia of cables, T_{ig} [K], the ignition temperature of cables and $T_g(t)$ [K], the ambient gas temperature.

For horizontal cable tray fires in open atmosphere, a value of 70 kW/m^2 for the incident heat flux from flames to the fuel surface ($\dot{q}''_{f,\infty}$) and a value between 1 and 2 mm for heated fuel distance (δc) are recommended in [17]. Simulations were performed with a value of 2 mm for the heating fuel distance.

Heat Release Rate

The correlation of the HRR is derived from work of Lee [18] who showed that the peak full-scale HRR of a cable tray in an open atmosphere can be predicted according to bench-scale HRR measurements performed on cable samples. This correlation is expressed as:

$$\dot{Q}_{fs} = 0.45\, S\, \dot{q}''_{bs} \quad (2),$$

where $\dot{Q}_{fs}$ [W] is the peak full-scale HRR, S [m^2] the total burning surface of cables involved in the fire at the peak full-scale HRR, $\dot{q}''_{bs}$ [W/m^2] the peak bench-scale HRR per unit area, under an irradiance of 60 kW/m^2, and 0.45 an empirical constant.

Due to the lack of available models for the fire spread on large-scale cable trays in the literature, the Lee's correlation, linked to the geometric consideration (i.e. the assessment of the burning surface of cables), is used at all times to simulate the flame propagation along the cable tray:

$$HRR = 0.45\dot{q}''_{bs}\chi(O_2)\frac{\Delta H_c}{\Delta H_{c,\infty}}\sum_i^n S_i(t) \quad (3),$$

where ΔH_c [J/kg] is the effective heat of combustion and $\Delta H_{c,\infty}$ [J/kg] that in open atmosphere, and $S_i(t)$ the instantaneous burning surface area of cables for the cable tray number *i*.

For a cable tray fire in an open atmosphere, equation (3) is written as:

$$HRR = 0.45\dot{q}''_{bs} \sum_{i}^{n} S_i\,(\mathrm{t}) \quad (4).$$

The difficulty in applying equation (4) lies in estimating the instantaneous burning surface area of the cables which depends on the horizontal fire spread along the cable trays and the vertical fire spread from one cable tray to another.

The surface area of the cables in contact with the surrounding gas depends on the load of the cables and their arrangement (tight or loosely) in the cable trays. For a small number of cables, this surface area is assumed to be equal to the total surface area of the cables. When the number of cables becomes high, the cables are stacked on top of each other, in several more or less compact layers depending on their arrangement. In this case, and for a tight arrangement, the cable surface area in contact with the surrounding gas corresponds to the free surface area of the cable layer. To take into account the cable stacking density when estimating the burning surface area of cables, a correction factor (α) is applied to the total surface area of cables when the number of cables becomes high, and the arrangement is tight. Thus, the instantaneous burning surface area of cables per cable tray is written as:

$$S(t) = \alpha\, n\, \pi\, d\, (x_b(t) - x_e(t)) = p\, (x_b(t) - x_e(t)) \quad (5),$$

where *n* [-] is the number of cables per cable tray, *d* [m] the diameter of cables, $x_b(t)$ [m] the abscissa of the flame front, $x_e(t)$ [m], the abscissa of the extinction front and *p* [m], the total perimeter of the cables in contact with the surrounding gas.

The abscissa of the flame front is given by:

$$x_b(t) = L_0 + \int_{t_{ig}}^{t} v_b\,(t)dt \quad (6),$$

and the abscissa of the extinction front is given by:

$$x_e(t) = x_b(t) - \int_{t_i(x_e)}^{t_e(x_e)} v_b(t)\,dt \quad (7),$$

where $v_b(t)$ [m/s] is the flame spread velocity, L_0 [m] the ignition length of the cable tray, $t_i(x_e)$ [s] denotes the crossing time of the flame front at the abscissa x_e and $t_e(x_e)$ [s] that of the extinction front at the same abscissa, and t_{ig} [s] the ignition time of the cable tray.

At a given abscissa x, from the ignition time of this area, the extinction time corresponds to the moment when all the fuel mass in this zone is consumed. It is given by:

$$\int_{t_i(x)}^{t_e(x)} p\dot{m}''_{c,\infty}\,\chi(O_2)dt = m'_c \quad (8),$$

where $\dot{m}''_{c,\infty}$ [kg/sm^2] is the fuel mass loss rate (MLR) per unit area and m'_c [kg/m] the mass of the fuel per unit length.

DEVELOPMENT OF THE IACA EXPERT SYSTEM

Calibration of the Knowledge Base

The knowledge base collects all the generic information from which the expert system will perform inferences. It determines the application domain of the expert system. A first step consists in delimiting the general framework of the study (horizontal cable trays in an open atmosphere in this case) and in defining the parameters and responses of the study and their variation ranges. In a second step, the SYLVIA database is built, and the conditional probability tables are computed.

Since the computation time using SYLVIA is short enough to perform millions of calculations, our approach consists in building a database by performing a Monte Carlo sampling. This Monte Carlo study is carried out by varying the input parameters of the simulation code. For each parameter of the study, a value is randomly drawn in its range of variation, creating a set of values of the parameters characterizing the SYLVIA calculation to be performed. By performing this simulation, we obtain the values of the responses associated with this parametric configuration. The Monte Carlo method consists in reiterating this procedure a large number of times. Thus, the database of the expert system is made up of all the data corresponding both to the parameters and responses. It can then be interpreted as a numerical transcription of the generic knowledge carried by the SYLVIA software.

Five parameters were taken into account in the study, corresponding to the parameters of the cable tray fire model to be calibrated in the absence of information. Their discretisation is reported in Table 2. The responses of the study are the HRR_{max}, the FGI and the THC. Their discretization is reported in Table 3. The variation ranges of the responses correspond to those of the observed experimental data and those of the parameters are based on engineering judgment.

Table 2 Discretisation of parameters

Parameter	Discretisation
Thermal inertia of cables [kW^2s/m^4K^2]	[0.2; 0.3] [0.3; 0.4] [0.4; 0.5] [0.5; 0.6]
Fuel mass fraction [-]	[0.1; 0.2] [0.2; 0.3] [0.3; 0.4] [0.4; 0.5]
Bench-scale HRR per unit area [kW/m^2]	[100; 150] [150; 200] [200; 250] [250; 300]
Ignition temperature of the cables [°C]	[200; 240] [240; 280] [280; 320] [320; 360]
Fire spread angle [°]	[0; 15] [15; 30] [30; 45]

Table 3 Discretisation of responses

Parameter	Discretisation
HRR_{max} [kW]	< 200 [200; 400] [400; 600] [600; 800] [800; 1000] [1000; 1500] [1500; 2000] [2000; 2500] [2500; 3000] > 3000
FGI [kW/s]	< 0.1 [0.1; 0.5] [0.5; 1] [1; 2] [2; 3] [3; 4] [4; 5] [5; 6] [6; 7] [7; 8]
THC [MJ]	< 100 [100; 500] [500; 1000] [1000; 1500] [1500; 2000] [2000; 2500] [2500; 3000] [3000; 3500]; [3500; 4000] [4000; 4500]

The SE-Toolbox (French acronym for expert system) was used to develop the IACA (French acronym for artificial intelligence applied to cables) expert system. This tool was developed by IRSN (now ASNR) to describe, generate and use an expert system based on a Bayesian network. Only the calculation launch part is not formally addressed in SE-Toolbox since it depends on the business application, the number of calculations to be performed, the CPU (*c*entral *p*rocessing *u*nit) time required for the execution of the calculations, and the resources available to perform them (power and number of processors, submission tool, etc.).

The minimum size of the database depends on the number of parameters, their discretization, and the number of realisations required to evaluate histograms of conditional probability tables. According to the discretization of the parameters (see Table 2), 740,000 SYLVIA calculations were performed to build the knowledge base of the IACA expert system. It took three days of CPU time spread over 60 cores.

Graphical User Interface of the IACA Expert System

The graphical user interface (GUI) for the IACA expert system was generated using the SE-Toolbox tool (see Figure 4). It displays the name and value classes for each parameter (top) and response (bottom) in the study. For each class, a tick box indicates the extent to which the value class for that parameter is involved in the inference. For each class, the associated probability of occurrence is displayed in the third column. In the centre, a button launches the inference engine.

The expert system enables inferences to be made:

– In prognosis mode: determine the possible responses for a configuration of input data;

– In diagnostic mode: identify the compatible input data for a configuration of responses;

– In mixed mode, i.e. inferences that combine both prognostic and diagnostic modes.

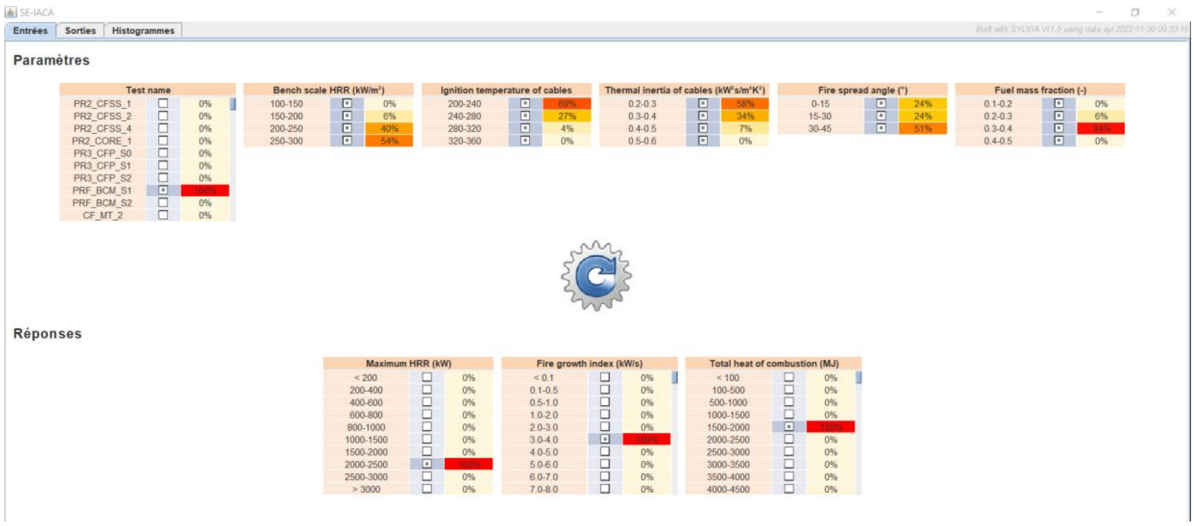

Figure 4 GUI of the IACA expert system

AI CONTRIBUTION TO CABLE TRAY FIRE MODELLING

The IACA expert system was used as a diagnostic tool. Only knowledge relating to the responses (experimental data for HRR_{max}, FGI and THC) is used as input data and the expert system informs us of the most likely values of the study parameters (see Figure 4).

Comparison Between Simulations And Experimental Data

In a first step, the simulations of the 29 fire tests were performed with default values of uncertain parameters in order to assess the contribution of AI to the modelling of cable tray fires. These values are shown in Table 4 and are those reported in [19] for the FLASH-CAT simulations of the CHRISTIFIRE tests. The simulations were then repeated for the 29 fire tests using the values of the uncertain parameters recommended by the expert system. An example is given in Figure 4 for the PRF_BCM_S1 test. Knowing the responses (HRR_{max}, FGI and THC) for this test, the expert system is used in diagnostic mode to identify the values of the uncertain parameters compatible with these responses. For each of the study parameter, the value retained is the central value of the most probable class. The results are shown in Figure 5, in the form of parity plots for the three responses of interest.

Table 4 Default values of uncertain parameters

Parameter	Thermoplastic Cables	Thermoset Cables
Thermal inertia of the cables [kW^2s/m^4K^2]	0.34	0.45
Fuel mass fraction [-]	0.25	0.25
Bench-scale HRR per unit area [kW/m^2]	250	150
Ignition temperature of the cables [°C]	218	330
Fire spread angle [°]	35	35

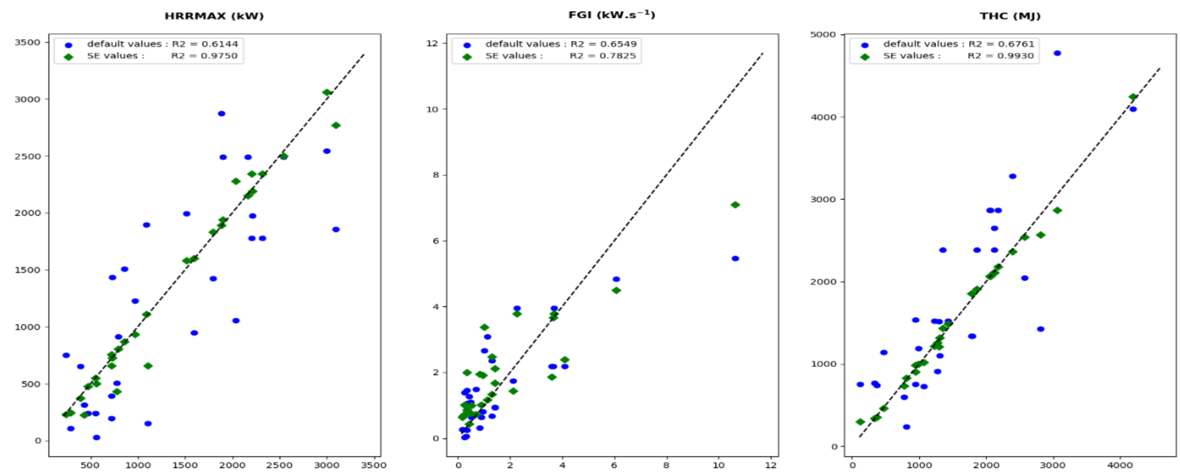

Figure 5 Comparison between simulations (y-axis) and experimental data (x-axis) – the blue points refer to the default values and the green to the values obtained y using AI

The results of the SYLVIA simulations using default values for uncertain parameters are shown in blue on the plots. For the three responses of interest, the R2 score is less than 0.68. The R2 score (also called R-squared) is defined as a number that tells you how well the independent variable(s) in a statistical model explain the variation in the dependent variable. It ranges from 0 to 1, where 1 indicates a perfect fit of the model to the data:

$$R2 = 1 - \frac{Unexplained\ variation}{Total\ variation} \quad (9).$$

The low R2 score reflects a deviation from the experimental data, indicating that one or more of the uncertain parameter plots), a high R2 score is obtained for HRR_{max} (0.97) and THC (0.99). For FGI, although the contribution of AI increased the R2 score from 0.65 to 0.78, it remains unsatisfactory, indicating that the modelling of the phenomenon linked has to be improved. Since FGI is defined as the ratio between HRR_{max} and the time needed to reach it, and since HRR_{max} is well reproduced with the contribution of AI, the modelling of the estimation of the time needed to reach HRR_{max} must be revisited.

In the SYLVIA model of cable tray fires, cables are assumed to ignite uniformly across the width of the cable tray (1D flame propagation). Depending on the width of the cable tray, cable ignition may not be uniform across the entire width of the cable tray. In addition, obstacles along an optical path (such as the presence of a cable trays) are not taken into account in the model of the radiative heat transfer, which leads to an error in the ignition delay of cable trays.

It should be noted that only the parameters of the FLASH-CAT model were selected in the study. The HRR of ignition by an external source is therefore not taken into account, although it may have an influence on FGI. However, experience gained from PRISME projects suggests that its influence is weaker than that of the other FLASH-CAT model parameters.

Influential Parameters

The SE-Toolbox was used to determine the degree of influence of the study parameters on the responses of interest, obtained from the Pearson's correlation coefficients[1] [20]. The results are shown in Figure 6.

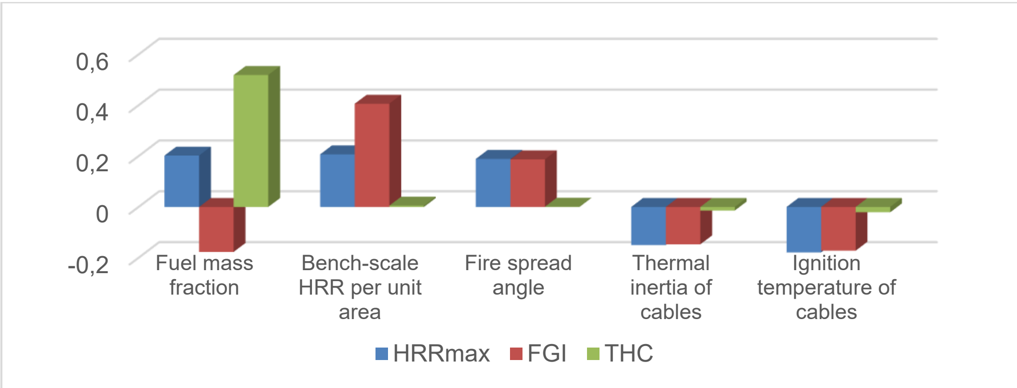

Figure 6 Degree of influence of study parameters on the responses of interest

As shown in Figure 6 for the THC, the only influential parameter is the fuel mass fraction, the other parameters only playing a role regarding the kinetics of fire growth. The five parameters have the same weight on the HRR_{max}, which means that information on all the study parameters is needed for a good estimation of the instantaneous burning surface area of the cables. Indeed, the position of the extinction front depends on the fuel mass loss rate, full-scall HRR is proportional to the bench-scale HRR per unit area, the fire spread angle has a direct effect on the ignition length of the cables, and the thermal inertia of the cables and their ignition temperature act on the fire spread velocity. The most influential parameter for FGI is the bench-scale HRR per unit area. This parameter plays an important role in the time required for the cables to ignite, through the radiative heat flux transmitted by the flames to the cable surface.

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1 Pearson's coefficients measure the linear correlation between two quantities. This is 1 when the variables are proportional and vary in the same direction and -1 if they vary in the opposite direction. The correlation is zero if the variables are independent. Although this is a linear coefficient, if its value is low, it is unlikely that the corresponding variable is influential.

Probability Density Functions

To assess their physical relevance, the input data optimised by the expert system are compared with the default values. Figure 7 shows the results for three inputs (fuel mass fraction, bench-scale HRR per unit area and ignition temperature of cables), comparing the distribution of optimized values with the default value. For the fuel mass fraction, the value that best reproduces the experimental data can be significantly different from the default value. This indicates that this parameter may be the cause of modelling that is too far from experiment. The findings for the other two input quantities also indicate that the default values are probably too restrictive to reproduce the experiments.

Figure 7 Comparison between the probability density functions of three input parameters (mass fraction, bench-scale HRR per unit of area and ignition temperature) and their default values for thermoset (TS) and thermoplastic (TP) cables

CONCLUSION

Modelling cable tray fires remains a complex issue, given the multitude of parameters involved in defining such a fire source. To overcome the difficulty of obtaining reliable input data on cable tray fires, an AI-driven expert system has been developed to analyse experimental uncertainties and guide modelling efforts by identifying areas for model improvement. Expert systems are powerful tools for improving the representativeness of simulations by identifying the most relevant parameters, as shown in this paper. The variability of default values of the uncertain parameters has also been highlighted, indicating that using the same default values to simulate all the fire tests is too restrictive to reproduce experiments.

The originality of our approach lies in proposing a method that takes into account, in a rigorous and systematic way, the dependencies that exist between the input data and the observations of the experimental results. The use of an expert system helps to analyse the extent to which the experimental uncertainty can account for or, on the contrary, is insufficient to explain the discrepancies with the numerical model. This enables a richer exploitation of the experimental results and contributes to the identification of needs in terms of experiments to be carried out or numerical models to be developed.

Expert systems based on Bayesian networks are ergonomic and comprehensible tools because they use symbolic AI based on easily interpretable formal reasoning unlike connectionist AI using machine learning. This is fundamental for modellers who cannot be satisfied with experimental results alone. They must understand the progression of phenomena that led to the result. In this way, expert systems act as a bridge between experimenters and modellers, ensuring a deeper understanding of modelling outcomes and driving further improvements in fire safety simulations.

REFERENCES

[1] United States Nuclear Regulatory Commission (U.S. NRC): Cable Fire At Browns Ferry Nuclear Power Station, NRC Bulletin BL-75-04, Washington, DC, USA, 1975, https://www.nrc.gov/reading-rm/doc-collections/gen-comm/bulletins/1975/bl75004.html.

[2] Sumitra, P. S: Categorization of Cable Flammability. Intermediate-Scale Fire Tests of Cable Tray Installations, Interim Report NP-1881, Research Project 1165-1, Factory Mutual Research Corp., Norwood, MA, USA, 1982.

[3] Institute of Electrical and Electronics Engineers (IEEE) Standards Association: IEEE-383-1974 Standard for Test of Class IE Electric Cables, Filed Splices and Connections for Nuclear Generation Stations, ISBN 1-55937-206-0, IEEE Standards Press, Piscataway, NJ, USA, 1974.

[4] Grayson S .J., et al.: Assessing the fire performance of electric cables (FIPEC), Fire and Materials, Volume 25, Issue 2, pp. 49-60, Wiley & Sons, April 2001, https://doi.org/10.1002/fam.756.

[5] McGrattan, K. et al.: Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE) Phase 1: Horizontal Trays, NUREG/CR-7010, Vol. 1, prepared for United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research, Washington, DC, USA, July 2012, https://www.nrc.gov/docs/ML1221/ML12213A056.pdf.

[6] McGrattan, K., S. Bareham, S., 2013. Cable Heat Release, Ignition, and Spread in Tray Installations During Fire (CHRISTIFIRE). Phase 2: Vertical Shafts and Corridors, NUREG/CR-7010, Vol. 2, , prepared for United States Nuclear Regulatory Commission (U.S. NRC) Office of Nuclear Regulatory Research, Washington, DC, USA, December 2013, https://www.nrc.gov/docs/ML1334/ML13346A045.pdf.

[7] Audouin, L., H. Prétrel, and P. Zavaleta: OECD PRISME 2 Fire Research Project (2011-2016) – Current Status and Perspectives, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 22, 13th International Seminar on Fire Safety in Nuclear Power Plants and Installations, September 18-20, 2013, Columbia, SC, USA, GRS-A-3731, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Köln, Germany, Dezember 2013, https://www.grs.de/sites/default/files/publications/grs-a-3731.pdf.

[8] Zavaleta, P., et al.: Multiple Horizontal Cable Tray Fire in Open Atmosphere, in: Proceedings of Thirteenth international conference on Fire and Materials, pp. 57 - 68 , San Francisco, CA, USA, January 2013, https://www.researchgate.net/publication/313902625_MULTIPLE_HORIZONTAL_CABLE_TRAY_FIRE_IN_OPEN_ATMOSPHERE#fullTextFileContent.

[9] Zavaleta, P., S. Bascou, and S. Suard: Effects of cable tray configuration on fire spread, in: Proceedings of Fifteenth international conference on Fire and Materials, pp.17-30 San Francisco, CA, USA, February 2017, https://www.researchgate.net/publication/314081269_EFFECTS_OF_CABLE_TRAY_CONFIGURATION_ON_FIRE_SPREAD#fullTextFileContent.

[10] Zavaleta, P., and L. Audouin: Cable tray fire tests in a confined and mechanically ventilated facility, Fire and Materials, Vol. 42, Issue 1, pp. 28-43, Wiley & Sons, Hoboken, NJ, USA, July 2017, https://doi.org/10.1002/fa,.2454.

[11] Zavaleta, P., S. Suard, and L. Audouin: Cable tray fire tests with halogenated electric cables in a confined and mechanically ventilated facility, Fire and Materials, Vol. 43, https://doi.org/10.1002/fam.2717

[12] Plumecocq, W., et al.: Common OECD/NEA FIRE and PRISME Cable Benchmark Exercise, Fire Safety Journal, Volume 139 (Issue 1):103815, , Elsevier, June 2023, DOI: 10.1016/j.firesaf.2023.103815, https://www.researchgate.net/publication/371373164_Common_OECDNEA_FIRE_and_PRISME_Cable_Benchmark_Exercise.

[13] Pearl, J.: Probabilistic reasoning in intelligent systems, Morgan Kaufmann Publishers – Burlington, MA, USA,1988.

[14] Chojnacki E., et al: SEVEN expert system: a decision support tool for fire analysis in the nuclear area, in: Röwekamp, M., H.-P. Berg (Eds.): Proceedings of SMiRT 25, 16th International Seminar on Fire Safety in Nuclear Power Plants and Installations, October 28-30, 2019, Ottawa, ONT, Canada, GRS-A-3963, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Köln, Germany, December 2019, https://www.grs.de/de/aktuelles/publikationen/grs-3963-smirt-25-16th-international-seminar-fire-safety-nuclear-power.

[15] Zavaleta P., R. Hanouzet, and T. Beji: Improved Assessment of Fire Spread over Horizontal Cable Trays Supported by Video Fire Analysis, Fire Technology, Vol. 55, no. 1, pp. 233-255, November 2018, https://doi.org/10.007/s10694-018-0788-x.

[16] Joret, J. P., and W. Plumecocq: SYLVIA - a software to study ventilation network, fire, and airborne contamination, RoomVent 2024, Swedvac (EMTF), Stockholm, Sweden. April 2024, https://asnr.hal.science/irsn-04649747v1/document.

[17] Quintiere, J.: Surface Flame Spread, SFPE Handbook of Fire Protection Engineering, 2002, Third Edition, Chapter 2-12, Society of Fire Protection Engineers (SFPE), National Fire Protection Association (NFPA) Inc., Quincy, MA, USA, 2002, https://rakandotcom.wordpress.com/wp-content/uploads/2016/05/sfpe.pdf.

[18] Lee, B. T: Heat Release Rate Characteristics of Some Combustible Fuel Sources in Nuclear Power Plants, NSBSIR 85-3195, National Bureau of Standards (NBS), Washington, DC, USA, 1985.

[19] Mowrer F., and R. Williamson: Flame Spread Evaluation for Thin Interior Finish Materials, in: Fire Safety Science, in: Proceedings of the Third International Symposium, pp. pp. 689 - 698, 1991, https://publications.iafss.org/publications/fss/3/689/view/fss_3-689.pdf.

[20] Rodgers, J. L., and W. A. Nicewander: Thirteen Ways to Look at the Correlation Coefficient, The American Statistician, Vol. 42, Issue 1. pp. 59-66, Taylor & Francis, February 1988), https://doi.org/10.1080/0003105.1988.10475524

[21] Zavaleta, P., S. Suard, and L. Audouin: Cable tray fire tests with halogenated electric cables in a confined and mechanically ventilated facility, Fire and Materials, 43, pp. 543 - 560, 2019, https://doi.org/10.1002/fam.2717.

The seminar itself ended with a short panel discussion initiated by the session chairs summarizing the highlights of their sessions and drawing some conclusions. These are briefly summarized in the following chapter.

4 Seminar Insights' Summary, Conclusions and Outlook

The 18th International Seminar on 'Fire Safety in Nuclear Installations' again clearly demonstrated the ongoing progress with respect to nuclear fire safety on a national as well as international level by all parties involved – licensees and operators of nuclear installations, regulators in charge for fire protection and experts from technical support organisations as well as from vendors and manufacturers of fire protection features for nuclear installations and other scientists involved in nuclear fire safety.

The seminar sessions covered the following major topics:

- Recent developments with respect to fire safety at nuclear installations;
- Specific challenges in fire safety assessment, such as combinations of fires and other hazards, and structural fire protection;
- Advancements in deterministic and probabilistic fire safety analyses, including recent results from experimental investigations and research, analytical methods and fire modelling tools for different purposes,

The presentations given in the frame of this seminar provided a non-negligible added value to the state-of-the-art in nuclear fire safety highlighting recent developments and improvements but also presenting still unresolved issues and remaining challenges in this area in an open manner.

The following conclusions have been drawn from the seminar sessions and the final panel discussion:

Remarkable progress has been achieved with respect to fire safety in nuclear installations and its assessment. And this trend observed already in former seminars of this series, is ongoing. This progress is also reflected in the most recent nuclear regulations, standards and guidance documents, both at national and international levels, e.g. by international organisations such as the International Atomic Energy Agency (IAEA) or the Western European Nuclear Regulators Association (WENRA), also including international peer reviews.

A specific focus of fire safety at nuclear reactor installations in countries with existing nuclear power stations close to the end of their commercial lifetime or already under decommissioning is on the post-commercial safe shutdown and the different decommissioning and dismantling phases, but also on fires during nuclear waste treatment, transport, and storage.

For countries continuing or starting to operate new nuclear power reactors, particularly with new and advanced reactor technologies, fire protection remains a risk significant topic with new challenges upcoming. The seminar therefore emphasized the importance of integrating fire safety considerations into the design and operation of such new technologies.

The seminar underpinned the need for continued research into cable fire behaviour including ageing effects, and complex fire scenarios involving multi-compartment configurations. Recent experimental programmes, including OECD/NEA initiatives, are addressing these gaps; however, additional studies are essential to refine predictive models and enhance fire protection strategies.

The discussions also highlighted that future efforts must focus on adapting fire safety provisions for decommissioning phases and nuclear waste management, where new types of fire events have been observed. Furthermore, the integration of advanced modelling techniques, artificial intelligence, and Building Information Modelling (BIM) into fire safety analysis offers promising opportunities to improve accuracy and efficiency in fire hazard and risk assessments.

International collaboration will remain a cornerstone of progress in nuclear fire safety. The seminar participants strongly supported the continuation of this series of expert meetings, fostering knowledge exchange and joint research initiatives.

The seminar attendees from Europe, Asia and North America representing the different parties involved in nuclear fire safety emphasized the benefits from the information exchange and the expert discussions in this seminar being shared within the nuclear fire experts' community including the technical visit of the EDF Fire Lab. Moreover, the participants strongly expressed their wish of continuing this series of fire safety seminars on a regular basis in time intervals of approximately two years in the future. The next, 19th seminar of this series is therefore planned for late summer 2027, either again in France or in Germany as another Post-conference Seminar of the 29th 'International Conference on Structural Mechanics in Reactor Technology' (SMiRT 29), which will take place in Lyon, France in August 2027 (see https://www.smirt29.com/). This will ensure that the dialogue on fire safety challenges and innovations continues to evolve in line with technological and regulatory developments.

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ISBN 978-3-910548-99-2