Vertiefte Untersuchungen zum hochenergetischen Versagen elektrischer Komponenten (HEAF) mit möglicher Brandfolge

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Gesellschaft für Anlagen-
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(GRS) gGmbH

Vertiefte Untersuchungen zum hochenergetischen Versagen elektrischer Komponenten (HEAF) mit möglicher Brandfolge

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Anmerkung:

Das diesem Bericht zugrunde liegende FE-Vorhaben 3611R01301 wurde mit Mitteln des Bundesministeriums für Umwelt, Bau, Naturschutz und Reaktorsicherheit (BMUB) durchgeführt.

Die Verantwortung für den Inhalt dieser Veröffentlichung liegt beim Auftragnehmer.

Der Bericht gibt die Auffassung und Meinung des Auftragnehmers wieder und muss nicht mit der Meinung des Auftraggebers übereinstimmen.

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Kurzfassung

Ziel des vom Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) geförderten Vorhabens 3611R01301 ist es, Brände infolge eines hochenergetischen Versagens elektrischer Komponenten mit Störlichtbögen, international als HEAF (englisch für *H*igh *E*nergy *A*rcing *F*aults) bezeichnet, aufgrund ihrer nicht unerheblichen sicherheitstechnischen Bedeutung vertieft zu untersuchen.

Der vorliegende Bericht gibt einen Überblick über bislang national wie international vorliegende Erkenntnisse zum hochenergetischen Versagen elektrischer Komponenten, die im Wesentlichen auf der Betriebserfahrung kerntechnischer Einrichtungen basieren.

Aus den Erkenntnissen der internationalen Betriebserfahrung resultiert zudem ein Versuchsprogramm der OECD Nuclear Energy Agency (NEA) zur Untersuchung des Komponentenversagens durch HEAF und mögliche Folgebrände in Kernkraftwerken in den Mitgliedsländern eingesetzten Komponenten, wie Schaltanlagen oder Transformatoren.

Die Ergebnisse der vertieften Analysen und experimentellen Untersuchungen sollen dazu dienen, mögliche Schadensbereiche infolge des hochenergetischen elektrischen Komponentenversagens in angemessener Art und Weise vorhersagen zu können. Die international erzielten Ergebnisse sollen dann im Hinblick auf eine Übertragbarkeit auf deutsche Anlagen an den realen Gegebenheiten in den deutschen Kraftwerken geprüft werden.

Abstract

Main objective of the project 3611R01301 performed on behalf of the Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) is an in-depth investigation of fires at electrical components induced by high energy arcing faults (HEAF) according to their non-negligible significance to nuclear safety.

This report provides an overview on the insights with respect to high energy arcing faults at electrical components mainly gained from investigations of the national as well as international operating experience from nuclear installations.

Moreover, the insights from the international operating experience have resulted in an experimental program carried out in the frame of a task by the OECD Nuclear Energy Agency (NEA) in order to investigate failures of electrical components, e. g. breakers, switchgears or transformers, installed in nuclear power plants of the member countries due to HEAF and potential consequential fires.

The results of the in-depth analyses and experimental investigations shall be used for identifying potential areas of damage in a suitable manner. The results based on inter-national research shall also be checked with respect to their applicability to the situa-tion in German nuclear power plants.

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1 Einführung und Zielsetzung

In der Vergangenheit hat es weltweit, wie auch in Deutschland eine nicht zu vernachlässigende Anzahl von zumeist explosionsartig verlaufenden Brandereignissen infolge eines hochenergetischen Versagens elektrischer Einrichtungen (meistens Hochspannungs-Schaltanlagen oder Transformatoren, aber auch Kabel) gegeben. Untersuchungen des Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in Frankreich sowie verschiedener Fachinstitutionen in den USA haben bereits vor etwa zehn Jahren die hohe sicherheitstechnische Bedeutung derartiger Ereignisse mit nicht zu vernachlässigenden Beiträgen zur Kernschadenshäufigkeit aufgezeigt. Daraus wurde national wie international seitens der Aufsichtsbehörden wie auch von Gutachtern und Fachleuten auf dem Gebiet des Brandschutzes in kerntechnischen Anlagen die Notwendigkeit abgeleitet, Brände infolge eines hochenergetischen Versagens elektrischer Komponenten mit Störlichtbögen, international als HEAF (englisch für *H*igh *E*nergy *A*rcing *F*aults) bezeichnet, eingehender zu untersuchen.

Auf deutscher Seite fanden daraufhin bereits im Rahmen des BMU-Vorhabens 3607R02582 eine Aufarbeitung des Standes von Wissenschaft und Technik sowie eine erste Auswertung der in nationalen wie internationalen Datenbanken verfügbaren internationalen Betriebserfahrung zu HEAF-Ereignissen in kerntechnischen Einrichtungen /ROE 09/ statt. Eine vertiefte Auswertung der entsprechenden Betriebserfahrung in deutschen Kernkraftwerken erfolgte im BMU-Vorhaben 3609R01310 /ROE 11a/.

International wurde seitens der OECD Nuclear Energy Agency (NEA) Working Group IAGE (WGIAGE) eine entsprechende Task Group "OECD HEAF" gegründet, die sich mit dem hochenergetischen Versagen elektrischer Komponenten und dessen Auswirkungen, d. h. Folgebrände einerseits und Beeinträchtigungen von Brandschutzmaßnahmen andererseits beschäftigte. Im Rahmen dieser internationalen Aufgabenstellung fand ab 2009 ein regelmäßiger Informationsaustausch zwischen Fachvertretern aus Kanada, Deutschland, Finnland, Frankreich, Japan, Korea und Schweden zur Thematik des hochenergetischen elektrischen Komponentenversagens statt. Die Arbeitsgruppe stellte nach Auswertung der Betriebserfahrung aus den beteiligten Mitgliedsländern übereinstimmend fest, dass Ereignissen mit High Energy Arcing Faults und ihren Schadensmechanismen in Kernkraftwerken verstärkt Bedeutung zugemessen werden sollte. Dazu wurde den internationalen Experten u. a. eine entsprechende Literaturstudie von Sandia National Laboratories (SNL) /BRO 08/ vorgelegt. Zudem zeigt auch die

Betriebserfahrung aus kerntechnischen Einrichtungen in Kanada, Deutschland, Japan und den USA nach Aussage von Teilnehmern der internationalen Arbeitsgruppe eine nicht zu vernachlässigende Bedeutung von HEAF-Ereignissen für die Sicherheit von Kernkraftwerken auf. Die Ergebnisse der OECD Task, an denen die GRS federführend beteiligt war /NEA 15/, resultierten in der Initiierung eines internationalen Versuchsprogramms der OECD NEA zur Untersuchung des Komponentenversagens durch HEAF an real in den Mitgliedsländern eingesetzten Komponenten.

Die wesentlichen Schwerpunkte dieses internationalen Versuchs- und Auswerteprojektes bestehen darin, um einen eine international abgestimmte technische Definition des hochenergetischen elektrischen Komponentenversagen (HEAF), wie es mit hoher Wahrscheinlichkeit an elektrischen Komponenten, wie Schaltern, Transformatoren usw., auftreten kann, zu geben sowie zum anderen Erkenntnisse aus der Betriebserfahrung, Forschungsaktivitäten und möglichen Strategien zur Verhinderung solcher Ereignisse zwischen den Fachleuten aus den beteiligten Mitgliedsländern auszutauschen.

Weiterhin sollen die diesen Ereignissen zugrunde liegenden physikalischen und chemischen Phänomene vertieft untersucht und aus der Perspektive der Branddynamik möglichst zutreffend charakterisiert werden. In diesem Zusammenhang ist ebenfalls beabsichtigt, ein vereinfachtes Modell bzw. eine deterministische Korrelation zu entwickeln, um die möglichen Schadensbereiche infolge des hochenergetischen elektrischen Komponentenversagens in angemessener Art und Weise und vergleichsweise schnell vorhersagen zu können.

Zudem sollen allgemein akzeptierte Eingangsdaten und Randbedingungen für eine Modellierung solcher Szenarien mittels CFD (*c*omputerized *f*luid *d*ynamics)-Codes definiert werden, welch auch Akzeptanz bei Betreibern wie Behörden und Gutachtern für die Bewertung finden. Last not least soll die Aktivität ggf. auch dazu dienen, die Notwendigkeit weiterführender experimenteller Untersuchungen für die Weiterentwicklung von Eingangsdaten und Randbedingungen der Modellierung von HEAF zu identifizieren, mittels derer sich dann die Modelle validieren und verifizieren lassen.

Die internationale Task OECD HEAF begann im Mai 2009 mit einem Kick-off-Meeting bei der OECD NEA in Paris, wobei Fachleute aus den Mitgliedsstaaten Kanada, Deutschland, Frankreich, Korea und den USA teilnahmen. Als Ergebnis wurde ein sogenannter State-of-the-art Report (SOAR) /NEA 15/ sowie eine Veröffentlichung zu den

Erkenntnissen der internationalen Fachleute über die sicherheitstechnische Bedeutung solcher Ereignisse in kerntechnischen Einrichtungen /ROE 11/ erstellt. Neben einer Darstellung der Auswertung der Betriebserfahrung in den Mitgliedsländern auf Basis eines im Rahmen des BMU-Vorhabens 3607R02582 entwickelten Fragenkatalogs zu HEAF-Ereignissen in Kernkraftwerken /ROE 07/ und /ROE 07a/ bestand eine Zielsetzung dieser internationalen Task in einer Erarbeitung von unter den internationalen Experten abgestimmten deterministischen Korrelationen, mittels welcher sich Schadensmechanismen und -bereiche von Ereignissen mit hochenergetischem elektrischem Versagen im Detail modelliert und die zugehörigen Eingangsparameter und Randbedingungen für solche vereinfachten Rechnungen festgelegt werden können. Dieses Ziel wurde innerhalb der zeitlich limitierten Task nicht erreicht, vielmehr ergab sich Im Verlauf der Aktivität die Notwendigkeit für weiterführende experimentelle Untersuchungen. Diese sollten im Rahmen eines OECD NEA-Versuchsprogramms durch das U.S. NRC (*N*uclear *R*egulatory *C*ommission) Office of Research und deren versuchsführende Institutionen, Sandia National Laboratories (SNL), National Institute of Standards and Technology (NIST) und KEMA ab Frühjahr 2012 durchgeführt werden /SNL 11/. Dabei ist die Beteiligung der NEA-Mitgliedsländer an diesem Projekt wie folgt: Während von U.S.-amerikanischer Seite die Versuchsdurchführung und -auswertung finanziert werden, erfolgt die Beteiligung der weiteren Mitgliedsländer an dem Versuchsprogramm mittels einer Bereitstellung von zu testenden Komponenten.

Von deutscher Seite war es demzufolge im Rahmen des Vorhabens 3611R01301 vorgesehen, in einem ersten Schritt geeignete Komponenten aus deutschen Kernkraftwerken für diese Versuche zu finden und bereit zu stellen. Das vorläufige Versuchsprogramm sollte dementsprechend hinsichtlich seiner Eignung überprüft und – soweit erforderlich – den deutschen Interessen angepasst werden. Weiterhin sollten die Versuche im Rahmen des Vorhabens 3610R01301 fachlich begleitet und die Ergebnisse im Hinblick auf die Entwicklung der o. g. entsprechenden deterministischen Korrelationen ausgewertet werden, um dann mögliche Schadensmechanismen und -bereiche von Ereignissen mit HEAF und möglicher Brandfolge im Detail modellieren und die zugehörigen Eingangsparameter und Randbedingungen für solche vereinfachten Rechnungen festlegen zu können. Dazu sollten die erzielten Ergebnisse an den realen Gegebenheiten in den deutschen Kraftwerken geprüft werden.

2 Ergebnisse der bisherigen Untersuchungen

Im Rahmen des Vorhabens 3610R01301 wurden Erkenntnisse aus der nationalen wie internationalen Betriebserfahrung mit HEAF-Ereignissen gewonnen und im Sinne der Zielsetzung, die zugehörigen Phänomene charakterisieren und gegen unzulässige Auswirkungen von HEAF-.Ereignissen in Kernkraftwerken Vorsorge treffen zu können, aufbereitet. Nachfolgend finden sich diese, bereits veröffentlichten Ergebnisse zeitlich aufsteigender Reihenfolge.

2.1 Bespielhafte Anwendungen der Datenbank OECD FIRE

Nachfolgend findet sich eine englischsprachige Veröffentlichung zur beispielhaften Anwendung der internationalen Datenbank OECD FIRE in Bezug auf HEAF mit Folge-bränden mit dem Titel „Exemplary Applications of the OECD FIRE Database“ /BER 10/.

EXEMPLARY APPLICATIONS OF THE OECD FIRE DATABASE

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Introduction

Currently, the OECD FIRE Database contains records for in total 344 fire events from nuclear power plants (NPP) in the following 12 OECD/NEA member countries constituting a reasonable source of qualitative and quantitative information.

Canada:	CNSC
Czech Republic:	NRI Rez
Finland:	STUK
France:	IRSN
Germany:	GRS
Korea:	KINS
Japan:	JNES
The Netherlands:	KFD VROM
Spain:	CSN
Sweden:	SSM
Switzerland:	ENSI
United States:	NRC

The first phase of the OECD FIRE Project was focused on collecting fire events in an appropriate format in order to achieve a consistent database of high quality being assured by a specific QA (quality assurance) process. During the second phase of the project, several OECD/NEA member countries participating in the OECD FIRE Project have started activities for testing the comprehensiveness of the chosen format and its applicability resulting in valuable improvements and retrieving existing information for specific purposes from the Database.

The Database is structured in narrative event descriptions as well coded fields. The coded fields are grouped into ignition phase, extinguishing phase, consequences and references. In the group “ignition phase” 11 coded fields are available requiring, e.g., information such as location of the fire, type of detection, fire loads available and involved, ignition mechanism and root cause. The current version of the OECD FIRE Coding Guideline, issued December 2008, is included in [1] as Appendix A.

Overview of German Applications of the OECD FIRE Database

One German experts application of the OECD FIRE Database is an analysis of events associated with explosions. A query in the Database on the potential combinations of fire and explosion events has indicated a significant number of explosion induced fires. Most of such event combinations occurred at transformers on-site, but outside of the NPP buildings or inside compartments with electrical equipment. Approximately 50 % of the fires were extinguished in the early (incipient) fire phase before the fire had fully developed. As a consequence of these indications, improvements concerning the fire protection of transformers are intended in Germany.

As there is no specific coded field in the Database to indicate explosions, the main source of information is provided by the event description field. The following terms were used as search filters:

- search for *explo* (explosion, exploded, etc.): 26 events
- search for *defla* (deflagration, deflagrated, etc.): no events
- search for *deto* (detonation, detonated, etc.): no events

In 3 of the in total 26 cases no explosion occurred according to the event description but the term “explo” was used in another meaning. In case of one event, the rapid release of ‘INERGEN’ gas from a gas cylinder occurred due to lack of knowledge of the involved personnel how to properly replace a cylinder. The 22 reported explosions amount to 6.4 % of the 344 events reported up to date. Some details of the explosions are listed in [1, 2].

Concerning the process of explosion distinction should be made between an explosion as a process of rapid combustion (chemical explosion) and an explosion as a physical process resulting from a sudden gas pressure rise by a high energy electric (arcing) fault (HEAF). A chemical explosion was found for only three events (solvent vapor, diesel fuel, hydrogen). In the other 18 cases, a HEAF event as a physical explosion obviously took place at the same time. In some of these cases the electric fault might have caused a fuel pyrolysis and/or spread and acted as an ignition source for a chemical explosion, thus a HEAF event and a chemical explosion may have taken place simultaneously. In one event, a fire led to the explosion of diesel fuel vapor while in another event a fire and an explosion occurred independently from each other in parallel. In all other cases explosions induced the fire.

It was observed that 13 (59 %) events took place outside buildings, 3 events occurred inside electrical buildings. A majority of 59 % of the reported explosions (again 13 events) started at transformers. The other 9 events took place at electrical cabinets, other electrical equipment, or process equipment (3 events each representing 14 %). External fire brigades were needed in 4 of 22 cases (18 %). The 22 events were also evaluated concerning the fire duration with the following results:

- Fire duration between 0 and less than 15 min 11 events
- Fire duration between 15 and less than 30 min 3 events
- Fire duration between 30 and 60 min: 3 events
- Fire duration longer than 60 min : 3 events

For the remaining 2 events no information on the fire duration has been provided. This is in good agreement with the fire durations recorded in the Database (see [1] and [2]) for all events, where for approx. 55 % of the events (128 out of 233 events with fire duration provided) a fire duration of less than 15 min could be found.

Since reportable filter fires have occurred in German NPP, there is an interest of the regulators to find out more details on the potential ignition sources, fire duration and circumstances. The OECD FIRE Database surprisingly contains only a relatively low number of filter fires. Fires at filters used for cleaning of gaseous media were specifically analyzed. These filters are mainly used in HVAC systems or as local filter systems at welding/cutting workplaces. As there is no specific coded field in the Database to indicate filter fires, the events of interest were searched by different fields using as search criteria different terms, such as “filter” or “precipitator” in the description field, “room for ventilation” as the type of room where the fires started, “other component” in connection with “filter” or “heater” as the component where the fire started, or “charcoal” as fuel/combustibles/fire loads.

By these criteria in total 35 events were found in the Database and analyzed. Within the 344 [1] events in the Database, for only 9 ones, representing 2.6% of the events, an air purification filter was actually involved in a fire (for more details see [1, 2]).

An amount of 3 fires occurred at filters belonging to HVAC systems. The typical source of ignition is a heater not being turned off after the fan of the system being turned off. Five events occurred at local filter systems for purifying air from welding or cutting processes. Hot work was always the ignition source. One event occurred in a charcoal filter vessel of the radiolysis gas re-combiner train, which was ignited either by self-ignition or an explosion. This event is somewhat unique compared to the other ones. The time of 125 h until the temperatures were normal again is extremely long. Furthermore, it is the only one out of the 35 selected events where the plant operation mode changed to shutdown mode. All filter fires were suppressed by manual fire fighting. External fire brigades were not needed.

National Applications from other OECD FIRE Member Countries

In Japan, ignition mechanisms have been analyzed (see reference [9] in [1]) in order to understand them and to identify potential fire sources for Fire PSA. The OECD FIRE Database and the fire database (reference [10] in [1]) being developed in Japan have been analyzed and the fire events have been categorized into seven classes with the result that the contribution of electric components from the perspective of ignition is significant.

After a fire in a switchgear room of a Swedish nuclear power plant in 2005 the need of improving the effectiveness of the existing pre-incident planning became apparent. A support to plan the missions is the information on different types of fires. "Type fire" is a short description of how a certain type of fire may develop, what its risks possibly are, and what choices of extinguishing agents and methods have to be used for different fires and plant locations. The focus is also on how to do pre-planning, to update instructions for the fire brigades, how to extinguish a fire and to perform drills and exercises on those types of fire dominating the risk (see [1]). Another important task in this project was to strengthen the dialog and responsibilities between the operators in the main control room and the main leader of the fire rescue brigades. This analysis is documented in the final SKI Report 2006:29.

One idea of another ongoing activity (see reference [8] in [1]) in Sweden is to develop fire event trees. By analyzing the OECD FIRE Database with all the events included, whatever the reporting criteria are, generic fire event trees may be derived based on the documented fire types, causes, and consequences. One goal of this project is to possibly identify some common features for those fire scenarios that result in the most severe consequences in the event trees. An interesting observation from this study is that there might be a need for a deeper analysis concerning the design and reliability of detection systems. It is observed in the study that the detection systems have not been triggered at all or had been triggered lately. The work will be documented in [3].

Comparison of the OECD FIRE Database to National Databases

Comparisons of the OECD FIRE Database to other national fire event databases have been made by IRSN in France and by U.S. NRC in the USA. One section of an appendix to [1] provides the methodology implemented by IRSN for the estimation of the fire frequency using the French operating experience feedback. The same methodology has been applied using the OECD FIRE Database revealing a good consistency between the French and the OECD FIRE Databases. This exercise has shown that the statistical use of the Database is easy and well adapted to define the reference numbers needed for the fire frequency estimation. Notably, the OECD FIRE Database is very useful for those countries whose operating experience feedback is insufficient for a statistical use of national fire events. Even if the national operating experience is sufficient, the use of OECD FIRE data may be very helpful for equipment for which no fire event occurred.

Currently, U.S. NRC is using two fire events databases based on the available U.S. NPP experience. The first database is essentially the EPRI fire events database (see reference [5] in [1]), which has had a few additional features added due to the NUREG/CR-6850 project. The second database contains events reportable to the regulators and some event data of smaller fires being used in the OECD FIRE Project. In the near future, NRC will try to integrate the best features of each database. Upon completion of that work, the NRC plans to examine the international OECD FIRE Database for insights which will improve the overall NRC database. The NRC currently views the OECD FIRE Database Project as a very effective program to better understand international NPP fire events.

Conclusions

In general, the data from NPP experience with fire events stored in the OECD FIRE Database can provide answers to several interesting questions and insights on phenomena, such as examples of frequent fire initiators and their root causes, of electrical equipment failure modes, of fire protection equipment malfunctions, and of fire barriers impaired.

Exemplary applications of the OECD FIRE Database show that it is already possible to retrieve reasonable qualitative information and to get to some extent also quantitative estimations, which can support the interpretation of the operating experience for specific events in the member countries participating in the OECD FIRE Project. The quantitative information will, of course, increase with the increasing number of reported events and a careful description of the respective events to provide as much information as available.

In the third phase of the Project starting in 2010, the OECD FIRE Database will be further analyzed with respect to applications for first probabilistic safety assessment considerations, e.g. the positive and negative role of human factor in the fire ignition on the one hand, and, on the other hand, in fire detection and extinguishing. This has to be investigated in more detail to generate Fire PSA results with a higher confidence. Positive effects of human behavior for fire extinguishing are already identified in the existing Database.

One of the main questions which could be answered by the OECD FIRE Database is how fires can propagate from the initial fire compartment to other compartments, even if there are protective means available for prevention of fire spreading. For generating meaningful event and fault trees for various safety significant fire scenarios, a clear and as far as possible detailed (with respect to time dependencies and safety significance) description of the initial fire event sequence and its consequences are essential. The coding of events has to reflect as far as feasible the needs of the analysts resulting in continuously updating the Coding Guidelines.

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2.2 Untersuchungen zu Ereignissen mit hochenergetischem Komponentenversagen infolge Störlichtbögen in Kernkraftwerken

Nachfolgend findet sich eine englischsprachige Veröffentlichung mit dem Titel „Investigation of High Energy Arcing Fault Events in Nuclear Power Plants" /BER 11/ zur Thematik von Ereignisse in Kernkraftwerken mit hochenergetischem Versagen elektrischer Komponenten infolge Störlichtbögen.

7

Investigation of High Energy Arcing Fault Events in Nuclear Power Plants

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1. Introduction

Operating experience from different industries has shown a considerable number of reportable events with non-chemical explosions and rapid fires resulting from high energy arcing faults (HEAF) in high voltage equipment such as circuit breakers and switchgears.

High energy arcing faults can occur in an electrical system or component through an arc path to ground or lower voltage, if sufficiently high voltage is present at a conductor with the capacity to release a high amount of energy in an extremely short time. High energy arcing faults may lead to the sudden release of electrical energy through the air.

The significant energy released in the arcing fault of a high voltage component rapidly vaporizes the metal conductors involved and can destroy the equipment involved. The intense radiant heat produced by the arc can cause significant damage or even destructions of equipment and can injure people. However, this problem has been underestimated in the past (Owen, 2011a and 2011b).

Arcing events are not limited to the nuclear industry. Examples for such events could be found, among others, in chemical plants, waste incineration plants, and in conventional as well as in nuclear power plants underlining that high-energetic arcing faults are one of the main root causes of fires in rooms with electrical equipment (HDI-Gerling, 2009).

An evaluation of several loss incidents in different types of industrial plants has shown that causes for the generation of arcing faults are mainly due to (HDI-Gerling, 2009):

- contact faults at the screw-type or clamp connections of contactors, switches and other components due to, e.g., material fatigue, metal flow at pressure points, faulty or soiled clamp connections,
- Creeping current due to humidity, dust, oil, coalification (creeping distances, arcing spots),
- Mechanical damage due to shocks, vibration stress and rodent attack,
- Insulation faults due to ageing (brittleness), introduction of foreign matter and external influences.

Investigations of HEAF events have also indicated failures of fire barriers and their elements as well as of fire protection features due to pressure build-up in electric cabinets, transformers and/or compartments, which could lead to physical explosions and fire. These events often occur during routine maintenance.

HEAF have been noted to occur from poor physical connections between the equipment and the bus bars, environmental conditions and failure of the internal insulation (Brown et al., 2009).
The interest in fire events initiated by high energy arcing faults has grown in nuclear industry due to more recent events having occurred at several nuclear installations.
In the ongoing discussion on an international level it appeared necessary to find a common understanding about the definition of high energy arcing faults.
Currently, high energy arcing faults are seen as high energy, energetic or explosive electrical equipment faults resulting in a rapid release of electrical energy in the form of heat, vaporized metal (e.g. copper), and pressure increase due to high current arcs created between energized electrical conductors or between an energized electrical conductor and neutral or ground.
Components that may be affected include specific high-energy electrical devices, such as switchgears, load centres, bus bars/ducts, transformers, cables, etc., operating mainly on voltage levels of more than 380 V (OECD/NEA, 2009a).
The energetic fault scenario consists of two distinct phases, each with its own damage characteristics and detection/suppression response and effectiveness:

1. First phase: Short, rapid release of electrical energy which may result in projectiles (from damaged electrical components or housing) and/or fire(s) involving the electrical device itself, as well as any external exposed combustibles, such as overhead exposed cable trays or nearby panels, that may be ignited during the energetic phase.
2. Second phase, i.e., the ensuing fire(s): this fire is treated similar to other postulated fires within the zone of influence.

However, a common definition of high energy arcing faults is expected as one result of a comprehensive international activity of the OECD on high energy arcing faults in the member states of the Nuclear Energy Agency (NEA) (see below).
A variety of fire protection features may be affected in case of high energy arcing faults events by the rapid pressure increase and/or pressure waves (e.g. fire barriers such as walls and ceilings and their active elements, e.g. fire doors, fire dampers, penetration seals, etc.).
The safety significance of such events with high energy arcing faults is non-negligible. Furthermore, these events may have the potential of event sequences strongly affecting the core damage frequency calculated in the frame of a probabilistic fire risk assessment.

2. High energy arcing faults and work safety

Although only the technical consequences for nuclear power plants and other nuclear installations in case of a HEAF event are discussed in the following in detail, another important hazard resulting from arcing faults should not be ignored. This is the possible injury of workers.
Based on previous statistics it is expected that solely in the U.S. more than 2,000 workers will be seriously burnt by the explosive energy released during arcing faults within one year (Lang, 2005). The magnitude of this problem is far reaching, and the following statistics are staggering (Burkhart, 2009):

- 44,363 electricity-related injuries occurred between 1992 and 2001,
- 27,262 nonfatal electrical shock injuries,
- 17,101 burn injuries,

- 2,000 workers admitted annually to burn centres for extended arc flash injury treatment.

Three main consequences for workers result from a high energy arcing fault: blinding light, intense heat and thermo-acoustic effects.

1. Blinding light:
   As the arc is first established, an extremely bright flash of light occurs. Although it diminishes as the arcing continues, the intensity of the light can cause immediate vision damage and increases the probability for future vision problems.
2. Intense heat:
   The electrical current flowing through the ionized air creates tremendously high levels of heat energy. This heat is transferred to the developing plasma, which rapidly expands away from the source of supply. Tests have shown that heat densities at typical working distances can exceed 40 cal/cm². Even at much lower levels, conventional clothing ignites, causing severe, often fatal, burns. At typical arc fault durations a heat density of only 1.2 cal/cm² on exposed flash is enough to cause the onset of a second-degree burn.
3. Thermo-acoustic effects:
   As the conductive element that caused the arc is vaporized, the power delivered to the arc fault rises rapidly. Rapid heating of the arc and surrounding air corresponds to a rapid rise in surrounding pressure. The resultant shock wave can create impulse very high sound levels. Forces from the pressure wave can rupture eardrums, collapse lungs and cause fatal injuries.

Most of these people will neither have been properly warned of the hazards associated with arc flash nor will they have been adequately trained in how to protect themselves.

While the potential for arc flash does exist for as long as plants have been powered by electricity several factors have pushed arc flash prevention and protection to the forefront.

The first is a greater understanding of arc flash hazards and the risk they pose to personnel. Research has started since a few years for quantifying energy and forces unleashed by arc flash events. This has resulted in the development of standards to better protect workers.

Arc-flash hazard analysis is important in determining the personal protective equipment required to keep personnel safe when working with energized equipment. Contact with energized equipment is a commonly known risk; however exposure to incident energy from an electrical arc is sometimes overlooked. On that background approach boundaries have been determined to improve the arc flash hazard protection (Lane, 2004)

There is much discussion regarding how thorough an arc-flash hazard assessment must be. A complete examination of the system would require assessment at each and every possible work location, a task that is unrealistic to complete. Even if this task was undertaken, some of the accepted analysis methods pose some concerns as to whether the assessment considers the 'most likely' fault scenarios.

The fundamentals of arc-flash hazard analysis are discussed in (Avendt, 2008 and Lane, 2004). The methodology used in the arc-flash hazard analysis is recommended in (IEEE, 2002) where techniques for designers and facility operators are provided to determine the arc flash boundary and arc flash incident energy. How to use this IEEE standard is described in (Lippert et al., 2005).

First and foremost, when considering arc-flash hazards four primary factors have to be mentioned which determine the hazard category:

1. System voltage.

2. Bolted fault current – calculated at the location/equipment to be assessed and subsequently used to calculate the theoretical arcing fault current.
3. Working distance – as measured from the personnel´s head/torso to the location of the arc source.
4. Fault clearing time.

Two of the four primary factors determining the arc-flash hazard category have a larger impact than the others: working distance and fault clearing time.

In (Avendt, 2008) it is underlined that fault clearing time plays the largest role in the arc-flash hazard category. A time-current curve is frequently used to show the relationship between current (amps) and response time (seconds). Most protective devices have an inverse characteristic: as current increase, time decreases. Examples of such curves are given in (Avendt, 2008).

In order to fulfil the obligation to protect workers, several standards and guidelines are currently updated or under development.

For example, the Electricity Engineers Association has developed a discussion paper on the issue of arc flash (EEA, 2010) that will enable the subsequent preparation of a guide which will provide best practice advice for employers and asset owners needing to determine the probability of an arc flash occurring, its severity, means of mitigation and relevant personnel protection equipment.

An overview of various arc flash standards for arc flash protection and arc flash hazard incident energy calculations are presented in (Prasad, 2010).

3. Systematic query of international and national databases

In order to confirm these indications by feedback from national and world-wide operating experience, the national German database on reportable events occurring at nuclear power plants as well as international databases, such as IRS (Incident Reporting System) and INES (International Nuclear Event Scale), both provided by the International Atomic Energy Agency (IAEA), or the OECD FIRE Database (cf. OECD/NEA, 2009) have been analysed with respect to high energy arcing faults events which resulted in a fire and high energy arcing faults events with only the potential of deteriorating fire safety.

That systematic query underlined that a non-negligible number of reportable events with electrically induced explosions and extremely fast fire sequences resulting from high energy arcing faults partly lead to significant consequences to the environment of impacted components exceeding typical fire effects.

All results of the international and national databases are presented in Tables 1, 2 and 3 in the same manner, containing in particular the current plant operational state in case of the event, the information in which component the cause of the event was identified, the voltage level, if only the impacted component was damaged, and information if fire barriers being available had been deteriorated.

3.1 International OECD HEAF activity

Due to the high safety significance and importance to nuclear regulators OECD/NEA/CSNI (Committee on the Safety of Nuclear Installations) has initiated an international activity on “High Energy Arcing Faults (HEAF)” in 2009 (OECD/NEA, 2009a) to investigate these phenomena in nuclear power plants in more detail as an important part of better understanding fire risk at a nuclear power plants which is better accomplished by an international group to pool international knowledge and research means. In this task it is stated:

"The main objectives of this common international activity are to define in technical terms a HEAF event which is likely to occur on components such as breakers, transformers, etc., to share between experts from OECD/NEA member states HEAF events, experiences, research and potential mitigation strategies. In addition, the physical and chemical phenomena of a HEAF event shall be investigated and characterized from a fire dynamics perspective. In this context, a simple model and/or deterministic correlation is intended to be developed to reasonably and quickly predict the potential damage areas associated with a HEAF.

Furthermore, generally acceptable input criteria and boundary conditions for CFD (computerized fluid dynamics) models shall be defined being likely to be accepted by industry and regulatory agencies. In a last step, the needs for possible experiments and testing to develop input data and boundary conditions for HEAF events to support the development of HEAF models shall be identified and the correlations and models developed be validated and verified."

The working group with members e.g. from Canada, France, Germany, Korea, and the United States decided during the Kick-Off Meeting at OECD/NEA in Paris in May 2009 that the goals of the task are to develop deterministic correlations to predict damage and establish a set of input data and boundary conditions for more detailed modelling which can be agreed to by the international community.

The output of the OECD activity may directly support development of improved methods in fire probabilistic risk assessment for nuclear power plant applications. The task may also result in the definition of experimental needs to be addressed later in a project structure (OECD/NEA, 2009a).

3.2 Information from of international databases

First information from the international operating experience collected within the IRS database - for more severe reportable incidents at nuclear power plants - and INES, both provided by IAEA, is given in Table 1.

In addition, applications of the OECD FIRE Database (cf. OECD/NEA, 2009) have indicated that a non-negligible contribution of approx. 6 % of the in total 343 fire events collected in the database up to the end of 2008 (cf. Berg & Forell et al., 2009) are high energy arcing faults induced fire events. Details can be found in Table 2.

At the time being, the existing data base on high energy arcing faults events in nuclear installations is still too small for a meaningful statistical evaluation.

However, the first rough analysis of the available international operating experience gives some indications on the safety significance of this type of events, which potentially will also result in relevant contributions to the overall core damage frequency.

Up to the end of 2009, thirty-eight high energy arcing faults events have been identified in the OECD FIRE Database. Details on these events are provided in the following paragraphs.

The database query was started in Germany. One application of the OECD FIRE Database selected by the German experts was an analysis of events associated with explosions. A query in this database on the potential combinations of fire and explosion events (cf. Berg & Forell et al., 2009) indicated a significant number of explosion induced fires. Most of such event combinations occurred at transformers on-site, but outside of the nuclear power plant buildings or in compartments with electrical equipment.

Year of Occurrence	Reactor Type	Plant State	Component	Voltage Level	Damage Limited to Component	Barrier Deteriorated	Fire / Explosion
2006	PWR	FP	transformer busbar	20 kV	yes	no	F
2006	BWR	FP	switchgear station	400 kV	yes	no	-
2001	PHWR	LP/SD	circuit breaker cables	not indicated	no	no	F
2001	PWR	FP	power switch	not indicated	no	no	E / F
2001	PWR	FP	circuit breaker	not indicated	no	yes	F
2000	PWR	FP	circuit breaker	6 kV	yes	yes	F
2000	PWR	FP	circuit breaker	12 kV	yes	no	F
1996	PWR	FP	power switch	not indicated	no	yes	E / F
1996	PWR	FP	lightning arrester	not indicated	no	no	F
1995	PWR	FP	circuit breaker	6 kV	no	no	E / F
1992	PWR	FP	switchgear room	6 kV	yes	no	F
1991	PWR	FP	control cabinet	6 kV	yes	no	F
1991	PWR	FP	busbar	0.4 kV	yes	no	F
1990	PWR	LP/SD	switchgear station	400 V	yes	no	-
1990	PWR	FP	busbar	6 kV	yes	no	-
1990	LGR	FP	busbar	6 kV	no	no	F
1989	PWR	FP	distribution	6.9 kV	no	no	E / F
1988	PWR	FP	distribution	13.8 kV	yes	no	E / F
1984	BWR	FP	main transformer	not indicated	no	yes	E / F
1983	GCR	LP/SD	control panel	5.5 kV	no	yes	E / F

Table 1. Operating experience from HEAF events reported to INES and IRS (from Berg & Forell et al., 2009)

Year of Occurrence	Reactor Type	Plant State	Component	Voltage Level	Damage Limited to Component	Barrier Deteriorated	Fire / Explosion
2007	PWR	FP	high voltage transformer	not indicated / 345 kV	yes	no	E / F
2006	PWR	FP	electrically driven pump	12 kV	yes	no	E / F
2006	PWR	FP	high voltage transformer	6 kV / 20 kV	no	yes	E / F
2006	PWR	LP/SD	medium and low voltage transformer - oil filled	not indicated / 400 kV	no	no	E / F
2005	BWR	FP	high voltage transformer	not indicated	yes	no	E / F
2005	PHWR	FP	high voltage transformer	not indicated / 500 kV	yes	no	E / F
2003	GCR	FP	high voltage transformer	6.6 kV / 400 kV	no	no	E / F
2002	BWR	LP/SD	high voltage transformer	not indicated	yes	no	E / F
2002	PWR	FP	high voltage breaker	34.5 kV	yes	no	E / F
2001	PWR	LP/SD	high or medium voltage electrical cabinet	6.6 kV	no	yes	E / F
2001	PWR	not indicated	high or medium voltage electrical cabinet	6.6 kV	no	no	E / F
1999	PWR	FP	high voltage transformer	20 kV / 161 kV	yes	no	E / F
1995	PWR	FP	medium and low voltage transformer – dry	not indicated / 130 kV	yes	no	E / F
1994	PWR	FP	high voltage transformer	not indicated / 400 kV	yes	no	E / F
1990	PWR	FP	high or medium voltage electrical cabinet	6.6 kV	yes	no	E / F
1988	PWR	LP/SD	high voltage transformer	20 kV / 400 kV	yes	no	E / F
1988	PWR	FP	high voltage transformer	20 kV / 400 kV	yes	no	E / F
1988	PWR	FP	high voltage transformer	20 kV / 400 kV	yes	no	E / F

Table 2. Operating experience from fire events with HEAF included in the OECD FIRE Database (from Berg & Forell et al., 2009)

Approximately 50 % of the fires in the database were extinguished in the early (incipient) fire phase before the fire had fully developed.
As there is no specific coded field in the database to indicate explosions, the main source of information is provided by the event description field. The following terms were used as search filters:

- search for *explo* (explosion, exploded, etc.): 26 events
- search for *defla* (deflagration, deflagrated, etc.): no events
- search for *deto* (detonation, detonated, etc.): no events

In three of the in total 26 cases no explosion occurred according to the event description but the term "explo" was used in another meaning.
In case of one event, the explosive release of 'INERGEN' gas from a gas cylinder occurred. The 22 reported explosions amount to 6.4 % of the 373 events reported up to date. Some details of the explosions are listed in (Berg & Forell et. al., 2009).
Concerning the process of explosion distinction should be made between an explosion as a process of rapid combustion (chemical explosion) and an explosion as a physical process resulting from a sudden gas pressure rise by a high energy arcing fault.
A chemical explosion was found for only three events (solvent vapour, diesel fuel, hydrogen). In the other 18 cases, high energy arcing faults events obviously took place at the same time indicating a physical explosion.
In some of these cases the electric fault might have caused a fuel pyrolysis/spread and acted as an ignition source for a chemical explosion, thus a high energy arcing fault event and a chemical explosion may have taken place simultaneously. In one event, a fire led to the explosion of diesel fuel vapour while in another event a fire and an explosion occurred independently from each other in parallel. In all other cases explosions induced the fire.
The buildings/locations where the events took place are also listed in (Berg et al., 2009). It was found that 13 (59 %) events took place outside buildings, 3 inside electrical buildings. A majority of 59 % of the reported explosions (again 13 events) started at transformers.
The other nine events took place at electrical cabinets, other electrical equipment, or process equipment (three each representing 14 %).
External fire brigades were needed in 4 of 22 cases (18 %). The 22 events were also evaluated concerning the fire duration with the following results:

- Fire duration between 0 and less than 15 min: 11 events
- Fire duration between 15 and less than 30 min: 3 events
- Fire duration between 30 and 60 min: 3 events
- Fire duration longer than 60 min: 3 events

For the remaining two events no information on the fire duration is provided. This result is in good agreement with the fire durations recorded in the database for all events, where for approx. 55 % of the events (i.e. 128 out of 233 events with fire duration provided) afire duration of less than 15 min could be found.

3.3 Information from of the German database

The German national operating experience from reportable events at nuclear power plants is summarized in Table 3. As one can see from this table different components were impacted, in particular – as expected – switchgears. In many cases the voltage level could not be identified. The damage was in most cases limited to the component where the HEAF occurred, only in one case a barrier was deteriorated. One third of these events were correlated with a fire.

Year of Occurrence	Reactor Type	Plant State	Component	Voltage Level	Damage Limited to Component	Barrier Deteriorated	Fire / Explosion
2007	BWR	FP	transformer	380 kV	yes	no	E / F
2007	PWR	FP	transformer	380 kV	yes	no	-
2006	BWR	LP/SD	auxiliary service pump	not indicated	yes	no	-
2006	PWR	FP	switchgear drawer	not indicated	yes	no	-
2006	BWR	FP	switchgear drawer	not indicated	yes	no	-
2005	BWR	FP	Switch	not indicated	yes	no	-
2004	PWR	LP/SD	emergency power feed line	not indicated	yes	no	-
2004	BWR	FP	diesel generator	6 kV	no	no	F
2004	BWR	FP	cable connection	not indicated	yes	no	F
2004	PWR	LP/SD	diesel generator. exciter	6 kV	yes	no	-
2003	BWR	FP	diesel generator. exciter	6 kV	yes	no	-
2003	PWR	FP	emergency power feed line	500 V	yes	no	F
2002	BWR	FP	emergency power busbar	500 V	no	no	F
2001	PWR	FP	generator transformer switch	not indicated	yes	no	-
2001	BWR	FP	emergency power distribution	660 V	yes	no	-
1999	PWR	FP	ventilation exhaust	not indicated	yes	yes	-
1998	PWR	FP	emergency power distribution	660 V	no	no	-
1996	BWR	FP	switch drawer	500 V	yes	no	F
1995	BWR	FP	switchgear drawer	not indicated	yes	no	-
1993	PWR	FP	currency converter	380 V	yes	no	-
1992	PWR	LP/SD	emergency power generator	not indicated	yes	no	F
1991	BWR	FP	emergency power busbar	10 kV	yes	no	-
1989	PWR	FP	switchgear feed cell	10 kV	no	no	F
1989	PWR	LP/SD	switchgear feed area	380 V?	no	no	F
1988	PWR	LP/SD	switchgear	220 kV	no	no	E / F
1987	BWR	FP	emergency diesel generator	not indicated	yes	no	-

Year of Occurrence	Reactor Type	Plant State	Component	Voltage Level	Damage Limited to Component	Barrier Deteriorated	Fire / Explosion
1987	PWR	FP	auxiliary service water system	not indicated	yes	no	-
1986	PWR	LP/SD	busbar	380 V	no	no	F
1984	BWR	LP/SD	auxiliary power supply	not indicated	yes	no	-
1981	PWR	FP	safety injection pump motor	not indicated	yes	no	-
1979	BWR	LP/SD	switchgear	400 V	yes	no	-
1979	PWR	LP/SD	control rod distribution	not indicated	yes	no	F
1978	PWR	FP	switchgear	220 kV	yes	no	-
1977	PWR	LP/SD	switchgear	350 V	yes	no	-
1977	BWR	LP/SD	emergency switchgear	not indicated	yes	no	-

Table 3. Operating experience concerning reportable HEAF events from German NPP (from Berg & Forell et al., 2009)

In all three tables the following abbreviations are used:

PWR:	pressurized water reactor	BWR:	boiling water reactor
PHWR:	pressurized heavy water reactor	GCR:	gas cooled reactor
FP:	full power	LP/SD:	low power / shutdown
E:	explosion	F:	fire

4. Questionnaire to gain further insights on HEAF

As a result of the evaluation of the above mentioned international databases IRS and INES, a questionnaire has been developed by German experts providing a list of questions, which mainly shall be answered by the licensees (see Röwekamp & Klindt, 2007 and Röwekamp et al., 2007).

The answers to this questionnaire shall provide further insights on the basic phenomena regarding high energy arcing faults and may allow the evaluation of such events as well as the identification of effective preventive measures to be taken in nuclear installations in the future.

This questionnaire has been discussed nationally and in an international experts group. The results of the international discussions as well as a first pilot completion of this questionnaire in a German nuclear power plant resulted in enhancing the questionnaire and its sub-division into two parts depending on the availability of experiences with this type of events in the plants under consideration.

The questions concerning events which occurred at the nuclear power plant cover the operating experience in the respective plant, consequences and effects of the events, fire suppression measures (if needed), event causes and resulting corrective actions.

Questions without plant-specific observations from events deal with preventive measures in the plant and assessment activities performed without direct observations from the events (Röwekamp & Berg, 2008 and Röwekamp et al., 2009). The complete list of elaborated questions is provided in the following.

Part I: Questions concerning events occurred at nuclear power plants

- Operating experience
  1. Does the operating experience of the nuclear power plant (including grid connection) reveal either reportable or minor, non-reportable events interconnected to a high energy electric (i.e. arcing) failure of electric components and equipment with $\geq$ 6 kV?
  2. What was the damage? What was the damage zone? Was there damage by the high energy release (explosion pressure wave, etc.), or by fire or by both?
  3. In which buildings / compartments / plant areas did the event occur?
  4. At what type of component was the fault initiated (e.g., switchgear, motor control centre, transformer (oil filled or dry ones), breakers, cables etc.)?
  5. What voltage level did the component operate at? What was the nominal current load available to the component?
  6. If known, what was the estimated overload current observed during the arcing fault?
  7. How was the HEAF observed or detected? Directly by fire detectors, visual or auditory detection in the location where the fault occurred or indirectly by faulty/spurious signals indirect fire alarms, etc.? (An as far as feasible detailed and exhaustive description of the event is needed.) What were the observations and findings?
  8. What was the arcing duration in case of arcing being the cause? How did the arcing stop? (Note: Due to expert judgment from international experts there may be a correlation between arcing duration and damage consequences/extent)
- Consequences / Effects
  9. Which consequences/effects including secondary ones (e.g. pressure waves, impact by missiles, i.e. induced high frequent voltage, etc.) to adjacent/nearby components (including cables) and compartments / plant areas have been observed besides the typical fire effects? Did, as a consequence, protective equipment fail or become ineffective?
  10. Was the damage limited to one fire compartment and or one redundant safety train or were further compartments / trains affected?
  11. Which functions of fire protection features (fire barriers and their elements as well as active means) have been impaired by the effects of high energy arcing faults, in particular by pressure waves and missiles?
- Fire suppression (if needed)
  12. Was fire extinguishing performed?
  13. If yes, which extinguishing means were applied? Which were successful?
  14. What was (rough estimate) the total fire duration?
- Event causes
  15. Was it possible to find out the causes of the high energy impacts observed? If yes, what were the potential causes?
  16. Were the initial causes (root causes) man-induced (mal-operation, errors), or purely technical ones, administrative causes, or combinations of different causes? Have the root causes been found? (Please list all the root causes.)
- Corrective actions
  17. What are the corrective actions after the event for prevention of recurrence?

Part II: Questions without observations from events at nuclear power plants

- Preventive measures
  18. In which compartments / plant areas are components and equipment with the potential of HEAF installed? Are there safety significant / safety related components available in these compartments / plant areas and/or adjacent ones? If yes, which ones? What are the preventive (structural) measures there against such events?
  19. Which measures are foreseen (originally in the design as well as improved ones after the event) to limit the consequences of such high energy arcing faults failures?
  20. Is it possible to practically exclude by the preventive measures that safety significant equipment is impaired?
  21. Are further measures intended for prevention of these faults (continuous controls, in-service inspections, etc.), and if yes, which ones?
- Assessment without direct observations from the events
  22. In how far are such high energy arcing fault events and their potential effects considered in the frame of periodic safety reviews (deterministic safety status analysis as well as probabilistic safety assessment)?

This German questionnaire could be the basis for gaining plant-specific information also from nuclear power plants in other countries.

5. Some examples of HEAF events in nuclear power plants

In the following, typical examples of high energy arcing fault events which occurred in different nuclear power plants in the last thirty years are provided.

5.1 HEAF in a 10 kV cable with a spontaneous short circuit

A high energy arcing faults event from a spontaneous short circuit with a longer time duration took place in a German nuclear power plant.

This event, which occurred in a 10 kV cable at a BWR type plant, has been analyzed in detail by the responsible expert organization on behalf of the regulator in charge (Berg & Katzer et al., 2009). Details on the electric circuit are provided in Figure 1.

The affected cable was routed from the station service transformer together with various other cables through an underground cable channel to the switchgear building.

Due to the conditions in the ground, cables were partly imbedded in so-called ‘cable cylinder blocks’ manufactured from concrete (see Figure 2).

The short circuit with a duration of some seconds occurred in a single 10 kV cable inside one of the cylinder blocks. Neighboring cables were not affected. During this time period, the PVC insulated cable including the copper conductor evaporated completely on a length of approx. 1 m (see photos in Figure 3).

The pyrolysis and/or evaporation of the PVC cable insulations caused a strong smoke release inside the cable channel.

The automatic fire detectors directly gave an alarm. Due to the typically high air humidity inside the channel, a smoke exhaust system was installed for the cable channel, which removed the smoke rapidly after actuation by the fire detectors.

The overpressure arising from the high voltage short circuit was relieved via open cable conduits to the transformer and leakages.

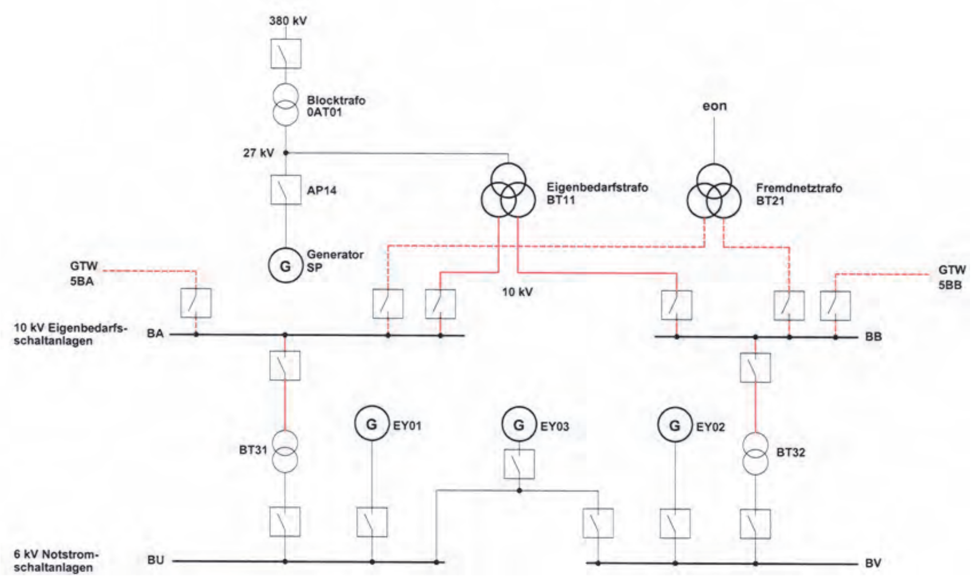

Fig. 1. Scheme of the electric circuit affected

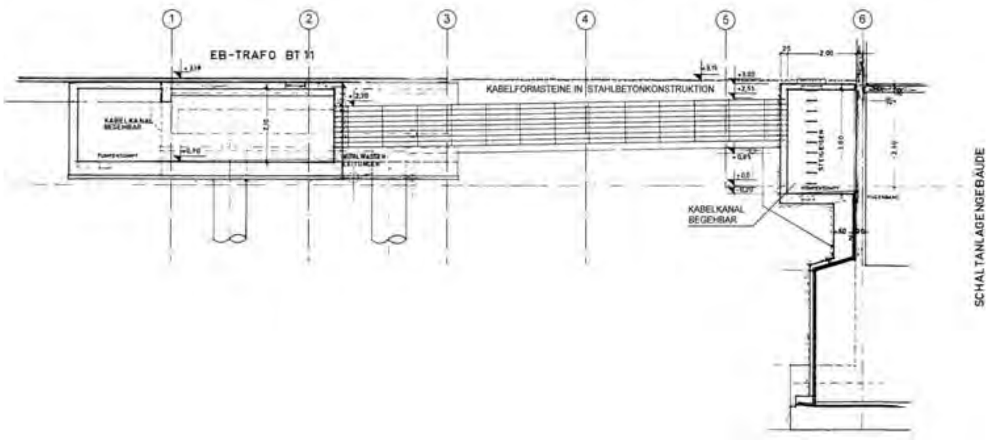

Fig. 2. Cross section of the cable tray inside the cable cylinder blocks inside ground between the buildings

Fig. 3. Photos of the cable damage; left: location of the damaged cable, right: damage by the cable fire/evaporation

Fig. 4. Cables with protection by intumescent coating; left: photo of the cable channel, right: photo of the coating

Unfortunately, the pressure value having really occurred during the event could not been determined. Damage to fire doors, dampers, or fire stop seals were not observed. The high energy short circuit did not result in any fire propagation; the combustion was limited to the location where the short circuit occurred. The fire self-extinguished directly after the electric current had been switched off. The fire duration was only a few seconds, however, the smoke release was high.

It has to be mentioned that all cables inside the cable channel were protected by intumescent coating (see Figure 4 above). This coating ensured the prevention of fire spreading on the cables.

The detailed analysis led to the definite result that the event was mainly caused by ageing of the 10 kV cables. The ageing process was accelerated by the insufficient heat release inside the cable cylinder blocks.

As a corrective action, all high voltage (mainly 10 kV) cables with PVC shielding being older than 30 years were replaced by new ones.

Another effect of the event was the smoke propagation to an adjacent cable channels via a drainage sump. As a preventive measure, after the event each cable channel was supplied by its own drainage system. Moreover, all the channels were separated by fire barriers with a resistance rating of 90 min.

5.2 Arcing fault in an electrical cabinet of the exciter system of an emergency diesel generator

This event occurred at a German nuclear power plant in 1987.

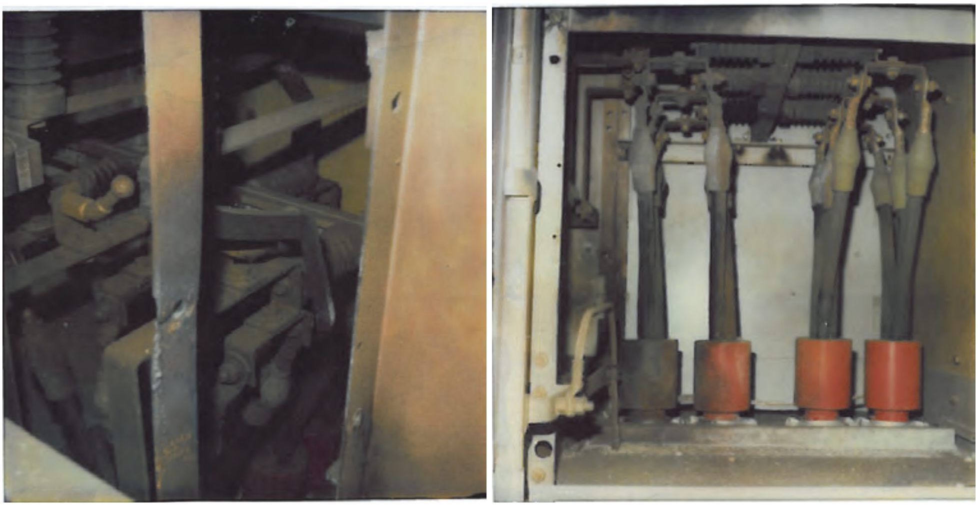

Fig. 5. Photographs: a) view into the exciter cabinet, in the foreground location where the screw loosened and b) view into the cabinet

Fig. 6. Photographs of the damaged fire door from outside the room

Performing a load test during a regular in-service inspection (usually at an interval of four weeks) of the emergency diesel generator, an arcing fault with a short-to-ground took place in the electrical cabinet of the exciter system of the emergency diesel generator (cf. Figure 5 above).

The ground fault is assumed to be caused by a loose screw. The ionization of air by the arc developed to a short circuit within approximately four seconds.

The coupler breakers between the emergency power bus bar and the auxiliary bus bar opened 0.1 s after the occurrence of the short circuit, due to the signal "overload during parallel operation".

1.5 s later the diesel generator breaker opened due to the signal "voltage < min" at the emergency power bus bar. Another 0.5 s later the emergency power bus bar was connected automatically to the offsite power bus bar.

The smouldering fire is believed to be caused by the short circuit of the emergency diesel generator.

Due to the high energy electric arcing fault a sudden pressure rise occurred in the room (room dimensions are approximately 3.6 m x 5.5 m x 5 m) that damaged the double-winged fire door.

Photographs of the damaged fire door from outside the room are shown in Figure 6 above.

5.3 Short circuit leading to a transformer fire

This event occurred at a German nuclear power plant in June 2007. A short circuit resulted in a fire in one of the two main transformers. The short circuit was recognized by the differential protection of the main transformer. Due to this, the circuit breaker between the 380 kV grid connection and the affected generator transformer (AC01) as well as the 27 kV generator circuit breaker of the unaffected transformer (AC02) were opened.

At the same time, de-excitation of the generator was actuated. The short circuit was thereby isolated. In addition, two of the four station service supply bus bars (3BC and 4BD) were switched to the 110 kV standby grid (VE). A simplified diagram is given in Figure 7 (Berg & Fritze, 2011).

Within 0.5 s, the generator protection system (initiating 'generator distance relay' by remaining current during de-excitation of the generator which still feeds the shot circuit) caused the second circuit breaker between the 380 kV grid connection and the intact generator transformer (AC02) to open. Subsequently the two other station service supply bus bars (2BB and 1BA) were also switched to the standby grid. After approx. 1.7 s, station service supply was re-established by the standby grid.

Due to the short low voltage signalization on station service supply bus bars the reactor protection system triggered a reactor trip.

As soon as the switch to the standby grid had taken place , feed water pump 2 was started automatically. After about 4 s the pump stopped injecting into the reactor pressure vessel and subsequently was switched off again. This caused the coolant level in the reactor pressure vessel to drop so that after about 10 min the reactor protection system actuated steam line isolation as well as the start-up of the reactor core isolation cooling system. About 4 min after the actuation of steam line isolation, two safety and relief valves were opened manually for about 4 min. This caused the pressure in the reactor to drop from 65 bar to approx.. 20 bar. As a result of the flow of steam into the pressure suppression pool, the coolant level in the reactor pressure vessel dropped further.

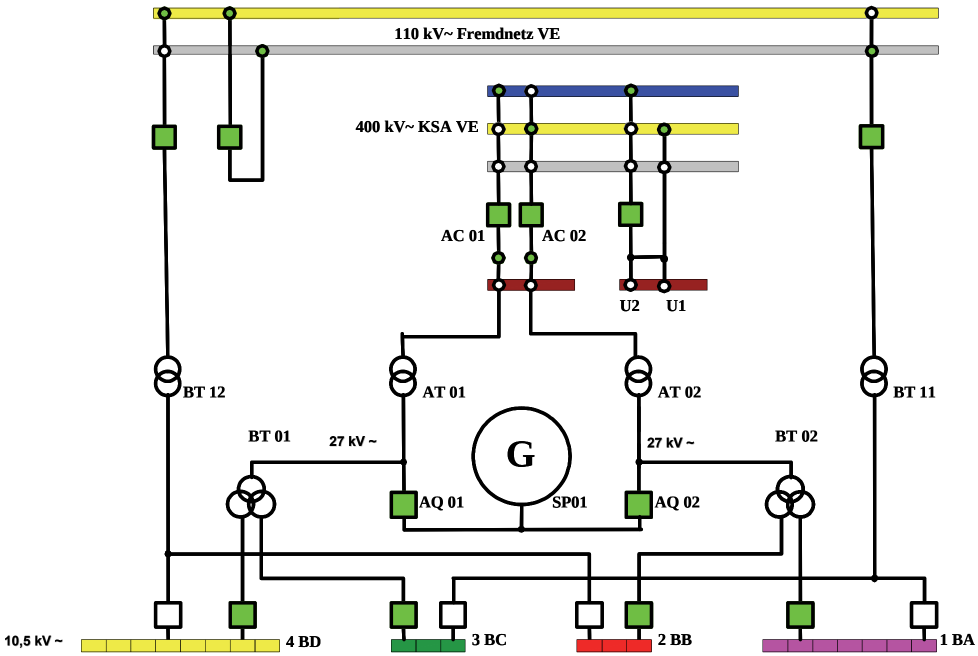

Fig. 7. Simplified diagram of the station service supply and the grid connection of the nuclear power plant

After closing the safety and relief valves the level of reactor coolant decreased further because of the collapse of steam bubbles inside the reactor pressure vessel. Thereby the limit for starting the high-pressure coolant injection system with 50 % feed rate was reached and the system was started up by the reactor protection system. Subsequently, the coolant level in the reactor pressure vessel increases to 14.07 m within 6 min. The reactor core isolation cooling system was then automatically switched off, followed by the automatic switch-over of the high-pressure coolant injection system to minimum flow operation. Subsequent reactor pressure vessel feeding was carried out by means of the control rod flushing water and the seal water.

Due to the damage caused by the fire in the transformer, the plant was shut down. The fire of the transformer showed the normal behaviour of a big oil-filled transformer housing, the fire lacks combustion air and produces a large amount of smoke (see Figure 8).

A detailed root cause analysis regarding the different deviations from the expected event sequence was carried out. The cause of the fire was a short circuit in the windings of the generator transformer. Due to the damages to the transformer it was not possible to resolve the failure mechanisms in all details.

To end the short circuit, the differential protection system of the generator transformer caused to open the circuit breaker between the 380 kV grid connection and the affected generator transformer as well as the generator circuit breaker to the unaffected transformer.

The generator circuit breaker to the affected transformer did not open since the generator circuit breakers are not able to interrupt the currents flowing during a short circuit. The

opening of the circuit breaker between the second 380 kV grid connection and the remaining intact generator transformer is caused by the remaining current after de-exciting the generator which initiates the distance relay of the generator protection system.
The loss of the operational feed water supply was caused by the time margins in between the opening of the two 380 kV circuit breakers. The logical sequence in the re-starting program of the feed water pumps could not cope with the specific situation of the delayed low voltage signals during the incident.
The further drop in the reactor pressure vessel level following the actuation of steam line isolation and the reactor core isolation cooling system was caused by the manual opening of the two safety and relief valves for 4 min. The manual opening of safety and relief valves was not needed in the case of this event sequence and at that point in time. The reason for the manual opening of two safety and relief valves will be part of a detailed human factor analysis which is not completed.
As a consequence of these indications, improvements concerning the fire protection of transformers are intended in Germany (Berg et al., 2010).

Fig. 8. Flame and smoke occurring at the generator transformer; the photo on the right hand shows the fire extinguishing activities

5.4 Phase-to-phase electrical fault in an electrical bus duct

A phase-to-phase electrical fault, that lasted four to eight seconds, occurred in a 12 kV electrical bus duct at the Diablo Canyon nuclear power plant in May 2000 (Brown et al., 2009). This bus supplied the reactor coolant and water circulating pumps, thus resulting in a turbine trip and consequently in a reactor trip.
The fault in the 12 kV bus occurred below a separate 4 kV bus from the start-up transformer, and smoke resulting from the HEAF caused an additional failure.
When the circuit breaker tripped, there was a loss of power to all 4 kV vital and non-vital buses and a 480 V power supply to a switchyard control building, which caused a loss of power to the charger for the switchyard batteries. After 33 hours, plant personnel were able to energize the 4 kV and 480 V non-vital buses.
This event was initiated due to the centre bus overheating causing the polyvinyl chloride (PVC) insulation to smoke, which lead to a failure of the adjacent bus insulation. Having only a thin layer of silver plating on the electrodes, noticeably flaking off in areas not directly affected by the arc, contributed to the high-energetic arcing fault event.

Other factors that caused the failure were heavy bus loading and splice joint configurations, torque relaxation, and undetected damage from a 1995 transformer explosion. Two photos of this failure are shown in Figure 9. More photos are provided in (Brown et al, 2009).

Fig. 9. Photographs of the damages at the Diablo Canyon nuclear power plant (from Brown et al., 2009)

5.5 Short circuit due to fall of a crane onto cable trays

This event occurs at a Ukrainian plant which was at that time under construction when work on dismounting of the lifting crane was fulfilled (IAEA, 2004).

The crane was located near the 330/6 kV emergency auxiliary transformers TP4 and TP5 which are designed for transformation 330 kV voltage to 6 kV for power supply of the 6kV AC house distribution system of the unit 4 and the emergency power supply system 6 kV for unit 3. They are located outside at a distance 50 m from the turbine hall of the unit 4. There are two metal clad switchgear rooms (with 26 cabinets and 8 switchers) about four meters from the emergency auxiliary transformers.

The supply of the sub-distribution buses building from the power centre rooms (see Figure 10), was ensured by a trestle with cable trays consisting of power, control and instrumentation cables for the units 3 and 4.

All trays were provided with the cut-off fire barriers. The transformer rooms were supplied by an automatic fire extinguishing system, which actuated when the gas and differential protection actuated.

The event started when the jib of the crane fell on the trestle with the cables passed from 330/6 kV transformer TP 4 and TP 5 to unit 4 and broke them. The cables fell on the ground. The diagram of the situation after the event is provided in Figure 10 (IAEA, 2004).

Damages of all cable trays lead to loss of instrumentation cables for relay protection of the transformers and the trunk line 6 kV.

As a result the earth fault of the cables 6kV could not be disconnected rapidly. The emergency relay protection of the transformers during earth fault 6 kV from the side 330 kV with the executive current from the storage buttery for open-type distribution substation 330 kV was not designed.

To remove this earth fault the plant was cut off from outside high-voltage transmission lines 330 kV by electrical protection actuation and the voltage on the power supply bus was decreased.

There was a loss of normal and emergency auxiliary power supply which resulted in a decrease of the frequency of ´the power supply buses of the main coolant pumps. The emergency protection was actuated and the reactors of units 2 and 3 were scrammed.
The long-term exposure of this earth fault (1 min and 36´sec.) caused a high earth fault currents which burn the cables. This lead to a fire spread to the 6 kV supply distribution buses and 6 kV metal clad switchgear rooms resulting inside these rooms in high temperature and release of the toxic substance. Also the equipment of the transformers TP 4 and TP 5 was damaged.

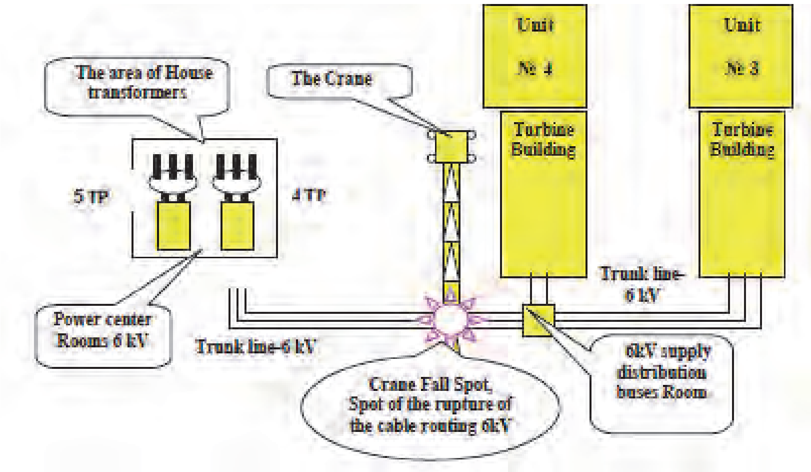

Fig. 10. Diagram of the situation after the event (from IAEA, 2004)

The earth fault has to be disconnected with differential protection of the line 330 kV but it was actuated with the output relays of the TP 4 and TP 5 which was damaged.
The fire was detected by the security guard, the on-site fire brigade was informed, including the outside agency. The automatic fire extinguishing system was activated but stopped working right away because of fire pump's power supply loss. There was no water in the fire mains.
Then the fire brigade laid fire-fighting hoses and provided water with a mobile pump unit. Then the fire brigade waited for the permission from the shift leader.
In compliance with a written procedure, after elimination of the short circuit and restoration of the house distribution power supply the fire brigades could start fire fighting and extinguished the fire about one hour and thirty minutes after detection.

5.6 A triple-pole short circuit at the grounding switch caused by an electrician

In December 1975, a safety significant fire occurred in unit 1 of a nuclear power plant in the former Eastern Germany (see, e.g., Röwekamp & Liemersdorf, 1993 and NEA, 2000) . At that time, two units were under operation. Unit 1 was a PWR of the VVER-440-V230 type. The reactor had 6 loops and 2 turbine generators of 220 MWe each.
An electrician caused a triple-pole short-circuit at the grounding switch between one of the exits of the stand-by transformer and the 6 kV bus bar of the 6 kV back-up distribution that

was not required during power operation. The circuit-breaker on the 220 kV side was defective at that time. Therefore, a short circuit current occurred for about 7.5 minutes until the circuit-breaker was actuated manually. The over current heated the 6 kV cable which caught fire over a long stretch in the main cable duct in the turbine building.

The reactor building is connected to the turbine building via an intermediate building, as typical in the VVER plants. The 6 kV distribution is located in this building and the main feed water and emergency feed water pumps all are located in the adjacent turbine building. In the main cable routes nearly all types of cables for power supply, instrumentation and control were located near each other without any spatial separations or fire resistant coatings. In the cable route that caught fire there were, e.g., control cables of the three diesel generators.

Due to the fire in the 6 kV cable, most of those cables failed. The cable failures caused a trip of the main coolant pumps leading to a reactor scram and the unavailability of all feed water and emergency feed water pumps. The heat removal from the reactor was only possible via the secondary side by steam release. Due to the total loss of feed water, the temperature and pressure in the primary circuit increased until the pressuriser safety valves opened. This heating was slow, about 5 h, due to the large water volumes of the six steam generators, 45 m^3 in each. In this situation one of the pressuriser safety valves was stuck open. Then the primary pressure decreased and a medium pressure level was obtained so that it was possible to feed the reactor by boron injection pumps. Due to cable faults, the instrumentation for the primary circuit was defective (temperature, pressuriser level). Only one emergency diesel could be started due to the burned control cables. The primary circuit could be filled up again with the aid of this one emergency diesel and one of six big boron injection pumps. With this extraordinary method it was possible to ensure the residual heat removal for hours.

The Soviet construction team personnel incidentally at the site then installed temporarily a cable leading to unit 2. With this cable one of the emergency feed water pumps could be started and it was possible to fill the steam generator secondary side to cool down the primary circuit to cold shutdown conditions. Fortunately, no core damages occurred.

Regarding the weak points with respect to fire safety, first of all, the cause for the fire has to be mentioned. This fire could only occur because there was no selective fusing of power cables.

Another very important reason for the wide fire spreading concerning all kinds of cables was the cable installation. Nearly all cables for the emergency power supply of the different redundancies as well as auxiliary cables were installed in the same cable duct, some of them on the same cable tray.

All the fire barriers were not efficient because the ignition was not locally limited but there were several locations of fire along the cable.

In the common turbine building for the units 1 to 4 of the Greifswald plant with its total length of about 1.000 m there were no fire detectors nor automatic fire fighting systems installed. Therefore, the stationary fire fighting system which could only be actuated manually was not efficient. The design as well as the capacity of the fire fighting system were not sufficient.

Although there were enough well trained fire fighting people, the fire-brigade had problems with manual fire fighting due to the high smoke density as there were no possibilities for an efficient smoke removal in the turbine hall.

5.7 Explosion in a switchgear room due to a failure of a circuit breaker

In December 1996, in a PWR in Belgium the following event occurred. The operator starts a circulating pump (used for cooling of a condenser with river water). This is the first start-up of the pump since the unit was shut down.

About eight seconds later, an explosion occurs in a non safety related circuit breaker room (located two floors below the control room), followed by a limited fire in the PVC control cables inside the cubicles. Due to some delay in the reaction time of the protection relays, normal (380 kV) and auxiliary (150 kV) power supply of train 1 are made unavailable. Safety related equipment of train 1 are supplied by the diesel generating set 1. Normal power supply of train 2 is still available.

The internal emergency plan is activated and the internal fire brigade is constituted. The fire is rapidly extinguished by the internal fire brigade.

As a direct consequence of the explosion five people were injured during the accident, one of them died ten days later.

The fire door at the room entrance was open at the moment of the explosion; this door opens on a small hall giving access to the stairs and to other rooms (containing safety and non safety related supply boards) at the same level; all the fire doors of these rooms were closed at the moment of the explosion and were burst in by the explosion blast. Three other fire doors were damaged (one of these is located on the lower floor); some smoke exhaust dampers did not open due to the explosion (direct destruction of the dampers, bending of the actuating mechanism). One wall collapsed, another one was displaced.

The explosion did not destroy the cubicle of the circulating pump circuit breaker; the supply board and the bus bar were not damaged, except for the effects of the small fire on the control cables; other supply boards located in the same room were not damaged. In the room situated in front of the room where the explosion occurred, the fire door felt down on a safety related supply board, causing slight damages to one cubicle (but this supply board remained available except for the voltage measurement).

A comprehensive root cause analysis has been performed and has shown that the explosion occurred due to the failure of the circuit breaker. The failure occurred probably when the protection relay was spuriously actuated 0.12 seconds after the start up of the pump (over current protection) and led to an inadvertently opening of the circuit.

Based on an investigation of the failing circuit breaker, it was concluded that two phases of a low oil content 6 kV circuit breaker did not open correctly and the next upstream protection device did not interrupt the faulting device. This has led to the formation of long duration high energy arcing faults inside the housing and to the production of intense heat release. This resulted in an overpressure with subsequent opening of the relief valve located at the upper part of the circuit breaker presumably introducing ionised gases and dispersed oil into the air of the cubicle/room. This mixture in combination with the arcs is supposed to be at the origin of the explosion. Indications of arcing between the three phases of the circuit breaker have been observed, resulting in a breach of the housing on two phases. Many investigations were conducted to identify the root cause of the circuit breaker failure (dielectric oil analyses, normal and penalising conditions tests, mechanical control valuations) but no clear explanation could be found. Moreover, the circuit breaker maintenance procedure was compared with the constructor recommendations and the practice in France. No significant difference was noticed.

Although the explosion occurred in a non safety related supply boards room, the event was of general importance, because the same types of circuit breakers were also installed in safety related areas. Therefore, this event was reported to IAEA and included in the IRS database.

6. First insights

Due to the safety significance of this type of events and the potential relevance for long-term operation of nuclear power stations there is a strong interest in these phenomena in various countries with nuclear energy. Investigations on high energy arcing faults are ongoing in several OECD/NEA member states.

The licensees of German nuclear power plants are principally willing and able to answer the questionnaire concerning HEAF events as far as possible and information being available. In particular, experts from nuclear power plants in Northern Germany have already answered this questionnaire. The licensees intend to use the feedback from the operational experience provided by the answers to the survey and by conclusions and recommendations from the analysis for potential improvements of fire protection features in this respect in their nuclear power plants.

The evaluation of the answers of the remaining licensees to the questionnaire is ongoing and is planned to be completed by the end of 2011.

Due to the most recent experience from German nuclear power plants, it is necessary from the regulatory point of view to investigate high energy arcing fault events. Moreover, it might be helpful to investigate precursors to such events in more detail.

Table 3 gives indications that more than 40 % of the reportable events in Germany related to high energy arcing faults have been reported since 2001. This underlines the increasing relevance of this type of events.

Moreover, nearly half of those events, for which information regarding voltage level is not available, are among the most recent events whereas usually specific information is more difficult to collect for events in the far past. All these different activities and explanations of the current state-of-the-art should be supported by the evaluation of the answers to the German questionnaire.

Concerning high energy arcing fault events, short circuit failure of high voltage cables (typically 10 kV) in cable rooms and cable ducts (channels, tunnels, etc.) is not assumed for German nuclear power plants at the time being. Moreover, a failure of high voltage switchgears (10 kV or more) and the resulting pressure increase are presumed to occur and to be controlled.

Specific investigations with respect to such scenarios have resulted in additional measures for pressure relief inside switchgear buildings of German nuclear power plants.

According to international fire testing standards (EN, 2009) fire barrier elements are designed predominantly against the thermal impact of fires given by the standard fire curve according ISO 834. The pressure build-up due to a HEAF is not considered as fire barrier design load. In the course of several events fire barrier elements such as fire doors were opened or deformed by a HEAF. One example is described in 5.7.

7. Concluding remarks and outlook

7.1 Improvement of the basic knowledge on HEAF

As soon as the questionnaire has been answered by the German nuclear power station licensees, the answers will be statistically examined and interpreted. In particular, potential consequences of events with this failure mechanism on equipment adjacent to that where the high-energetic arcing faults occurred (particularly safety related equipment including cables, fire protection features) as well as HEAF events in plant areas exceeding the typical fire effects (smoke, soot, heat, etc.) shall be identified. The major goal of this task is to provide first, still rough estimates on the contribution of high energy arcing faults events to the core damage frequency.

The results of the German survey may reveal additional findings on the event causes, possible measures either for event prevention or for limiting the consequences of such faults such that nuclear safety is not impaired. In this context, additional generic results from the OECD HEAF activity are expected.

A review of secondary effects of fires in nuclear power plants (Forell & Einarsson, 2010) based to the OECD FIRE database showed that HEAFs did not only initiated fire event but were also secondary effect of a fire. In two events included in the database, fire generated smoke propagated to an adjacent electrical cabinet, which was ignited by a HEAF. This can be interpreted as a special phenomenon of fire spread. In one case smoke from an intended brush fire spread between the near 230 kV lines and caused a phase-to-phase arc.

As soon as the answers to the questionnaire have been analyzed in detail and the results from the operation feedback are known, a discussion between licensees, reviewers and regulators can be started on the general conclusions and potential back fitting measures and improvements inside the nuclear installations.

Based on the international operating experience, state-of-the-art information and data on high energy arcing faults of electric components and equipment shall be collected and assessed with respect to the phenomena involved. In particular, potential consequences of events with this failure mechanism on adjacent equipment (particularly safety related equipment, fire protection features) and high energy arcing faults events in plant areas exceeding the typical fire effects (smoke, soot, heat, etc.) shall be identified. Based on the collected information and data a more comprehensive and traceable assessment can be performed.

7.2 HEAF assessment

The high energy arcing fault assessment approach developed in (USNRC, 2005) primarily represents an empirical model. As such, it depicts observations mainly based on a single event and characterizes a damaging zone affected this event. To capture variations in current and voltage level, insulation type and cabinet design a mechanistic model has been developed (Hyslop et al., 2008).

Some recent studies have further developed the understanding of the high energy arcing faults phenomena through experimentation and re-evaluation of previous theories.

Damage to cables and equipment by high energy impulses from arcing faults has been shown to be different from that caused by fires alone. Specific components, such as transformers, overhead power lines, and switchgears, have been identified as vulnerable to arc events. However, when looking at the dynamic nature of high energy arcing faults, there are still many factors being not well understood.

Computational fluid dynamics models have also been used to measure the pressure and temperature increase (e.g. in switchgear rooms) and present reasonable results on arc events (Friberg & Pietsch, 1999). However, fires were not evaluated.

The existing research is mainly limited in scope and has not yet addressed all factors important to perform a full-scope probabilistic fire risk assessment including high energy arcing faults. In general, high energy arcing faults events have been minimally explored but improvements in the early quantitative results have been made. In particular, fire PSA needs to assess the event behaviour beyond the initial arc-fault event itself (as past research has focussed) so as to encompass the issues related to the enduring fire. Issues that go beyond the initial arc fault event include the characterization of the potential for ignition of secondary combustibles, characterization of the fire growth and intensity following the enduring fire, and the effectiveness and timing of fire suppression efforts.

In order to improve the probabilistic fire safety assessment approach, further research including experimental studies with respect to the arc mechanisms and phenomena as well as to the damage criteria of the relevant equipment affected by high energy arcing faults is needed. To better address the needs of probabilistic fire safety assessment, the scope of the testing will need to be expanded as compared to past studies. These research activities will be started in the U.S. in the near future (Hyslop et al., 2008), partially together with other countries interested in high energy arcing faults and their significance.

7.3 Strategies for reducing arc flash hazards

An arc flash fault typically results in an enormous and nearly instantaneous increase in light intensity in the vicinity of the fault. Light intensity levels often rise to several thousand times normal ambient lighting levels. For this reason most, if not all, arc flash detecting relays rely on optical sensors to detect this rapid increase in light intensity. For security reasons, the optical sensing logic is typically further supervised by instantaneous over current elements operating as a fault detector. Arc flash detection relays are capable of issuing a trip signal in as little as 2.5 ms after initiation of the arcing fault (Inshaw & Wilson, 2004).

Arc flash relaying compliments existing conventional relaying. The arc flash detection relay requires a rapid increase in light intensity to operate and is designed with the single purpose of detecting very dangerous explosive-like conditions resulting from an arc flash fault. It operates independently and does not need to be coordinated with existing relaying schemes.

Once the arc flash fault has been detected, there are at least two design options. One option involves directly tripping the upstream bus breakers. Since the arc flash detection time is so short, overall clearing time is essentially reduced to the operating time of the upstream breaker. A second option involves creating an intentional three-phase bus fault by energizing a high speed grounding switch. This approach shunts the arcing energy through the high-speed grounding switch and both faults are then cleared by conventional upstream bus protection. Because the grounding switch typically closes faster than the upstream breaker opens, this approach will result in lower incident energy levels than the first approach. However, it also introduces a second three-phase bolted fault on the system and it requires that a separate high speed grounding switch be installed and operational (Inshaw & Wilson, 2004).

To prevent or alleviate HEAF effects, manufacturers have been working to develop arc arrestors and arc detection methods and to improve composite materials in the switchgear interior. The experiments conducted (see e.g. Jones et al., 2000) indicated that research and testing are required to determine the voltage level, insulation type, and construction where bus insulation may help extinguish or sustain arc once established. The use of such devices would likely impact estimates of fire ignition frequency for such events, but no methods currently exist to account for the presence, or absence, of such equipment.

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2.3 Hochenergetisches Versagen elektrischer Komponenten (HEAF) – Aktualisierung der deutschen Betriebserfahrung

Nachfolgend finden sich eine englischsprachige Veröffentlichung zur deutschen Betriebserfahrung mit dem hochenergetischen Komponentenversagen elektrischer Komponenten mit dem Titel „Investigation of High Energy Arcing Faults (HEAF) – Update of the German Operating Experience“ /KAT 11/ und die zugehörige Folienpräsentation dazu.

HIGH ENERGY ARCING FAULTS (HEAF) – UPDATE OF THE GERMAN OPERATING EXPERIENCE

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ABSTRACT

The operating experience of nuclear installations worldwide has provided a reasonable number of high energy arcing fault (HEAF) events characterized by a rapid release of energy resulting in explosive failures of the affected components with the potential of consequential fires. These events typically occur at high voltage electrical components such as switchgears and circuit breakers, or at high voltage cables.

Such electric arcs have led in some events internationally observed to partly significant consequences to the environment of these components exceeding typical fire effects. In-depth investigations have indicated failures due to the rapid pressure increase of those fire barriers and fire protection features not designed against such impacts.

Due to the high safety significance and importance to nuclear authorities OECD/NEA/CSNI has initiated an international activity on "HEAF" in 2009 for analyzing these phenomena in nuclear power plants in more detail for a better understanding of the fire risk due to this type of incidents accomplished by an international experts group to pool international knowledge and research means.

One input into this OECD project is an in-depth analysis of the German operating experience with HEAF in nuclear power plants based on a questionnaire for collection of the necessary data and information on these events.

After having analyzed the first events from the German database on reportable events at nuclear power plants the investigations have meanwhile been completed providing on the one hand insights on some typical HEAF phenomena and, on the other hand, the need for specific experiments to be carried out at equipment where HEAF typically arise.

INTRODUCTION

The operating experience of nuclear installations worldwide has provided a reasonable number of high energy arcing fault (HEAF) events resulting in explosive failures of the affected components with the potential of (partly very rapid) fires. As defined on an international basis within a specific task group "HEAF" of OECD Nuclear Energy Agency (NEA), high energy arcing faults (HEAF) are energetic or explosive electrical equipment faults characterized by a rapid release of energy in the form of heat, light, vaporized metal and pressure increase due to high current arcs between energized electrical conductors or between energized electrical components and neutral or ground. These events typically take place in high voltage electrical components such as switchgears and circuit breakers, or they occur at high voltage cables. HEAF events may also result in projectiles being ejected from the electrical component or cabinet of origin and result in fire.

In a first step, the national German database on reportable events [1] as well as the international databases for reporting incidents from nuclear installations, IRS (Incident Reporting System) and INES (international nuclear event scale), have been searched for HEAF events. The systematic query gave indications (see also [2] and [3]) that a reasonable number of reportable events with explosions and rapid due to high energy arcing faults (HEAF) have under some circumstances resulted in significant consequences to the environment of impacted components with the potential of endangering nuclear safety. In-depth investigations of these events have also identified failures of fire barriers and of a variety of fire protection features (such as fire doors, dampers, penetration seals, and the barriers themselves) due to pressure build-up and/or pressure waves.

As a result of these indications from the operating experience worldwide and first research results, an international activity has been started by OECD Nuclear Energy Agency (NEA) CSNI (Committee on the Safety of Nuclear installations) Working Group IAGE in 2009 for preparing a state-of-the-art report on HEAF of electrical components and equipment based on the operating experience of the partners in this project. More details on this activity are provided in [4].

After having analyzed the first events from the German database on reportable events at nuclear power plants [1] in 2009 (see also [2] and [3]), the investigations with respect to the German nuclear power plant operating experience have meanwhile been completed providing on the one hand insights in some typical HEAF phenomena and, on the other hand, indications on the need for experimental research to be carried out at equipment where HEAF typically arise. In the following, the German operating experience is summarized.

INSIGHTS FROM THE OPERATING EXPERIENCE WITH RESPECT TO HEAF EVENTS AT NUCLEAR POWER PLANTS IN GERMANY

As a result of analyzing the international event databases IRS and INES as mentioned before, a questionnaire has been developed covering a list of questions mainly to be answered by the licensees of nuclear power plants. Major goal of this query is to gain insights on the basic HEAF phenomena and to make possible the evaluation of such events and the identification of preventive measures in the future.

This questionnaire has been developed under the lead of experts from Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS) and from Germanischer Lloyd Bautechnik GmbH (GL) with the aim to collect all the information and data needed for a meaningful analysis of the operating experience at nuclear stations and as a prerequisite for assessing the significance of HEAF events in probabilistic risk analysis. The corresponding analysis of the licensees' response has been done based on this query.

The insights of these investigations will also be generically processed and the feedback from the national German operating experience will be forwarded to the licensing and supervisory authorities, to the German licensees, and to the member of the OECD/NEA activity on HEAF to be used in the state-of-the-art report probably to be published in 2012.

Update of the Feedback from the German Operating Experience on HEAF at Nuclear Power Plants

The results of searching the German database on reportable events at nuclear installations [1] for HEAF events provided – based on the most recent definition of HEAF provided by the international experts in the frame of the OECD/NEA task on HEAF the results presented in Table 1, containing – in particular – the current plant state in case of the event, the component where the HEAF started, the voltage level of the HEAF component (if only the impacted component was damaged) and if existing fire barriers had been deteriorated or damaged.

From this table it can be concluded that different components were impacted, in particular switchgears and circuit breakers, as expected. In some cases it was not possible to identify the voltage level in case of the HEAF occurrence. In the majority of the events, the damage was limited to the component where the HEAF itself occurred; a fire barrier was deteriorated only in case of the HEAF events listed, and only 11 events were correlated to a fire.

Table 1 Operating experience with respect to reportable HEAF events from German NPP (from [1])

Year of Occurrence	Reactor Type	Plant State	Component	Voltage Level	Damage Limited to Component	Fire Barrier Deteriorated	Fire and/or Explosion
2009	BWR	FP	transformer	400 kV	yes	no	-
2008	PWR	FP	circuit breaker	0.66 kV	yes	no	F
2007	BWR	FP	transformer	400 kV	yes	no	E / F
2007	PWR	FP	transformer	400 kV	yes	no	-
2006	BWR	LP/SD	auxiliary service pump	0.40 kV	yes	no	-
2006	BWR	FP	switchgear drawer	0.66 kV	yes	no	-
2006	BWR	FP	switchgear drawer	0.66 kV	yes	no	-
2005	BWR	FP	circuit breaker	6 kV	yes	no	-
2004	PWR	LP/SD	emergency power feed line	6 kV	yes	no	-
2004	BWR	FP	cable connection	10 kV	yes	no	F
2004	BWR	LP/SD	Diesel generator. exciter	unknown	yes	no	-
2003	BWR	FP	Diesel generator. exciter	unknown	yes	no	-
2003	PWR	FP	emergency power feed line	0.5 kV	yes	no	-
2002	BWR	FP	emergency power busbar	0.5 kV	**no**	no	F
2001	PWR	FP	generator transformer switch	400 kV	yes	no	-
2001	BWR	FP	emergency power distribution	0.66 kV	yes	no	-
1999	PWR	FP	ventilation exhaust	unknown	yes	no	-
1998	PWR	FP	emergency power distribution	0.66 kV	yes	no	-
1996	BWR	FP	switch drawer	0.5 kV	yes	no	F
1995	BWR	FP	switchgear drawer	unknown	yes	no	-

Year of Occurrence	Reactor Type	Plant State	Component	Voltage Level	Damage Limited to Component	Fire Barrier Deteriorated	Fire and/or Explosion
1993	PWR	FP	currency converter	0.38 kV	yes	no	-
1992	PWR	LP/SD	emergency power generator	unknown	yes	no	F
1991	BWR	FP	emergency power busbar	10 kV	yes	no	-
1989	PWR	FP	switchgear feed cell	10 kV	**no**	no	F
1989	PWR	LP/SD	switchgear feed area	0.38 kV	no	no	F
1988	PWR	LP/SD	switchgear	220 kV	**no**	no	E / F
1987	BWR	FP	emergency diesel generator	unknown	yes	no	-
1987	PWR	FP	auxiliary service water system	unknown	yes	no	-
1986	PWR	LP/SD	busbar	0.38 kV	**no**	no	F
1984	BWR	LP/SD	auxiliary power supply	unknown	yes	no	-
1981	PWR	FP	safety injection pump motor	unknown	yes	no	-
1979	BWR	LP/SD	switchgear	0.4 kV	yes	no	-
1979	PWR	LP/SD	control rod distribution	unknown	yes	no	F
1978	PWR	FP	switchgear	220 kV	yes	no	-
1977	PWR	LP/SD	switchgear	0.35 kV	yes	no	-
1977	BWR	LP/SD	emergency switchgear	unknown	yes	no	-

Abbreviations:

PWR: pressurized water reactor   BWR: boiling water reactor   FP: full power
LP/SD: low power / shutdown   E: explosion   F: fire

Results of the In-depth Investigations on HEAF Events at German Nuclear Power Plants

The German Questionnaire [5] covers questions directly with respect to HEAF events occurred at nuclear installations as well as questions referring to HEAF phenomena without explicit observations from events having occurred.

The questions regarding HEAF events focus on the operating experience itself including the type and size of damage, the components and plant areas affected the detection and/or identification of the HEAF and its duration, but also on the direct as well as indirect effects of the HEAF. This also includes potential consequences to nuclear safety. In case of a consequential fire the performance of fire protection means should be outlined. In addition, the licensees should provide ass far as possible information on the event causes and corrective actions taken in the affected plant.

The more general questions without observations from HEAF events occurred on site concern preventive measures taken in the plant against HEAF and the consideration of HEAF events and their potential effects in the frame of periodic safety reviews (deterministic safety status analyses as well as probabilistic risk assessment).

After the already well known more significant HEAF events presented in [2] having occurred inside a cable channel underground and at a main transformer, the German operating experienced has revealed further HEAF events, which fortunately had only limited consequences and no direct effects on the plant safety, but nevertheless the potential of impairing nuclear safety under different boundary conditions.

One event occurred at a 400 kV transformer of a Konvoi type PWR in 2007 during full power. In the area of the 400 kV electrical lead-off area, a short to ground occurred in one phase due to an electric arc. The arc induced short to ground was caused was caused by harsh weather conditions during a big storm. The short to ground was stopped by the electrical fuse for grid protection. This resulted in isolation/separation of the nuclear plant from the 400 kV external grid and an auxiliary power changeover.

The HEAF event was detected by spurious signal in the main control room. The HEAF itself was limited to the transformer area where it occurred (lead-off area) and did fortunately neither cause harm to nuclear safety nor result in a fire.

Another HEAF event, this accompanied by fire, occurred in 2008 at a PWR plant. The plant was under full power conditions. After hooking up a high pressure (HP) transfer pump from the main control room fire detectors in the corresponding switching panel of the 660 V switchgear were actuated automatically. It was not possible to switch off the pump from the main control room; therefore the corresponding busbar was switched off.

A high energetic arc occurred at the circuit breaker of the pump in the switchgear building (switchboard room) due to incorrect position of the switching contacts points. The root caused could not be identified with 100 % confidence, but it is assumed with high confidence that foreign particle impingement in the circuit breaker was the original cause.

A smoldering fire occurred as a result of the HEAF being detected in due time by the automatic detectors. The fire, which could be directly confirmed, was successfully suppressed by the on-site fire brigade by a portable fire extinguisher with CO_2 as extinguishing medium within approx.15 min.

Last not least, in 2009 another HEAF event occurred at a small oil filled transformer in a German BWR plant. A short circuit occurred at a 400 kV generator transformer located outside in the yard next to the turbine building resulting in an automatic reactor scram. Up to now, the root cause has not yet been identified. Due to the high energy release with a rapid pressure increase in the transformer vessel oil was released in the area of the flanges; however there was fortunately no ignition. In case of ignition the event potentially might have impaired the plant safety.

The HEAF was immediately recognized and identified at the main control room through faulty signals arising. The event was limited to the transformer and did neither result in fire or explosion nor to a deterioration of fire protection features.

GENERAL INSIGHTS

The operating experience with HEAF in German nuclear power plants has revealed strong indications that only few components are typically endangered to experience a HEAF with the potential of explosion and/or fire, resulting impacts on fire protection features, mainly due to the strong and rapid pressure increase, or even endanger nuclear safety.

Typically, there are specific areas and only few high voltage components affected by HEAF as outlined in Table 2 for an exemplary reference plant.

Table 2 Example for potential NPP areas with typical HEAF components

Component / Plant Area	Voltage Level		
	10 kV	***6 kV***	***0.4 kV***
Reactor Building	2		
Switchgear Building	2		4
Turbine Building	2		
Emergency Diesel Building		3	
Cooling Water Pump Station	2	2	
Transformer Switchyard	3 / 11	6	

CONCLUSIONS AND OUTLOOK

The in-depth investigations of the German operating experience with HEAF in nuclear power plants based on a query to the NPP licensees has provided several insights on the type of equipment, where such events typically occur, and the corresponding voltage levels the components affected are operated on.

HEAF as defined by the international OECD/NEA task group "HEAF" mainly occur at switchgears and circuit breakers as well as on high voltage cables. Another type of equipment showing similar behavior is high and medium voltage transformers, most of them oil filled ones, of different sizes.

Most of the equipment affected is operated on voltage levels of 0.4 kV, 6 kV and 10 kV.

All 36 HEAF events having occurred at and reported so far from German nuclear stations have been detected and identified by faulty or spurious signals of electric equipment indicating a malfunction. In case of heavy smoke arising, the events were additionally been detected by the automatic fire detection systems

Due to complex in-depth fire protection concepts being realized in all German NPP with a very high level of separating redundant safety trains the effects were always limited to only one train, if they had occurred in safety related areas. There were no relevant effects observed as a result of the explosions.

For two of in total five HEAF events with consequential fire, smoke propagation from the fire compartment or fire area to other compartments/buildings occurred

In the case of four of the events presented in this paper fire fighting was necessary for the HEAF induced fire, in three of these events the fire could be directly successfully suppressed by a portable extinguisher only. Only in one case, several attacks were needed.

Although it has been observed on an international basis that HEAF events may seriously deteriorate or even destroy firer barriers and other fire protection features either by heat and/or smoke impact or by the rapid and strong pressure rise, no such effects occurred in the German plants.

The root causes, although not always identified with 100 % confidence, were mainly technical reasons, often in combination with human failures. The more recent events have also provided strong indication that ageing of the typical HEAF related components, e.g. of the cables or the transformer windings, may play an important and increase the frequency of HEAF events.

One important result of the analysis of the German operating experience with high energy arcing faults (HEAF) is that the following prevention measures are essential:

- Quick detection and identification of the event occurrence and its location and reaction to these occurrences by the operator installing features for electric arc detection, mainly via pressure sensors in connection with overcurrent monitoring (500 ms on 100 ms);
- Timely detection/identification of slowly proceeding damages by oil monitoring and periodic inspections of insulation resistances;
- Prevention of a relevant pressure build-up by installation of pressure relief openings
- Consideration of deterioration aspects by replacement of (ageing) components such as transformers, control units, cables.

All this has already been recognized by the regulators and the NPP operators in Germany so that a variety of adequate provisions has meanwhile been taken by the German NPP licensees.

Fortunately, none of the events having occurred in German nuclear installed so far did jeopardize the plant safety. However, it is well recognized that such type of events always has the potential to result in explosions and/or fires which could impair nuclear safety or which could lead to deterioration of fire protection features essential to protect equipment of the redundant safety trains.

Therefore, the German experts see a strong need for further in-depth investigations of HEAF phenomena and to develop, based on experimental research with regard to typical HEAF components, a mechanistic model to account for the potential failure modes and consequence portions of high energy arcing faults. This should also support a better characterization of high energy arcing faults in the probabilistic risk assessment of fires.

It is therefore intended by the German experts trying to support the HEAF testing program of the United States Nuclear regulatory Commission (NRC) Office of Research to be carried out in the frame of an OECD/NEA Project by providing typical high voltage equipment to be tested. The German licensees of nuclear power plants have already been contacted and seem also be interested in the testing program and its results.

ACKNOWLEDGEMENTS

Several experts from various German as well as international institutions contributed to the work of the international experts group on High Energy Arcing Faults, HEAF. The investigations of GRS and GL were co-sponsored by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the German

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HIGH ENERGY ARCING FAULTS (HEAF)
Update of the German Operating Experience

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12th International Seminar on
“FIRE SAFETY IN NUCLEAR POWER PLANTS AND INSTALLATIONS“
Munich, Germany; September 13th – 15th, 2011

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HEAF – Update of the German Operating Experience

- Introduction
- Questions Concerning Events Occurred at Nuclear Power Plants
- Update of the Feedback from the German Operating Experience
- Results
- Conclusion

HEAF – Update of the German Operating Experience

Introduction

From the national and international operation experience in nuclear facilities in the recent past a series of explosive fire events were recorded in consequence of a highly energetic failure of electrical equipment.

Accordingly the safety significance of events with highly energetic failures of electrical components (High Energy Arcing Faults, HEAF) in nuclear facilities is recognised by the experts (operator, surveyors and supervisory authorities).

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Definition of High Energy Arcing Fault (HEAF)

High energy, energetic, or explosive electrical equipment faults resulting in a rapid release of electrical energy in the form of heat, vaporized metal (e.g. copper), and pressure increase due to high current arcs created between energized electrical conductors or between an energized electrical conductor and neutral or ground

Components affected may include specific high energy electrical devices, such as switchgears, load centers, bus bars/ducts, transformers, cables, etc., operating on high voltage levels

HEAF – Update of the German Operating Experience

Introduction (continued)

Such events have the potential to result in internal fires. In this respect such events have to be examined in regard to the transferability of their possible causes to all German plants.

Besides the cause investigation of the respective events this also includes the clarification of specific questions, such as

- the possible failure of fire sealings after pressure build-up
- effects of the affected redundancy on nearby redundancies and components
- the potential for prevention of the pressure build-up

HEAF – Update of the German Operating Experience

Introduction (continued)

A questionnaire was prepared in line with a project of experts of GRS and Germanischer Lloyd (GL) Bautechnik GmbH.

Supported by the operators of German nuclear power plants these questions were answered by the licensees for relevant events.

System specific operational experiences were gained.

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Questions Concerning Events Occurred at Nuclear Power Plants

Operating experience

- Does the operating experience of the nuclear power plant (including grid connection) reveal either reportable or minor, non-reportable events interconnected to a high energy electric (i.e. arcing) failure of electric components and equipment **≥ 0.4kV**?
- What was the damage? What was the damage zone? Was there damage by the high energy release (explosion pressure wave, etc.), or by fire or by both?
- In which buildings / compartments / plant areas did the event occur?
- At what type of component was the fault initiated (e.g., switchgear, motor control centre, transformer (oil filled or dry ones), breakers, cables, etc.)?
- What voltage level did the component operate at?
What was the nominal current load available to the component?

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Questions Concerning Events Occurred at Nuclear Power Plants

Operating experience (continued)

- If known, what was the estimated overload current observed during the arcing fault?
- How was the HEAF observed or detected? Directly by fire detectors, visual or auditory detection in the location where the fault occurred or indirectly by faulty/spurious signals indirect fire alarms, etc.? (An as far as feasible detailed and exhaustive event description is needed.) What were the observations and findings?
- What was the arcing duration in case of arcing being the cause? How did the arcing stop? (Note: Due to expert judgment from international experts there may be a correlation between arcing duration and damage consequences/extent)

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Questions Concerning Events Occurred at Nuclear Power Plants

Consequences / Effects

- Which consequences/effects including secondary ones (e.g. pressure waves, impact by missiles, i.e. induced high frequent voltage, etc.) to adjacent/nearby components (including cables) and compartments / plant areas have been observed besides the typical fire effects? Did, as a consequence, protective equipment fail or become ineffective? In which buildings / compartments / plant areas did the event occur?
- Was the damage limited to one fire compartment and or one redundant safety train or were further compartments / trains affected?
- Which functions of fire protection features (fire barriers and their elements as well as active means) have been impaired by the effects of HEAF, in particular by pressure waves and missiles?

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Questions Concerning Events Occurred at Nuclear Power Plants

Fire suppression (if needed)

- Was fire extinguishing performed?
- If yes, which extinguishing means were applied? Which were successful?
- What was (rough estimate) the total fire duration?

Event causes

- Was it possible to find out the causes of the high energy impacts observed? If yes, what were the potential causes?
- Were the initial causes (root causes) man-induced (mal-operation, errors), or purely technical ones, administrative causes, or combinations of different causes? Have the root causes been found?

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Questions Concerning Events Occurred at Nuclear Power Plants

Corrective actions

- What are the corrective actions after the event for prevention of recurrence?

Preventive measures

- In which compartments / plant areas are components and equipment with the potential of HEAF installed? Are there safety significant / safety related components available in these compartments / plant areas and/or adjacent ones? If yes, which ones? What are the preventive (structural) measures there against such events?
- Which measures are foreseen (originally in the design as well as improved ones after the event) to limit the consequences of such HEAF failures?
- Is it possible to practically exclude by the preventive measures that safety significant equipment is impaired?
- Are further measures intended for prevention of these faults (continuous controls, in-service inspections, etc.), and if yes, which ones?

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Update of the Feedback from the German Operating Experience

After having finished the query, GRS has analysed the overall feedback from nuclear power plants in Germany with respect to HEAF events.

The results are to be discussed with national and international experts (amongst others in line with the international activity OECD HEAF) and are used as a possible basis for further in-depth scientific studies.

Since it is difficult to collect reliable and enough detailed information on events from the far past, the investigations of relevant events in German nuclear power plants have been limited to the last 13 years.

The events of interest are provided in detail in the table below.

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Year of Occurrence	Reactor Type	HEAF Component	Voltage Level	Damage Limited to Component	Barrier Deteriorated	Explosion / Fire
2009	BWR	Transformer	400 kV	yes	no	-
2008	PWR	Switchgear	0.66 kV	yes	no	F
2007	BWR	Transformer	400 kV	yes	no	E/F
2007	PWR	Transformer	400 kV	yes	no	-
2006	BWR	Switchgear drawer	0.66 kV	yes	no	-
2006	BWR	Switchgear drawer	0.66 kV	yes	no	-
2006	BWR	Auxiliary service pump	0,4 KV	yes	no	-
2005	BWR	Switch	6 kV	yes	no	-
2004	BWR	Cable connection	10 kV	yes	no	E/F
2004	PWR	Diesel generator excitor	6 kV	yes	no	-
2003	PWR	Emergency power feed line	0.5 kV	yes	no	-
2002	PWR	Emergency power feed line	0.5 kV	no	no	F
2002	BWR	Switchgear	0.4 kV	yes	no	F
2001	PWR	Transformer	400 kV	yes	no	-
2001	BWR	Emergency power distribution	0.66 kV	yes	no	-
1998	PWR	Emergency power distribution	0.66 kV	yes	no	-

HEAF – Update of the German Operating Experience

Results and Insights

Typical components:	transformer, switchgear, cable
Voltage level:	0.4 kV – 400 kV
HEAF detection/identification:	- 100 % via malfunction messages - In case of heavy smoke, via fire detection system
Separation of redundant trains:	100 % ensured
Components and plant areas affected:	- No effects by explosions - 2 occurrences of smoke propagation in case of 5 consequential fires
Fire fighting:	Necessary in 4 events, thereof 3 times successful by a portable extinguisher
Fire protection features affected:	No
Cause:	Technical reasons, human factor, aging

HEAF – Update of the German Operating Experience

Results and Insights

Voltage Level / Plant Areas	10 kV	6 kV	0.4 kV
Reactor Building	2	-	-
Switchgear Building	2	-	4
Turbine Building	2	-	-
Emergency Diesel Building	-	3	-
Cooling Water Pump Station	2	2	-
Transformers	3 / 11	6	-

HEAF – Update of the German Operating Experience

Conclusions

As part of (within the scope of) the evaluation. the following measures to prevent HEAF events are highlighted:

- Quick cognition and reaction by installation of electric arc detection via pressure sensors in connection with overcurrent monitoring (500 ms on 100 ms)
- Timely detection/identification of slowly proceeding damages by oil monitoring and periodic inspections of insulation resistances
- Prevention of a relevant pressure build-up by installation of pressure relief openings
- Consideration of deterioration aspects by replacement of components (transformers, control units, cables)
- All this has already been recognized and provisions have been taken by the German NPP licensees ☺

HEAF – Update of the German Operating Experience

Example 1

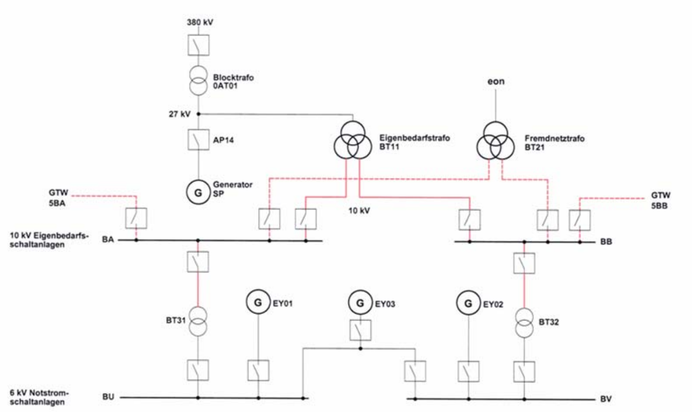
Spontaneous short circuit with a longer time duration occurred in a 10 kV cable at a BWR type plant

The affected cable was routed from the station service transformer together with other cables through an underground cable channel to the switchgear building

Cables were partly imbedded in so-called ‘cable cylinder blocks’ from concrete PVC insulated cable including the copper conductor evaporated completely on a length of approx. 1 m

HEAF – Update of the German Operating Experience

Scheme of the electric circuit affected



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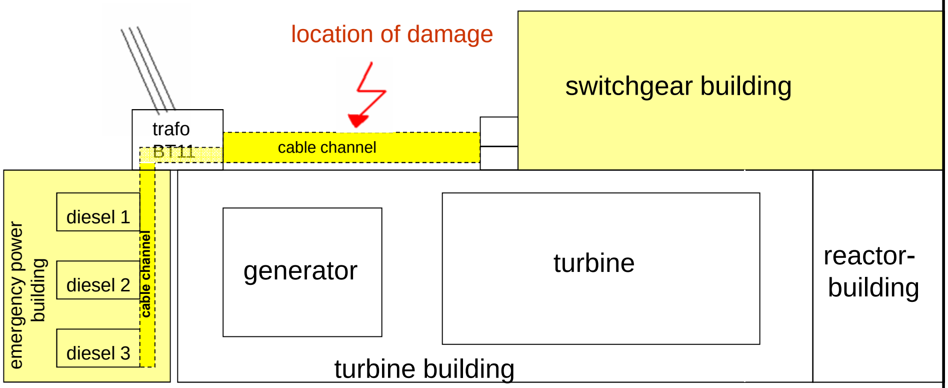
Scheme of the location of damage



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Cable channel with
fire protected cables

Protective cable coating
with soot damage

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Damage by the cable fire / evaporation

Location of the damaged cable
after opening

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Example 2 – Fire at a transformer at a BWR type plant

The cause was a short-circuit in a generator transformer 400 kV. Immediately after the short-circuit a boiler explosion took place with subsequent fire. The transformer is filled with 70 t oil. Approximately 10 – 20 t oil leaked out.

The overpressure caused by the short circuit caused a rupture of the boiler. The pressure was then reduced by openings in the building.

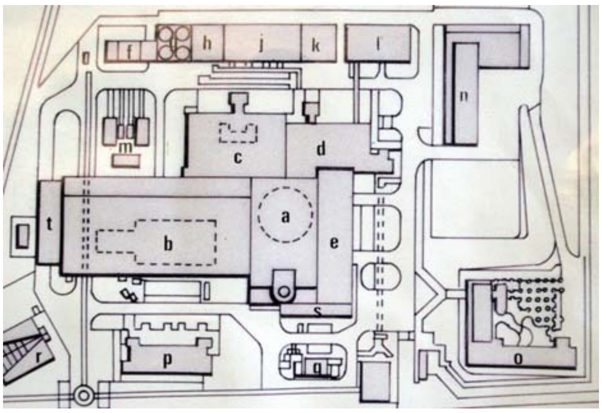
No damages were found on fire doors, dampers and fire walls.

The spraywater deluge system initiated automatically, but could not extinguish the fire.

The fire brigade carried out the fire fighting through precise control/extinction by means of extinguishing foam at the location of fire (inside the boiler). The fire lasted 2.5 days.

HEAF – Update of the German Operating Experience

Scheme of the nuclear power plant



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The transformer is on fire

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Surge arrestor is on fire

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Fire fighting by fire brigade

|| No. 27

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Fire fighting by fire brigade with water based foam

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Extinguishing foam left after the event

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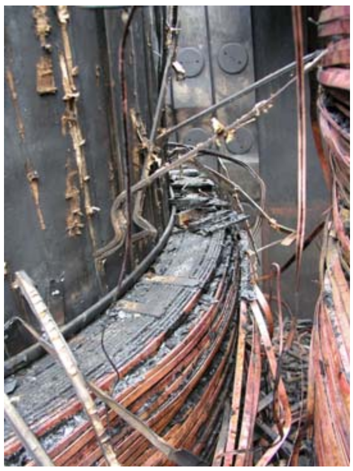
HEAF – Update of the German Operating Experience

Damaged transformer windings with insulation burned



| No. 30

GL Group

GRS Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH

GL

HEAF – Update of the German Operating Experience

Transformer is taken away

Thank you for your attention!

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2.4 Weiterführende Untersuchungen zum hochenergetischen Versagen elektrischer Einrichtungen mit sicherheitstechnischer Bedeutung in Kernkraftwerken

Nachfolgend findet sich eine kurze Zusammenfassung der Veröffentlichung „Untersuchungen zum hochenergetischen Versagen elektrischer Einrichtungen mit sicherheitstechnischer Bedeutung in Kernkraftwerken“ /ROE 11a/. Der gesamte, seitens der GRS zusammen mit dem Unterauftragnehmer Germanischer Lloyd (GL) Bautechnik GmbH erstellte Bericht GRS-A-3630 findet sich auf der Website der GRS.

Die Betriebserfahrung aus kerntechnischen Einrichtungen hat – gerade auch in der jüngeren Vergangenheit – eine Reihe explosionsartig verlaufender Brandereignisse infolge eines hochenergetischen Versagens elektrischer Einrichtungen, sogenannten High Energy Arcing Faults, HEAF aufgezeigt. Diese Versagensart von Komponenten in Folge von Störlichtbögen hat nach Ansicht von Fachleuten aus dem In- und Ausland Derartige HEAF-Ereignisse haben das Potential zu anlageninternen Bränden und Beeinträchtigungen von Brandschutzeinrichtungen mit der möglichen Folge redundanzübergreifender Schäden.

Dementsprechend wurden solche Ereignisse einer vertieften Betrachtung unterzogen, um ihre Ursachen zu ermitteln und spezielle Fragen in Bezug auf ihre Auswirkungen und die dem Versagen zugrunde liegenden physikalisch-technischen Phänomene versuchen zu klären. Dazu gehören auch aufsichtsrelevante Themen, wie das mögliche Versagen von Brandabschlüssen bei Druckaufbau aufgrund des Brandes, die Entrauchung im Schaltanlagengebäude sowie die Möglichkeit redundanzübergreifender Auswirkungen bei dem hochenergetischen Versagen einzelner Komponenten.

Erkenntnisse aus der deutschen Betriebserfahrung

Die Auswertung der Betriebserfahrung zu HEAF-Ereignissen in deutschen Kernkraftwerken anhand eines Fragenkataloges hat insgesamt eine nicht unerhebliche Anzahl von 31 Ereignissen aufgezeigt. Dabei hat sich herausgestellt, dass nur an ganz bestimmten Komponenten ein hochenergetisches Versagen (HEAF) zu erwarten ist. Dabei handelt es sich vorwiegend um Schaltanlagen und Transformatoren, aber auch um Kabel oder Anschlusskästen auf verschiedenen Spannungsebenen im Bereich zwischen 0,4 kV und 400 kV.

Alle in deutschen Kernkraftwerken aufgetretenen HEAF-Ereignisse wurden innerhalb kurzer Zeit detektiert und über Störmeldungen signalisiert. Sofern es zu einer relevanten Rauchentwicklung kam, erfolgte eine Alarmierung über die Brandmeldeanlage.

Bei allen HEAF-Ereignissen in deutschen Anlagen war die Redundanztrennung sichergestellt, durch das explosionsartige Versagen kam es nicht zu einer Beeinträchtigung der ordnungsgemäßen Funktion brandschutztechnischer Einrichtungen und Abtrennungen oder zu einer unzulässigen Beeinträchtigung weiterer Komponenten.

Als Ursachen für solche HEAF-Ereignisse haben sich vorwiegend technische Ursachen herausgestellt, gefolgt von menschlichen Fehlhandlungen. Alterungserscheinungen und Fehler in Prozeduren spielen zusammen mit anderen Gründen ebenfalls eine Rolle bei dieser Art des Komponentenversagens.

Zu einer besseren Vermeidung hochenergetischer Versagenserscheinungen wird bzw. wurde mittlerweile in den deutschen Kernkraftwerken bereits eine Vielzahl sinnvoller Maßnahmen ergriffen.

Internationale Erkenntnisse

Erste im Rahmen der internationalen Task OECD HEF gesammelte Erkenntnisse aus der Betriebserfahrung in Mitgliedsländern der OECD NEA zeigen auf, dass eine nicht unerhebliche Anzahl von Ereignissen mit hochenergetischen Störlichtbögen aufgetreten ist. Viele davon haben Brände zu Folge gehabt und/oder zu einer Beeinträchtigung der ordnungsgemäßen Funktion von Brandschutzeinrichtungen, häufig durch den kurzzeitigen hohen Druckaufbau, geführt. Mehr als 10 % der bisher in der Datenbank OECD FIRE zu Brandereignissen in Kernkraftwerken waren HEAF-Ereignisse.

Großteils waren Schaltanlagen bzw. Schaltschränke auf Spannungsebenen im Bereich zwischen 0,4 kV und 10 kV betroffen, HEAF entsprechend der internationalen Definition trat aber auch an Sammelschienen, Rangierverteilern sowie an Hochspannungskabeln auf.

Zwar waren nur wenige der Ereignisse sicherheitstechnisch relevant, nahezu alle HEAF-Ereignisse sind aber zumindest als Precursor für sicherheitstechnisch bedeutsame Ereignisse zu betrachten.

Bisher wurden Ereignisse mit hochenergetischem Versagen elektrischer Komponenten nicht explizit in probabilistischen Sicherheitsanalysen berücksichtigt, die Erfahrungen legen jedoch eine angemessene Berücksichtigung der Betriebserfahrung zu HEAF nahe. Um HEAF besser modellieren und charakterisieren zu können, sind aus Sicht der internationalen Fachleute weitere vertiefte Untersuchungen zwingend erforderlich.

2.5 Erkenntnisse aus Untersuchungen zu Ereignissen mit hochenergetischen Versagen elektrischer Komponenten in deutschen Kernkraftwerken

Nachfolgend finden sich die englischsprachige Zusammenfassung der federführend seitens der GRS zusammen mit Fachleuten von der ‘Germanischer Lloyd (GL) Bautechnik GmbH‘ und dem Bundesamt für Strahlenschutz (BfS) erstellten Veröffentlichung „Insights from Investigations of High Energy Arcing Fault ”HEAF“ Events in German Nuclear Power Plants“ /ROE 12/ sowie die zugehörige Folienpräsentation seitens der GRS. Der vollständige Beitrag unterliegt dem Copyright des Veranstalters, American Nuclear Society (ANS) und kann dort angefordert werden.

„*The operating experience from nuclear installations worldwide has provided a non-negligible number of mostly explosive plant internal fire events due to high energy arcing equipment faults (HEAF). These typically occur at higher voltage electrical components such as switchgears and circuit breakers, or at high cables.*

In some of the events, the electric arcs have led to partly significant consequences to the environment of the affected components exceeding typical fire effects. In-depth investigations have indicated failures of those fire barriers and protection features not designed against such impacts induced by the rapid pressure increase.

The potential safety significance of HEAF events has caused the OECD Nuclear Energy Agency (NEA) to initiate a task on “HEAF” for in-depth investigations on this type of events in member states, their damage mechanisms and root causes as an important part of better understanding fire risk at NPP which is better accomplished by an international group to pool knowledge and research means.

Major goal is to develop deterministic correlations to predict damage and to establish a set of input data and boundary conditions for more detailed modeling. The output may directly support development of improved treatment methods in fire PRA for NPP applications.

One input into this OECD task is an in-depth analysis of the German operating experience with HEAF in nuclear power plants based on a questionnaire specifically developed for collecting the necessary data and information on these events. This survey has provided more than 30 events. The investigations demonstrate that HEAF only *occur at few specific components such as switchgears and transformers, but also at cables and distribution connections on typical voltage levels between 0,4 kV and 400 kV.*

All high energy arcing faults reported from German nuclear power plants were detected within a short time period and signaled via fault indications. In case of a relevant release of smoke there was a fire alarm by the fire detection system. The separation of redundant trains was ensured in case of all events. Neither the required function of fire protection means nor additional components were impaired by the explosive failure.

Technical causes have been found to be the major root causes for the high energy arcing faults. Other causes are human failure, ageing effects and faulty procedures in combination with other root causes. A variety of reasonable preventive measures have already or are to being taken in German nuclear power plants for improving nuclear safety."

Insights from Investigations of High Energy Arcing Fault "HEAF" Events in German Nuclear Power Plants

Marina Röwekamp[a],
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ICONE20-POWER2012
Anaheim, CA, USA
July 30 – August 3, 2012

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Introduction

- Nuclear operating experience worldwide has provided a non-negligible number of plant internal events with explosions and consequential fires due to HEAF
- HEAF typically occur at components on higher voltage levels such as switchgears, circuit breakers, or high voltage cables
- In some events, electric arcs have resulted in partly significant consequences to the environment of components affected exceeding typical fire effects
- In-depth investigations have indicated failures of fire barrier elements and other protection features not designed against such impacts induced by the typically occurring rapid pressure increase
- OECD Nuclear Energy Agency (NEA) has initiated task on "HEAF" for in-depth investigations on this type of events in member states

Introduction (contd.)

- Goals of the OECD/NEA task on HEAF:
  - Insights on damage mechanisms
  - Understanding of root causes

  for better understanding fire risk due to HEAF at NPP
- OECD/NEA task aims on developing deterministic correlations for predicting damage and to establish a set of input data and boundary conditions for more detailed modeling which can be agreed on by the international community
- Task output may directly support developing improved methods for fire PRA
- Task input: in-depth analysis of the German operating experience with HEAF at NPP based on a questionnaire specifically having provided 31 events from mid-seventies up to early fall 2011

In-depth investigations of German NPP Operating Experience

- 31 HEAF events obligatory reported over > 30 years
- Development of questionnaire to licensees of German NPP

No.	Event Date	Plant	Type	POS	Component Affected by HEAF	Damage Limited to Component	Explosion	Fire	Barrier Deteriorated	Root Cause
01	2009-07-04	GER14	BWR	FP	HV transformer (400 kV main transformer, oil filled)	yes	no	no	no	T, A
02	2008-03-14	GER03	PWR	FP	circuit breaker(660 V)	yes	no	yes	no	T
03	2007-06-28	GER14	BWR	FP	HV transformer (440 kV main transformer)	yes	yes	yes	no	T, A
04	2007-01-18	GER10	PWR	FP	HV transformer (380 kV main transformer)	yes	no	no	no	T
05	2006-10-25	GER14	BWR	FP	motor junction box (660 V)	yes	no	no	no	T
06	2006-08-18	GER14	BWR	LPSD	motor junction box (660 V)	yes	no	no	no	T
07	2006-02-16	GER09	BWR	FP	switchgear (380 V switchgear subassembly)	yes	no	no	no	T
08	2005-06-15	GER09	BWR	LPSD	HV switchgear (6 kV)	yes	no	no	no	T
09	2004-10-14	GER27	PWR	LPSD	HV cabinet (6 kV conductor)	yes	no	no	no	H
10	2004-08-23	GER09	BWR	FP	HV cable(10 kV)	yes	no	yes	no	A, T
11	2003-08-16	GER18	PWR	LPSD	circuit breaker(500 V injection)	yes	no	no	no	H
12	2002-10-30	GER09	BWR	FP	switchgear (400 V)	no	yes	yes	no	T, H
13	2002-08-11	GER17	PWR	FP	switchgear (500 V)	no	no	yes	no	T
14	2001-03-06	GER14	BWR	FP	switchgear (660 V)	yes	no	no	no	T
15	1998-11-10	GER10	PWR	FP	circuit breaker (660 V)	no	no	no	no	T
16	1996-02-08	GER17	PWR	FP	electrical cabinet (500 V busbar, breaker subassembly)	yes	no	yes	no	U
17	1992-05-05	GER04	PWR	LPSD	motor generator (reversible)	yes	no	no	no	T
18	1989-09-08	GER01	PWR	LPSD	HV switchgear (10 kV, injection cell)	no	no	yes	no	T

T: technical. H: human. P: procedures. A: aging, U: unknown

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German NPP Operating Experience (contd.)

No.	Event Date	Plant	Type	POS	Component Affected by HEAF	Damage Limited to Component	Explosion	Fire	Barrier Deteriorated	Root Cause
19	1989-05-17	GER25	PWR	LPSD	switchgear (380 V switchgear, injection area)	yes	no	yes	no	T, H
20	1988-04-19	GER24	PWR	FP	HV switchgear (220 kV)	yes	yes	yes	no	T
21	1987-09-09	GER22	BWR	FP	electrical cabinet (emergency diesel)	yes	yes	yes	yes	T, H
22	1987-02-06	GER01	PWR	FP	motor of a pump	yes	no	no	no	T
23	1986-05-30	GER11	PWR	LPSD	busbar (380 V)	no	no	yes	no	U
24	1984-06-08	GER28	BWR	LPSD	HV switchgear (30 kV cables)	yes	no	no	no	H
25	1981-02-17	GER01	PWR	FP	motor of a pump (safety injection pump)	yes	no	no	no	T
26	1979-08-11	GER27	PWR	LPSD	circuit breaker (subdistribution board)	yes	no	yes	no	T
27	1979-07-13	GER28	BWR	LPSD	switchgear	yes	no	no	no	H
28	1979-01-11	GER23	PWR	LPSD	contactor	yes	no	no	no	P, T, H
29	1978-05-25	GER27	PWR	LPSD	generator breaker (220 kV switchgear)	yes	no	no	no	T
30	1977-10-31	GER24	PWR	LPSD	switchgear (busbar in 380 V cabinet)	yes	no	no	no	H
31	1977-09-28	GER15	BWR	LPSD	switchgear (emergency switchgear)	yes	no	no	No	T, P

- Questionnaire based on entire state-of-the-art information on HEAF available from nuclear installations worldwide and potentially applicable to German NPP
- Due to HEAF safety significance root causes and potential failures of fire barrier elements events have been investigated in detail

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Plant Specific Results (1)

- Most recent event (2008)
  - After electric current measurement at subassembly of HV circuit breaker (660 V, 420 A) of emergency busbar, CVCS system should be brought back to normal operation
  - Pump was again switched on, but could not be switched off from MCR
  - Electric arc (~ 6 min) in circuit breaker of a CVCS discharge pump caused overcurrent of max. 2.5 kA and smoldering fire in the subassembly detected by automatic smoke detectors
  - Fire was confirmed and extinguished by on-site fire brigade (portable fire extinguishers, approx. 30 min)
  - Affected busbar supplies components of one safety train for RHR being unavailable
  - At the same time, emergency power supply of another redundant train emergency diesel generator was disconnected for maintenance, which had to be stopped
  - Corrective measures: increased controls with respect to impurities in case of breaker exchange and personnel training

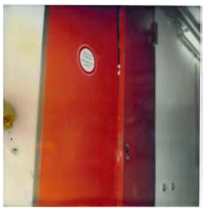
Plant Specific Results (2)

- August 2004: HEAF initiated by short circuit 10 kV cable at older BWR
  - Short circuit (few sec) resulting in overcurrent of ~ 30 - 35 kA during FP
  - Affected cable routed from station service transformer with other cables through underground cable channel to electrical building with cables partly imbedded in concrete cable cylinder blocks
  - PVC insulated cable including copper conductor evaporated completely on length of approx. 1 m
  - Strong smoke release actuated automatic fire detectors; smoke exhaust system removed smoke
  - Overpressure relieved via open cable conduits to transformer and leakages
  - Root cause: cable aging
  - No fire propagation, combustion limited to location where short circuit occurred; fire self-extinguished
  - Corrective action: all safety related 10 kV cables with PVC shielding replaced by new ones; separation of all channels by 90 min barriers

Plant Specific Results (3)

- September 1987: HEAF with explosion and fire at PWR during FP
  - Arc in electrical cabinet of emergency diesel generator during in-service inspection load test initiated short to ground in the cabinet

  - Cause of short to ground: loose screw ionizing air by arc within ~ 4 s resulting in emergency busbar insulation after 0.1 s
  - Explosion with smoldering fire by short circuit of emergency diesel generator
  - HEAF caused sudden pressure increase in room (dimensions about: 3.6 m x 5.5 m x 5 m) damaging two-wing fire door



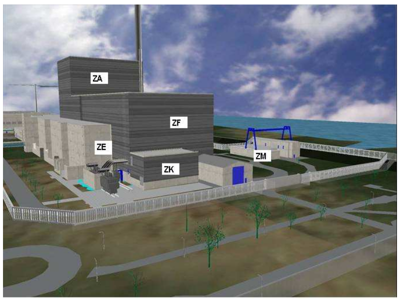
Generic Insights from German NPP Operating Experience

- HEAF typically observed:
  - at switchgears, transformers, electric cabinets, cables, connecting boxes and circuit breakers
  - on voltage levels between 0.4 kV and 400 kV
- Major contributions:
  - High energy switchgears and circuit breakers: 60 %
  - Transformers: 10 %
- All HEAF in German NPP were immediately signaled via alarm signals
- Relevant smoke release was directly detected by fire detection systems
- 35 % of HEAF events resulted in fire
- Physical separation of redundant trains was always ensured
- Damage not limited to the component where HEAF occurred: 20 %
- Explosions due to HEAF (13 %) did neither impair components / plant areas other than initial ones nor required fire protection function

Generic Insights from German NPP Operating Experience (contd.)

- Root causes:
  - Technical causes: ~ 77 %
  - Erroneous human actions: ~ 16 %
  - Ageing: ~10 %
  - Faulty procedures and/or administrative reasons: ~ 7 %
- Measures taken for HEAF component fault prevention:
  - Replacement of components by improved ones
  - Replacement of (low amount) oil filled circuit breakers by vacuum breakers
  - Installation of electric arc detection via pressure cells together with overcurrent detection
  - Oil monitoring for transformers
  - Visual inspections of relevant electric equipment
  - Inspection of insulation resistances
  - Provision or optimization of measures for pressure relief

HEAF Event Relevant Plant Areas - Example of a German NPP



Voltage Level / Plant Area	10 kV	6 kV	0.4 kV
Reactor Building ZA	2		
Electrical Building ZE	2		4
Turbine Hall ZF	2		
Emergency Diesel Building ZK		3	
Circulating Water Structure ZM	2	2	
Transformer Yard	3/11*	6	

Note:
3 transformers > 10 kV
(main transformer,
service transformer)

Conclusions and Outlook

- Investigations on German NPP operating experience demonstrate that HEAF only occur at few specific components /(circuit breakers, switchgears and transformers), but also at cables and distribution connections typically between 0,4 kV and 400 kV
- Short circuit failure of HV cables (typically 10 kV nominal voltage) in cable rooms and ducts is not assumed for German NPP
- Failure of HV circuit breakers and switchgears (10 kV nominal voltage or more) and resulting pressure increase are presumed to occur and to be controlled
- Specific investigations of such scenarios have resulted in additional measures for pressure relief inside electrical buildings of German NPP
- Germany does participate in OECD HEAF experimental program expecting further valuable insights on physical phenomena and fault characteristics

Thank you for your attention!

For questions please contact:

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Bundesamt für Strahlenschutz

2.6 Projekt OECD FIRE – Topical Report Nr. 1: Analyse von Brandereignissen infolge hochenergetischen Versagens elektrischer Komponenten

Nachfolgend findet sich die englischsprachige Zusammenfassung der federführend seitens der GRS erstellten Veröffentlichung des OECD NEA-Datenbankprojekts OECD FIRE mit dem Titel „OECD FIRE Project – Topical Report No. 1, Analysis of High Energy Arcing Fault (HEAF) Fire Events" /NEA 13/. Der vollständige Bericht /NEA 13/ kann der OECD Website entnommen werden.

„*Operating experience from nuclear installations has shown a non-negligible number of reportable events with non-chemical explosions and rapid fires resulting from high energy arcing faults (HEAF) in high voltage equipment such as circuit breakers and switchgears. Such electric arcs have led in some events to partly significant consequences to the environment of these components exceeding typical fire effects. Investigations of this type of events have indicated failures of fire barriers and their elements as well as of fire protection features due to pressure build-up in electric cabinets, transformers and/or compartments.*

Due to the high safety significance and importance to nuclear regulators OECD/NEA/CSNI has initiated in 2009 an international activity on 'High Energy Arcing Faults (HEAF)' to investigate these phenomena in nuclear power plants in more detail as to better understand fire risk at a nuclear power plants. It is believed that this is better accomplished by an international group that can pool international knowledge and research means.

The main objective of the current analysis is to examine if HEAF is a common phenomenon and how HEAF develops, in order to extend the existing knowledge of this particular fire phenomenon, and to improve electrical safety standards and to design proper preventive measures.

The report presents the results of the analyses of the HEAF events in the OECD FIRE Database [1]."

2.7 OECD NEA CSNI WGIAGE Task zum hochenergetischen Versagen elektrischer Komponenten

Nachfolgend findet sich die englischsprachige Kurzfassung des federführend von der kanadischen Aufsichtsbehörde CNSC zusammen mit der GRS erstellten abschließenden Berichts zu der OECD NEA CSNI WGIAGE Task on High Energy Arcing Fault Events (HEAF) /NEA 15/, welcher in 2014 vom CSNI zur Veröffentlichung freigegeben wurde. Der vollständige Bericht /NEA 15/ kann der OECD Website entnommen werden.

"*High Energy Arcing Faults (HEAFs) have the potential to cause extensive damage to the failed electrical components and distribution systems along with adjacent equipment and cables within the zone of influence (e.g. an area affected by the HEAF). Furthermore, the significant energy released during a HEAF event can act as an ignition source to other combustibles resulting in fires. Operating experience indicates that HEAF events have occurred in nuclear power plants throughout the world and in some cases affected adjacent items important to safety. Current modelling techniques are limited in characterising the risks associated with the phenomena. Because of the potential safety significance of HEAF events the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA) initiated a project to provide an in-depth investigation on HEAF events in NEA member states [1].*

The general objective of the study was to determine damage mechanisms, extent of areas affected, methods of protecting systems, structures and components (SSCs) and possible calculation methods for modeling of HEAF events as applicable to fire protection in nuclear power plants (NPP). However, it turned out during the task that to fully meet all objectives, large scale experiments are needed.

It has been concluded that HEAF events have occurred throughout the world in NPP's and have shown that they have the potential to damage safety related SSCs. These events are still too small in number to allow meaningful statistical evaluation. The critical details related to determination of arc fault energy and arc durations are not always available for model development and validation. Also, variables related to electrical equipment and exposed materials are not provided by the HEAF operating experience. In addition, current methods of predicting effects of HEAF have in a number of cases under-predicted the HEAF zone of influence and resulting damage to adjacent SSC.

To be able to better characterise HEAF events it is recommended to perform a series of experiments to obtain comprehensive scientific fire data on the HEAF phenomenon known to occur in NPPs through carefully designed experiments to be able to:

- *Develop a more realistic model to account for failure modes and consequences of HEAF events as well as correlations based on ignition time using variations of incident heat flux.*
- *Validate current models to assess SSC damage potential.*
- *Provide better characterisation of HEAF in fire Probabilistic Risk Assessment (Fire PRA) and assist in developing more realistic PRA tools to model the risk in PRA.*
- *Provide guidance in predicting potential damage from HEAF events, e.g. for regulatory oversight.*

This report therefore presents:

- *A review of the current calculation methods used to predict damage from HEAF events to SSC.*
- *A summary of the operating experience with HEAF events that have occurred in NPPs.*
- *Recommendations for additional research work needed to better understanding fire risks associated with HEAF events resulting from this task*."

3 Planung der Folgeaktivitäten im Rahmen eines internationalen Forschungsprojekts zu HEAF

Derzeit werden im Rahmen eines internationalen Experimentalprojektes der OECD NEA die Entstehungsmechanismen des hochenergetischen Versagens elektrischer Komponenten und die daraus folgenden Ereignisabläufe (insbesondere Folgebrände) und deren Auswirkungen, d. h. vor allem Schädigungen von Bauteilen, Systemen und Komponenten durch den HEAF selbst und seine Folgen einschließlich deren zugehörigen Mechanismen anhand experimenteller Untersuchungen vertieft analysiert.

Deutschland beteiligt sich im Rahmen des vom BMUB geförderten Forschungs- und Entwicklungsvorhabens 3614R01590 aktiv an diesem internationalen HEAF-Versuchsprogramm mit dem Titel ‘Joan of Arc‘. Dazu wurden seitens eines deutschen Betreibers zwei geleichartige Hochspannungsschaltanlagen (6,9 kV) für die bei KEMA in deren Versuchseinrichtung in Chalfont, PA (USA) im Auftrag der der U.S. NRC durchgeführten Versuchsserie zur Verfügung gestellt.

Die Versuchsplanung stellt sich zum Ende des Vorhabens 3611R01301 wie folgt dar:

Insgesamt sollen noch je vier Versuche mit japanischen und US-amerikanischen Komponenten, je zwei mit deutschen, französischen und koreanischen sowie drei Versuche mit finnischen Komponenten stattfinden. Grundsätzlich finden diese Versuche bei Nominalspannungen von 480 V bis 10 kV statt. Dabei wird pro Versuch ein Lichtbogen von einer vorher definierten Dauer erzeugt. Die zu zerstörenden Komponenten werden mit einer Vielzahl von Messeinrichtungen, u. a. zur Messung der beobachteten Wärmefreisetzungsraten, ausgestattet.

Nachfolgend findet sich eine Auflistung der wesentlichen Charakteristika der zu untersuchenden Komponenten:

- Japan:
  Elektrische Schaltschränke mit Metallgehäuse vom Typ VF-40 DM-BA und VF-40 DM-BAZ, mit Nominalspannung: 7,2 kV, Gewicht: 170 kg und Frequenz 50 Hz,

- Deutschland:
  Hochspannungsschalter, mit Nominalspannung: 10 kV bei 100 kA, Gewicht: 170 kg, , Abmessungen 7,35 m x 6,85 m x 6,85 m und Frequenz: 50 Hz,

- Korea:
  Hochspannungsschalter der Klassen E7 & ES High Voltage Air Breaker von GEC mit Nominalspannung: 6,9 kV und Frequenz: 50 Hz sowie magnetischer Schalter Procel-line vom Typ CHP Magnetic Air Circuit Breaker der Firma Westinghouse mit Nominalspannung: 6,9 kV und Frequenz 50 Hz,

- Finnland:
  Elektrische Schaltschränke mit Nominalspannung 480 V und Frequenz: 60 Hz sowie

- USA:
  Schaltanlagen mit Nominalspannung 480 V und Frequenz: 60 Hz sowie Sammelschienen vom Typ ITE Non Segregated Bus Bar mit Nominalspannung von 4,16 kV bei einer Unterbrechungskapazität von 30 kA und 3 s Dauer, Abmessungen von -2.5 m x 1 m x 5 m und einer Frequenz von 60 Hz.

Die Lichtbögen werden bei diesen versuchen innerhalb der Umschließungen mittels Kurzschlüssen über alle drei Phasen der Sammelschienen mittels eines Metalldrahtes von 2 – 6 mm Durchmesser erzeugt. Die Sammelschienen werden außerhalb der Umschließung der jeweils zu testenden Komponente horizontal zur Instrumentierung von KEMA geführt. Seitens der versuchsführenden Institution wird davon ausgegangen, dass der erste Lichtbogen entlang der vertikalen Schiene die horizontale Schiene nicht zerstört, so dass mehrere Entstehungsorte der Lichtbögen in den Schaltschränken untersucht werden können. Die äußeren Felder der Schaltschränke sind mit Lüftungsschlitzen versehen, um hohe Überdrücke zu verhindern.

Der Lichtbogen kann einen Folgebrand erzeugen, welcher sich über die Kabel und andere brennbare Materialien ausbreiten kann. Der Folgebrand kann sich entweder weiterentwickeln, bis er von selbst verlöscht, oder bis eine Branddauer von 30 min erreicht ist. Danach werden Löschmaßnahmen ergriffen. Die NRC installiert eine Haube zur Sauerstoffverbrauchskalorimetrie über der zu untersuchenden Komponente, mit welcher die Verbrennungsprodukte gesammelt und außerhalb der Versuchsanordnung analysiert werden.

Die nachfolgende Tabelle gibt einen Überblick über die geplanten Versuche.

Tab. 3.1 Übersicht über die geplanten Versuche der HEAF-Versuchsserie

	Test #	Voltage	Current	Duration	Notes	Delta/Wye
German Breakers	Test 1	10 kV	15-35 kA	2-2.5 sec	3φ, 50 Hz	Wye
	Test 2	10 kV	15-35 kA	2-2.5 sec	3φ, 50 Hz	Wye
Korean Cabinets	Test 3	6.9 kV	10-35 kA	2-3 sec	3φ, 60 Hz	Delta
	Test 4	6.9 kV	10-35 kA	2-3 sec[1]	3φ, 60 Hz	Delta
Japanese Cabinets	Test 6	7.2 kV	10-20 kA	3-5 sec[1]	2φ, 50 Hz	Delta
	Test 7	7.2 kV	10-20 kA	3-5 sec[1]	3φ, 50 Hz	Delta
	Test 8	7.2 kV	10-20 kA	3-5 sec[1]	3φ, 50 Hz	Delta
	Test 9	7.2 kV	30-35 kA	2-3 sec[1]	3φ, 50 Hz	Delta
US Bus Bar	Test 5	4.160 kV	20-35 kA	2-3 sec[1]	3φ, 60 Hz	Delta
Finnish Breakers	Test 10	480 V	10-60 kA	2-10 sec	3φ, 60 Hz	Delta
	Test 11	480 V	10-60 kA	2-10 sec	3φ, 60 Hz	Delta
	Test 12	480 V	10-60 kA	2-10 sec	3φ, 60 Hz	Delta
US Switchgear	Test 13	480 V	10-60 kA	2-10 sec	3φ, 60 Hz	Delta
	Test 14	480 V	10-60 kA	2-10 sec	3φ, 60 Hz	Delta
	Test 15	480 V	10-60 kA	2-10 sec	3φ, 60Hz	Delta

Die Instrumentierung, welche auch Videoaufnahmen und Fotos seitens KEMA zu den Versuchen enthält, beinhaltet zwölf metallische, sogenannte „slug"-Kalorimeter, die um die zu untersuchende Komponente räumlich verteilt angeordnet werden, zwei Drucksensoren zur Messung des Innendrucks der Komponente sowie Kombinationen von Abzweigungen (shunts) für die Messungen von Strom- und Spannungswellenverlauf

[1] Dauer abhängig von der Wahl des Stromes, ggf. sind 4-5 sec möglich

entsprechend IEEE C37.20.7. Zusätzlich wird eine angemessene Anzahl von Thermoelementen installiert, deren räumliche Anordnung jedoch erst nach Errichtung aller sonstigen Testeinrichtungen erfolgen kann und wird. Die Wärmemessungen werden durch eine Wärmebildkamera ergänzt.

Die Datenaufnahme und -auswertung der Versuche erfolgt mit Geräten von NRC und NIST; diese Institutionen werden auch die Auswertung der Rohdaten vollständig übernehmen.

4 Weiteres Vorgehen im Rahmen des internationalen HEAF-Projekts ‘Joan of Arc‘

Auf der Basis der im Rahmen der in den Kapitel 2 dargelegten Ergebnisse der vorangegangenen Arbeiten werden durch Fachleute von GRS und TÜV NORD Bautechnik GmbH auf deutscher Seite wie durch Experten der am Versuchsprogramm beteiligten Fachinstitutionen aus dem Ausland (u. a. IRSN (Frankreich), KINS und KAERI (Korea), CRIEPI (Japan), STUK (Finnland), CNS (Spanien), NRC und NIST (USA)) die Versuche an den als besonders anfällig für HEAF identifizierten Komponenten, wie Hochspannungsschalter, Hoch- und Mittelspannungstransformatoren und Leistungskabel (Spannungsebene $\geq$ 400 V) fachlich analytisch begleitet.

Dabei sollen auch die bei den von KEMA in den USA durchzuführenden Versuchen beobachteten physikalischen und chemischen Phänomene vertieft analysiert und als dynamische Vorgänge charakterisiert werden.

Aufbauend auf den Ergebnissen der fachlichen Begleitung der Versuche unter Gesichtspunkten des Brandschutzes der sich daraus ergebenden vertieften Untersuchungen und Aufbereitung der Ergebnisse soll ein Instrumentarium zur Bewertung des hochenergetischen Versagens elektrischer Komponenten mit möglicher Brandfolge entwickelt werden.

Aus fachlicher Sicht der in dem aktuellen experimentellen Vorhaben der OECD NEA beteiligten Experten wird ggf. die Notwendigkeit gesehen, diese Versuchsserie durch weitere Versuche an weiteren Komponenten, bei denen es entsprechend der Auswertung der internationalen Betriebserfahrung sicherheitsrelevante HEAF-Ereignisse gegeben hat, wie u. a. Hoch- und Mittelspannungstransformatoren, zu ergänzen. Damit könnte das Spektrum der möglichen Versagensmechanismen und Vorgänge vollständig abgedeckt werden. Eine solche Entscheidung kann aber erst nach Vorliegen der Ergebnisse der aktuellen Versuche getroffen werden.

5 Zusammenfassung und Ausblick

Die Ergebnisse des Vorhabens 3611R01301 lassen sich insbesondere für eine Verbesserung des Erkenntnisstandes in Bezug auf Ereignisse mit hochenergetischem Versagen elektrischer Komponenten, deren sicherheitstechnischer Bedeutung, entsprechender Vorsorgemaßnahmen gegen HEAF-Ereignisse und mögliche Maßnahme zur Begrenzung der Folgeschäden nutzen.

Die Erkenntnisse aus der Betriebserfahrung mit HEAF haben zudem bereits Eingang in das deutsche lerntechnische Regelwerk /BMU 15/, /KTA 15/ gefunden.

Aufbauend auf den Ergebnissen der geplanten vertieften Untersuchungen soll ein Instrumentarium zur Bewertung des hochenergetischen Versagens elektrischer Komponenten mit möglicher Brandfolge entwickelt werden und aus den nach Auswertung der Versuchsergebnisse zur Verfügung stehenden wissenschaftlichen Erkenntnissen möglichst auch Empfehlungen zur Vorbeugung und Vorsorge gegen HEAF-Ereignisse abgeleitet werden. Dazu wurde mittlerweile das internationale OECD-Versuchsprogramm zu HEAF ‘Joan of Arc‘ initiiert.

Insgesamt soll die Mitwirkung an dem experimentellen Projekt der OECD NEA mit den zugehörigen vertieften Untersuchungen zu einer Weiterentwicklung des Standes von Wissenschaft und Technik bzgl. HEAF beitragen.

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