# Appendix B Relevant scenarios and boundary conditions

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# 1 Introductory remark

A definition of initial and boundary conditions as well as the characterisation of the materials involved has obviously to precede model calculations and were thus discussed at an early stage of the project. Later, the Preliminary Safety Analysis Gorleben (Vorläufige Sicherheitsanalyse für den Standort Gorleben, VSG) /FIS 13/ was performed specifying the safety relevant aspects of a possible repository at this particular site. These considerations have partly outdated the earlier results. They are nevertheless outlined in section 2 for completeness.

However, in the framework of VSG it became apparent that flow of brine in a back-filled drift cannot be predicted without considering unsaturated flow or even two-phase flow /LAR 13/. This draws attention to the backfill in the vicinity of a drift seal which will be in the focus of the THM-models presented in section 4 of the main report. This will also be the first THM-model for compaction of crushed salt that uses calibrated data for the changing compaction behaviour under the influence of a changing moisture content.

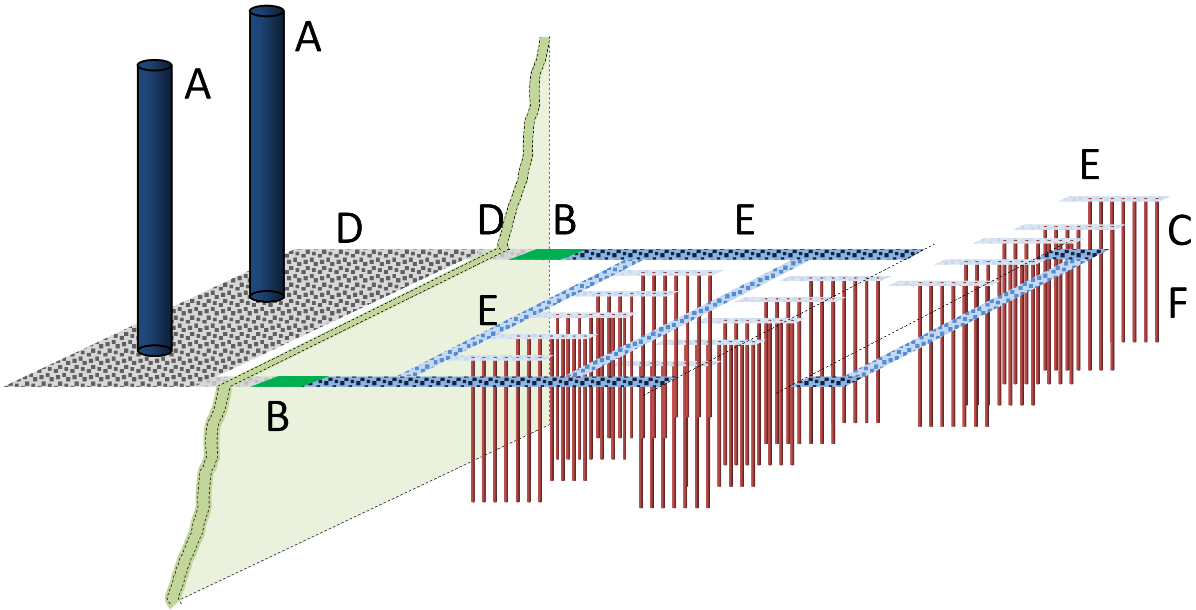
# 2 Early discussed relevant scenarios and boundary conditions

## 2.1 Components of a generic repository

In order to define relevant inflow scenarios a repository in a salt dome is defined as a basis for subsequent THM-modelling. The repository is orientated at concrete plans but nevertheless sufficiently abstract to gain an insight from the modelling that allows a later transfer to variants of the original concept. Relevant components of the repository are

- shafts
- infrastructure area
- development drifts
- crosscuts
- access drifts
- deposition boreholes

Between the infrastructure area and the field of deposition boreholes a vertical anhydrite layer is assumed. The whole set-up is depicted in Fig. 2.1. A typical cross-section of a drift is shown in Fig. 2.2. The geotechnical openings are filled by geomaterials constituting buffer, backfill or seals. The assignments of sealing, backfill or buffer materials to the repository components are compiled in Tab. 2.1.




| Legend | Function | |
|---|---|---|
| shaft | A | A – shaft sealing |
| deposition borehole | C, F | B – drift sealing |
| infrastructure area | D | C – borehole sealing |
| development drift | D | D – backfill (gravel) |
| development drift | E | E – backfill (crushed salt) |
| crosscut | E | F – buffer |
| access drift | E | |
| drift seal | B | |
| anhydrite | | |

**Fig. 2.1** Components of a generic repository in salt rock

In the following the materials involved are roughly characterised. Note that concrete specifications may be outdated at the time of printing. As no credit is taken from these data no effort was undertaken to update them.

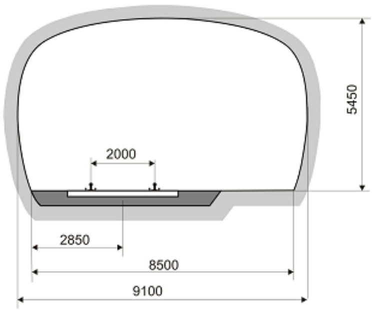



**Fig. 2.2** Sketch of a typical cross-section of a drift

**Tab. 2.1** Assignment of materials to the repository components

| Component | Function | Material |
|---|---|---|
| shafts | A - shaft sealing | various |
| Infrastructure area | D - backfill (gravel) | gravel |
| development drifts | D - backfill (gravel) | gravel |
| | B - drift sealing | sorel-concrete and abutment |
| | E - backfill | crushed salt |
| crosscuts | E - backfill | crushed salt |
| access drifts | E - backfill | crushed salt |
| deposition boreholes | F - buffer | crushed salt |
| | C - borehole sealing | solid core and crushed salt |

**Material A – Shaft seal**

A good description of presently envisaged shaft seals can be found in /KOC 13/: “The shaft seals are complex structured columns of approx. 500 m height. They contain seals of Sorel-concrete (permeability: $5 \cdot 10^{-17}$ m²), salt-concrete (permeability: $7 \cdot 10^{-19}$ m²) and bentonite (permeability: $7.8 \cdot 10^{-17}$ to $1 \cdot 10^{-17}$ m²) as well as one long-term barrier consisting of pre-compacted salt grit (10 % porosity). Furthermore, a reservoir for fluids consisting of highly porous gravel was incorporated into the shaft sealing structure.” The referring sketch in Fig. 2.3 is taken from /BOL 13/.

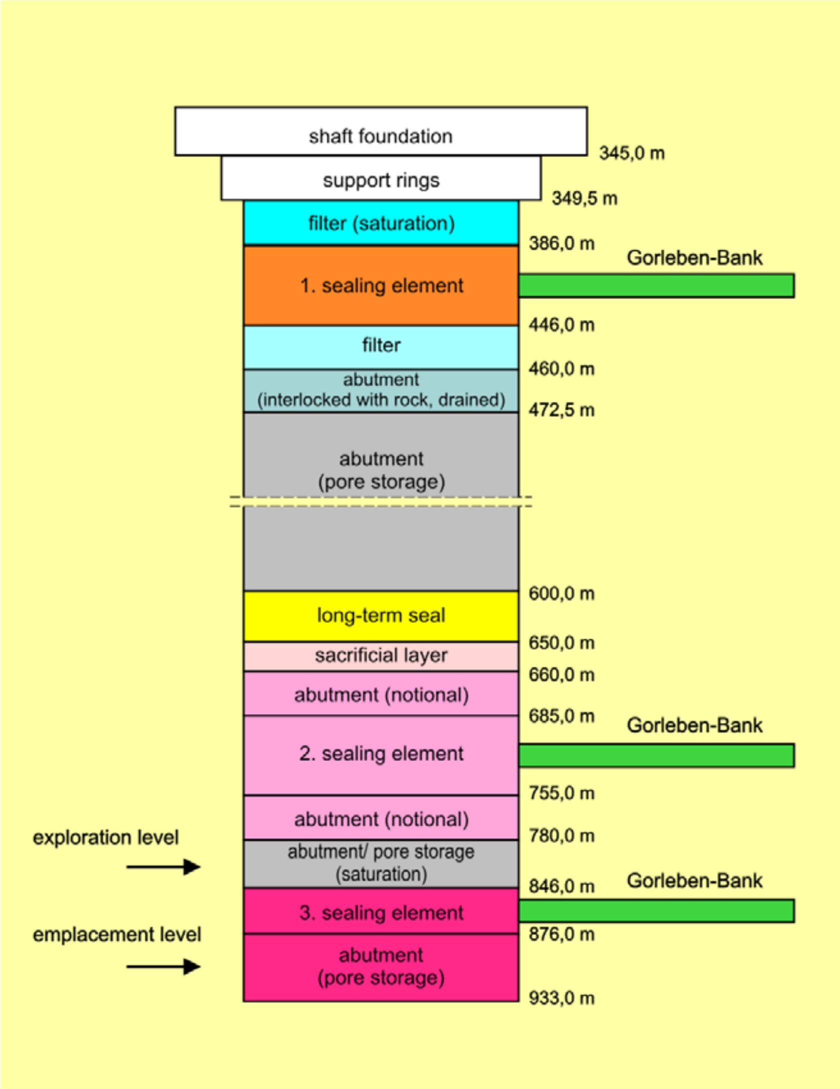



**Fig. 2.3** Sketch of a shaft seal; from /BOL 13/

### Material B – Drift seal

Compaction of backfill in drifts is a comparatively slow process during which safety against brine inflow must nevertheless be guaranteed. Drift seals that can quickly and effectively impede brine flow will therefore be emplaced at strategic locations in the raccess drifts in a repository. The sealing element is envisaged to consist of a 50 m long section of sorel-concrete that is supposed to have an average permeability of $5 \cdot 10^{-17}$ m² including the excavation damaged zone (EDZ) /KOC 13/. It is kept in place by concrete abutments of 15 m length. The drift seal is considered to have a limited life-time. Failure might occur at about 1000 years after contact with brine.

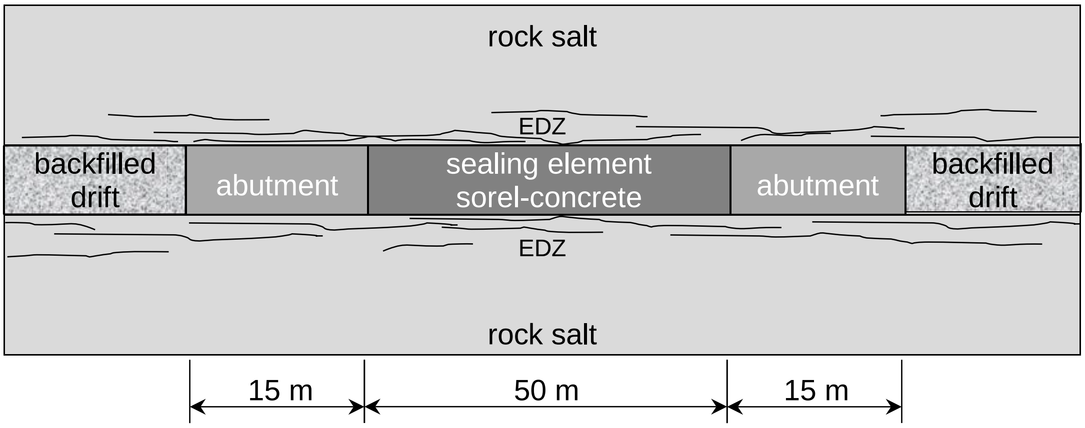



**Fig. 2.4** Sketch of a drift seal

**Material C – Borehole seal**

A possible borehole seal can consist of a massive rack salt bore core where the remaining open annulus is filled with crushed salt. A failure of the borehole is not expected.

**Material D – Backfill (gravel)**

According to present plans the open space between the shafts and the drift seals will be filled with gravel which can be considered to be incompressible. The remaining large space provides a considerable storage capacity for brine or gas /KOC 13/.

**Material E – Backfill (crushed salt)**

Crushed salt from excavation works is planned to be used as backfill of drifts. Maximum grain size will be 31 mm and a initial porosity of about 35 % is expected (e.g. /KRÖ 09/).

**Material F – Buffer**

Crushed salt is also foreseen as the buffer in the deposition boreholes. It is basically the same as Material E except that the maximum grain size amounts only to 8 mm. Since hydraulic and mechanical properties are mainly controlled by the grain fractions of little diameter no difference is made here between materials E and F.

## 2.2 Scenarios and boundary conditions

### Normal evolution

The expected evolution in a repository in rock salt includes saturated brine at the top of the shaft seals at a hydrostatic pressure corresponding to a depth of about 350 m. Moreover, pressurized brine pockets up to a volume of 1000 m³ can discharge to the drifts in the vicinity of the drift seal. It is assumed here that larger pocket cannot go undetected if they have the potential to connect to the drifts.

### Altered evolution A

This scenario is a variant of the normal evolution where a shaft fails prematurely. Saturated brine thus reaches the drift seal and the pore space is completely filled with brine. Hydrostatic pressure at the seal can again be assumed[1].

### Altered evolution B

Another scenario is also a variant of the normal evolution. In this case failure of the drift seal is assumed instead of failure of a shaft. However, rather little unpressurised water can be found at the drift seal in this scenario.

# 3 Conceptual considerations for brine inflow at a drift seal

In case of brine passing the drift seal and entering a previously dry backfill two radically different paths of development can be conceived depending on the flow rate. Crucial for distinction is the ratio $r$ of the brine inflow rate $q_i$ and the rate $q_e$ at which water evaporates at the water-air interface in the pore space. If the inflow rate is in the range of the evaporation rate or lower ($r \leq 1$), the pathway for brine is expected to become clogged by the precipitating salt that remains after evaporation of brine. But if brine inflow is fast-

[1] If a residual permeability would remain in the shaft and if the infrastructure area was filled with crushed salt compaction would squeeze the brine towards the shafts and thus increase the hydraulic pressure at the drift seal.

er than evaporation ($r > 1$), the pores should become brine-filled fast enough to prevent serious precipitation. The latter issue is addressed further on.

As the previous basic considerations are based on a view at pore size level, a distinction of effects can only be done on a local scale. It is therefore necessary to take not only the total inflow rate into account but also the distribution of flow over the backfill boundary. Localized flow via the EDZ, for instance, can meet the criterion $r > 1$ at a much lower total flow rate than an equally distributed inflow over the whole face of the drift seal.

**Hydraulics (H)**

A sufficiently high inflow leads initially to a volume of brine in the pore space of the backfill at the drift-backfill contact whose evolution is basically controlled by gravity and capillary forces. A plume-like increase of this volume prevails as long as the hydrostatic pressure is lower than the capillary pressure (see Fig. 3.1 a)). When the weight of the brine exceeds the capillary pressure, though, it starts moving downwards essentially forming a pool of brine at the bottom of the drift with an unsaturated fringe on top of the free brine surface (Fig. 3.1 b)). This pool tends to spread due to the capillary forces at the front and due to pressure differences according to a decreasing height of the free surface. There are thus three possible driving forces for brine migration in the backfill: capillary forces, gravity and hydraulic pressure differences.

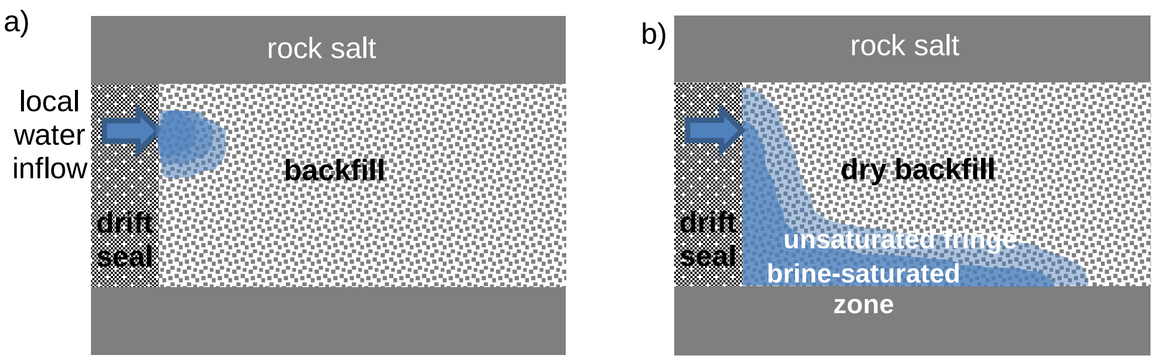



**Fig. 3.1** Modes of water migration in the backfill;
a) by capillary forces only, b) capillary forces plus influence of gravity

**Mechanics (M)**

An isotropic stress distribution prevails in the undisturbed rock salt. This state becomes disturbed by excavations, initiating creep of the rock salt towards the geotechnical openings. Convergence of drifts and boreholes can thus be observed right after excavation.

With the continuing displacement of the drift contour after installation of the crushed salt backfill, the compaction of the backfill commences. Compaction, in turn, activates the mechanical resistance of the backfill to further convergence thus beginning to counteract the drift convergence.

It is highly likely that a gap at the ceiling of the drift will remain for procedural reasons. In case of pre-wetted crushed salt, the weight of the backfill itself can additionally lead to a collapse of the backfill. In the beginning, convergence will therefore be most pronounced in the vicinity of the gap at the ceiling as long as no resistance to creep is experienced by the host rock (Fig. 3.2 a)). With further progress of rock salt creep, the backfill resistance increases, thereby building-up normal stresses at the drift contour as well as slowing down the compaction process (Fig. 3.2 b)). Displacement of the drift contour and thus compaction of the backfill come to an end when the deviatoric stresses in the rock salt reach a minimum (Fig. 3.2 c)).

**Heat flow (T)**

Hydraulic as well as mechanical processes can be influenced by the heat produced by the radioactive waste. This concerns a variety of parameters and processes such as the hydraulic conductivity of fluids, creep, and thermal expansion. Even heat flow itself is influenced by temperature via the thermal conductivity and the specific heat capacity. Generally speaking, increasing temperature accelerates other processes.

**THM-coupling**

Each of the previously described processes influences, at least theoretically, each other process. Increased temperature accelerates compaction as well as brine flow via temperature-dependent hydraulic and mechanical parameters.

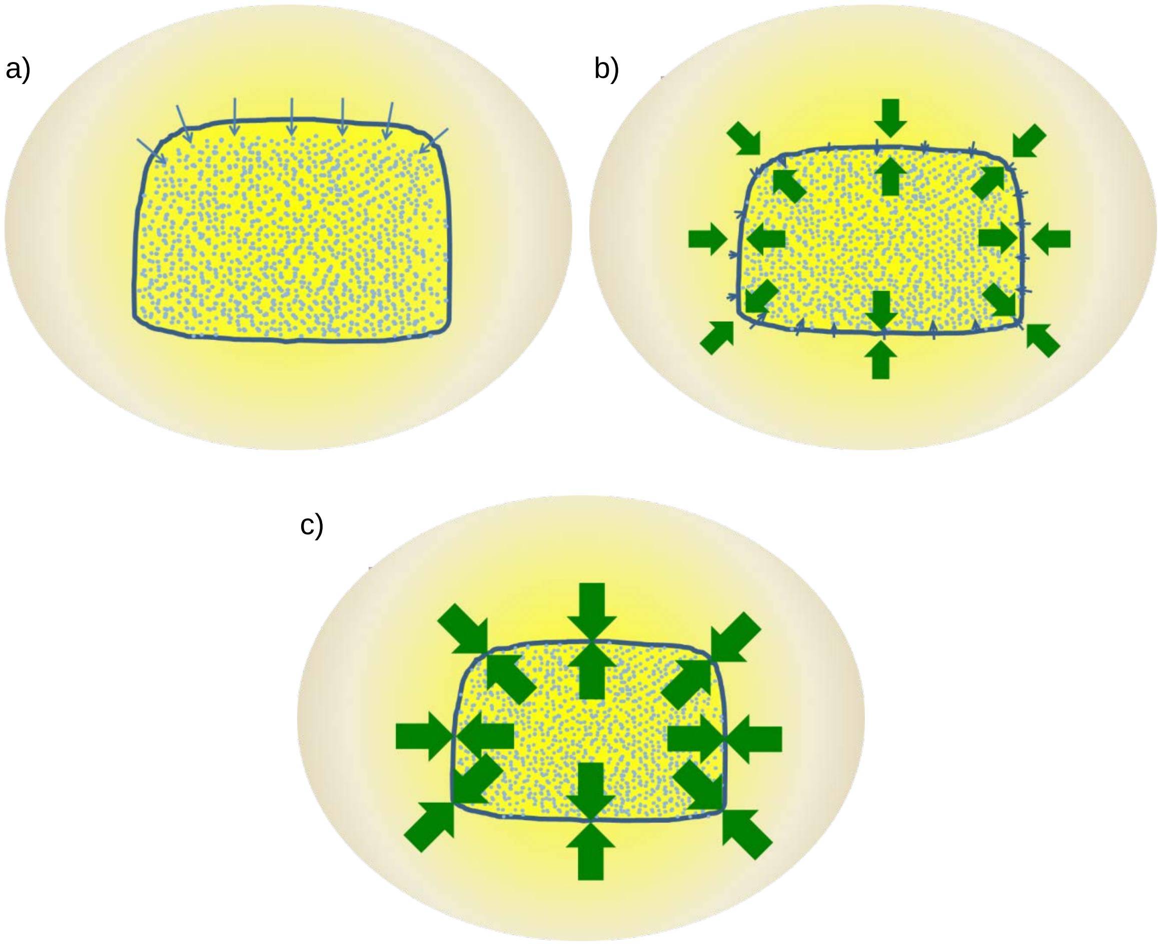



**Fig. 3.2** Characteristic phases of backfill compaction

A comparatively little moisture content in the crushed salt can reduce backfill resistance to mechanical stresses considerably thus accelerating compaction. Flow distributing brine in the pore space of the backfill can thus change the compaction behaviour considerably. By filling the pores with brine the effective heat conductivity as well as the effective specific heat is increased, accelerating heat flow even if not necessarily accelerating the spreading of temperature changes. It has to be conceded, though, that this effect becomes less and less significant during compaction because of the decreasing porosity.

Since the compressibility of a single grain in the crushed salt backfill can be considered to be negligible in the context of backfill compaction, this process means basically a reduction of pore space and a constriction of flow channels. Compaction thus also throttles brine flow. With a view to flow driven by capillary pressure, this is expected to slow down further spreading. Visualising flow channels as a bundle of capillary tubes, compaction reduces the tube diameter, but the resulting increase of the capillary pressure cannot compensate the decrease of permeability. A final consequence of compaction is that heat flow is increased due to the rather high thermal conductivity of rock salt.

It is thus that inflow of brine into the drift backfill poses a thermo-hydro-mechanically (THM) coupled problem where

– heat flow,
– unsaturated brine flow including phase changes and solution/precipitation of salt,
– elastic deformation,
– creep, and
– FADT

need to be addressed simultaneously as indicated by Fig. 3.3. The dashed arrows in the sketch on the left hand side imply that the coupling of brine flow to heat flow as well as of compaction to heat flow is comparatively weak. As phase changes and solution/precipitation of salt are not considered in the following investigation for the sake of simplicity, they are also not included in the sketch on the right hand side in Fig. 3.3.

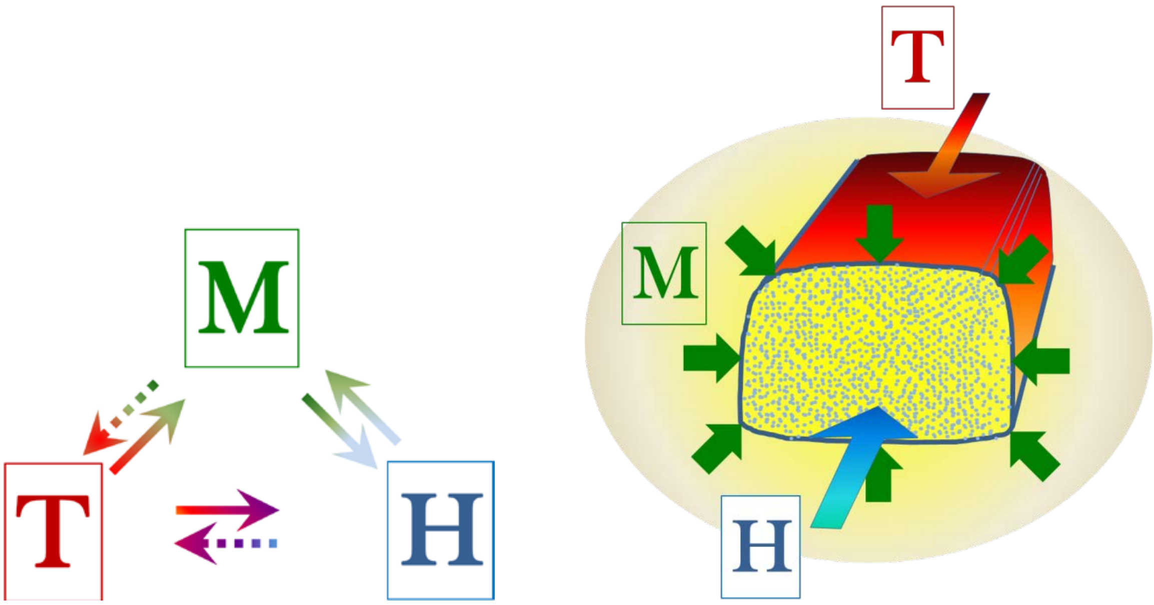



**Fig. 3.3** Process coupling during compaction of crushed salt

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