DRY INTERIM STORAGE OF RADIOACTIVE MATERIAL IN GERMANY

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Abstract - In accordance with the waste management concept in Germany, spent fuel is stored in interim storage facilities for a period of up to 40 years until deposition in a geological repository. In twelve on-site interim storages in the vicinity or directly on the sites of the nuclear power plants, spent fuel elements from reactor operation are stored after the necessary period of decay in wet storage basins inside the reactors. Additionally, three central interim storage facilities for storage of spent fuel of different origin are in operation.

The German facilities realize the concept of dry interim storage in metallic transport and storage casks. The confinement of the radioactive material is ensured by the double lid system of the casks, of which the leak tightness is monitored constantly. The casks are constructed to provide adequate heat removal and shielding of gamma and neutron radiation.

Usually the storage facilities are halls of thick concrete structures, which ensure the removal of the decay heat by natural convection.

The main safety goal of the storage concept is to prevent unnecessary exposure of persons, material goods and environment to ionizing radiation. Moreover any exposure should be kept as low as reasonable achievable. To reach this goal the containment of the radioactive materials, the disposal of decay heat, the sub criticality and the shielding of ionizing radiation has to be demonstrated by the applicant and verified by the licensing authority.

In particular accidents, incidents and disasters have to be considered in the facility and cask design.

This includes mechanical impacts onto the cask, internal and external fire, and environmental effects like wind, rain, snowfall, flood, earthquakes and landslides. In addition civilizatoric influences like plane crashes and explosions have to be taken into account.

In all mentioned cases the secure confinement of the radioactive materials has to be ensured.

On-site storage facilities have to consider the interplay with the nearby facilities too.

The facilities have to be monitored upon aging effects. This includes recurrently checks of the casks to ensure the manageability and the save confinement of the materials.

1. Introduction

The goal of the article is to provide a comprehensive overview over the safety assessment structure in Germany for storage facilities of spent fuel. This also includes depicture of necessary tasks performed to meet the requirements set by the legal authorities based on national law.

By the term "storage facility for spent fuel" the article refers to the dry interim storage facilities build for the storage of spent fuel casks like the CASTOR® series. Those facilities are located either on-site with the nuclear power plants or as a centralized storage facility on a separate site.

The on-site facilities are solely storing said spent fuel casks, while the central storage facilities also store additional types of radioactive waste. The presented article will only deal with the spent fuel casks, although the safety requirements depicted are also valid for casks storing highly active conditioned radioactive waste or other radioactive waste in general.

Main safety element of the storage facilities are the storage casks themselves, they provide the necessary confinement of the radioactive waste. The inventory integrity is provided by the structural stability of the steel cask, the special holding structure for the fuel inside and the rod claddings. Leak tightness is usually secured by a double lid closing. Proper shielding of radiation is achieved by the casks and inbuilt neutron moderator material.

For the licensed radioactive inventory the cask provides thermal stability of the waste, the radiation shielding, the sub criticality and the leak tightness. The storage facilities in Germany are buildings of concrete with wall thicknesses between 80cm and 1.2 m. They are sectioned to provide separate rooms for reception, repair and maintenance and storage respectively.

The licensing procedure is defined by the German law for nuclear power (AtG [**76**]) supplemented by the requirements stated in the regulations StrSchV[**77**] and the RSK guidelines [**78**].

The applicant, private or governmental company, has to apply for a licence (in this case) at the Federal Bureau for Radiation Protection (BfS). Compliance to the above mentioned requirements has to be demonstrated by the applicant and is then reviewed / checked and validated by the BfS with the support of external expert organisations. The demonstration of compliance has to follow the state of scientific knowledge and can be performed by experiments and/or simulations.

The licences for the storage facilities are given for a specific period of time (40 years).

Furthermore the licences for the casks are divided into one for transport and one for storage only.

[76] AtG – Gesetz über die friedliche Verwendung der Kernenergie und den Schutz gegen ihre Gefahren (Atomgesetz) – in the present valid version

[77] StrSchV – Verordnung über den Schutz vor Schäden durch ionisierende Strahlen (Strahlenschutzverordnung) – in the present valid version

[78] RSK Guides – Leitlinien der Reaktor-Sicherheitskommision

Enclosed in the licensing process is the check of the performed actions inside the facility in normal operation. In addition a set of so called design based accidents is identified which set the impacts / events the facility and casks have to withstand without violating the limits set in the regulation rules.

The following section 2 will therefore deal with the normal operation and section 3 will focus on the design based accidents. Due to the recent events, an inquiry into the safety margins provided by the layout of the facility and properties of the casks was indicated. Section 4 describes a qualitative examination of extreme events by extrapolation on the design based accidents.

2. Assessment of normal operation

When the facility runs in normal operation the confinement of the radioactive material and the prevention of unnecessary exposition to ionizing radiation have to be provided.

Furthermore the decay heat has to be safely transported outside of the facility.

To provide continuously confinement, the leak tightness of the cask has to be monitored regularly.

As for the CASTOR-Series casks there are pressure sensors installed to the double-lid system that report automatically all irregularities to the working staff. The double-lid system is constructed in a way that it will induce an error long before actual release of radioactive material will happen. This way a maintenance and repair schedule can take action to restore the leak tightness.

Since commissioning of the storage facilities and installing the automated pressure monitoring of the casks there has been no reported leakage of the casks due to malfunctioning lids, only malfunctioning pressure sensors were detected so far [79].

Unnecessary exposition to radiation for the public is avoided due to the shielding of the cask and the concrete facility building. At the nearest reachable point for the public persons, the radiation is shielded down to a sub natural radiation level.

For the working personal, prescript working schedules as well as the sectioning of the facility building reduces the exposition as much as reasonable achievable. Keeping track of the actual exposition of the working personal through calibrated dosimeters (calibrated by the responsible legal authority) ensures abiding the legal dose limits for the staff.

The decay heat removal is an integral part of the safety of the casks and the facility. The decay heat of the radioactive inventory is transported by heat conduction to the cask surface and removed via natural convection out of the facility. The facility is designed to provide effective passive cooling for the maximum licensed decay heat at any outside conditions. Due to these regulations the building integrity as well as the working temperatures for facility components is secured.

In addition the lid-temperatures inside the casks stay in a secure level to provide the leak tightness for the storage time. The stability of the inventory (like fuel rod claddings) and the moderation material is also secured.

[79] D. Wolff, U. Probst: Beurteilung bisher aufgetretener Ausfälle des Druckschalters DPS 220 hinsichtlich systematischer Versagensursachen., BAM III.4/10 299-DS Dezember 2010

Keeping track of the leak tightness is only a part of the undertaken periodic safety measures.

The casks and the facility are repeatedly checked for ageing effects. This includes corrosion checks on the casks, on the facility components, the facility structure.

3. Design based Accidents

Design based accidents are either natural events that can strike the storage facility or man made accidents in or outside of the facility. All such events shall not have any impact on the safety of the facility that can violate the radiation release limits as in StrSchV §49 [80**]**.

All design based accidents and their respective results have to be assessed in order to get a license for the facility. The events are assessed by a combination of deterministic and probabilistic inquiries.

The following design based accidents are included:

a) Dropping of Casks / dropping onto casks / collisions

Casks have to withstand collisions of the cask with other casks or facility structures while handled with the facility crane. In addition the computer driven crane is programmed to avoid collision on its own.

Furthermore droppings of casks inside the facility are considered for all possible accidents connected with handling, for instance the storage process or maintenance handling. The facility specific topology (steps), layout (sectioning, doors ...) is taken into consideration while identifying possible events.

Dropping of facility parts onto the casks are also considered but conservatively assessed by the design based accident for an accidental plane crash as described below.

b) Earthquakes

Earthquakes are by nature events hard to assess, as there is no absolute way to access the real impact strength due to the incomplete knowledge of the internal processes and status of the geology at the facility site. An interplay of deterministic (assessment based on historic events, geological structure …) and probabilistic (rate of occurrence for quakes with certain strength in given time …) methodologies have to be used to derive the so called design earthquake. In Germany each facility site has to be earthquake risk assessed for earthquakes based on the regulations stated in KTA 2201 [81]. The facility itself has to sustain the derived “design earthquake” to ensure the safety. Furthermore it has to be proved, that casks won’t topple in case of the said earthquake and therefore no mechanical impact can change the condition of the casks.

c) Fires

The design based accident fire for casks is either 600°C for 1h or 800°C with 30min in duration.

The cask has to withstand those fire conditions without substantial release of radioactive material.

Due to the high mass and specific heat of the cask material, the thermal impact is mostly limited to near surface areas within the cask. The possibility of such a fire is greatly reduced by the facility itself,

[[80]] StrSchV §49 - Release for a design based accident shall not exceed 50mSv.
[[81]] KTA 2201 - Design of Nuclear Power Plants against Seismic Events

as the amount of burnable substances in the storage facility is kept as low as possible and there are no ignition sources inside.

d) Flood

The casks have to be designed in a way that they withstand submerging into water at a depth of 200m. Furthermore the sub criticality has to be proven even for a cask filled with water (which is highly unlikely as the cask is leak tight under the submerging mentioned.) The risk of such a submersion depth is practical impossible in the case of storage in the facility.

The facilities themselves are designed against the flood height which has an occurrence probability of

10^{-4} per year. This is achieved by a heightened building site and/or temporary deployable flood protection systems.

e) Plane crashes (accidental from military vessel) (FLAB)

In safety assessment the accidental crash of a small military aircraft hitting the storage facility is considered. It is assumed that a turbine shaft hits the casks right on top. It has to be proven that the impact onto the cask does not lead to a substantial release even including the assumed fire cause by the accident. The protecting properties of the concrete building are usually neglected for this scenario.

f) Explosions

Explosions of for instance burnable gases have to be considered at the closest reasonable vicinity of the facility in the assumed available amount. This includes especially the transport by ships as the on-site storage facilities are often close to rivers with active transport routes like the NPP themselves. The strength of the explosion is derived from the maximum transport amount and ideal conditions for the explosion. The facility has to withstand the explosion without structural damage and therefore without impact onto the casks.

4. Extreme Scenarios

By the Term “Extreme Scenarios” we summarize a set of events that exceed the design based accidents. We will use those to assess safety margins of the storage facilities. Therefore the scenarios are not on a quantitative but qualitative level to identify the scaling of accident consequences in dependence of the accident/disaster extent. Wherever possible the consequences of the scenarios are assessed by extrapolating the consequences starting from the most alike design based accident.

The following procedure is used to pin down the scenarios:

First we identify events which cause radiation consequences near or above the radiation limits. Based on those limits we try to identify the types of impacts that can lead to such consequences. The possible disasters or accidents that can lead to those impacts are then considered. By choosing an extreme (but feasible) extent of such disasters we estimate the consequences based on extrapolations starting from the alike base design accident. The consequences (radioactive) of such disasters have to be compared to the limits again. Following the above depicted procedure we end up with the following scenarios:

a) Flooding

Even extreme floods that exceed the design based flood disaster can’t create any substantial release as the casks are leak tight up to 200m submerge. Furthermore the submerging in water won’t have any negative thermal impact on the casks. Assuming that floods are no permanent conditions, a corrosive damage to the cask can be excluded, especially as the casks can be checked in the following cleaning procedure. Besides very fast rising flood events (Tsunami etc.) it is also very unlikely that the storage facility itself will be damaged, and therefore the casks are also safely enclosed at the storage area.

In an event damaging the facility structure, one could argue about consequences comparable to the ones of an extreme Earthquake as described below.

b) Earthquakes

Extreme earthquakes can lead to two possible results, firstly tipping of the casks which are a mechanical impact, and secondly burying of the casks under debris of the facility which will lead to a long term thermal impact. It is secure to assume that the case of tipping casks is the one more likely to happen instead of the facility collapse. Therefore we will take the toppled casks scenario as given when considering the facility collapse.

1) Toppling of the casks in the storage facility:
The mechanical impact of a toppling is much lower than the impact of the design based accident FLAB. Therefore it is conservative to assess the releases of this case by this design base accident (FLAB). When extrapolating the releases to the amount of casks possibly affected at the storage facility it leads to no unsustainable consequences.

2) Burying the cask below debris due to collapse of the facility building:

In an event of overwhelmingly strong earthquakes, the possibility of partly or full collapse of the facility building is feasible. The casks will then be toppled and buried below debris.

However the mechanical consequences for the casks of such a collapse are not stronger than the ones coming from the FLAB. It is feasible to assume the releases to be in the same dimension. Therefore main focus lies on the thermal impact due to reduced air cooling of the casks.

Under realistic assumptions the heat up of the cask will take weeks until the final temperature is reached. Furthermore the reached temperatures are below temperatures harming the integrity of the casks. Nevertheless, special attention is advised for the working personal in the recovery / retrieval of the casks, as the neutron moderator material will be lost in the long run, imposing special attention to radiation protecting of the working personal.

c) Fire

As seen in the former scenario the thermal condition of the cask is an important issue. While due to an earthquake the thermal impact is on a daily/weekly scale, a fire scenario is of much shorter duration.

In the design based accidents the duration is 1 h at maximum.

Fires with longer durations than 1h are very unlikely to happen from natural sources.

Even including man made burnable substances it is highly unlikely to sustain a fire for a longer period due to the sheer amount of needed material. In addition the response time of fire-fighters is not to be expected to exceed hours.

Anyhow, assuming fires with varied duration shows that fire of several hours can lead to a cask temperature inside, so that the lid seal maximum temperature is exceeded.

In such a case the radiation release would be gradually higher than the releases calculated for the design based accidents, depending on fire duration. A temperature endangering the overall integrity of the cask is not feasible with substances viable in an accidental/disaster situation.

d) Explosions

Including explosions of sources closer and/or stronger lead basically to the same impacts as earthquakes. Moreover an explosion has a much shorter “burning” time, so that the assumptions made in the extreme fire scenario cannot be reached. And therefore the thermal/mechanical consequences are more of theoretical value than actual feasible.

In summary, Table 1 shows a collection of the results. Given the extreme scenario one can clearly see that the feasible scenarios are not leading to radiological consequences above the legal limits.

The row “feasible as accident/disaster” describes whether the accident/disaster is imaginable as natural event or accident or the overall probability of the disaster extent. Finally row “not radiological impact to the surrounding area” is assessing the probable damage to the surroundings, as for instance civilian buildings. By earthquake 1 we address the earthquake that topples the casks but does not damage the facility, while earthquake 2 is assessing an earthquake strong enough to damage and collapse the facility itself.

The disasters fall mainly in 2 categories. One is the feasible disasters, which have a very low probability but are imaginable, the other are the scenarios which are not feasible as a pure accidental situation. The first category leads to no radiological consequences exceeding the legal limits, but have disastrous effects on the surroundings. The second category is only affecting the close vicinity without damage to the civilian buildings in greater distance. The possible radiological consequences are possible in the dimension of the radiological limits. It must be kept in mind however, that due to the not feasible nature they are not relevant for a pure safety assessment situation.

Table 1**. Extreme Scenarios - Overview**

Accident/ Disaster	Radiologic consequences compared to limits	Feasible as accident/disaster	Not radiological impact to surrounding area
Flood	Very limited to none	Unlikely in the extreme extent	Severe flood damage in a large surrounding area
Earthquake 1	Safely below limits	Yes	Depending on the structural integrity, high damage to buildings in the area
Earthquake 2	Safely below limits for a timeframe of several weeks[82]	Yes	Devastating effects on even strong concrete buildings and therefore for most civilian buildings
Fire	Below limits, limits are reachable for long durations (several hours)	No[83]	Only close vicinity will be affected
Explosion	Safely below limits	No[83]	Only close vicinity will be affected

5. Conclusion

The licensing process for radioactive waste interim storage facilities in Germany as defined by law secures a traceable and reliable way for storage of radioactive waste. The safety of the facilities has to be demonstrated by the applicant and is checked by the regulatory body. This includes the normal operation as well as so called design based accidents for which has to be proven that the consequences stay safely below the regulatory limits. As presented in the article, a wide range of nature based events and man-made accidents are covered. Extrapolations of those events to extreme scenarios show that the storage facilities in Germany include a high level of safety margins. It is therefore safe to assume that the interim storage facilities and stored casks are safe for the investigated events.

[82] Depending on the time buried the release scales.
[83] The amount of burnable/explosive material is not feasible originating from an accidental situation.

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Workshop on Safety Assessment of Fuel Cycle Facilities –

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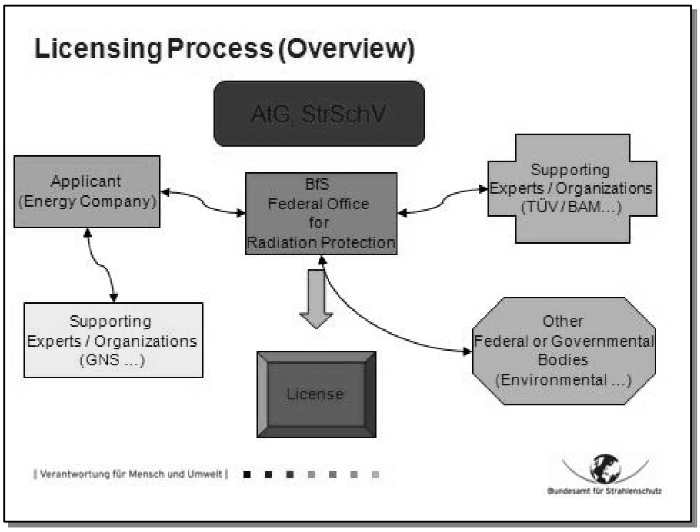

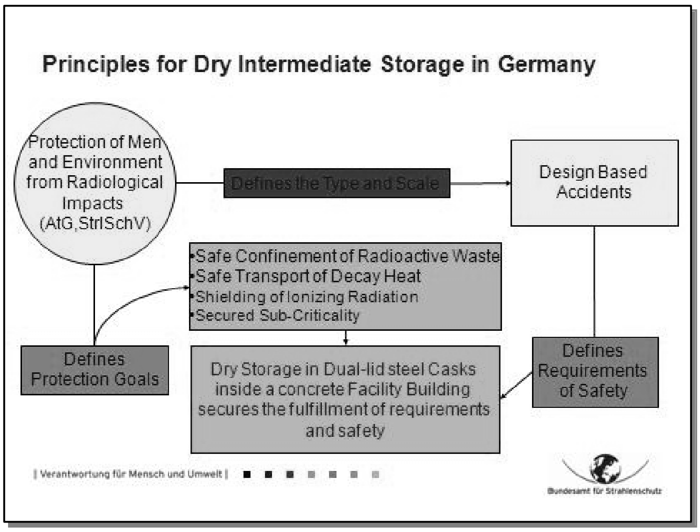

Aspects Covered in the Licensing process

- Protection / Safety Goals
- Normal Operation (Cask handling, Surveillance, Maintenance ...)
- Design Based Accidents
- Protection of Environment
- Protection of Public (Dose limits for public etc.)
- Protection of Workers (Dose limits for working personal)

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Design Based Accidents

- Wind / Rain / Snow / Lightning ...
- Flood
- Earthquake
- Handling Accidents (Cask Dropping, Collisions etc.)
- Fire (inside / outside)

- Crash of an military Aircraft
- Explosion of combustible Gases (from outside)

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„Assessment" of Extreme Events

- Events exceeding the prior mentioned design based accidents are NOT covered in the licensing process.
- The following inquiry is based on extrapolation and good knowledge.
- Aim of the inquiry is to indentify safety margins and the grade of aggravation of event consequences.

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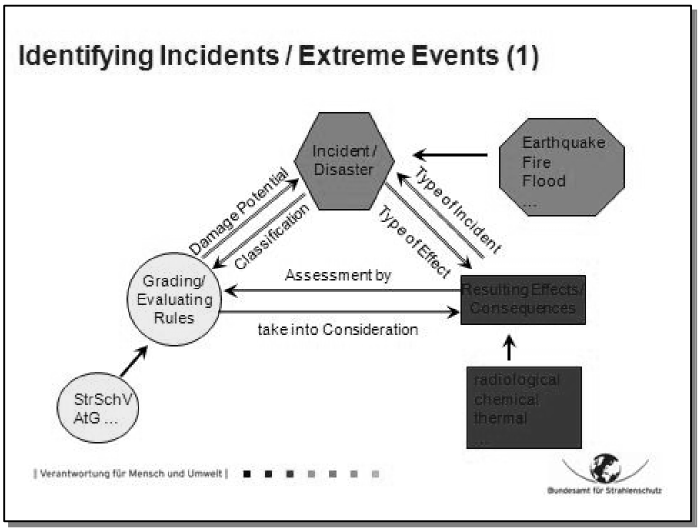

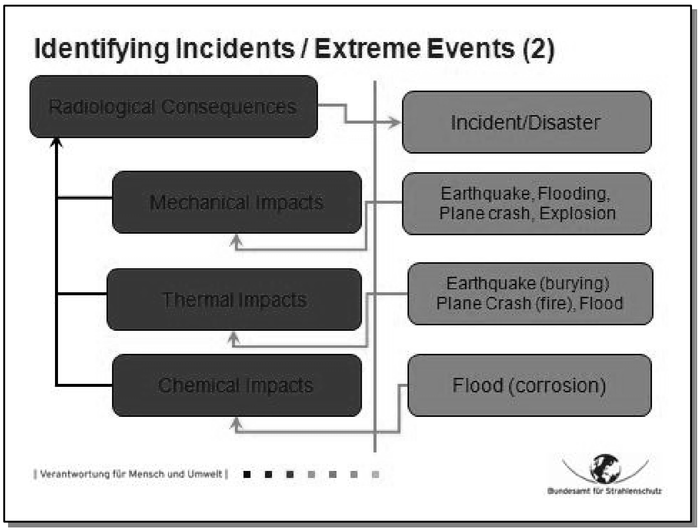

Extreme Event: Flood

Assessing the Impacts:

— **Chemical Impact:**
- Very little, if any, as casks are protected against corrosion and the metal thickness is way too large for corrosion in a short timeframe.

— **Mechanical Impact:**
- Little to none, as casks (toppling due to flooding nearly impossible)

— **Thermal Impact:**
- None as water is effectively cooling the casks.

Resulting Consequences:

— **Very little to none**

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Extreme Event: Earthquake

Assessing the Impacts:

- Chemical Impact: none
- Mechanical Impact:
  - Toppling of casks – already considered in handling accidents and conservative below effects of a airplane crash onto a cask.
  - Burying of casks with debris – dropping of Building parts onto the cask is conservatively below the effects of an airplane crash.
- Thermal Impacts:
  - Burying of casks with debris – reduced thermal conductivity and convectional cooling of the casks.
  - Timeframe for reaching a final heat up temperature is several weeks but safely below critical values.
  - Special arrangements have to be made when recovering the casks due to increased neutron radiation (loss of moderation material)

Resulting Consequences:

- Save below dose limits for several weeks of buried casks.

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Extreme Event: Fire

Assessing the Impacts:

- Chemical Impact:
  - Little, at worst oxidation damages at the surface of the casks
- Mechanical Impact:
  - Little to none as the cask materials have comparable heat expansion rates (except the moderation material)
- Thermal Impact:
  - Depending on the fire duration the thermal impact can lead to a temperature exceeding the design temperature of the lid system
  - Necessary for this is a fire duration of several hours.

Resulting Consequences:

- Gradually increasing consequences with fire duration.
- However there is no reasonable way to accumulate the amount of necessary burnable material by a natural event or accident.

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Extreme Scenarios Summary

Accident/ Disaster	Radiologic consequences compared to limits	Feasible as accident/disaster	Not radiological impact to surrounding area
Flood	Very limited to none	Unlikely in the extreme extent	Severe flood damage in a large surrounding area
Earthquake (toppling)	Safely below limits	Yes	Depending on the structural integrity, high damage to buildings in the area
Earthquake (burying)	Safely below limits for a timeframe of several weeks[1]	Yes	Devastating effects on even strong concrete buildings and therefore for most civilian buildings
Fire	Below limits, limits are reachable for long durations (several hours)	No[2]	Only close vicinity will be affected
Explosion	Safely below limits	No [2]	Only close vicinity will be affected

[1] Depending on the time buried the release scales.
[2] The amount of burnable/explosive material is not feasible originating from an accidental situation.

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