REPORT

IRSN
INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

Enhancing nuclear safety

Storage of nuclear spent fuel: concepts and safety issues

IRSN Report No 2019-00181

Report written in response to a request from the French Parliamentary Inquiry Committee on the Safety and Security of Nuclear Facilities

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MEMBER OF ETSON

This report is the English translation of the IRSN report n°2018-00003 entitled “*Entreposage du combustible nucléaire usé : concepts et enjeux de sûreté*” issued in June 2018.

REPORT SUMMARY

The Chair of the Parliamentary Inquiry Committee on the Safety and Security of Nuclear Facilities, set up by the French National Assembly in 2018, wrote to the French Institute for Radiological Protection and Nuclear Safety (IRSN) on 26 March 2018 to seek its opinion on the nuclear safety issues associated with a strategy for managing irradiated nuclear fuel (also known as spent fuel) based on the storage of that fuel only in a pool (or underwater so called wet storage) or also in dry storage facilities.

IRSN has made a review of the existing concepts of spent fuel storage worldwide and in France. The institute also made a review of the associated safety issues, taking into account the characteristics of different types of fuel and the various types of storage (wet or dry, on-site or centralised).

From this review, IRSN has identified the following key points.

Spent fuel from nuclear power plants requires interim storage after being unloaded from the reactor. Its initial residual heat is too high. So decay of the radioactivity that it contains, which gradually reduces this heat, is necessary to enable it to be transported and managed using the chosen method. In all cases, it is stored initially in the reactor spent fuel pool. Then, depending on the chosen management option (reprocessing or disposal), two practices are used throughout the world.

If the spent fuel is to be reprocessed (as it is in France, Japan and Russia), the reprocessing plants have pools to store it before reprocessing (generally during five to ten years after it is unloaded from the reactor). This type of storage is essentially linked to the processes of these plants, the pools in which the fuel is placed being directly connected to the reprocessing workshops. In addition, the capacity of these pools is generally very large to provide a buffer between activity at the reactors and activity at the plant and to allow additional cooling. Once they are separated, the uranium and plutonium are sent for recycling into fuel assemblies made from plutonium (MOX) or from enriched reprocessed uranium (ERU). The storage methods for spent MOX and ERU fuels then depend on the planned future of these fuels in the countries concerned.

If spent fuel is not reprocessed (as in most places in the world), the unloaded fuel is generally placed in dry storage facilities once it has cooled down sufficiently in a pool. Current storage concepts are based on the average residual heat of fuel assemblies being around 2 kW. To a certain extent, it should be possible to adapt these concepts.

The residual heat per unit of the fuel assemblies to be stored is a decisive factor in determining the type of storage to be used. Storage in a pool is essential for spent fuel with high residual heat and dry storage is suitable for fuel that has cooled down significantly.

In any case, the two types of storage are complementary, but the decision to use one or the other after an initial cooling phase, of necessity in a pool, depends to a large extent on national choices regarding spent fuel management.

In France, the decision to store spent fuel in a pool is linked primarily to the choice for reprocessing spent fuel to recycle the plutonium and uranium.

Spent uranium oxide-based fuels (ENU) are reprocessed and are therefore stored in pools at the ORANO Cycle plants at La Hague until this can happen. Spent ERU and MOX fuels are managed in a similar way, but their reprocessing is differed. Pending a decision about their future, EDF plans to create a centralised storage pool to store spent MOX and ERU fuels for around a hundred years.

Spent ERU fuels have similar characteristics to spent ENU fuels. The ENU fuels currently used by EDF could, with the current concepts, be stored in dry conditions after cooling for around five years. However, because of the amount of time remaining before they are reprocessed, there seems to be little point in using this type of storage. If a spent fuel reprocessing plant were to be unavailable for a long period (eventually causing saturation of the existing storage capacity), using this type of storage could be one solution.

Fresh MOX fuels loaded into a reactor have a high plutonium content to give them an equivalent burnup to that of the ENU fuels used with them in the reactor. Due to this plutonium content and its isotopic composition, spent MOX fuels have a higher residual heat. Because of their higher transuranium element content, their residual heat is also slower to decay. The cooling time before they can be placed in dry storage is therefore substantially longer than for spent ENU fuel, i.e. it takes several decades to reach a residual heat per fuel assembly of 2 kW. The use of dry storage could therefore be envisaged only beyond this period of time.

Wet storage is particularly suitable for fuels with a high residual heat, which can therefore not remain in air without deterioration of their cladding. Water is an effective coolant and active cooling systems that use it can keep fuel cladding at low temperatures. In addition, a pool has considerable thermal inertia, making it easier to deploy emergency systems if the cooling systems are lost.

The main safety requirements for wet storage are to maintain a sufficient water inventory in the pool and to have cooling systems available in all plausible circumstances. Because of the high residual heat per unit of the spent fuels contained in the pool, a prolonged loss of cooling without water makeup could have very significant consequences for the environment. In case of such a situation it becomes impossible to go near the pool because of the high dose rate induced by the fuel in the absence of any attenuation of the radiation by water.

Consequently, a spent fuel pool, particularly if it receives spent fuel that has hardly cooled, must be of a particularly robust design, with sufficient margins to cope with any risks that can be envisaged, and its operation must allow appropriate monitoring of both the installation itself and the fuel it contains.

Experience feedback from the Fukushima accident lead safety approaches for controlling these risks to be reinforced, aiming to maintain a sufficient water inventory in extreme situations of natural origin.

Current industrial techniques enable pools to be built that control the risks of fuel uncovering, with the buildings housing the pool providing protection against external hazards (particularly the airplane crash shell).

It generally takes about a decade to build a facility of this kind, based on current experience feedback from nuclear facilities built in France.

Dry storage is usually dedicated to fuel that has cooled sufficiently (to around 2 kW on average per fuel assembly with current concepts). Consequently it has the advantage of generally using passive cooling systems, which limits operating constraints, and it lends itself particularly well to modular construction, adapting to needs or even enabling old modules to be replaced over time.

The safety requirements are the maintenance of passive cooling and the quality of the containment barriers between the radioactive materials and the environment.

This type of storage has the advantage of a simpler, more robust design and less operational intervention. Depending on the design, direct monitoring of the condition of the fuel cladding (the first containment barrier), which is subject to the most demanding thermal conditions, is generally not possible.

In any case, if an accident occurs, the smaller number of fuel assemblies and their lower residual heat will mean fewer consequences for the environment.

It generally takes around five years to build this type of facility, depending on its modularity and whether or not existing cask concepts are used.

Moreover, regardless of the type of storage, significantly longer storage periods than the usual periods (of a few decades) will require the definition of appropriate requirements (particularly in terms of the design of the civil engineering structures and in terms of safety margins).

For IRSN, one particularly important point for the safety of spent fuel management is controlling the ageing of zirconium fuel cladding, which depends on storage temperature. This cladding is the first containment barrier for the radioactive materials. In addition, its mechanical strength is important for the operations to take place after storage (transport, reprocessing or disposal).

Wet storage offers guarantees in this respect, given the low temperatures and the potential for direct examination of cladding. Countermeasures (canisters for defective fuel) can also be taken if ageing phenomena are detected. There is a significant experience feedback available in France and throughout the world on the behaviour of cladding underwater, at least for periods of a few decades.

With dry storage, it is more difficult to examine fuel cladding directly. Any inspections made are at best indirect (no release of gases into the cask cavity, etc.), or impossible (fuel canisters sealed by welding constituting the second and final confinement barrier); they do not enable the detection of ageing mechanisms.

Any guarantees that the ageing of cladding is controlled are based primarily on studies, which have notably defined the maximum acceptable temperature for cladding in storage. No examinations of fuel carried out to date, as far as IRSN is aware, have challenged the findings of these studies. However, many studies are ongoing. Moreover, there is limited information available for fuels with a high burnup (more than 45 GWd/t), for MOX fuel (especially with a high initial plutonium content) and generally for long storage periods (more than 40 years).

To conclude, IRSN considers that decisions about the type of storage to be used for spent fuel must be assessed in the light of the following considerations.

The two types of spent fuel storage that could be envisaged (wet or dry) do not serve exactly the same needs, since wet storage is absolutely necessary for fuel that has hardly cooled and dry storage is suitable for fuel that has cooled substantially.

The type of spent fuel (ENU, MOX or ERU) affects any decision about which type of storage to be used, at least for a certain period of time, because MOX fuels have a higher residual heat for longer period.

From a safety point of view, regardless of the type of storage, the decisive parameter is the residual heat of the fuel to be stored. Wet storage, which generally contains hotter fuel, requires more substantial safety measures than dry storage, for which more passive measures can be implemented. In dry storage, cladding (the first containment barrier) is subject to greater thermal stress and is more difficult to inspect.

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1 PRESENTATION OF THE REQUEST AND IRSN'S APPROACH

The Chair of the Parliamentary Inquiry Committee on the Safety and Security of Nuclear Facilities, set up by the French National Assembly in 2018, wrote to the French Institute for Radiological Protection and Nuclear Safety (IRSN) on 26 March 2018 (see letter in Appendix 1 to this report) to seek its opinion on the nuclear safety issues associated with a strategy for managing irradiated nuclear fuel (also known as spent fuel) based on the storage of that fuel only in a pool (or underwater so called wet storage) or also in dry storage facilities.

The Committee's initial work had revealed that spent fuel management presents particular issues. The operation of nuclear power reactors leads to the generation of spent fuel, which then has to be stored for a period of time dictated by national choices regarding the management of radioactive materials and waste (reprocessing/recycling, long-term storage, etc.).

In this context, the Committee learned of EDF's plan to build a centralised spent fuel pool facility, designed to store spent fuel for a period of one hundred years. It also found that storage in a pool is not the only option and that an increasing share of spent fuel in many countries is put into 'dry' storage using large containers (or 'casks'). It therefore wanted more detailed information to enable it to give an opinion about storage facilities and, where appropriate, draw conclusions and make recommendations.

According to the request of the Parliamentary Inquiry Committee on the Safety and Security of Nuclear Facilities in France, the objective of this report by IRSN is to present the existing concepts of spent fuel storage, as well as the associated safety issues, taking into account the characteristics of different types of fuel and the various types of storage (wet or dry, on-site or centralised).

The examples presented in this report are only intended as an illustration of the diversity of spent fuel storage concepts throughout the world, whether dry or wet; they are not intended to promote a particular technology or manufacturer or to be exhaustive.

2 BACKGROUND

Fuels used in French nuclear power plants

Most of the nuclear spent fuel generated in France comes from France's fleet of 58 pressurised water reactors currently operated by EDF for power generation. The reactors in this fleet are located at 19 nuclear power plants (NPPs); there are 34 of the 900 MW reactors, there are 20 of the 1,300 MW reactors, and there are four 1,450 MW reactors. The EPR reactor (1,650 MW) at the Flamanville site is currently in the process of completion.

The fresh fuel used in these reactors consists of uranium oxide (UOX), slightly enriched with uranium-235 (known as enriched natural uranium fuel or ENU), or mixed uranium and plutonium oxides (MOX fuel). The plutonium used comes from the reprocessing of spent ENU fuels at the ORANO Cycle plant at La Hague. MOX fuel is currently used at 22 of the 900 MW reactors in the CPY series (though 24 are licensed to use this fuel).

The fuel used in France can also consist of uranium oxide from the reprocessing of ENU fuels (enriched reprocessed uranium known as ERU). However, this type of fuel, used in the four reactors of the Cruas NPP, has not been used since 2013; EDF plans to resume using it in the next few years.

International and French spent fuel management strategies

Two main national policies for managing spent fuel have been developed throughout the world: fuel reprocessing aimed at using recyclable materials in new fuels (the 'closed' fuel cycle) or direct disposal ('open' fuel cycle). In both cases, interim storage of the spent fuel is necessary pending implementation of the chosen option (several storage facilities, which may be of different types, may be used in succession).

The technical solutions used by different countries for this storage are:

- wet storage in the pool attached to the reactor;
- wet storage in a pool on site or in a centralised facility (shared by several sites);
- dry storage on site[1] or in a centralised facility (shared by several sites).

A survey of international practices is presented in Appendix 2 to this report.

International experience feedback shows that, where spent fuel is destined for direct disposal, wet and dry storage are used and the use of dry storage facilities is growing. The solution used in many countries is therefore to store the spent fuel in the pools attached to NPPs (used mainly for refuelling), then in dry storage facilities once their radioactivity and the heat that they release have diminished sufficiently. This strategy is used notably in the USA. In 2015, around 80% of spent fuel in the USA was stored underwater and 20% was in dry storage (though the latter percentage is steadily increasing).

When spent fuel is reprocessed, it is stored underwater as the length of time before the fuel can be reprocessed is often similar to the time it takes to cool down sufficiently to be transferred to a dry storage facility. When reprocessing is delayed, dry storage may also be used. Japan, because of its current situation, has planned in 2018 to commission a dry storage facility for spent fuel at Mutsu, while continuing its policy of reprocessing spent fuel. The Japanese Minister for Industry is planning the construction of between three and six installations of this kind by 2050.

France has chosen to recycle plutonium and uranium; instead of being viewed as waste, these materials are now considered to be sources of recoverable energy, the intention being to reuse them in future. According to this strategy, the spent fuels (ENU, MOX and ERU) from France's nuclear power plants are not destined for direct disposal. Spent ENU fuel is reprocessed at the Orano Cycle plants at La Hague ready for the fabrication of MOX fuels at the Orano MELOX plant (or of ERU fuels at the Framatome plant at Romans-sur-Isère, once this type of spent fuel management has been implemented). In the case of spent MOX and ERU fuels, as stated in the National Plan for the Management of Radioactive Materials and Waste (PNGMDR 2016-2018), "*the industrial management of these fuels today preferred by EDF is recycling in generation IV fast neutron reactors (FNR)*". Spent MOX and ERU fuels are currently stored until they can be recycled. The nuclear fuel cycle of France's pressurised water power reactors is presented in Appendix 3 to this report.

This choice has been confirmed by Programme Act No 2006-739 of 28 June 2006 on the sustainable management of radioactive materials and waste, which institutes Article L.542-1-2 of the Environment Code, in particular setting out guidance for the PNGMDR, including "*every effort must be made to reduce the quantity and toxicity of radioactive waste, in particular through spent fuel reprocessing and radioactive waste treatment and conditioning*".

1 Facilities for on-site storage of spent fuel are often referred to internationally as ISFSI (*Independent Spent Fuel Storage Installations)*.

For the record, spent fuel reprocessing consists of extracting the uranium and plutonium by a mainly chemical process, while the fission products[2] and transuranium elements[3] other than plutonium (known as 'minor actinides') are conditioned in a glass matrix and stored awaiting a long-term management solution (permanent disposal in a deep geological formation, the Cigeo project), as specified in the PNGMDR 2016-2018.

Stages of spent fuel management in France

After it has been unloaded from a reactor, spent fuel has a very high residual heat (because of its radioactivity), which decreases very rapidly. For example, the core of a 900 MW reactor, made up of 157 fuel assemblies, has a total residual heat of around 200 MW just after the reactor is shut down, which decays to around 40 MW one hour after shutdown, then to around 16 MW after one day. This decay process then slows down because the short-lived radioactive elements (i.e. those with a short radioactive half-life) have disappeared.

Because of the radioactivity and the high residual heat of spent fuel in the first few months after unloading, for which substantial cooling is required to prevent cladding degradation, a decay or cooling period in the pool adjoining each power reactor is necessary before the spent fuel is taken to a storage[4] (or disposal) facility. The decay kinetics of the residual heat depend on the fuel type, as shown by figure 1 below. In practice, under the transportation licences currently valid in France, the maximum residual heat of a spent fuel assembly that can be transported on a public road is 6 kW; it depends on the transport package model used.

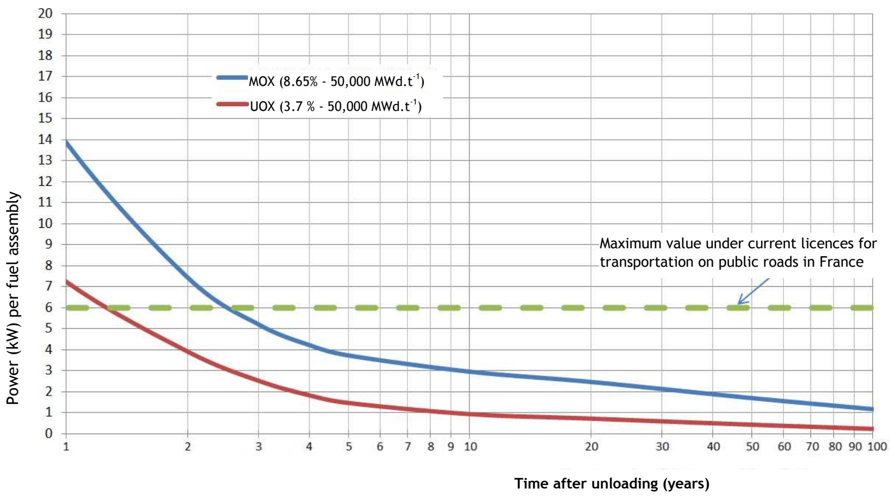


Figure 1: Curves for decay of the residual heat of a UOX fuel assembly and a MOX fuel assembly irradiated in a PWR in France

In France, spent fuel is stored in 'fuel' building (BK) pools (see figure 2) after being unloaded from reactors, and is then transported to the Orano Cycle site at La Hague, where it is stored in one of the four pools (see figure 3) currently in operation at the site. The minimum cooling time in the BK pools before the fuel can be transported is around 18 months for spent ENU and ERU fuels and around 30 months for spent MOX fuels currently in reactors.

2 Fission products are chemical elements resulting from the fission of a fissile element (a nucleus). They come from the fission of uranium and plutonium atoms: caesium, strontium, iodine, xenon, etc. They are mostly radioactive, and over time transform by themselves into other elements.

3 The transuranium elements are the group of chemical elements heavier than uranium (atomic number 92). The main transuranium elements are neptunium (93), plutonium (94), americium (95), and curium (96).

4 Storage is different from disposal because it implies the eventual retrieval of the stored objects (spent fuels) and the monitoring and active maintenance of the installations.

Figure 2: Photo of a BK pool

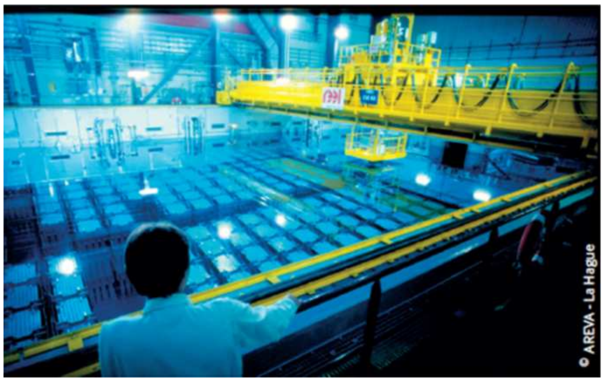


Figure 3: Photo of one of the pools at the Orano Cycle site at La Hague

Spent ENU fuels are stored in a pool until they are reprocessed in the plants on the Orano Cycle site at La Hague (reprocessing generally takes place after around 10 years' cooling).

ERU and MOX fuels, which are not reprocessed, are currently stored in the pools at the La Hague site. Because EDF's current strategy is to store them underwater and to reprocess them in due course (after 2050) in order to use the plutonium in future generations of reactors, e.g. fast neutron reactors (FNRs), the storage time of these fuels, their future and therefore their final destination depend on decisions about the development of these new generations of reactors.

A specific analysis of the operation of EDF's fuel cycle (fabrication, use in a reactor, then reprocessing) is regularly carried out. EDF sends it to the French Nuclear Safety Authority (ASN) and it is assessed by IRSN. The analysis, carried out by EDF in collaboration with the other French operators, aims in particular to ensure that there is adequate capacity for storing and reprocessing radioactive materials and waste. The assessments carried out within this framework in 2016 by EDF concluded that the storage capacity for spent fuels in existing pools could reach saturation by 2030.

Article 10 of the Order of 23 February 2017, issued in application of Decree No. 2017-231 of 23 February 2017 (see Article L. 542-1-2 of the Environment Code) setting out the requirements for the PNGMDR 2016-2018, requires EDF to submit by 31 March 2017 its strategy for managing storage capacity for spent fuel from PWRs (spent ENU, ERU and MOX fuels) and the timetable for building new storage capacity and, by 30 June 2017, the technical and safety options for the creation of new storage capacity.

In 2017 EDF submitted to ASN the Safety Options Report (DOS) for a new centralised wet storage facility, designed to increase spent fuel storage capacity. This report is currently being examined by IRSN. EDF plans to submit the construction licence application for this facility in 2020, with a view to commissioning it by 2030.

EDF has chosen wet storage for these spent fuels rather than dry storage because it believes that wet storage offers better guarantees as regards their retrieval and subsequent reprocessing. The new centralised wet storage facility will be intended mainly for spent ERU and MOX fuels, especially those currently stored in pools on the Orano Cycle site at La Hague.

In France, spent fuels from EDF's reactors that are not stored in the BK pools of those reactors are currently stored centrally in the pools on the Orano Cycle site at La Hague. As regards transport flows, EDF's decision to build a new centralised wet storage facility will lead to an increase of transport flows during the transitional phase when the spent MOX and ERU fuels will be transferred from the La Hague site to this new facility. However, once normal operation will be set, it should not significantly increase transport flows (around 220 transport movements per year at present), since spent ENU fuel will go to the pools on the Orano Cycle site at La Hague and the spent MOX and ERU fuels will go to the centralised wet storage facility.

3 GENERAL INFORMATION ABOUT STORAGE FACILITIES

In France, storage is defined by the Act of 28 June 2006 as follows: "*the storage of radioactive materials or waste is the operation consisting of placing these substances temporarily in a surface or near-surface facility designed specifically for this purpose, with the expectation of retrieving it*". A storage facility for radioactive materials is a nuclear installation or part of a nuclear installation which is firstly intended to store radioactive materials in conditions that are safe for the public and the environment and secondly designed to enable their retrieval at a later time.

The safety measures for nuclear installations are defined in accordance with the defence-in-depth principle. This principle uses a series of different measures, representing successive levels of defence that are sufficiently independent of one another, with the aim of providing robust protection against the hazards induced by the installation. These risk control measures are defined to take account of accident situations that can arise as a result of hazards, whether external (earthquake, etc.) or internal (fire, etc.), or because of equipment failures or errors linked to human or organisational factors. They concern the normal, incident and accident operation of the facility.

The defence-in-depth principle is represented by five levels of defence. The first three aim to prevent and control incidents and accidents. The purpose of the last two levels is to limit the impact of a severe accident on humans and on the environment.

For storage facilities, these measures aim to meet the following fundamental safety objectives:

- to protect people and the environment from ionising radiation by minimising the doses received throughout the entire process of managing radioactive objects;
- to contain the radioactive materials by controlling all transfers of radioactive elements to the environment in normal and incident situations and by limiting releases in the event of an accident. To do this, containment is achieved by placing a sequence of barriers between the radioactive materials and the environment;
- to prevent criticality accidents (meaning an uncontrolled divergent fission chain reaction)[5];
- to remove the residual heat emitted by radioactive materials by maintaining sufficient cooling.

The design of a storage facility should also, throughout the facility's life, ensure the radioactive objects stored in it can be retrieved safely within an appropriate time scale. This means it is necessary to:

- monitor and manage (traceability, radiological inventory, characterisation, etc.) the stored radioactive objects;
- have the necessary equipment to retrieve these objects.

5 Fissile materials, of which the main ones are uranium-235 and plutonium-239, have the property of being able to sustain fission chain reactions when certain conditions are in place. Criticality risk is the risk of creating the conditions necessary to set off and sustain fission chain reactions. Criticality risks are present at all stages in the fuel cycle, at installations receiving fissile materials and during operations to transport these materials. Prevention of these risks consists of determining the conditions to ensure subcriticality, i.e. to not trigger these uncontrolled chain reactions. These conditions are transposed into design criteria to be met when designing equipment and into operating rules to be followed.

In this context, the importance of the safety role played by the cladding (a metal tube made from zirconium and sealed tight) in which the fuel pellets are placed, should be highlighted. This cladding plays a part in the containment of the radioactive materials; it constitutes the first containment barrier (closest to the material).

Its integrity is important in order that the fuel can be retrieved safely and in optimal operating conditions for reprocessing or conditioning to be ready for its disposal. Its mechanical characteristics also need to be monitored over time (leaktightness, integrity, etc.).

Given the ageing mechanisms of cladding (corrosion, hydriding, creep, etc.), safety requirements are defined for spent fuel storage facilities (temperature conditions, control of the chemistry of its surrounding medium, etc.).

In the case of dry storage facilities, because these phenomena are activated by heat, a maximum temperature is defined for cladding (of around 400°C in most countries), which in practice limits the residual heat of the spent fuel that can be stored there. For storage in casks (see section 5 of the report), the residual heat is around 1 to 2 kW per fuel assembly. As shown by figure 4 concerning the residual heat of spent fuel, this means that spent fuel needs to be cooled first underwater (for a few years in the case of spent ENU fuels or a few decades in the case of spent MOX fuel).

It is also worth pointing out that the internal pressure of the cladding, which is likely to have an impact on ageing mechanisms, is greater in spent MOX fuels than in spent ENU fuels.

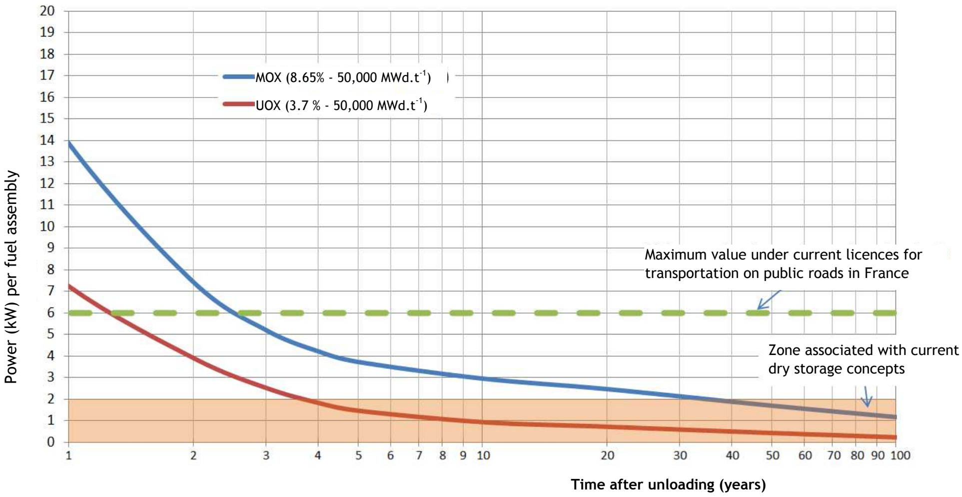


Figure 4: Cooling period necessary before dry storage, for fuels irradiated in a PWR in France

At a high temperature (above 600°C), violent oxidation of the zirconium in the spent fuel cladding can occur, particularly in the presence of water vapour. This phenomenon causes rapid deterioration of the cladding (loss of integrity) and the production of large amounts of hydrogen gas (causing an explosion risk). In addition, runaway of this reaction is likely because it is strongly exothermic. This leads, for example, to particular measures being taken to prevent the risk of uncovering of fuel stored underwater or, to a lesser extent, to the use of an inert gas in the internal atmosphere of containers used for dry storage.

The design data of spent fuel storage systems mainly concern the characteristics of the materials to be stored (dimensions, radioactivity, dose rate, mechanical strength, residual heat, etc.) and the operating measures (storage and handling measures) and safety measures (protection from ionising radiation, containment of materials, prevention of criticality risks, etc.). With spent fuels, particularly important characteristics are their initial enrichment with uranium-235 (or plutonium), in view of the need to prevent criticality risks, and their residual heat (which depends on their burnup[6] and their cooling time since being unloaded from the reactor), in view of the need for cooling and radiation shielding. There are greater constraints with spent MOX fuels due to their plutonium content, because they emit more neutron radiation and heat.

In view of the potentially long storage periods of spent fuels, the design of a storage facility must ensure:

- simple, proven components are used that are as passive as possible;
- changes in thermal conditions are slow (thermal inertia) in incident and accident situations;
- ageing processes are taken into account over the entire planned operating period (for example, when defining requirements for the chemistry of the surrounding medium, etc.);
- appropriate maintenance and monitoring programmes are drawn up, particularly to ensure the fuel can be retrieved, including to maintain the integrity of the fuel over time;
- the traceability of the spent fuel and the keeping of records about it.

Finally, the design must address the risks from hazards of internal origin (falling loads, fire, flood, etc.) and external origin (earthquake, flood, industrial environment, aircraft crash, etc.).

Regarding the amount of time it generally takes to build a spent fuel storage facility, IRSN does not have enough information to assess the time necessary to complete the industrial and regulatory stages leading to the commissioning of this kind of facility. However, with current French regulatory procedures and based on experience feedback from the construction of recent nuclear installations, it could take around 10 years, or possibly five years for modular dry storage facilities.

4 WET STORAGE

Wet storage facilities for spent fuel generally have large radiological inventories (several hundred or even several thousand spent fuel assemblies) and a high residual heat. The safety issues for these facilities are also substantial.

4.1 Wet storage concepts

Because of the residual heat of spent fuel assemblies in the first few years after unloading from the reactor and because of the decision to reprocess ENU fuels around 10 years after they have been unloaded, pools are used to store these fuels on site at French nuclear power plants and at fuel reprocessing plants.

Wet storage facilities for spent fuel, or spent fuel pools, can be built above ground or semi-buried or, more rarely, underground (CLAB facility in Sweden). In the case of reactors, they are built at height because of their connection to the reactor pool. They are monobloc structures made from reinforced concrete, and their walls often help to provide protection from ionising radiation. They can be modular in design. The storage facilities can be one large pool or several ‘small’ pools connected to one other by transfer channels. Finally, ancillary pools or pits (which are deeper than the storage pools), in which the spent fuel is loaded into or unloaded from transport packages, are connected to the spent fuel pools via doors and gates (so that they can be isolated). The internal faces of the pools are covered with a metal liner, which helps to contain the radioactive materials (second containment barrier).

[6] Burnup is the energy produced by nuclear fissions per unit mass of fuel; it represents the level of irradiation of a fuel and is measured in Gigawatts or Megawatts per day per metric ton of fuel (GWd/t or MWd/t).

The water in the pools plays two key safety functions:

- The cooling of the fuel;
- The radiation protection of the operators (there are approximately three to five metres of water above the fuel). The water level must be adjusted to the maximum height of the fuel during the different handling operations. The water is also continuously purified.

There are two main wet storage concepts:

- vertical storage of the fuel in racks assembled and placed on the pool floor. In this case, the height of the water must take into account handling of the fuel above the racks for the radiation shielding of the operators. This is the design used for reactor BK pools (see figure 2);
- vertical storage of the fuel in baskets. The baskets are filled in a pit that is deeper than the pools (for radiation shielding purposes during handling of the fuel) or from special enclosures made of thick concrete; the spent fuel pools are shallower because only the baskets are handled in them and they are only lifted slightly above the pool floor (the fuel assemblies do not have to be lifted over the stored baskets). This is the design used for the pools on the Orano Cycle site at La Hague (see figure 3).

4.2 Safety functions of wet storage facilities

As explained above, the fundamental safety objectives are protection of people and of the environment from ionising radiation (referred to hereinafter as radiation shielding), containment of the radioactive materials, maintenance of subcriticality and removal of the residual heat emitted by the radioactive materials. In addition, the facility must enable the fuel to be retrieved.

Given the residual heat of the spent fuel in storage, the feared situation for pool safety is spent fuel to be exposed to air due to a significant drop in the water inventory, leading to violent oxidation of the cladding and a substantial release of radionuclides. For the record, the water is held in the pool by a liner and the engineered structures of the spent fuel pool.

Protecting people and the environment from ionising radiation

The water in the pool acts as radiation shielding. Maintaining a minimum water level under all conditions (normal, incident and accident) is a way of protecting workers against ionising radiation around the pool.

For example, access to the edge of the pool is only possible in an accident situation if the depth of water covering the spent fuel stored there or currently being handled is around one metre.

Containment of radioactive materials

The first containment barrier is the fuel cladding. This first containment barrier is supplemented by the water in the pool and the ventilation in the spent fuel pool area to constitute the first containment system. The water captures some of the radionuclides that would be released if the integrity of any cladding is lost. The water is held in the pool by a liner and the engineered structures of the spent fuel pool and the building.

A second containment system is provided by the building and its ventilation system (which compensates for the building's lack of airtightness). The dynamic confinement (ventilation system)[7] of the pool area filters the gaseous effluents that would be released if the cladding of the fuel in the pool were to fail. A pool water purification

[7] The primary function of the ventilation at a nuclear installation is to establish the direction of air movement from the least contaminated areas to the most contaminated areas by gradually introducing a negative air pressure through the different areas of the installation (negative pressure cascades).

system is also used (e.g. filtration using ion exchange resins). It limits the quantities of radioactive materials transferred to the atmosphere of the pool area through evaporation of the water.

In addition to filtering the air before it is discharged into the environment, ventilation controls the temperature and humidity of the air in the pool area. The building that houses the pool must be kept at negative pressure compared to the outside (dynamic confinement).

For accident situations that can lead to boiling of the water of the pool, opening a vent to remove water vapour to the outside is tolerated on a temporary basis to prevent a pressure increase in the atmosphere in the spent fuel building[8]. In any case, it must be possible to start up a pool water cooling system to stop the water from boiling and restore the containment provided by the building.

If the installation has a dry unloading cell for the fuel (or using a thick concrete enclosure), once the transport package is open, the two containment barriers are provided by the fuel cladding and the walls of the unloading enclosure, together with the building's ventilation system (see figure 5 and figure 6).

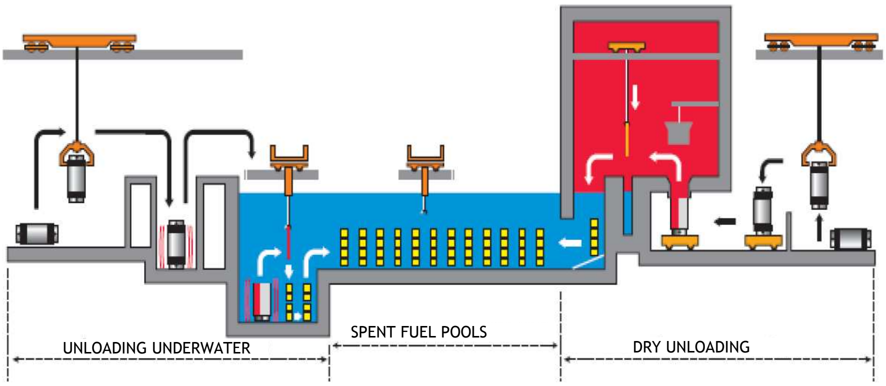


Figure 5: Principle of unloading the fuel underwater or in dry conditions

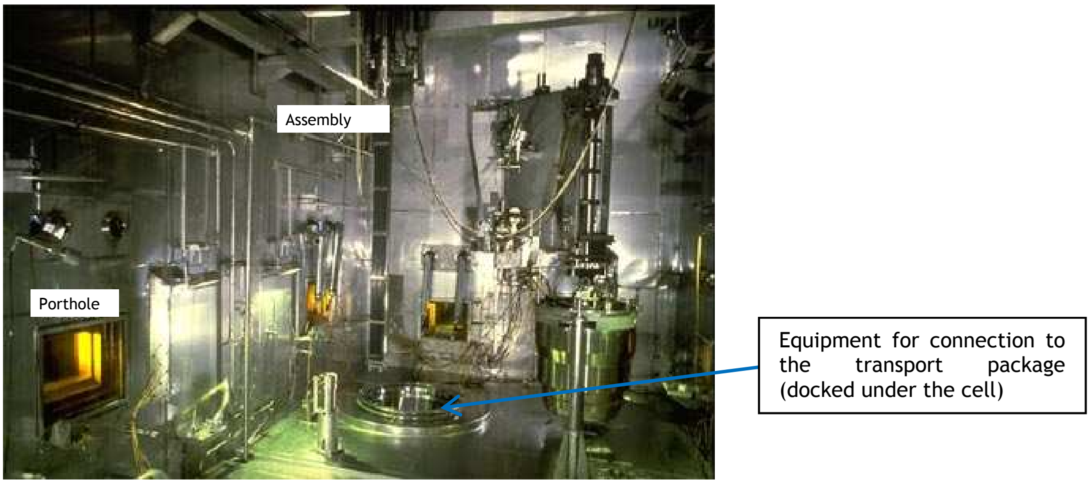


Figure 6: View of the inside of the dry unloading cell in workshop T0 on the Orano Cycle site at La Hague

8 If there is a total loss of cooling of the pool water, the fuel cladding is not damaged as long as it is not uncovered. The water level in the pool is therefore made up if there is a prolonged loss of cooling, to compensate for evaporation and stabilise the water level. The steam released outside during this accident transient is only slightly contaminated. The radiological consequences are therefore small.

Maintaining subcriticality

The subcriticality of an wet storage facility for spent fuel is maintained by means of the geometry of the storage systems (racks or baskets) and the presence of water (which acts as a neutron absorber). Neutron-absorbing materials can also be used.

Residual heat removal

Residual heat removal from the spent fuel stored in the pool relies on keeping the spent fuel underwater and cooling this water using a heat sink to prevent it from boiling. If the water inventory is lost (because of a leak or prolonged boiling), spent fuel uncovering will be possible, causing significant degradation of the fuel depending on its residual heat, particularly due to violent oxidation of the zircaloy used for the fuel cladding.

The design measures therefore aim to make it extremely improbable with a high degree of confidence that accidental emptying of large quantities of water from the pool could occur due to the loss of integrity of a structure. Particular attention is therefore given to protecting the spent fuel pool from internal or external hazards that could cause it to degrade (explosion, earthquake, falling load, aircraft crash, etc.). Pools of more recent design (EPR, EDF's centralised nuclear spent fuel wet storage project) have an airplane crash (APC) shell to protect against aircraft crashes. Finally, the design of the structural elements of the pool must offer substantial margins as regards accidental loading that could occur during the installation's operating life.

The pool cooling system is designed to keep the water temperature below around 50°C in normal operation. If the residual heat removal is not sufficient, the water temperature could increase significantly until it boils, which could lead to spent fuel uncovering. In addition, a significant increase in the water temperature would lead to shutdown of the ventilation systems making the pool area containment defective. It would also cause stresses to structures such as the pool liner and the storage racks due to expansion.

Because spent fuel pools are usually designed to contain very significant residual heat levels, active cooling must be provided. The cooling system must be robust, and its operability must be guaranteed in all normal, incident or accident operating modes (e.g. it must be possible to restart it after a prolonged loss of cooling that caused the water in the pool to boil and the pool water level to change). It has redundant trains to compensate for equipment failure.

Two types of system are used in France: a set of circuits to circulate the water of the pool through heat exchangers outside the pool (BK pools) or heat exchangers submerged in the pool, cooled by a circuit outside the pool connected to cooling towers (pools on the Orano Cycle site at La Hague). The latter system prevents the transfer of any potentially contaminated water outside the pool and significantly limits the risks of part of the pool being accidentally emptied (line break). However, its cooling capacity is smaller.

Where the installation has a dry fuel loading or unloading cell, special measures are put in place to provide cooling during transfer between the transport package and the pool, taking account of normal, incident and accident situations (failure of handling equipment, etc.). If there is no active cooling (loss of ventilation systems for concrete enclosures), the residual heat of a fuel assembly being handled individually between the package and the pool must not cause its cladding to exceed a critical temperature (threshold for violent oxidation of the zirconium used in the cladding, causing a 'zircaloy fire').

Retrieval of the fuel

The possibility of retrieving fuel means that there are requirements in terms of equipment design and the organisation of operation.

It requires certain equipment to be dual use (for unloading and loading the fuel from/into the transport packages) and means that destocking has to be taken into account when the installation is designed.

This means:

- being able to remove the fuel from the storage baskets (or racks), including after an earthquake, for example;
- guaranteeing the mechanical integrity of the fuel in normal operation.

Depending on the length of storage of the fuel, the operator must anticipate at the design stage any changes to equipment (e.g. the transport packages).

The necessary equipment for monitoring the stored fuel and any changes to this equipment must also be anticipated at the design stage.

4.3 On-site wet storage

Regardless of the chosen spent fuel management option (reprocessing or direct disposal), operators of nuclear power plants internationally and in France can use spent fuel pools attached to the reactor (BK pools in France) to cool the fuel for an initial period after it is unloaded from the reactor, if residual heat levels are very high, and to address the problems of removing the fuels.

The larger the pool storage capacity, the longer operators of nuclear power plants that have chosen to use dry storage following this initial wet storage period can cool their spent fuel to limit the residual heat in each dry storage unit (optimisation).

<u>Presentation of the BK pools</u>

The spent fuel pool is located at height (see figure 7) in the fuel building (BK) and consists of a reinforced concrete structure from foundation level to roof level. Only the BK of the EPR reactor at Flamanville has an APC shell to protect it from a large and heavy aircraft crash, from all angles and points of impact.

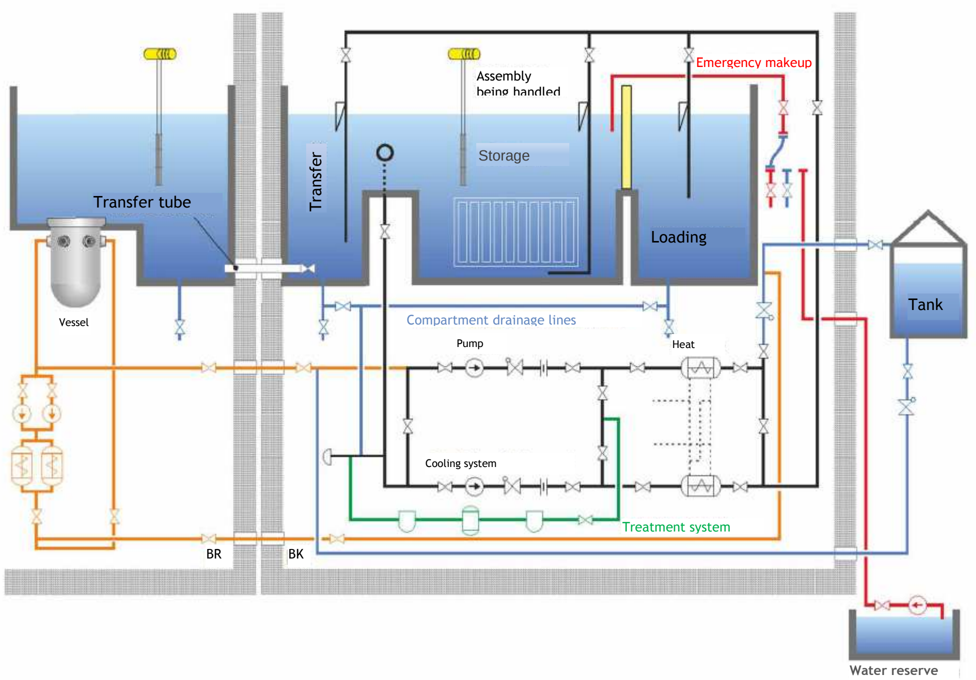


Figure 7: Cutaway view of the reactor cavity in the reactor building (BR) and the spent fuel pool in the fuel building (BK)

The BK pool has three compartments (main storage, transfer and loading) separated by doors or gates with elastomer seals to make them leaktight. A stainless steel liner makes the pool leaktight. The liner is welded to metal sections sealed into the concrete.

The transfer compartment, which has drainage pipes, connects to the pool in the reactor building via a transfer tube through which the fuel passes on its way to or from the reactor. This explains why the pool is high up in the BK building.

The spent fuel is removed from the BK pool in transport packages after a storage period enabling it to be transported to the Orano Cycle site at La Hague. The transport packages are loaded underwater in the loading compartment (P4-type 900 MW and 1300 MW reactors) or are docked under the loading compartment (P'4-type 1300 MW reactors, 1450 MW reactors and EPRs). This second system avoids the handling of the transport packages, which weigh more than 100 metric tons, at height and limits the contamination of the packages.

The height of water in the storage compartment, where storage racks are used, is between 12 m and 14 m depending on the reactor series, which is around three times the height of the fuel assemblies. As a reminder, a depth of water above the fuel assemblies of more than about 2.7 m keeps the edge of the pool and the handling equipment control posts under normal radiation shielding conditions.

The number of storage positions (cells) in the storage compartment racks in which the fuel assemblies are placed, ranges from 382 (900 MW series) to 960 (EPR), which corresponds to a total capacity of between 145 (900 MW series) and 655 (EPR) metric tons of initial heavy metal (tIHM) of fuel.

The water in the pool is cooled by a circuit outside the pool. In the EDF reactors in operation, the water is drawn through pipes several metres below the surface of the pool. The cooling circuit has two parallel trains, each with a pump and a heat exchanger. The cooled water is reinjected in pipes in the lower part of the pool. These pipes have a vacuum relief valve, which can stop accidental emptying if a break or alignment error occurs. The systems necessary to operate the two cooling trains are redundant and have an emergency power supply (there is an emergency diesel generator to supply electrical power to each train). This cooling system design, which is technically suitable for the high residual heat of the fuels stored there, can lead to accident scenarios in which a leak occurs outside the pool. Specific analyses are being carried out on these scenarios. The pool of the EPR reactor at Flamanville has three separate trains and the layout of the suction and injection lines has been improved to reduce the risks of uncovering of the stored fuels.

The residual heat of the fuel stored in a BK pool depends mainly on the operating state of the reactor: it is at its greatest during reactor outages, when all the fuel assemblies are unloaded from the reactor vessel. It also varies according to the reactor power, the fuel used and the pool storage capacity.

The maximum residual heat of the fuel stored in the BK pools at 900 MW, 1300 MW and 1450 MW reactors and at the EPR reactor at Flamanville are 10 MW, 13 MW, 14 MW and 20 MW respectively.

Dealing with the saturation of storage capacity of the pools attached to the reactors, several countries have adopted a 'reracking' solution, which consists of replacing the fuel storage racks with more compact racks so that more spent fuel can be stored in the same area. This solution can be used to buy time until the residual heat of the spent fuel has decayed enough to be transferred to dry storage facilities.

EDF has considered 'reracking' its BK pools and submitted a report on it, regarding its 900 MW CPY-series reactors, to the ASN in October 2010. The report was examined by the IRSN, which was of the opinion that it could not conclude from the evidence provided by EDF that the risks associated with this modification were satisfactorily controlled.

Later on, as part of its review of the extension of the service life of the reactors beyond their fourth ten-yearly safety reviews, IRSN took the view that EDF's 'reracking' plan was inappropriate from a safety point of view in comparison to designing and commissioning modern facilities specifically for this purpose. The ASN then asked EDF in September 2013 to look at solutions other than 'reracking' to store spent fuel.

To increase wet storage capacity, the other alternative consists of creating an on-site spent fuel pool. This solution is not widely used internationally, but a few examples are worth mentioning.

On the site of the Olkiluoto nuclear power plant in Finland, TVO[9] commissioned a spent fuel pool in 1987 known as TVO-KPA-STORE (see figure 8 and figure 9), to address the saturation of reactor spent fuel pools. This facility, which has a planned operating life of 60 years, is independent of the reactors on the site and will be maintained after the TVO 1 reactor has been decommissioned. The facility has enough capacity to store all the spent fuel from 30 years' operation of the TVO 1 and 2 reactors, i.e. around 1,400 tonnes of uranium. In addition, the facility is designed in such a way that the storage capacity can be extended if necessary.

The spent fuel is transferred to the facility after spending at least one year cooling in the reactor pool and will remain in storage at the facility for more than 40 years. The spent fuel is transferred by means of a transfer package in which the spent fuel is kept underwater (to limit the temperature and thermal shocks).

Figure 8: Cutaway view of the spent fuel pool known as TVO–KPA–STORE (Olkiluoto site, Finland)

Figure 9: Photo of the spent fuel pool known as TVO-KPA-STORE (Olkiluoto site, Finland)

Other international examples include the pool of the 'fuel storage building' at the Gösgen nuclear power plant in Switzerland (see figure 10), commissioned in 2008, and the centralised interim wet storage building at Tihange in Belgium (see figure 11), commissioned in 1997. These facilities can accept the spent fuel (including MOX fuel) from the sites where they are located. The spent fuel is transferred from the reactor pools to these facilities using a package in which the spent fuel is kept underwater. The pool at the Gösgen nuclear power plant has a passive cooling system.

9 TVO for Teollisuuden Voima Oy.

Figure 10: Photo of the pool of the 'fuel storage building' at the Gösgen NPP (Switzerland)

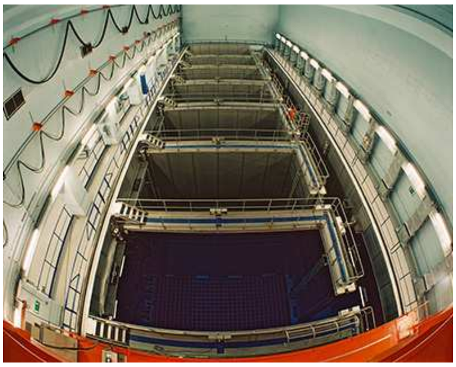


Figure 11: Photos of the pools in the centralised interim wet storage building at the Tihange NPP (Belgium)

The installation of an additional pool must take into account the technical constraints of the site and any safety constraints. In the case of France's nuclear power plants, the installation of an additional pool next to the BK is not possible because there is not enough space available and because of the impact on existing structures. The creation of a direct connection between the BK pool and the additional pool is also excluded because of the risks of the pool emptying and the distance between the two buildings. Spent fuel should be transferred from the BK pool to an additional pool on the site using transport packages filled with water (the same type of transfer operations as the 'inter-reactor' transfers performed by EDF between two BK pools on the same site) with a constraint concerning the duration of the transfer operation to avoid excessive heating of the transported fuel.

Taking into account the international experience feedback, the technical feasibility of an on-site pool is proven. However, appropriate methods of transferring the spent fuel would be needed and, for some sites, the power plant perimeter would need to be extended to implement this solution.

4.4 Centralised wet storage

Both internationally and in France, there are a number of centralised wet storage facilities either in existence or planned. Among these, a distinction can be made between pools at reprocessing plants for spent fuels awaiting reprocessing, and centralised spent fuel pools for storing spent fuels until a decision is made about their fate (future reprocessing or direct disposal).

In existence abroad

The facilities in existence abroad include the CLAB[10] facility at Oskarshamn (Sweden), operated by SKB since 1985. The originality of this facility, in which all the spent fuel from the operation of Sweden's nuclear power plants is stored pending disposal, lies in its underground location (see figure 12). The spent fuel pools (see figure 13) are at a depth of 30 metres below ground level and the spent fuel, placed in baskets, is covered by eight metres of water. The facility's current capacity is 8,000 metric tons of heavy metal. SKB has submitted an application to extend this capacity to 11,000 metric tons (by using compact baskets throughout). At the end of 2016, 2,622 tonnes of heavy metal (31,817 spent fuel assemblies) had been stored.

[10] CLAB for Centralt Lager för Använt Bränsle (Centralised spent fuel storage facility)

Figure 12: Cutaway view of the CLAB facility at Oskarshamn (Sweden)

Figure 13: Photo of the pools at the CLAB facility at Oskarshamn (Sweden)

In existence in France

The spent fuel reprocessing plants on the Orano Cycle site at La Hague have four spent fuel pools in operation (see figure 14). The total storage capacity is 17,600 tIHM, distributed between the four pools, which are connected to one another: the NPH pool (commissioned in 1981, capacity 2,000 tIHM), the C pool (commissioned in 1984, capacity 4,800 tIHM) at INB 117 (UP2 800 plant), the D pool (commissioned in 1986, capacity 4,600 tIHM) and the E pool (commissioned in 1988, capacity 6,200 tIHM) at INB 116 (UP3 plant). It should be noted that the total operational capacity is limited to around 13,990 tIHM, particularly because of the design of the storage baskets used in these pools and some operating constraints (waste stored and areas where waste cannot be stored to enable handling operations to be carried out). For information, the equivalent in mass per basket is 4.4 tIHM (the baskets contain nine fuel assemblies).

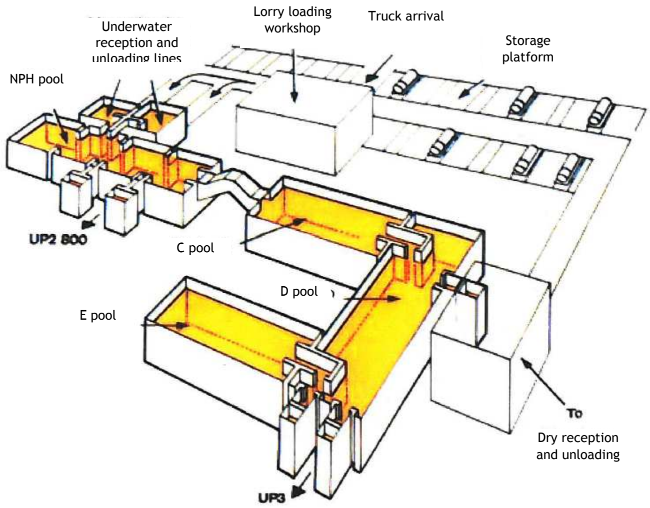


Figure 14: Schematic diagram of the layout of the spent fuel pools on the Orano Cycle site at La Hague

The design principles used for each of the C, D and E pools are:

- a reinforced concrete building with a metal superstructure roof covered by cladding;
- a spent fuel pool below ground level made from reinforced concrete with an internal stainless steel liner to make the pool leaktight; this pool is separated from the building that houses it, in particular by reinforced neoprene bearing pads.

The spent fuel is stored in baskets. Around four metres of water cover the top of the spent fuel. Handling operations on the baskets are carried out at a low height above the bottom of the pool.

The maximum residual heat in the spent fuel pools is 8 MW for the NPH pool, 8 MW for the C pool, 16 MW for the D pool and 10 MW for the E pool. Cooling is provided by a closed cooling water loop with 'Nymphéa' heat exchanger units submerged in the pool on the heat source side, and 'dry' cooling towers outside the building on the heat sink side. The pool water therefore always stays inside the pools.

The transport packages containing spent fuel are unloaded underwater or in dry conditions. Dry unloading has the advantage of minimising the risks associated with handling the packages and avoids contamination of the external surfaces of the packages (see figure 5).

Planned in France

In 2017 EDF submitted a safety options report for its centralised spent fuel wet storage project, which it plans to commission by 2030. The pool is intended to receive particularly MOX and ERU fuel (including the fuel currently stored in pools on the Orano Cycle site at La Hague), which is not expected to be reprocessed in the short or medium term. This report is currently being assessed by IRSN.

The facility capacity will be around 10,000 tIHM split between two pools. The buildings housing the pools, which will be underground (the water level will be at around ground level), will have reinforced walls that can withstand external hazards (APC shell). The pool design will on the face of it be similar to that of the pools on the Orano Cycle site at La Hague, in particular using storage baskets and a cooling system with heat exchangers submerged in the pool.

4.5 Assets and limiting factors of wet storage

The table in Appendix 4 summarises the main characteristics of wet and dry storage facilities.

4.5.1 Assets of wet storage

Wet storage of spent fuels has several assets, some of which are inherent in the water in which the fuels are immersed. Specifically, these assets are:

- effective shielding of operators from gamma and neutron radiation. In addition, the water is not degraded by the ionising radiation emitted by the fuel assemblies;
- significant fuel cooling capability (making this type of storage the only option for fuel assemblies that still have a very high residual heat), when the water is maintained at a low temperature;
- significant thermal inertia of the storage facility, especially in the case of centralised pools, due to the large volume of water they contain, making it easier to implement measures in accident situations;
- storage density, which is also high.

In particular, because fuel cladding can be maintained at low temperatures (of around 40 to 50°C outside the cladding), wet storage conditions limit the ageing of spent fuel, which is a favourable factor. In addition, controlling the chemistry of the water can in particular control corrosion.

Handling spent fuel in a pool also presents no difficulties. Putting spent fuel into storage and removing it are easy (it is not necessary to seal or weld storage containers, for example). The water also allows visual monitoring of operations and confirmation at any time of the position of the spent fuel.

In this context, with wet storage, detailed monitoring of the spent fuel can be carried out and direct inspections can be made of the fuel; however, some of these inspections may require a team of experts.

There is a large amount of experience feedback available nationally and internationally for all spent fuels (ENU, MOX and ERU).

4.5.2 Limiting factors of wet storage

One of the main characteristics of wet storage is the high radiological inventory in a spent fuel pool and, if the stored spent fuel is uncovered, the risk of a large release of radioelements (particularly because of violent oxidation of the zircaloy cladding at high temperatures) and the appearance of a very high dose rate around the pool, preventing any direct human intervention.

From a safety point of view, because of the huge potential consequences of fuel uncovering (countermeasures are necessary even long distances away), events that can cause this must be made physically impossible or ‘extremely improbable with a high degree of confidence’. Work was done on this as part of experience feedback from the Fukushima accident, which involved taking extreme hazards into account (worse than those taken into account in the design phase), conducting a deterministic analysis of a scenario involving a major leak from a spent fuel pool, and increasing the methods for water makeup in the pools, the aim being to maintain an adequate water inventory in the pool. For the record, the behaviour of the spent fuel pools and keeping the stored spent fuel covered were one of the major concerns during the Fukushima accident.

Another limiting factor of wet storage is the fact that the safety functions are at least partially maintained by active systems (cooling, maintaining the purity of the pool water, water makeup). This means that there are particular operational requirements (operation, maintenance, monitoring, etc.).

Because of the number of spent fuel assemblies to be stored and the volume of the spent fuel pools, wet storage requires very large buildings made from reinforced concrete. Moreover, because the safety functions are protected from external hazards by these buildings, strict requirements apply to them as regards behaviour and strength. The dimensioning of these buildings and the requirements that apply to them make them complex to design.

Their design must incorporate significant margins, since it would take a long time (several years) to remove, for safety reasons, the spent fuel stored in them due to the number of spent fuel assemblies that they contain; this also assumes that a facility is available to receive these fuel assemblies.

If the cladding of a spent fuel assembly (the first containment barrier) loses its integrity, the difficulty of detecting and locating exactly which fuel assembly is affected is another limitation, particularly because of the large volume of water in the pool. The same is true for cracks affecting the pool liner.

Lastly, it should be noted that, compared to storage in a BK pool, storage at a centralised pool has the advantage of much greater thermal inertia because of the volume of the pools and the lower residual heat of the fuel[11]. The lower elevation of the pools at centralised spent fuel wet storage facilities (the water level of the spent fuel pools at the centralised wet storage facility planned by EDF is at ground level) and the design of their cooling and handling systems means that their design is more robust.

[11] For the maximum residual heat that can be envisaged, the thermal inertia of a BK pool before it boils ranges from 4 to 8 hours depending on the reactor series, and the time before spent fuel uncovering in the absence of water makeup is between 30 and 60 hours.

5 DRY STORAGE

5.1 Dry storage concepts

Three main dry storage concepts for spent fuel have been developed throughout the world:

- vault storage[12];
- silo storage;
- cask storage.

As with wet storage, spent fuel can be stored on the site of the reactor or at a centralised site, which means that it has to be transported on public roads.

With dry storage, the spent fuel needs to be conditioned first by placing it, as appropriate:

- in a basket which is itself placed in a cask with a screwed closure system (one or more lids with seals); with this type of conditioning, if the right installations and equipment are available, it is possible to reopen a cask (for inspection or unloading);
- in a container, first fitted with a basket when appropriate, on to which the lid is then welded to make it leak tight. This is placed in a storage module (pit, horizontal or vertical concrete structure); with this conditioning method, the containment is better but the fuel assemblies can only be monitored indirectly (by taking measurements from outside the container or even the storage structure).

The operations to load the spent fuel into casks or containers can be done in a spent fuel pool, particularly one attached to a reactor, or at a special facility (e.g. a dry conditioning facility). Special facilities may be required, particularly a 'hot cell'[13], to open a cask or container during storage (for maintenance, repair, inspection, removal from storage, etc.) or afterwards, if degradation of the fuel assemblies is suspected. However, most dry storage sites throughout the world do not have such facilities.

Finally, to limit the risks of corrosion and degradation of spent fuels, particularly cladding, containers and casks are dried (so that only tiny quantities of residual water are left in them) and are usually filled with an inert gas, mainly helium, which assists heat removal. Special measures are taken to deal with fuel assemblies that have lost their integrity during irradiation and potentially contain water.

5.1.1 Dry storage in vaults

Spent fuel is stored in vaults (sometimes known as cells) at surface or semi-buried facilities made of concrete or metal structures, the walls of which protect the operators and the environment from ionising radiation and protect the facility from external hazards.

They are mainly buildings in which the spent fuel, placed in sealed containers, is put into pits. These pits are generally vertical tubes closed with a plug. At the top of the pits there is a thick concrete slab, which strengthens the structure and the pits and provides protection from ionising radiation. The pits can either rest on the building's basement at the bottom or be suspended from the slab at the top.

The spent fuel assemblies are brought (in dry conditions or underwater) to the facility in transfer containers (on site) or transport packages (to centralised storage facilities). They are then prepared (drying, etc.) and placed in steel containers. The containers are inserted into the pits at the facility vertically (using a transfer cask travelling

[12] In French, 'entreposage en casemates ou puits'.
[13] Thick concrete enclosure that performs a containment function and provides protection from ionising radiation.

over the slab above the pits, to provide radiation shielding, or a crane above the slab, in which case the building provides radiation shielding).

Air circulating around the pits enables the residual heat to be extracted from the spent fuel and can guarantee a maximum temperature for the spent fuel and storage structures. The air circulates either through natural convection (generally using a tall chimney), making the storage facility a completely passive system, or by forced convection; in this case the ventilation system is redundant, as are the utilities necessary for it to operate.

This type of facility can be used specifically for the on-site spent fuel storage, but it can also be used for centralised storage. Some examples of facilities are presented in sections 5.3.1 and 5.4.1 of this report.

5.1.2 Dry storage in silos

Silos are concrete structures with cavities (or cells) in which the spent fuel canisters are placed. They are modular[14] and generally each contains one canister. They are designed solely for storage and are independent from the nuclear installations on the site (in particular they have their own handling equipment). They can be:

- monobloc structures with horizontal or vertical loading;
- modular container-type structures (vertical loading).

figure 15 below shows a dry storage site with monobloc structures loaded horizontally and container-type structures.

Figure 15: Conceptual view of a storage facility project in the United States

With the silo concept, the spent fuel is placed in metal canisters filled with an inert gas, and the lid is sealed by welding. Each canister is inserted into a cell in a concrete structure using a transfer package. This standard or high density concrete structure provides radiation shielding and is designed to withstand external hazards (particularly earthquakes), just like a normal nuclear installation. However, the small size of these structures means that the design is simpler. In addition, air circulating through the concrete structure by means of natural convection cools the storage containers. Because of this cooling method (outside the container), the spent fuel temperature can be high (several hundred degrees Celsius) even if its residual heat is fairly low (around 1 to 2 kW on average at the time of loading).

Dry storage in silos is mainly used on the site of reactors, especially in the United States. Some examples of facilities are presented in sections 5.3.2 and 5.4.2 of this report.

[14] These facilities are often referred to as ISFSIs (Independant Spent Fuel Storage Installations).

5.1.3 Dry storage in casks

This concept concerns so-called ‘dual purpose casks’, for both transport and storage. These casks meet both the regulatory requirements for the transportation of radioactive materials on public roads, and the safety requirements of the storage sites. They therefore reduce the need of spent fuel reconditioning operations.

Two types of cask are used: metal casks and concrete casks.

Metal casks

Metal casks mainly consist of a cylindrical forged steel shell several tens of centimetres thick, a layer of neutron-absorbing polymer with heat conductors through it for heat exchange with the outside, and an external steel shell; the casks are closed by one or two lids with seals. The mass of the casks is generally between 100 and 150 t (loaded) and the overall size is approximately Ø3 m x 7 m in the transport configuration and Ø2.5 m x 5.5 m in the storage configuration (the mechanical protective devices used to meet the requirements for transport on public roads are replaced by smaller protective devices for storage). The total residual heat that they contain can be between 20 and 40 kW, for around 30 spent fuel assemblies (PWR type).

Concrete casks

Similarly, concrete casks are made almost entirely from concrete, with fine steel shells to provide mechanical stability or to withstand certain hazards. They are cheaper than metal casks but larger. The external diameter of the cask body can be between 3 and 3.5 m and its mass can be between 160 and 190 t when loaded. The residual heat of the spent fuel assemblies in these casks is similar to that of the metal casks.

Some silo concepts are similar to the concrete cask concept. The difference is that it must be possible to transport spent fuel in a concrete cask.

The casks, which are loaded vertically underwater or in a dry ‘hot cell’, are designed to be emptied of the water that they contain, and to be dried and sealed with bolted lids. They are then placed vertically in an outdoor area or a storage building that provides protection particularly against bad weather, or more rarely in an underground tunnel.

The casks are cooled by natural convection of the air in contact with their walls, and there are cask spacing constraints due to handling and monitoring requirements.

The system of dry storage in casks is the most flexible system (because they can be moved without having to be reconditioned). Spent fuel can be stored in these casks both on site and at a centralised facility. Some examples of this type of storage are presented in sections 5.3.1 and 5.4.1 of this report.

5.2 Safety functions of dry storage

The main safety functions to be performed at these storage facilities are:

- protection from ionising radiation;
- containment;
- prevention of criticality risks;
- residual heat removal.

It must also be possible to retrieve the stored fuels safely and their ageing must be controlled, in line with the waste management policy.

Protection from ionising radiation

This is provided by the concrete structures of the cells in which the storage containers are placed or by the shell of the storage cask. When casks are placed in a building, the building can provide additional radiation shielding. In the case of storage in underground or semi-buried pits, the soil, the concrete structure and the pit closure plug provide radiation protection.

Containment

The radioactive materials are contained both by the fuel assembly cladding (first barrier) and by the pits, canisters or casks used (second barrier).

To prevent the risk of corrosion of the cladding, but also of the canisters/casks, the fuel must be dried and the canisters/casks filled with an inert gas.

The leaktightness of the canisters or casks is generally monitored (internal pressure measurement, etc.). The cladding is discussed below.

Prevention of criticality risks

Criticality risks are prevented by the geometry of the storage devices used (e.g. the gap between the pits or the basket cavities), possibly combined with the presence of neutron poisons (e.g. boron in the material used to make the baskets).

Residual heat removal

The spent fuels are cooled by natural air convection around the storage structures. This system is passive; only the monitoring of the absence of air circulation system clogging is needed. On this point, the risk of collapse of the structures housing the storage facility or the obstruction of air intakes by external hazards must be eliminated.

In the case of underground or semi-buried storage facilities, the distance between non-ventilated pits must be calculated on the basis of the spent fuel to be stored, the thermal conductivity of the soil and the temperature criterion set for the fuel.

Retrieval and monitoring requirement

In addition to containment of the radioactive materials, controlling the ageing of the fuel cladding is also important for the retrieval of the spent fuel and its subsequent management.

Unlike with wet storage, with dry storage facilities it is not possible to monitor spent fuel cladding directly. It is not accessible and only indirect monitoring methods can easily be used (measurements from the outside of the containers (thermal profiles, etc.), monitoring of the atmosphere in the storage container, etc.). Keeping the spent fuel cladding at a high temperature can encourage ageing mechanisms. Finally, it should be pointed out that the pressure inside the cladding, and therefore the internal stresses generated, increases with the temperature. Because of the residual heat that they release, MOX fuels therefore have a significantly higher internal pressure than ENU fuels.

The ageing of cladding in dry storage facilities has for several years been a subject of study and of a number of in-situ examinations, looking at legacy ENU fuels. To IRSN's knowledge at the time of writing this report, controlling the ageing of ENU fuel cladding is not an issue during the storage periods considered (a few decades).

Research programmes are ongoing, in particular on high burnup fuels (above 45 GWd/t) and fuels stored for long periods (of more than 40 years). Few studies are available for MOX fuel. In fact, it is worth noting that this type of fuel has only recently been put into dry storage (particularly in Germany), and that the fuel in question had a lower initial plutonium content than the fuels currently used in France.

Usually, dry storage in metal casks, which have lids that are screwed on, makes it easier to inspect spent fuel during storage. However, inspection is a major operation (container extraction, opening, etc.) requiring special facilities (e.g. a 'hot cell'). Moreover, for vault or silo concepts, because the casks are welded shut, this type of inspection means that the container has to be replaced.

5.3 On-site dry storage

5.3.1 On-site dry storage in vaults

A good example of the concept of vault storage is the MVDS (Modular Vault Dry Store - see figure 16). The storage facility of this kind on the nuclear site at Paks in Hungary (see figure 17) went into operation in 1997 for a period of 50 years. It is to be used solely for the dry storage of spent fuels from the four VVER-440/213 reactors on the site.

It is split into three main areas: the transfer package reception building, the charge hall where fuel handling operations are done and the storage vault area (see figure 18). The spent fuel is transported on site from the at-reactor pool building to the reception building in a transfer cask.

The fuel passes into a drying tube before being loaded into a fuel handling machine. This machine takes the fuel to the vault area and loads the fuel into a vertical storage tube.

The facility can accept up to 527 fuel assemblies per module (building); the first 16 modules are limited to 450 fuel assemblies, with a maximum total capacity of 16,159 assemblies split between 33 modules under current conditions. At the end of 2016, 8,707 fuel assemblies had been stored at the facility for a capacity of 9,308 (20 modules). Each storage position, which measures approximately 4.5 m, consists of a carbon steel tube with an aluminium liner, which passes through a concrete slab approximately 1 m thick (lined with steel). Each tube can receive a single VVER fuel assembly with a maximum residual heat of 720 W, and is filled with inert dry nitrogen. The tube is sealed by an instrumented concrete plug more than one metre thick. There are openings at the bottom of the building to bring in air from outside to cool the tubes (via a labyrinth system for radiation shielding reasons), and the hot air leaves via an outlet stack.

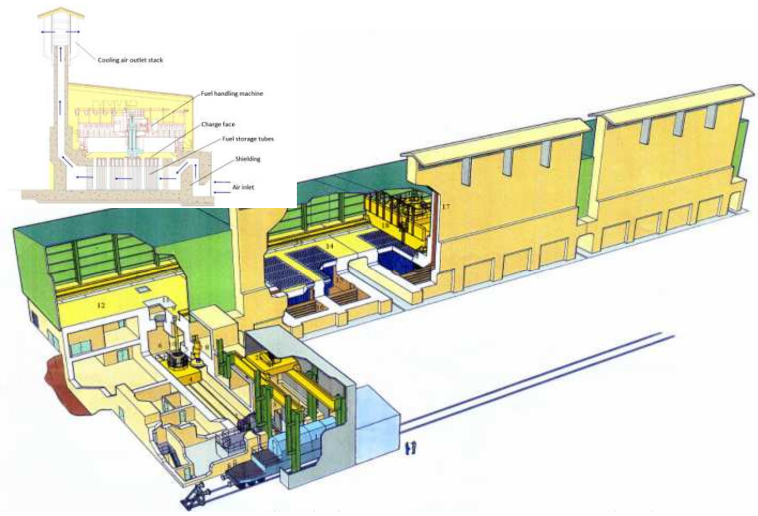


Figure 16: Cutaway view of the MVDS (Modular Vault Dry Store) concept

Figure 17: Photo of the MVDS storage facility on the Paks nuclear site (Hungary)

Figure 18: Photo of the storage tubes at the MVDS storage facility on the Paks nuclear site (Hungary)

This Modular Vault Dry Store (MVDS) concept has also been used since 1991 for spent fuel from the high temperature gas-cooled reactor (HTGR) on the Fort St. Vrain site (USA); this reactor was shut down in 1989 (see figure 19 and figure 20).

Figure 19: Photo showing an exterior view of the MVDS-type storage facility on the Fort St. Vrain site (USA)

Figure 20: Photo showing an interior view of the MVDS-type storage facility on the Fort St. Vrain site (USA)

5.3.2 On-site dry storage in silos

Horizontal loading silo concept

A good example of a horizontal loading silo storage facility is Orano TN's NUHOMS® (see figure 21), which contains a large amount of the spent fuel in dry storage in the USA (see Figure 22). The NUHOMS® system consists of reinforced concrete storage modules and metal canisters. The principle is that spent fuel loaded into a canister with a welded lid is taken in a transfer cask to a concrete module. The cask performs the safety functions while the canister is being transferred, and the canister is loaded horizontally by a ram system once the cask has docked with the module. The welded canisters, which could potentially be reused for final disposal[15], perform the containment and criticality safety functions. Each module provides radiation shielding and protection from external hazards. The modules have air inlets at the bottom and air outlets at the top for cooling by natural convection. The NUHOMS® concept was recently updated to enable modules to be stacked in two layers to reduce the footprint ('MATRIX' model).

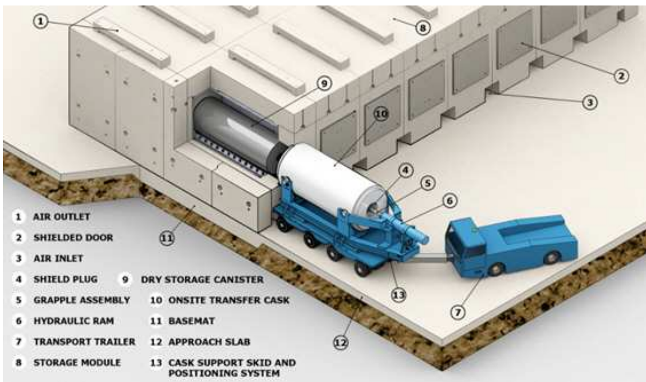


Figure 21: Diagram of a NUHOMS® module

Figure 22: Photo of a NUHOMS® module storage facility on the San Onofre site (USA)

This concept is also used in other countries, for example the VVER power plant site of Metzamor in Armenia.

[15] This is the Multi Purpose Canister (MPC) concept, i.e. it can be used for transport, storage and disposal. This concept is widely used throughout the USA.

Vertical loading silo concept

A representative example of the storage concept involving the vertical loading of surface silos is AECL's MACSTOR® (Modular Air-Cooled STORage)[16] (see figure 23), mainly developed in Canada, for example on the Gentilly site (see figure 24). This concept consists of modular concrete blocks placed in the open air, with openings and internal chicanes to encourage air circulation and heat exchange. The canisters containing the CANDU[17] fuel bundles are loaded vertically into cylinders. The canisters are made of zinc-coated carbon steel; the lid is welded to the body. Each canister receives 10 stainless steel fuel baskets, which are welded shut, and each basket contains 60 spent fuel bundles that have been dried first. Each cylinder is closed by a plug topped with a steel cover. The cylinders are therefore leaktight and their internal atmosphere can be checked by sampling (monitoring of the first barrier consisting of the fuel cladding). Consequently the silo has a containment function as well as providing radiation shielding.

The residual heat of CANDU spent fuel is much lower than that of PWR spent fuel. A MACSTOR 200 module of dimensions 21.6 x 8.1 x 7.5 m^3 can therefore contain 73 kW of CANDU fuel in the form of 12,000 bundles, i.e. about 2,300 metric tons of uranium, which would be the equivalent of 480 PWR fuel assemblies. The residual heat is only 150 W per fuel assembly. A maximum temperature of 160 to 180°C is specified for the cladding of CANDU fuel in storage (compared to 350 to 450°C for PWR cladding in other storage concepts).

The dry storage concept developed by AECL is used in other countries that use CANDU reactors. This is the case at Wolsong in South Korea (see figure 25) and Cernavoda in Romania (see figure 26).

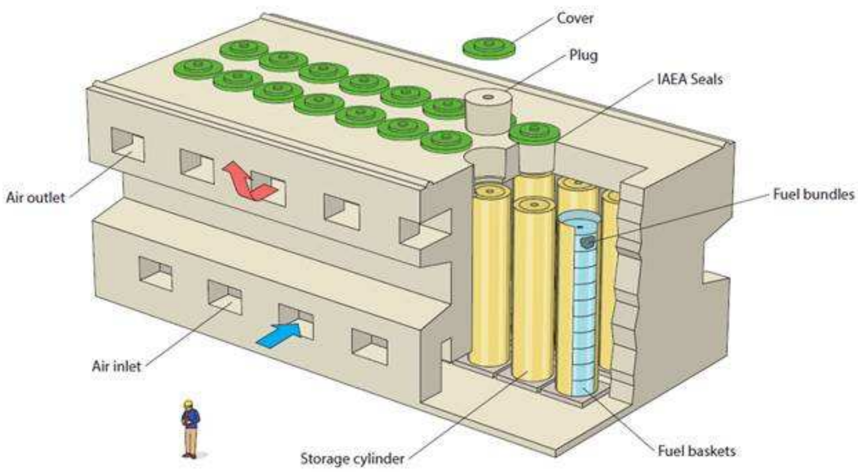


Figure 23: Cutaway view of the MACSTOR® storage facility concept

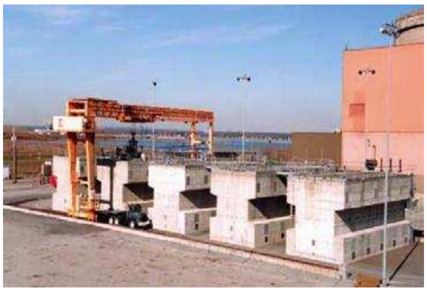


Figure 24: Photo of a MACSTOR® storage facility at Gentilly (Canada)

Figure 25: Photo of a MACSTOR® storage facility at Wolsong (South Korea)

Figure 26: Photo of the DICA MACSTOR® storage facility at Cernavoda (Romania)

16 AECL for Atomic Energy of Canada Limited

17 The CANDU reactors (contraction of CANada Deuterium Uranium), which were invented in Canada, use deuterium oxide (also known as 'heavy water') as a moderator and natural (non-enriched) uranium as fuel.

Vertical loading semi-buried silo concept

The vertical loading semi-buried silo concepts developed include those developed by the company HOLTEC International, the HI STORM 100U and UMAX. They are similar to vaults and are used to store spent fuel from light water reactors such as PWRs and BWRs, with a power of around 35 kW per cavity. This concept accepts welded canisters containing 24 or 32 PWR fuel assemblies, or 68 BWR fuel assemblies. Several facilities of this kind have been built on nuclear power plant sites in the USA such as the San Onofre Nuclear Generating Station (SONGS), Humbolt Bay Power Plant and Ameren's Callaway nuclear power plant sites.

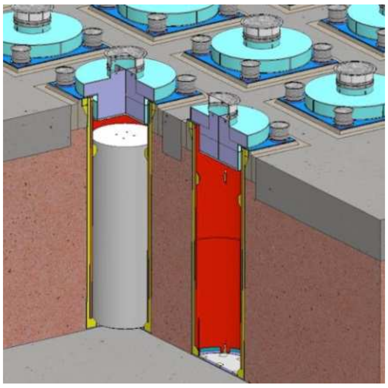


Figure 27: Cutaway view of the HI–STORM UMAX concept

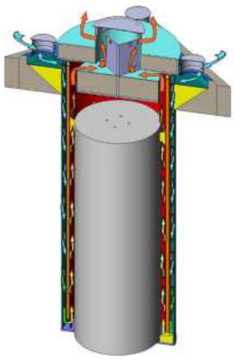


Figure 28: Cutaway view of a cavity of the HI-STORM UMAX concept

Figure 29: HI-STORM UMAX type storage facility - Callaway nuclear power plant (USA)

A dry storage concept of this kind has also been used since 1953 at the WMA 'B' facility on the Chalk River site in Canada for storing waste and fuel from experimental reactors. This facility consists of a network of sealed concrete tubes on a pad also made from concrete at a depth of around 5 m below ground level (see figure 30). The space between the tubes is filled with sand, and a concrete plate with holes in above each of the tubes covers the vault. The tubes have a liner around the inside and accommodate baskets containing fuel in canisters from experimental reactors; the modules are sealed by plugs, which provide radiation shielding. Because corrosion has been found on some of the canisters and fuel, the spent fuel stored at this facility is currently being retrieved and reconditioned.

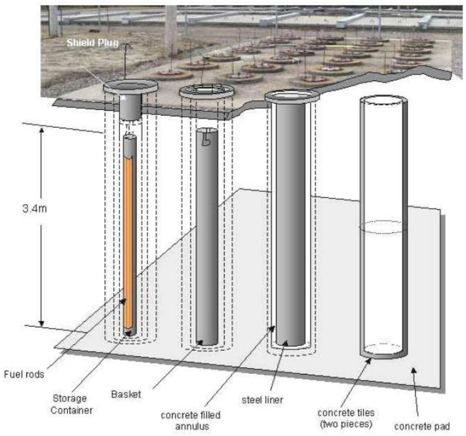


Figure 30: Cutaway view of the WMA 'B' facility at Chalk River (Canada)

‘Overpack’ silo concept

The concept of modular ‘overpack’ type silos is similar to that of casks, the difference being that the ‘overpacks’ are not designed for transportation on public roads.

With this concept, mechanical strength and radiation shielding are provided by the standard or high-density concrete structure of the overpack.

An example is the HI-STORM 100 by the company HOLTEC International (see figure 31 and figure 32), which is used for storing spent fuel from PWR and BWR reactors, with a total power of 37 kW per overpack. These overpacks accept welded canisters containing 24 or 32 PWR fuel assemblies, or 68 BWR fuel assemblies.

The body of the HI-STORM 100 consists of two steel cylinders (of 19 and 32 mm) with a 68 cm thickness of concrete sandwiched between them. There is an air inlet at the bottom of the silo and an air outlet at the top. The body is sealed by a 10 cm steel screw-on lid under which there is a concrete block. It is 3.4 m in diameter and 5.9 m high and has a maximum mass under load of 163 metric tons.

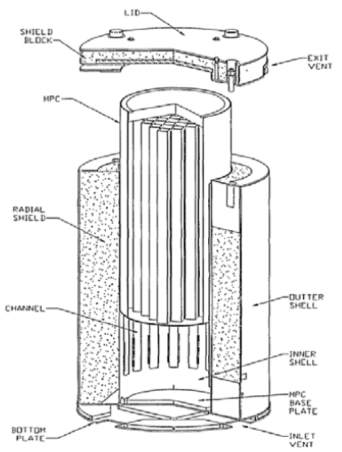


Figure 31: Cutaway view of the HI-STORM 100 concept

Figure 32: Photo of a storage facility using the HI-STORM 100 concept

Similar models such as the NAC-UMS have been developed by the NAC company, a subsidiary of Hitachi.

For the storage of CANDU spent fuel, a concrete container also called a ‘silo’ has been developed by AECL in Canada. The Point Lepreau (see figure 33) and Whiteshell (see figure 34) sites use this concrete silo.

Its capacity varies depending on the site of use (from 1.9 to 10.3 metric tons of fuel). The silos are placed vertically on a concrete basement. They are loaded in situ by opening the plug at the top and lowering the fuel assemblies in baskets made from stainless steel. Dissipation of the heat (of around 1 to 2 kW per silo) is achieved by natural convection around the container.

Figure 33: Storage facility on the Point Lepreau site (Canada) using AECL's concrete silo

Figure 34: Storage facility on the Whiteshell site (Canada) using AECL's concrete silo

The dry storage concept developed by AECL is used in other countries that use CANDU reactors. This is the case in Argentina (Embalse nuclear power plant) and South Korea (Wolsong site).

Figure 35: Storage facility on the Embalse site (Argentina) using AECL's concrete silo

Figure 36: Storage facility on the Wolsong site (South Korea) using AECL's concrete silo

5.3.3 On-site dry storage in casks

Numerous dual-purpose (transport and storage) cask concepts have been developed since the 1990s (CASTOR® and CONSTOR® by GNS, the TN®24 family by TN International, the HI-STAR 100 by HOLTEC International and the different versions of the NAC-STC in the USA, etc.).

Illustrations of on-site storage in metal casks

In Switzerland and Belgium, spent fuel is stored in metal transport and storage casks from the TN®24 family by Orano TN, such as the TN®24 DH. The TN® 24 DH has a forged carbon steel body around 20 cm thick with a stainless steel liner covered by a 13 cm thick layer of neutron-absorbing resin and external steel plates 2 to 3 cm thick. There are copper heat conductors through the resin. The TN®24 DH is sealed by a primary steel lid more than 30 cm thick and a secondary lid more than 8 cm thick, both fastened by screws to the flange of the forged steel body. It is 3 m in diameter and 6.4 m high and has a maximum mass under load of 125 metric tons. It can accommodate up to 28 PWR fuel assemblies with a total power of more than 33 kW.

For transportation (see figure 37), it has shock absorbing systems designed to protect it in the event of an accident. These are removed for storage (see figure 38) to reduce its size and mass.

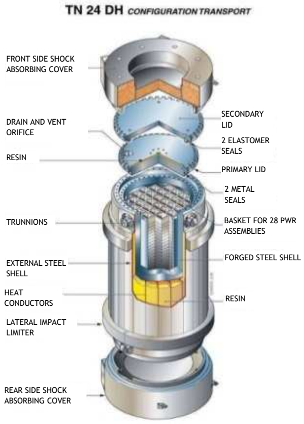


Figure 37: Cutaway view of the TN®24 DH cask in its transport configuration

Figure 38: Cutaway view of the TN®24 DH cask in its storage configuration

These TN®24 DH casks are currently destined for spent fuel storage on the Doel site in Belgium, which has a storage facility that can accommodate 165 casks (see figure 39 and figure 40).

Figure 39: Photo of the exterior of the dry storage building on the Doel site (Belgium)

Figure 40: Photo of TN®24 DH casks stored in the dry storage building on the Doel site (Belgium)

The design of all the casks in the TN®24 family, intended for PWR and BWR fuels, is based on largely the same design principles, since the total residual heat per cask can be as much as 40 kW.

In Germany, spent fuel is stored in CASTOR® series transport and storage casks. The body of a CASTOR® cask is made of 30 to 40 cm thick ductile iron. It is approximately 6 m long and 2 m in diameter, and its mass under load is 140 metric tons. There are several models, such as the CASTOR® V/19 (see figure 41), which can store up to 19 PWR fuel assemblies with a maximum total residual heat of 39 kW, and the CASTOR® V/52 (see figure 42), which can be used to store up to 52 PWR fuel assemblies with a maximum total residual heat of 40 kW.

Figure 41: Cutaway view of the CASTOR® V/19 cask

Figure 42: Cutaway view of the CASTOR® V/52 cask

There are two different storage facility design options:

- The WTI/GNS concept (see figures below), which are or will be used on the sites of the power plants at Biblis, Grafenrheinfeld, Gundremmingen, Isar and Philippsburg;

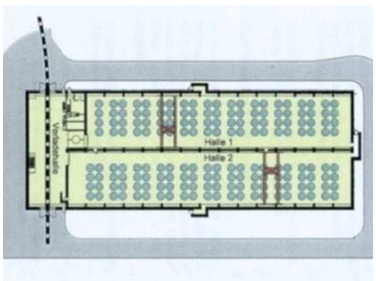


Figure 43: Layout of the WTI/GNS concept

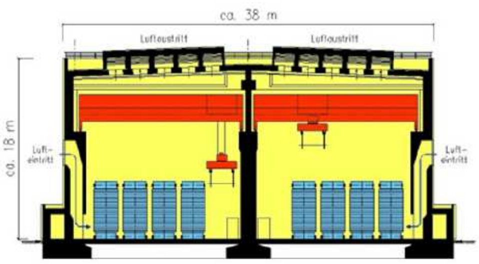


Figure 44: Cross-sectional view of the WTI/GNS concept

Figure 45: Photo of the exterior of a WTI/GNS storage building

Figure 46: Photo of the interior of a WTI/GNS storage building

- The STEAG concept (see figures below), which offers better radiation shielding and better resistance to aircraft crashes with its thicker walls and roof slab, is or will be used on the sites of the nuclear power plants at Brokdorf, Brunsbüttel, Grohnde, Krümmel, Lingen and Unterweser.

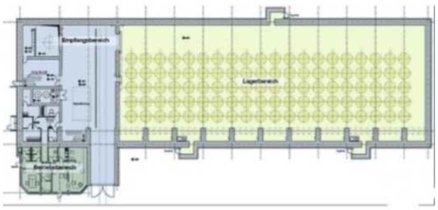


Figure 47: Layout of the STEAG concept

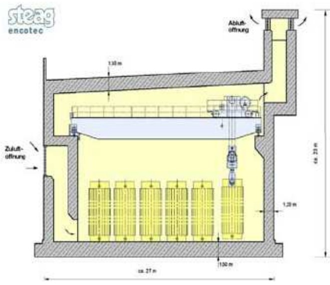


Figure 48: Cross-sectional view of the STEAG concept

Figure 49: Photos of the exterior and interior of a STEAG storage building

With both concepts, there is no need for high lifting of the casks, which minimises the height from which a load can be dropped.

On the site of the nuclear power plant at Neckarwestheim, the storage facility used since 2006 to house spent fuel casks consists of two shallow tunnels (15 m) that are 84 and 90 m long respectively. The underground architecture of the storage facility makes use of the site's particular configuration (see figures below).

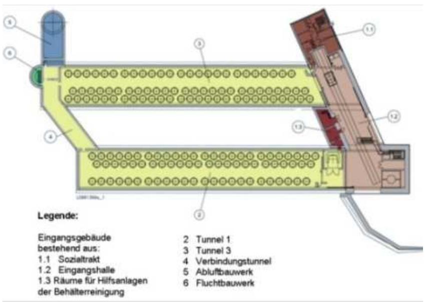


Figure 50: Layout of the tunnel storage facility at Neckarwestheim (Germany)

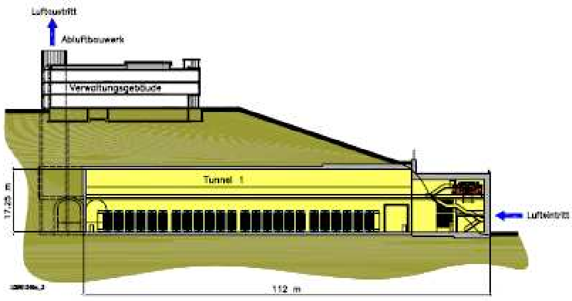


Figure 51: Cutaway view of the tunnel storage facility at Neckarwestheim (Germany)

Figure 52: Photos of the exterior and interior of the tunnel storage facility at Neckarwestheim (Germany)

The CASTOR® cask storage process is also used in the Czech Republic (VVER power plant at Dukovany – see figure 53) and in Lithuania (RBMK power plant at Ignalina). In the latter case, the casks are stored outside in a concrete enclosure (see figure 54).

Figure 53: Storage in CASTOR® casks on the Dukovany nuclear power plant site (Czech Republic)

Figure 54: Storage in CASTOR® casks on the Ignalina nuclear power plant site (Lithuania)

<u>Illustrations of on-site storage in concrete dry storage casks in Canada</u>

A cask developed by the company OPG (see figure 55) can hold 384 CANDU fuel assemblies with a total mass of 75 metric tons (including 8.8 metric tons of fuel with a total residual heat of less than a kilowatt). The cask has reinforced concrete walls sandwiched between two steel shells. The inner liner constitutes the containment system, while the outer liner is designed to enhance the structural integrity of the cask and facilitate decontamination of its surface. OPG casks are placed in a metal building, which protects them from bad weather (see figure 56).

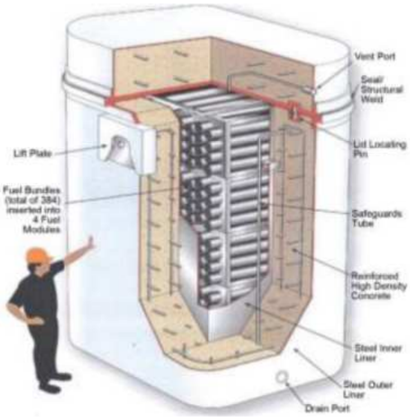


Figure 55: Cutaway view of the concrete cask developed by OPG

Figure 56: Photo of a storage facility containing concrete dry storage casks developed by OPG

5.4 Centralised dry storage

5.4.1 <u>Centralised dry storage in vaults</u>

Although dry storage of spent fuel from EDF's PWR reactors is not regularly used in France, since 1990 the French Alternative Energies and Atomic Energy Commission (CEA) has operated a dry storage vault for spent fuel (CASCAD) on the Cadarache site (see figure 57).

In particular, this facility stores spent fuel from the operation of the EL4 heavy water reactor at Brennilis, which is currently being decommissioned. The facility design is based on a semi-buried concrete storage vault with 319 vertical stainless steel storage tubes suspended from the vault's upper slab. There is an unloading and handling cell above the slab (see figure 58). It also has thick concrete walls to provide radiation shielding. The maximum residual heat per tube is 600 W.

The transport package is taken into the unloading and handling cell, and then opened. The canisters are held, extracted from the package, moved to the top of a tube and then inserted into the tube by a remotely operated crane.

Each storage tube is leak tight (see figure 59), and constitutes a dual containment system with the canisters. The tubes are cooled by natural convection cooling of the storage vault; a forced and filtered ventilation system can be connected if contamination is detected.

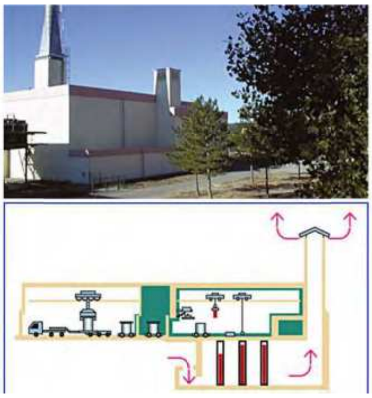


Figure 57: Elevation views of the CASCAD facility operated by the CEA/Cadarache

Figure 58: Photo of the unloading and handling cell at the CASCAD facility operated by the CEA/Cadarache

Figure 59: Photo of top of the storage pits at the CASCAD facility operated by the CEA/Cadarache

In the Netherlands, the HABOG[18] facility operated by COVRA[19] on the Borsele site stores most of the high-level and intermediate-level long-lived waste and spent fuel from the two Dutch research reactors. The facility was commissioned in 2003 for a service life of 100 years and is split into different storage compartments. It can receive eight different types of transport package and accommodate twelve types of waste package. The storage pits, which are leaktight and filled with argon, contain vitrified waste packages and spent fuel in canisters filled with inert helium gas. The pits are cooled by natural convection ventilation.

[18] HABOG for Hoogradioactief Afval Behandelings- en OpslagGebouw – High level radioactive waste processing and storage building.

[19] COVRA for Centrale Organisatie Voor Radioactief Afval – Central radioactive waste organisation.

Figure 60: Photo of the exterior of the HABOG facility (Borsele – Netherlands)

Figure 61: Photo of the top of the storage pits at the HABOG facility (Borsele - Netherlands)

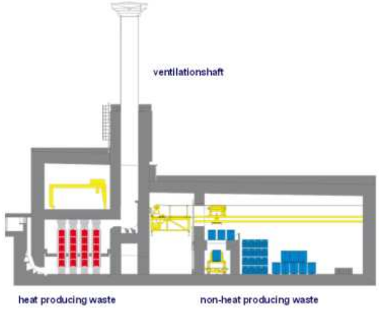


Figure 62: Cross-sectional view of the HABOG facility (Borsele – Netherlands)

In Russia, the MCC[20] site at Zheleznogorsk has a centralised dry storage facility for all the spent fuel from the operation of the RBMK-1000 and VVER-1000 reactors awaiting possible reprocessing. This facility, of which the first building was commissioned in 2012 and the second in 2016, uses the vault storage concept (see figure 63). It is expected to operate for 50 years.

Figure 63: Photos of construction of the vaults and the centralised storage facility on the MCC site (Zheleznogorsk – Russia)

5.4.2 Centralised dry storage in silos

A centralised dry silo storage facility using the concept developed by Holtec International presented in section 5.3.2 is currently being built in Ukraine to store spent fuel from the Rivne, Khmelnytsky and South Ukraine nuclear power plants. It is designed to store 12,500 VVER-1000 spent fuel assemblies and 4,000 VVER-400 spent fuel assemblies.

Furthermore, an application has been submitted in the USA for a licence to build a facility of this type at Lea County (New Mexico). This facility would ultimately be able to store 10,000 canisters of spent fuel (see figure 64).

[20] MCC for Mining and Chemical Combine, or Gorno-Kimichesky Kombinat (GKhK), or Krasnoyarsk-26.

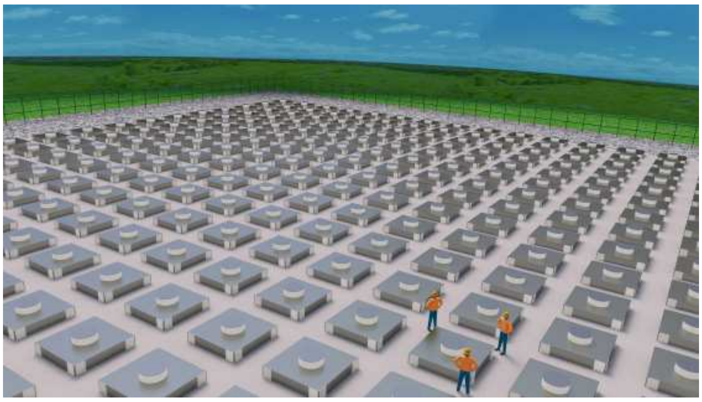


Figure 64: Conceptual view of the centralised dry storage facility in Lea County (USA)

5.4.3 Centralised dry storage in casks

Several European countries have one or more centralised storage facilities for spent fuel in casks, e.g. Germany and Switzerland.

In Germany, the centralised storage facilities at Gorleben and Ahaus (see figures below), built using the WTI/GNS concept presented in section 5.3.3, are designed specifically for storing PWR and BWR fuels and HLW packages in CASTOR® casks. These facilities can accommodate 420 casks each.

Figure 65: Aerial view of the Gorleben site (Germany)

Figure 66: Photo of the interior of the centralised storage facility on the Gorleben site (Germany)

Figure 67: Aerial view of the Ahaus site (Germany)

Figure 68: Photo of the interior of the centralised storage facility on the Ahaus site (Germany)

In Switzerland, a centralised storage facility for PWR fuel (including MOX) and vitrified HLW, of a similar design to the German centralised storage facilities, has been operated by ZWILAG at Würenlingen since 2001 (see figure 69). The storage hall (see figure 70) can accommodate 200 transport and storage casks from the TN®24 family (Orano TN), which corresponds to 50 years' production by Switzerland's five nuclear reactors.

Figure 69: Photo of the ZWILAG centralised storage building (Switzerland)

Figure 70: Photo of the storage hall of the ZWILAG facility (Switzerland)

Finally, as explained in Chapter 2, in 2018 Japan has planned to commission a centralised dry storage facility for spent fuel at Mutsu (see figure 71), while continuing its policy of reprocessing spent fuel. This facility will house spent fuel in transport and storage casks pending future reprocessing. The total capacity of the storage facility will ultimately be 5,000 t uranium.

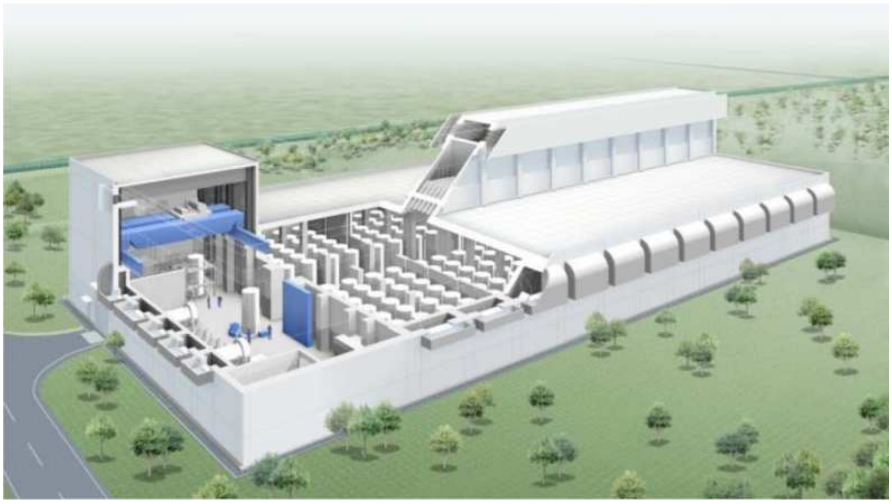


Figure 71: Cutaway view of the future centralised storage facility at Mutsu (Japan)

5.5 Assets and limiting factors of dry storage

The table in Appendix 4 summarises the main characteristics of wet and dry storage facilities.

5.5.1 Assets of dry storage

Most of the safety functions are performed by passive systems that are easy to implement:

- The radiation shielding is provided by the storage structure (module or cask);
- the second containment barrier is provided by closed and sealed barriers. Its mechanical and thermal protection is provided by the facility structures (silos, concrete slabs in the case of pits, thick steel or concrete shells in the case of storage casks);
- the heat is mainly removed passively, through natural air convection. In closed concepts (hangars, pits), it can still be necessary to use an active system (forced convection).

The operation of this type of storage facility is therefore generally simple: operating tasks are almost non-existent and inspections and checks are limited. This type of storage facility also offers a large amount of flexibility and modularity of the storage capacity, which can be extended as needed.

With silo and cask concepts, the source term in the event of a major accident is potentially lower because of the spacing between storage modules. Countermeasures off the site, which would be necessary, would also be less extensive than those for wet storage facilities in a similar situation. However, this is linked to the fact that, by design, dry storage facilities can only receive fuel that has cooled sufficiently.

5.5.2 Limiting factors of dry storage

The use of dry storage facilities is constrained by their limited spent fuel heat removal capability. For example, in the case of the TN®24 family of casks, the contents of each cask must have a residual heat of less than 40 kW, which means an average heat per fuel assembly of 2 kW. This corresponds, for example (see figure 72) to an ENU fuel initially enriched to 3.7% uranium-235, irradiated at 50 GWd/tU and cooled for five years.

For a MOX fuel with 8.65% plutonium irradiated at 50 GWd/tU, this corresponds to a cooling time of more than 50 years.

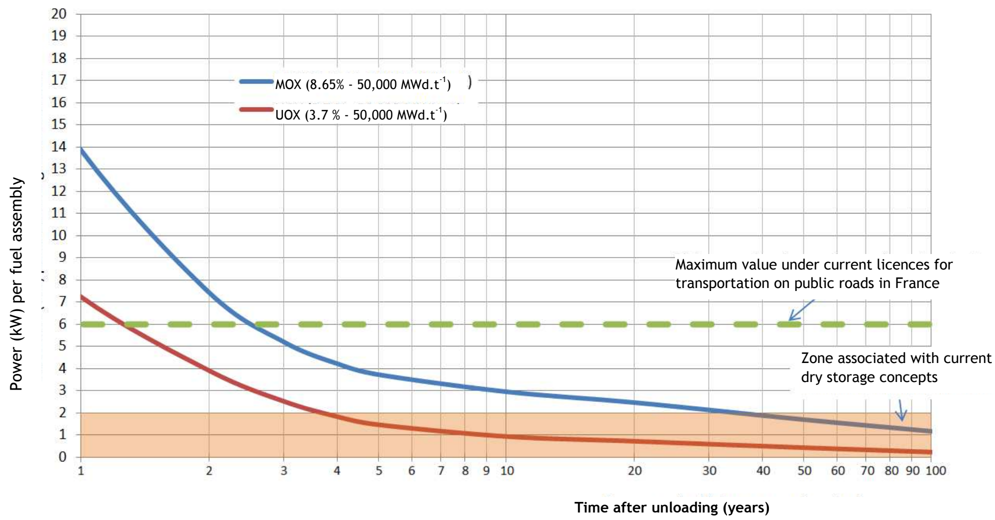


Figure 72: Cooling time necessary before dry storage, for fuels irradiated in a PWR in France

This limitation is due mainly to the fact that the temperature of fuel cladding generally must not go above 350 to 450°C in the case of zircaloy, to limit ageing.

So unless the number of fuel assemblies per cask is reduced in the case of fuels with a high residual heat (which would reduce the storage capacity), these fuel assemblies have to be kept in a pool to cool for longer.

As regards monitoring, it is difficult to inspect spent fuel in dry storage directly. However, this fuel needs to be monitored to check for degradation of the cladding, which is the first containment barrier of the storage. This degradation would also negatively affect the operations to be carried out after the storage period. Depending on the type of storage, a 'hot cell' on the site may be necessary for adequate monitoring of the fuel.

On this point, many studies are in progress on the ageing of fuel cladding, but there are yet very few on high burnup spent fuel and MOX fuel.

Finally, dry storage facilities are often less dense than wet storage facilities, and they therefore occupy more land. New concepts are being developed, however, to enable modules to be stacked and reduce their footprint.

6 CONCLUSION

Spent fuel from nuclear power reactors requires interim storage after being unloaded from the reactor. Its initial residual heat is too high. So decay of the radioactivity that it contains, which gradually reduces this heat, is necessary to enable it to be transported and managed using the chosen method. In all cases it is stored initially in the spent fuel pool adjoining the reactor. Then, depending on the chosen management option (reprocessing or disposal), two practices are used throughout the world.

If the spent fuel is to be reprocessed (as it is in France, Japan and Russia), the reprocessing plants have pools to store it before reprocessing (generally during five to ten years after it is unloaded from the reactor). The use of this type of storage is essentially linked to the processes of these plants, the pools in which the fuel is placed being directly connected to the reprocessing workshops. In addition, the capacity of these pools is generally very large to provide a buffer between activity at the reactors and activity at the plant and to allow additional cooling. Once they are separated, the uranium and plutonium are sent for recycling into fuel assemblies made from plutonium (MOX) or from enriched reprocessed uranium (ERU). The storage methods for spent MOX and ERU fuels then depend on the planned future of these fuels in the countries concerned.

If spent fuel is not reprocessed (as in most places in the world), the unloaded fuel is generally placed in dry storage facilities once it has cooled sufficiently in a pool. Current storage concepts are based on the average residual heat of fuel assemblies being around 2 kW. To a certain extent, it should be possible to adapt these concepts.

The residual heat per unit of the fuel assemblies to be stored is a decisive factor in determining the type of storage to be used (see figure 73).

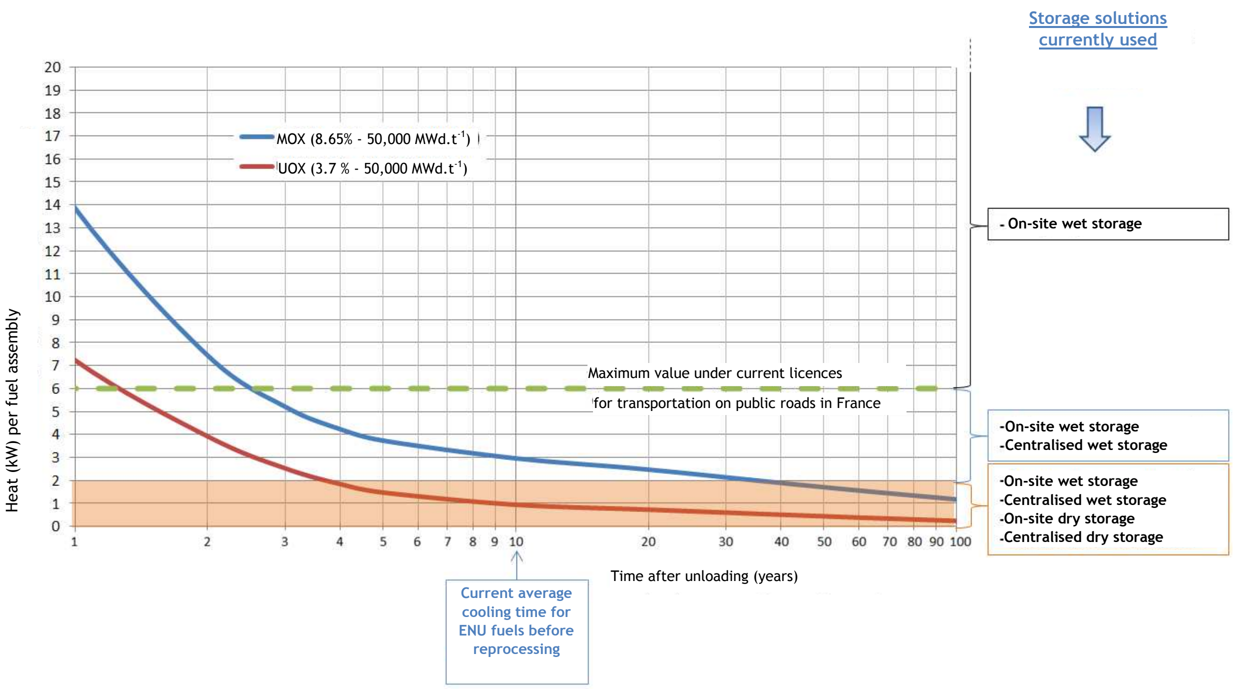


Figure 73: Suitability of storage solutions based on the residual heat of the spent fuel

In any case, the two types of storage are complementary, but the decision to use one or the other after an initial cooling phase, necessarily in a pool, depends to a large extent on national choices regarding spent fuel management.

In France, the decision to use pool storage is linked primarily to the choice for reprocessing spent fuels to recycle their plutonium (24 of the 900 MW reactors are currently licensed to use MOX fuel) and uranium (four 900 MW reactors are currently licensed to use ERU fuels).

After being unloaded from the reactor, ENU spent fuels are:

- stored in a reactor pool until their characteristics are compatible with transportation to the Orano Cycle site at La Hague, particularly when their residual heat is around 6 kW per fuel assembly with current packages and under current transport licences;
- stored in pools on the Orano Cycle site at La Hague until they are reprocessed, which happens approximately 10 years after the end of their irradiation in a reactor.

Spent ERU and MOX fuels are managed in a similar way, but their reprocessing is differed. Pending a decision about their future, EDF plans to create a centralised storage pool to store spent MOX and ERU fuels for around a hundred years.

Spent ERU fuels have similar characteristics to spent ENU fuels. The ENU fuels currently used by EDF could, with the current concepts, be stored in dry conditions after cooling for around five years. However, because of the amount of time remaining before they are reprocessed, there seems to be little point in using this type of storage. If a spent fuel reprocessing plant were to be unavailable for a long period (eventually causing saturation of the existing storage capacity), using this type of storage could be one solution.

Fresh MOX fuels loaded into a reactor have a high plutonium content to give them an equivalent burnup to that of the ENU fuels used with them in the reactor. Due to this plutonium content and its isotopic composition, spent MOX fuels have a higher residual heat. Because of their higher transuranium element content, their residual heat is also slower to decay. The cooling time before they can be placed in dry storage is therefore substantially longer than for spent ENU fuel, i.e. it takes several decades to reach a residual heat per fuel assembly of 2 kW. The use of dry storage could therefore be envisaged only beyond this period of time.

Wet storage is particularly suitable for fuels with a high residual heat, which can therefore not remain in air without deterioration of their cladding. Water is an effective coolant and active cooling systems that use it can keep fuel cladding at low temperatures. In addition, a pool has considerable thermal inertia, making it easier to deploy emergency systems if the cooling systems are lost.

The main safety requirements for wet storage are to maintain a sufficient water inventory in the pool and to have cooling systems available in all plausible circumstances. Because of the high residual heat per unit of the spent fuels contained in the pool, a prolonged loss of cooling without water makeup could have very significant consequences for the environment. In case of such a situation it becomes impossible to go near the pool because of the high dose rate induced by the fuel in the absence of any attenuation of the radiation by water.

Consequently, a spent fuel pool, particularly if it receives spent fuel that has hardly cooled, must be of a particularly robust design, with sufficient margins to cope with any risks that can be envisaged, and its operation must allow appropriate monitoring of both the installation itself and the fuel it contains.

Experience feedback from the Fukushima accident lead safety approaches for controlling these risks to be reinforced, aiming to maintain a sufficient water inventory in extreme situations of natural origin.

Current industrial techniques enable pools to be built that control the risks of fuel uncovering, with the buildings housing the pool providing protection against external hazards (particularly the APC shell).

It generally takes about a decade to build a facility of this kind, based on current experience feedback from nuclear facilities built in France.

Dry storage is reserved for fuel that has cooled sufficiently (to around 2 kW on average per fuel assembly with current concepts). Consequently it has the advantage of generally using passive cooling systems, which limits operating constraints, and it lends itself particularly well to modular construction, adapting to needs or even enabling old modules to be replaced over time.

The safety requirements are the maintenance of passive cooling and the quality of the containment barriers between the radioactive materials and the environment.

This type of storage has the advantage of a simpler, more robust design and less operational intervention. Depending on the design, direct monitoring of the condition of the fuel cladding (the first containment barrier), which is subject to the most demanding thermal conditions, is generally not possible.

In any case, if an accident occurs, the smaller number of fuel assemblies and their lower residual heat will mean fewer consequences for the environment.

It generally takes around five years to build this type of facility, depending on its modularity and whether or not existing cask concepts are used.

Moreover, regardless of the type of storage, significantly longer storage periods than the usual periods (of a few decades) will require the definition of appropriate requirements (particularly in terms of the design of the civil engineering structures and in terms of safety margins).

For IRSN, one particularly important point for the safety of spent fuel management is controlling the ageing of zirconium fuel cladding, which depends on storage temperature. This cladding is the first containment barrier for the radioactive materials. In addition, its mechanical strength is important for the operations to take place after storage (transport, reprocessing or disposal).

Wet storage offers guarantees in this respect, given the low storage temperatures and the potential for direct examination of cladding. Countermeasures (canisters for defective fuel) can also be taken if ageing phenomena are detected. There is a significant experience feedback available in France and throughout the world on the behaviour of cladding underwater, at least for periods of a few decades.

With dry storage, it is more difficult to examine fuel cladding directly. Any inspections made are at best indirect (no release of gases into the cask cavity, etc.), or impossible (fuel canisters sealed by welding constituting the second and final confinement barrier); they do not enable the detection of ageing mechanisms.

Any guarantees that the ageing of cladding is controlled are based primarily on studies, which have notably defined the maximum acceptable temperature for cladding in storage. No examinations of fuel carried out to date, as far as IRSN is aware, have challenged the findings of these studies. However, many studies are ongoing. Moreover, there is limited information available for fuels with a high burnup (more than 45 GWd/t), for MOX fuel (especially with a high initial plutonium content) and generally for long storage periods (more than 40 years).

To conclude, IRSN considers that decisions about the type of storage to be used for spent fuel must be assessed in the light of the following considerations.

The two types of spent fuel storage that could be envisaged (wet or dry) do not serve exactly the same needs, since wet storage is absolutely necessary for fuel that has hardly cooled and dry storage is suitable for fuel that has cooled substantially.

The type of spent fuel (ENU, MOX or ERU) affects the type of storage to be used, at least for a certain length of time, since MOX fuels have a higher residual heat for a longer period of time.

From a safety point of view, regardless of the type of storage, the decisive parameter is the residual heat of the fuel to be stored. Wet storage, which generally contains hotter fuel, requires more substantial safety measures than dry storage, for which more passive measures can be implemented. In dry storage, cladding (the first containment barrier) is subject to greater thermal stress and is more difficult to inspect.

Appendix 1. **LETTER OF REQUEST**

ASSEMBLÉE NATIONALE

RÉPUBLIQUE FRANCAISE
LIBERTÉ - EGALITÉ - FRATERNITÉ

Commission d'enquête sur la sûreté
Et la sécurité des installations nucléaires

Paris, le 26 mars 2018

Monsieur le Directeur général,

À la lumière des premiers travaux de notre commission d'enquête, l'enjeu de l'entreposage du combustible nucléaire irradié nous apparaît comme un point crucial pour la sûreté et de la sécurité nucléaire dans notre pays. En effet, les choix de gestion du combustible conduisent à ce qu'une partie ne soit pas retraitée. La saturation progressive des capacités disponibles dans les piscines de désactivation, adossées à chaque réacteur et dans les piscines des usines de retraitement de La Hague conduit à un phénomène d'accumulation progressive des quantités de combustibles usés et de manque de capacités d'entreposage.

Nous mesurons progressivement, à travers nos auditions, le potentiel de danger que présente ce combustible irradié et les enjeux importants que la maîtrise de son entreposage représente vis-à-vis de la sûreté et de la sécurité nucléaires. Nous avons dans ce contexte pris connaissance du projet d'EDF consistant à développer de nouvelles capacités d'entreposage sous la forme d'une piscine d'entreposage centralisée, dimensionnée pour entreposer le combustible usagé sur une période de cent ans, dont la mise en service ne semble toutefois pas prévue par l'exploitant avant un horizon 2030.

Nous avons parallèlement observé que l'entreposage en piscine n'est pas la seule option technique envisageable et appris qu'une part croissante du combustible usé fait l'objet dans un nombre important de pays d'un entreposage dit à sec, dans des « châteaux » eux mêmes conservés à l'air libre ou, de façon plus pérenne, dans des ouvrages d'entreposage en surface. Enfin, les experts que nous avons auditionnés jusqu'ici expriment des avis très contrastés quant aux bénéfices respectifs pour la sûreté et la sécurité de l'entreposage sous eau et de l'entreposage à sec du combustible usé.

Lors de votre audition, vous nous avez déclaré que l'Institut que vous dirigez n'avait pas engagé d'étude comparative des mérites de ces deux options mais qu'il serait sans doute en mesure de le faire. Nous sollicitons dès lors auprès de vous cet éclairage qui nous semble indispensable pour nous permettre de formuler des conclusions et, le cas échéant, des recommandations sur cette question essentielle.

Nous souhaiterions ainsi disposer avant la fin de nos travaux, et si possible début juin, d'un avis de l'Institut de radioprotection et de sûreté nucléaire sur les enjeux associés, en termes de sûreté nucléaire, à une stratégie de gestion du combustible reposant sur un entreposage en piscine uniquement ou faisant appel à un entreposage à sec. Au vu des différents éléments d'appréciation que nous avons d'ores et déjà identifiés, nous aimerions en particulier que cet avis nous éclaire sur :

- les différentes solutions existantes et envisageables et leurs principales caractéristiques en matière d'entreposage sous eau (piscines décentralisées en réacteur ou centralisées comme à La Hague, avec ou sans densification…) et d'entreposage à sec (décentralisé sur les sites des réacteurs ou centralisé, à l'air libre ou en ouvrage dédié…), en intégrant dans un cas comme dans l'autre le degré possible de « bunkerisation » ;

- les avantages et inconvénients respectifs du point de vue de la minimisation des risques de ces deux types d'entreposage, en fonction de leurs caractéristiques et leur capacité à maintenir le confinement du combustible usé dans différentes conditions dégradées ;

- les délais nécessaires, en fonction notamment de la nature du combustible, avant son transfert éventuel de l'entreposage sous eau pour désactivation à l'entreposage à sec, et les durées maximales d'entreposage envisageables pour le combustible dans ces deux options ;

- les délais prévisibles de mise en œuvre de nouvelles options, qu'il s'agisse de conception, d'autorisation, de construction des conteneurs ou de nouvelles installations, de transfert d'un mode d'entreposage à un autre voire de transport d'un site à un autre ;

- les implications croisées entre les choix de gestion du combustible et les options d'entreposage, en particulier l'articulation des conditions d'entreposage avec les choix futurs de retraitement différé ou de stockage définitif des combustibles usés concernés ;

- et plus généralement, une appréciation générale de la capacité des différentes stratégies envisageables à réduire le potentiel de danger de l'entreposage et sa vulnérabilité.

Nous souhaitons enfin, si vous acceptez de mener cette analyse pour éclairer nos travaux, que l'Institut intègre dans cette démarche le panorama international du retour d'expérience et des options retenues dans d'autres pays disposant d'un important programme nucléaire.

Vous remerciant par avance, je vous prie d'agréer, monsieur le directeur général, l'expression de mes sentiments les meilleurs.

Le Président Paul CHRISTOPHE

Cordialement

Appendix 2. **SURVEY OF INTERNATIONAL PRACTICES**

The table below lists international practices as presented in the national reports issued by the signatories to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. Only countries with nuclear power reactors are listed in the table.

Country	On-site pool storage	Centralised pool storage	On-site dry storage	Centralised dry storage	Spent fuel management
South Africa	In the pools adjoining the reactors.	Not applicable (only one site).	A building for dry storage in metal casks (CASTOR) is used to store on the Koeberg site legacy spent fuels from the reactors on this site.	Not applicable (only one site).	'Wait-and-See' strategy: (choice not made between direct disposal and reprocessing)
Germany	In the pools adjoining the reactors (18 pools in operation). The Obrigheim site has one extra wet storage facility (currently being emptied).	No	12 sites have a facility for dry storage in metal casks (CASTOR type).	There are two facilities for centralised storage in metal casks (CASTOR type) in Ahaus and Gorleben.	Reprocessing stopped Direct disposal.
Argentina	In adjoining pools: - on the Atocha site: in three pools, including one where 'reracking' (compacting) has taken place; - on the Embalse site: in a pool for at least 6 years.	No	On the Atocha site: plan to build a silo storage facility. On the Embalse site: ASECQ facility (storage in concrete silos).	No	Decision on reprocessing postponed until 2030.

Country	On-site pool storage	Centralised pool storage	On-site dry storage	Centralised dry storage	Spent fuel management
Armenia	In the pools adjoining the reactors.	No	Yes, at two horizontal silo type storage facilities (NUHOMS concept); transfer is possible after a cooling period of between five and 12 years in a pool depending on the type of fuel.	No	'Wait-and-See' strategy.
Belgium	In the adjoining pools: - two on the Doel site; - two on the Tihange site. One building houses eight additional pools on the Tihange site for the spent fuel from the three reactors on the site.	No	A dry storage facility on the Doel site (storage in metal casks in a building for this purpose). A similar storage facility is planned on the Tihange site.	No	Reprocessing stopped. 'Wait-and-See' strategy.
Brazil	In (reracked) pools adjoining each of the reactors.	No	A dry storage facility with horizontal and vertical silos is planned.	No	'Wait-and-See' strategy.
Bulgaria	In adjoining pools for at least three years. The Kozloduy site also has a wet storage facility with four pools.	No	A building for dry storage in concrete DCSs (CONTOR) is used for long-term storage on the Kozloduy site of spent fuels from the reactors on this site.	No	Reprocessing abroad (Russian Federation).

Country	On-site pool storage	Centralised pool storage	On-site dry storage	Centralised dry storage	Spent fuel management
Canada	In pools adjoining the reactors (for six to 10 years depending on the specific site needs).	No	Dry storage facilities at the different sites using different concepts such as vertical loading surface silos (MACSTOR), concrete container-type silos or concrete dry storage casks.	No	Study looking at direct disposal.
China	In pools adjoining the reactors.	Centralised wet storage in the pilot reprocessing plant on the JAEC (Jiuquan Atomic Energy Complex) site.	In existence at Qinshan: Dry storage in vertical loading surface silos (MACSTOR) for CANDU spent fuel after at least six months' cooling. Under construction: two facilities for dry storage in metal casks on the Daya Bay and Tianwan sites.	No	Pilot reprocessing plant on the JAEC (Jiuquan Atomic Energy Complex) site. Industrial reprocessing plant project at the negotiating stage.
South Korea	In pools adjoining the reactors. In the case of PWR pools, saturation managed by reracking or distributing between pools.	No	Dry storage facilities for CANDU spent fuel (in MACSTOR vertical loading surface silos and in concrete silos) on the Wolsong site.	Centralised dry storage facility project (site to be defined).	Direct disposal.
Croatia	In the pool adjoining the reactor.	Not applicable (only one site).	'Container'-type silo dry storage facility planned on the Krsko site.	Not applicable (only one site).	Direct disposal.

Country	On-site pool storage	Centralised pool storage	On-site dry storage	Centralised dry storage	Spent fuel management
United Arab Emirates	In the pools adjoining the reactors (dimensioned to store spent fuel corresponding to 20 years' operation).	Not applicable (only one site).	One dry storage facility is already at the planning stage.	Not applicable (only one site).	Direct disposal.
Spain	In adjoining pools that have been reracked.	No	Dry storage facilities on the Trillo site in metal casks (of the ENSA-DPT type) and on the José Cabrera and Asco sites in container-type silos (HI-STORM 100 concept). Similar facilities are planned for the Santa María de Garoña, Almaraz and Cofrentes sites.	The grouping of spent fuel and waste at the Vilar de Canas site is planned.	Reprocessing stopped. Direct disposal.
United States	In pools adjoining the reactors.	No	71 on-site dry storage facilities are licensed (34 states have at least one facility of this kind). The most widely used types of storage facility are surface silos that load horizontally (NUHOMS type) or vertically (HI-STORM 100 type), semi-buried silos that load vertically (Hi-STORM UMAX type) or concrete container type silos.	No (Yucca Mountain project on standby).	Reprocessing of the spent fuel from power reactors was stopped at the end of the 1970s. Direct disposal.

Country	On-site pool storage	Centralised pool storage	On-site dry storage	Centralised dry storage	Spent fuel management
Russian Federation	In pools adjoining the reactors (for at least three years).	In the reprocessing plant pools (PA-Mayak and MCC).	Several on-site dry storage facilities.	Centralised facility for dry storage in a vault on the MCC site (for spent fuel from operation of the RBMK-1000 and VVER-1000 reactors).	Reprocessing at several plants (including PA-Mayak).
Finland	In the pools adjoining the reactors (for one to five years). Each site has a wet spent fuel storage facility for spent fuel awaiting the availability of the deep geological disposal facility.	No	No	No	Direct disposal.
France	In the BK pools adjoining the reactors.	In the four pools in operation on the Orano Cycle site at La Hague. + EDF project to build a centralised storage pool (mainly for MOX and ERU fuel).	No	No, except for the CASCAD facility (storage of EL4 fuel).	Reprocessing at the plants on the Orano Cycle site at La Hague (ENU fuel).
Hungary	In pools adjoining the reactors (for around four years at least).	No	On-site dry storage in a vault storage facility (Modular Vault Dry Storage concept).	No	Reprocessing abroad (Russian Federation).

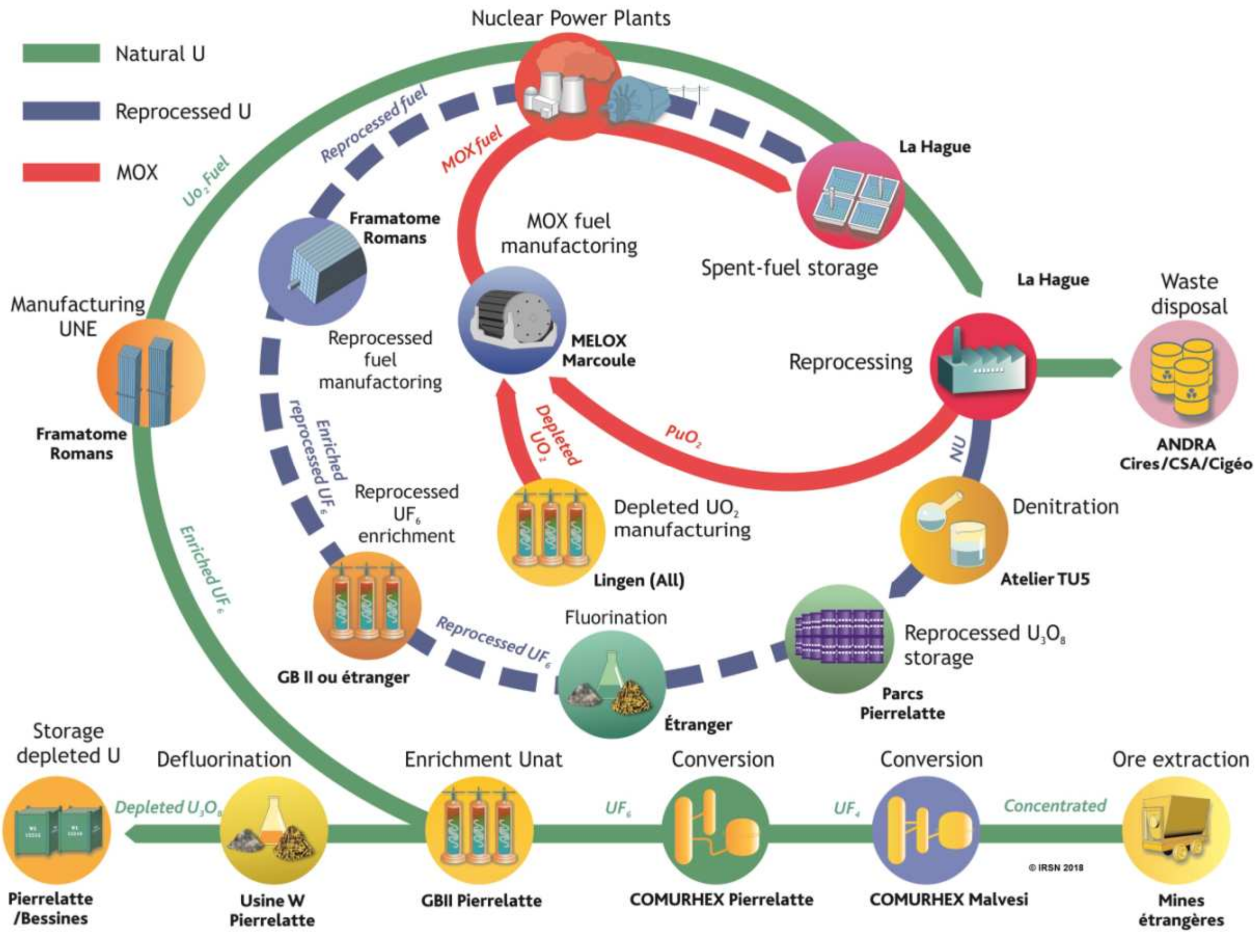
Country	On-site pool storage	Centralised pool storage	On-site dry storage	Centralised dry storage	Spent fuel management
Italy	No	Centralised wetstorage facility known as AVOGADRO on the Saluggia site.	No	No	Reprocessing abroad (France).
Japan	In the pools adjoining the reactors (on 17 sites). The damaged Fukushima Daiichi nuclear power plant also has a pool on site.	The pools at the reprocessing plant at Rokkasho have a centralised storage facility awaiting spent fuel reprocessing.	Two sites (Fukushima Daiichi and Tokai 2) have facilities for on-site dry storage in metal casks.	A centralised facility for dry storage in metal casks is currently under construction in Mutsu.	Reprocessing (plant waiting to be restarted).
Kazakhstan	No	No	No	Centralised dry storage (in mixed metal and concrete dry storage casks) on the Baikal-1 site (Kurchatov).	'Wait-and-See' strategy.
Lithuania	In adjoining pools (for at least five years); several compartments can contain whole or fragmented assemblies (in cells).	Not applicable (only one site).	Two facilities on the Ignalina site: - one area (with perimeter walls but no roof) for storage in metal (CASTOR type) and concrete (CONSTOR type) casks; - a building for storage in concrete dry storage casks (CONSTOR type).	Not applicable (only one site).	Direct disposal.
Netherlands	In adjoining pools (before being sent to France for reprocessing).	No	No	No	Reprocessing abroad (France).

Country	On-site pool storage	Centralised pool storage	On-site dry storage	Centralised dry storage	Spent fuel management
Czech Republic	In pools adjoining the reactors (for at least seven years on the Dukovany site and at least five years on the Temelin site).	No	Two facilities for dry storage in metal casks (CASTOR) on the Dukovany site. One facility for dry storage in metal casks (CASTOR) on the Temelin site.	No	The preferred solution is direct disposal but the other options are not excluded.
Romania	In adjoining pools (for at least six years).	Not applicable (only one site).	Facility known as DICA for dry storage in silos loaded vertically (MACSTOR) on the Cernavoda site.	Not applicable (only one site).	Direct disposal.
United Kingdom	In pools adjoining the reactors.	Yes, in pools at the Sellafield and Dounreay reprocessing plants.	Facility for dry storage in container-type silos (HI-STORM MIC concept) on the Sizewell B site.	No	Reprocessing plants shut down.
Slovakia	In pools adjoining the reactors (for three to seven years).	Yes, at Jaslovské Bohunice (the pool has been reracked).	No	Plans for a centralised storage facility (a priori in silos) at Jaslovské Bohunice.	Direct disposal.
Slovenia	In a pool adjoining the reactor.	Not applicable (only one site).	'Container'-type silo dry storage facility planned on the Krsko site.	Not applicable (only one site).	Direct disposal.

Country	On-site pool storage	Centralised pool storage	On-site dry storage	Centralised dry storage	Spent fuel management
Sweden	In pools adjoining the reactors (for at least nine months).	CLAB facility at Oskarshamn for the storage of all spent fuel in underground pools pending disposal at a geological disposal facility.	No	No	Direct disposal.
Switzerland	In pools adjoining the reactors. The Gösgen site has an extra wet storage facility.	No	Facility known as ZWIBEG for dry storage in metal casks (type TN 24) on the Beznau site.	Facility known as ZWILAG or ZZL for centralised dry storage in metal casks (type TN 24) on the Würenlingen site.	Reprocessing stopped. Direct disposal.
Ukraine	In the pools adjoining the reactors. A facility known as ISF-1 is used for wet storage of spent fuel from the reactors on the Chernobyl site.	No	Storage on the Zaporizhia site, in concrete container-type silos (VSC24). A facility known as ISF–2 under construction, will be used for the dry storage of spent fuel from the reactors on the Chernobyl site currently stored at the ISF-1 facility.	Project to build an additional facility for storage in concrete container-type silos (HI-STORM 190 concept) on the Chernobyl site (in the exclusion zone).	Reprocessing abroad.

Appendix 3. **THE FRENCH FUEL CYCLE**

The operation of EDF's nuclear reactors requires facilities and logistics equipment to supply fresh fuel, store and reprocess spent fuel unloaded from reactors, recycle certain materials and manage the waste produced by the reactors and related facilities. The term 'French pressurised water reactor nuclear fuel cycle' (also known as the 'French fuel cycle') refers to all these operations. At its 'front end', it consists in particular of the stages of conversion and enrichment of the uranium with the fissile isotope uranium-235 and the fuel fabrication stages, whether it is uranium oxide fuel or a mixed uranium and plutonium oxide fuel. The 'back end' of the cycle consists of the storage and reprocessing of the spent fuel and the management of the recyclable materials produced by the reprocessing (uranium and plutonium) and the radioactive waste. The fuel cycle front end and back end installations are presented in the diagram below.



Appendix 4. MAIN CHARACTERISTICS OF WET AND DRY STORAGE FACILITIES

	On-site or centralised wet (pool) storage	Dry storage
Facility type	Large concrete buildings, or very large in the case of centralised storage pools. Non-modular construction	Vault storage: concrete buildings with metal structures, generally of intermediate size. Non-modular storage. Silo storage: concrete structure (vertical or horizontal) containing a spent fuel canister. Modular construction. Dry cask storage: metal, concrete or mixed casks, usually stored in dedicated buildings. Modular construction.
Cooling capacity/operating range	Pools adjoining reactors (BK pools): Very significant. Can be used to store spent fuel that has hardly cooled (residual heat of more than 10 kW per fuel assembly) Centralised storage pool: Significant. Can be used to store spent fuel with a residual heat of less than 10 kW per fuel assembly.	Limited (on average 1 to 2 kW per fuel assembly for current concepts)
Storage conditions with regard to ageing, particularly of the spent fuel cladding	Low temperatures (of around 40 or 50°C), limiting ageing phenomena. Control of the chemistry of the water aimed at controlling corrosion in particular.	High temperatures (several hundred degrees at the time of loading). Drying and inerting of storage canisters to limit corrosion phenomena.
Radiological shielding	Performed by the water. Low dose rate around the edge of the pool.	Vault storage: performed by the building structures. Silo storage: performed by the silos. Cask storage: performed by the casks and completed by the storage buildings.

	On-site or centralised wet (pool) storage	Dry storage
Mode of operation	Cooling system: – in the case of pools adjoining reactors (BK pools), active system generally with limited thermal inertia (pool water boils in a few hours); – in the case of centralised pools, usually an active system generally with significant thermal inertia (pool water boils in a few days). System proven for all fuel types Significant operational action (operation, monitoring, maintenance, etc.)	Cooling provided by air circulation by natural convection Almost zero operation.
Monitoring of fuels/retrieval condition	Direct with the possibility of extracting rods for detailed analysis. Possibility of intervention on fuels (e.g. overpacking)	Indirect. Control of ageing relies on studies of fuel degradation mechanisms. 'Hot cell' needed for direct monitoring of fuel.
Fuel retrieval/interface with transport	Permanent function, part of everyday operation	Non-permanent function that will depend on the possibility of transporting the storage devices and on maintenance of the mechanical characteristics of the cladding.
External hazards	Requirements placed on buildings, making them complex to design because of their size	Requirements sometimes placed on buildings in the case of storage in modules or pits, making them complex to design because of their size. In other cases (smaller concepts), the requirements are placed on the silos, canisters or casks.

LIST OF ABBREVIATIONS USED IN THE REPORT

ASN	French Nuclear Safety Authority
BK	Fuel building, in the case of a PWR, where the spent fuel pools (BK pools) are located
NPP	Nuclear power plant
DOS	Safety Options Report
EDF	Electricité de France
EPR	European pressurized reactor
IRSN	French Institute for Radiological Protection and Nuclear Safety
MOX	Mixed uranium and plutonium oxide fuel
MW	Megawatt electric
PNGMDR	National Plan for the Management of Radioactive Materials and Waste
RBMK	Thermal neutron reactor using graphite as moderator and boiling light water as coolant (abbreviation of Reactor Bolshoï Moshchnosti Kalani)
BWR	Boiling water reactor
PWR	Pressurized water reactor
FNR	Fast neutron reactor
tIHM	Tons of initial heavy metal
ENU	Enriched natural uranium
UOX	Uranium oxide
ERU	Enriched reprocessed uranium
VVER	Pressurized water reactor of Soviet, then Russian, design (abbreviation of Vodo-Vodianoï Energuetitcheski Reaktor)