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Critical reflooding of spent fuel packages

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Abstract

The transport of spent fuel in type B fissile packages is done dry, without the presence of water in the package. This measure relates to demonstrations done in the safety analysis report concerning radiolysis, criticality and pressure aspects related to water contents. This measure implies that after the loading of the packages in spent fuel pools, the packages are drained and dried.

In case there is a non-conformity of the package relative to the package approval certificate or an operational problem causing the transport to be delayed or annulled, the package often needs to be unloaded or re-opened. To unload the spent fuel or re-open the package lid, the package needs to be reflooded. This is an unusual and critical procedure for most NPPs since the unloading normally occurs at the receiving end: reprocessing or waste facility.

The fuel in the package has increased in temperature after the drying process. The adding of relatively cold water could cause a thermal shock for the spent fuel and the production of steam is to be avoided. This can cause a pressure rise in not only the package but also in the installation. By re-adding water in the spent fuel package, neutronic moderation is increased and precautions have to be taken to avoid criticality problems.

After reflooding the spent fuel cask, there can be a need for cooling. The temperature of the spent fuel has risen due to the dry atmosphere in the cask. Before re-immersion in the spent fuel pool and to avoid thermal shock, the spent fuel could be cooled inside the package. The Transnubel experience has shown that this operation can be executed safely with the proper precautions and preparations.

Introduction

After loading the packages in a pool, a lot of effort is going to the draining and drying of spent fuel packages to achieve a certain level of dryness. This level is taken into account in the safety analysis report which has to deal with subjects such as radiolysis, criticality and pressure aspects which are caused by water in a strong radiant, closed environment as for example a spent fuel package. Therefor the drying of the internal cavity ensures the safe transport or storage of the spent fuel.

At the receiving facility the spent fuel package can be unloaded or stored. However due to certain events or non-conformities, the necessity to unload or re-open the spent fuel package at the sender NPP can arise. This unloading or re-opening process requires the spent fuel packages to be reflooded before they are unloaded in the spent fuel pool.

In this paper, first the reasons or causes of such a critical reflooding are discussed. Then the technical steps of the reflooding procedure are discussed followed by an extensive discussion on the two most important steps, the reflooding and the cooling of the spent fuel package. The associated risks of these operations are discussed including the means to reduce these risks. To conclude this paper two real world examples of critical refloodings of spent fuel packages in Western Europe NPPs are presented followed by a conclusion.

Causes

The need for the unloading or re-opening of spent fuel packages can have different reasons. Most of these reasons have their origin in a non-conformity in some form. Two main categories of causes can be dissociated: operational aspects and licensing non-conformities.

An operational problem can arise such as a blockage of the transport, a malfunction of an overhead crane, a problem with a lifting beam or a specific tool … These kind of problems cause a non-conformity of the normal procedure and can immobilize the evacuation of the spent fuel. Solutions can always be found but the nature of the equipment and tools which are used for these spent fuel loadings is relatively specific so that back-up equipment or other compatible tools are rare.

Not only operational problems can be the reason to take the decision to re-open the package but licensing non-conformities are getting more and more frequent. For the loading of spent fuel in a transport or storage packaging, a great number of licenses can be involved: package approval license, transport license, storage license, exploitation license of the loading building, etc. Any problem with any of these licenses can cause a stop in the normal evacuation procedure of the spent fuel. Luckily, most of them can be detected and resolved before the loading of the spent fuel. However there are unexpected non-conformities that can arise during loading, transport or during storage of the spent fuel.

Non-conformities of the package with its package approval certificate can arise. These are mainly due to fabrication defects which have remained invisible before loading or which become noticeable after a storage phase: leaking gasket, failing shielding, defective cooling fins, damaged shock absorber, etc. These events can have an influence on the safety functions of the package therefor causing a non-conformity of the package approval certificate. A non-conformity of the content is possible: leaking fuel, residual heat production is too high, burn-up rate too low, dose rate not conform, mechanical deformations of fuel elements, etc.

If the unfortunate and unexpected event cannot be resolved in a relatively short time phase, whether it is an operational problem or a licensing issue, it can be decided to re-open and even unload the spent fuel. Whether the package is merely re-opened or is unloaded depends on the non-conformity at hand. The decision to go ahead with this reverse procedure is not taken lightly since it will generate a waste of resources and will probably cause planning issues, not only for the NPP but for all parties involved.

Procedure

The re-opening of the spent fuel package can rarely be done dry because of the large dimensions and weight of the packages. Hot cells of this size are rather rare. Therefor an underwater opening in the same way that the packaging was loaded is advised. There is often no other solution since the transportation elsewhere is not considered possible. The procedure for the re-opening therefor typically implies a critical reflooding followed by a cooling phase before placement of the package in the pool. Most spent fuel packages have a brief unloading procedure available in their safety analysis report.

Critical Reflooding

Since the package has been dried, a controlled reflooding of the package cavity needs to be established. A controlled inlet of water is achieved and an outlet for possibly contaminated air/helium/nitrogen (whichever the filling medium was) is foreseen. The filling water can be water taken from the spent fuel which is usually borated or can be clean demineralized water.

Since the package filled with spent fuel was dry, the temperature inside and on the outside has increased as compared to the situation in the pool. The fuel in the package has increased in temperature due to the lowering of the convection cooling by taking out the water. This has for effect that the adding of relatively cold water could cause a thermal shock for the spent fuel and inside the package steam can be generated.

A measure to control the first risk can be the preheating of the ingoing water but which would require a relatively large heat source. Another more applied method can be to simply fill the package at a much reduced filling rate from 500 to 2000 l/h depending on the residual heat of the spent fuel. During the filling, a follow up of the temperature of the outgoing flow and the temperature of the package lid and body are strongly advised. A maximum contact temperature of 85°C is allowed for an approved type B package according to [1] to avoid the risk of burns.

The ingoing water comes into contact with the spent fuel which has risen in temperature. There is a possibility of steam generation. This can cause a pressure rise in not only the package but also in the installation at the outlet of the package. Installations and piping which are not normally foreseen to be able to handle steam discharges and relatively hot media, are put to the test. Safety measures to apply are the permanent follow up of the pressure in the packaging at the outlet. It is essential that any excess pressure can be evacuated by the NPPs ventilation system. Since the steam production can be significant, the clogging of pipes due to local condensation of steam should be evaluated. Local pressure build ups could lead to the damaging of the piping or installation with contaminated discharge as a consequence. Steam traps can be used to evacuate any condensate in the piping or installation to avoid this clogging. The same rule applies here that a reduced filling rate implies a lower steam production rate and therefor reduces theses associated risks.

Another essential aspect to the reflooding procedure is the criticality aspect. By re-adding water in the spent fuel package, neutronic moderation is increased and criticality needs to be discussed. According to [1] §673, the safety analysis report of the spent fuel package has to take into account the subcriticality regarding the leakage of water into or out of packages during the design of the package. The result are spent fuel packages which have safety measures incorporated in their design such as borated baskets, spacing between spent fuel elements, overall configuration of the fuel in the package, etc. Therefore, in theory, it should be safe for an approved type B fissile spent fuel package to be reflooded with demineralized clean water instead of borated pool water from the pools. A careful examination of the safety analysis report and the consultation of the designer and constructor of the package is however advised. If in doubt, a criticality calculation can probably relieve any issues that potentially remain. A possibility to increase the safety margin can be the reflooding of the package with borated pool water instead of clean demineralized water.

It is not always convenient to follow up the level of water inside the spent fuel package cavity. The application of a level indicator is not always possible. A precise logging of the ingoing flowrate followed by an integration needs to be combined with an estimation of the volume of the package reduced by the volume of the spent fuel. The result could provide a level indication just as well and can provide an easy follow-up of the progress of the reflooding procedure. When the package is completely full, a visual indication of water coming out of the outlet confirms that the package has been completely reflooded.

Cooling

Once the package has been filled completely, the outlet temperature of the outgoing water must be noted. A difference of temperature of the outgoing water as compared to the spent fuel pool temperature is to be expected since the ingoing water has cooled the relatively hot spent fuel. In the same way as during the reflooding procedure a risk of thermal shock could arise from placing the relatively hot spent fuel in the relatively cold spent fuel pool. Therefore, before submersion of the spent fuel package in the pool, a cooling procedure is implemented.

There are basically two ways to cool the spent fuel inside the package: cooling inside and/or outside the package. Cooling of the spent fuel inside the package is evident since one can proceed with the filling procedure and continue adding relatively cold water. However, this method results in an increase of possibly contaminated water which is expensive to treat. An alternative can be the circulation of the outgoing water back towards the inlet and provide passive or forced cooling of the circulated water during the backflow in the installation and piping.

Another way of cooling the spent fuel (and the package) is by cooling on the outside of the package. The design of the package must allow this and the presence of external cooling fins on the package makes this method more effective. A skirt (cylinder) is placed over the spent fuel package to cover the package's body. Clean demineralized water is then circulated through the skirt to cool down the package and its contents through convection of the circulating water. In most cases, this outside cooling method can already be implemented during the reflooding phase. No liquid waste is generated by using this type of cooling.

The spent fuel can be the source of residual heat of the orders of several tens of kW. The amount of cooling ($Q_{cooling}$) in terms of kW needs to be larger than the residual heat of the spent fuel for the fuel to be cooled down:

$$Q_{cooling} = \frac{\dot{Q}.\rho}{3600}.c.(T_{out} - T_{in}) > P_{fuel}$$

In which:

$$\dot{Q}: Volumetric\ flow\ rate\ \left[\frac{m^3}{h}\right]$$

$$\rho: Density\ of\ water\ [\frac{kg}{m^3}]$$

$$c: Thermal\ heat\ of\ water\ \left[\frac{kJ}{kg.K}\right] \sim 4.187$$

$$T_{out}: Outlet\ temperature\ [K]$$

$$T_{in}: Inlet\ temperature\ [K]$$

$$P_{fuel}: Residual\ heat\ spent\ fuel\ [kW]$$

The cooling is continued until the outlet temperature is in the same range as the spent fuel pool temperature. More precision on this minimal outlet temperature can be found mostly in the safety analysis report or reflooding procedure. The cooling time depends very much on the configuration of the fuel, the package design, the external cooling (if applicable), surrounding temperature, flow inside the package, etc. Once the spent fuel has been sufficiently cooled, the package can be submersed and re-opened under water and if needed the spent fuel can be unloaded.

Examples

This paragraph presents two real world data sets of critical reflooding procedures in two West European

NPPs. In the figures the outlet temperature, ingoing flowrate and the water level inside the package are plotted versus the time taken from the start of the reflooding. Each example will be discussed with a short presentation of the cause of this critical reflooding and the boundary conditions.

Example 1

For this example the cause or reason for the critical reflooding was the discovery of fission product gas Kr-85 inside the drying cavity of the spent fuel package. This was a good indication for a leaking fuel rod therefor the content was not conform to the approved content. Because of this an unloading procedure was needed. The residual spent fuel heat was relatively low and amounted up to a mere 6,2 kW. The pool temperature was about 23°C and was the source of the ingoing (borated) water. A skirt was used for outside cooling not only during the cooling period but also before, during reflooding. The inlet and outlet temperature of the cooling water flowing through the skirt were 27°C and 28°C respectively.

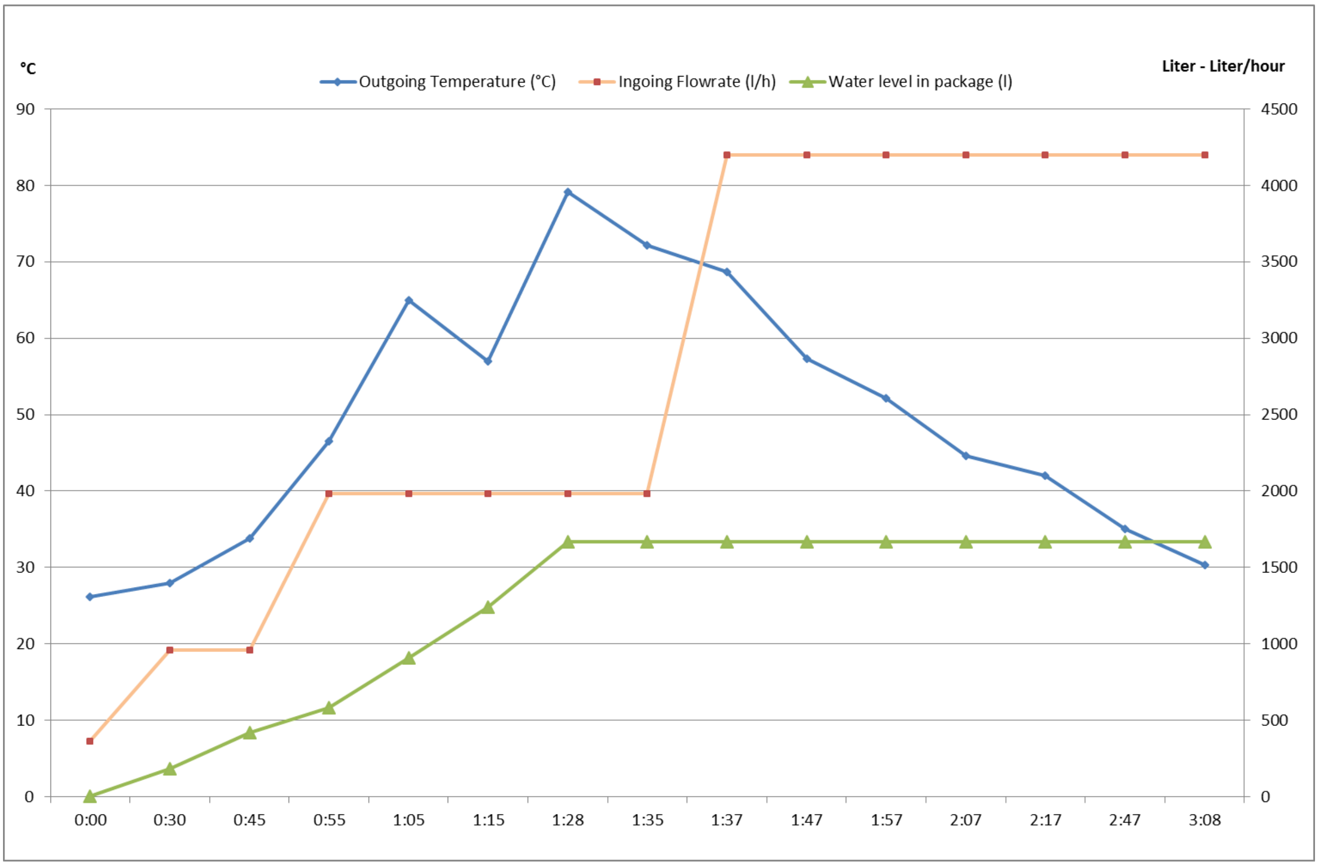

Figure 1 - Critical reflooding parameters example 1

In Figure 1 one can see that the reflooding phase took about 1,5 hours and the cooling phase took about the same amount of time. With ~1700 liters in the package's cavity, this package is rather small. In the beginning the reflooding rate was gradually increased in steps. The increase from 1000 l/h to 2000 l/h resulted in a sudden jump a bit later in outlet temperature (outgoing nitrogen) at 1:15 (a bit later) due to the thermal inertia of the complete system. One can see that the maximum outlet temperature was reached when the package was completely filled up. Afterwards the package was cooled on the inside and outside and the outlet temperature gradually decreased. After 10 minutes of cooling it was decided to accelerate the cooling phase to 4200 l/h. At about 30°C outlet temperature it was decided to place the package in the pool and to unload.

Example 2

For this example the cause or reason for the critical reflooding was a leaking gasket of the primary lid causing a non-conformity with the package approval certificate and storage license therefor issuing the necessity to change the lid and undertake a critical reflooding. The residual spent fuel heat was relatively high and amounted up to 20 kW. The temperature of the incoming clean demineralized water was about room temperature. No pool water was used for the reflooding and no cooling skirt was applied. This was not possible due to the design of the packaging.

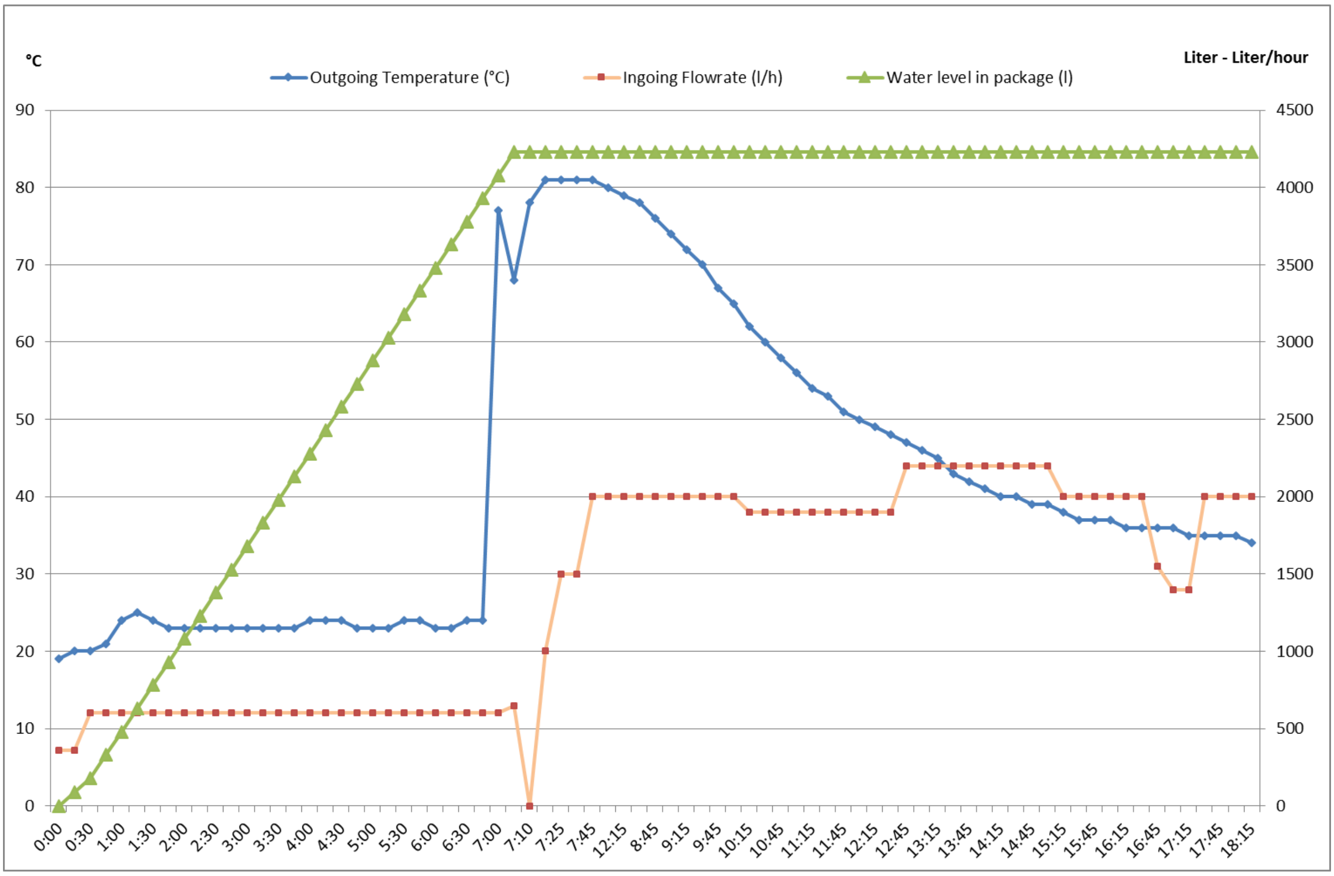

Figure 2 - Critical reflooding parameters example 2

In Figure 2 one can see that the reflooding phase took about 7 hours and the cooling phase took about 11 hours. With ~4200 liters in the package's cavity, this package is rather large. In the beginning the reflooding rate was gradually increased in steps but was then held stable at 600 l/h for the rest of the reflooding phase. The increase from 360 l/h to 600 l/h resulted in a sudden jump in outlet temperature (outgoing helium) at 1:30 (a bit later) due to the thermal inertia of the complete system. It has been noted that the outlet temperature remained relatively stable during the reflooding phase and then makes a sudden jump once the package was completely filled up. This can be explained due to the placement of the temperature sensor. This sensor was placed on the outside of the outlet piping and not inside the piping as it was compared to example 1. Once the hot outlet water arrived at the piping the convection was suddenly increased resulting in a temperature rise of the piping now just seen by the sensor. This maximum temperature then degreased when the cooling phase started. After about 30 minutes of cooling it was decided to accelerate the cooling phase to 2000 l/h. At 34°C outlet temperature, it was decided to place the package in the pool, to re-open the lid and change the lid.

Conclusion

The causes of a critical reflooding have been explained. These are always traced back to a non-conformity either from an operational point of view or a licensing issue. The overall procedure for critical reflooding has been elaborated and the reflooding and the cooling phase were discussed in more detail. The most important risks are presented accompanied by propositions of safety measures to be able to cope with these risks. As an overall result, it is essential to monitor these main parameters during a critical reflooding: cavity pressure, temperature of lid and body, outgoing medium temperature and the water level inside. It is of a critical importance that the outlet of the package remains pressureless and that any steam generation is managed to avoid pressure build ups in the piping or installation. The criticality is an important issue to tackle before the reflooding procedure. If a careful evaluation and verification of the safety analysis report with the designer and constructor does not provide a relief for any potential issues, than a supplementary criticality calculation probably will. A reflooding phase using borated pool water instead of clean demineralized water is always a possibility to increase the safety margin and to reduce the amount of liquid waste generated.

References

[1] IAEA SSR-6 Regulations for the Safe Transport of Radioactive Material 2012 Edition