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Transport and Storage Solutions for Defective Spent Fuel

Pierre Lefebvre
Orano TN, Montigny le Bretonneux, France

Pierre Cavelius
Orano TN, Montigny le Bretonneux, France

Abstract

Fuel assemblies can become **defective fuel** during the irradiation cycle in a reactor or during storage in a cooling pool, for example due to corrosion of the cladding. Two main categories define defective fuel:

- Leaking fuel rods
- Damaged fuel rods

No internationally common definition of" defective fuel" currently exists, but the IAEA has defined a classification on which individual countries make direct decisions depending on the local regulatory requirements, available technologies, and the stage of the fuel cycle, i.e., wet or dry storage, transportation, placement in repository or reprocessing.

In the first part of this presentation, the general definitions, classifications and current approaches for the management of defective spent fuel are presented. Depending on the different criteria to be respected and functions to be fulfilled for the transport and/or the dry storage of defective fuel rods (DFR), the following approaches may be implemented:

- No encapsulation
- "Nuclear material" encapsulation
- "Gas-leak-tight" encapsulation

Orano TN has designed many cask for the transportation of defective fuel assemblies, and specific operations have been implemented for preparing the defective fuel for transport. Interim dry storage of defective fuel assemblies has been implemented for decades in the USA. Specific operations prepare the defective fuel which is then stored, along with intact spent fuel assemblies, in the dry storage system.

Worldwide solutions and approaches for the long-term dry storage of defective fuel, compliant with direct disposal safety requirements, are mostly still in the qualification phase.

Orano TN's technologies and worldwide solutions for the transportation and/or the dry storage of defective fuel are presented in the second part of this paper.

The risk concerning hydrogen generated by radiolysis of residual moisture is of great importance during transportation and/or storage of defective spent fuel. This paper will present Orano TN's current status on specific R&D programs which started 10 years ago to prevent and/or limit this risk.

1. Introduction

Today, nuclear utilities and organizations in charge of back-end issues have to assess their spent fuel assembly management policy for all types of fuel assemblies, including those that are defective. Even when implementing new build projects, the stakeholders are asked by the Safety Authorities to present a comprehensive solution for final management of intact and defective fuel assemblies. The management of defective fuel is therefore becoming a matter of concern for all nuclear operators especially for those who are facing the decommission phase.

In December 2005, the IAEA held a meeting with representatives from the nuclear industry from over 20 countries to discuss the handling of damaged spent fuel. These participants jointly defined the following terms concerning damaged fuel rods, reaching a common worldwide consensus:

- Defect: Any unintended change in the physical as-built condition of the Spent Nuclear Fuel (SNF) with the exception of normal effects of irradiation (e.g. elongation due to irradiation growth or assembly bow). Examples include missing rods, broken or missing grids or grid straps (spacers), springs, etc., and gross structural damage, such as sheared tie rods or a missing top nozzle. SNF having a defect is considered damaged only if it cannot meet its intended safety, regulatory or operational functions.
- Damaged Fuel Assembly (DFA): Assemblies containing fuel rods with known or suspected cladding defects greater than hairline cracks or pinhole leaks. The extent of cladding damage in the fuel assembly is to be limited such that a fuel assembly may be handled with a mast on a fuel bridge or with a fuel handing tool, each with a head assembly that attaches to the top end fitting, and retrievability is assured following normal and off-normal conditions of storage using the same handling methods. Missing fuel rods are allowed.
- Failed Fuel: Ruptured fuel rods, severed fuel rods, loose fuel pellets, or fuel assemblies that cannot be handled with a mast on a fuel bridge or with a fuel handing tool that attaches to the top end fitting. Failed fuel assemblies may contain breached rods, grossly breached rods, and other defects such as missing or partial rods, missing grid spacers, or damaged spacers

to the extent that the assembly cannot be handled by normal means. Fuel debris and fuel rods that have been removed from a fuel assembly and placed in a rod storage basket are also considered as failed fuel.

- Leaking/Breached Fuel Rods (also called gas-leaking fuel): The cladding contains small holes or hairline cracks. No nuclear material can exit the cladding, but gas can be released from the openings of the fuel rod.
- Pinhole Leaks or Hairline Cracks: Minor cladding defects that will not permit significant release of particles matter from the spent fuel rod, and therefore present a minimal concern during fuel handling and retrieval operations.
- Grossly Breached SNF Rod: A subset of breached rods. A breach in spent fuel cladding that is larger than a pinhole leak or a hairline crack. An acceptable measure of a gross breach is the visual exposure of the fuel pellet surface through the breached portion of the cladding.
- Debris: Any fuel rod or assembly material that cannot be retrieved as part of a fuel assembly.

According to the IAEA Nuclear Energy Series (2009) [1], a spent (or used) fuel assembly is categorized as either damaged or defective or not, based on its ability to carry out its designated functions without requiring the fuel assembly to be handled in a non-standard manner. Regarding confinement defects, DFA can be classified into three main categories:

Leaking fuel rod (see Figure 1): The cladding contains small holes or hairline cracks. No nuclear particles can exit the cladding.

Figure 1 Leaking fuel rod

Damaged fuel rod (see Figure 2): The cladding contains larger holes or cracks; the fuel rod is broken or the end plug is missing. Loss of nuclear particles cannot be excluded.

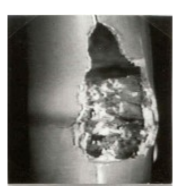

Figure 2 Damaged fuel rod

Fuel debris (see Figure 3): Residual materials containing nuclear fuel, e.g. nuclear pellets, fragments of pellets, or fuel powder.

Figure 3 Fuel debris

2. Damaged fuel management approaches

A specific report was established [1] defining how to manage damaged nuclear fuel. The main approaches for managing damaged spent fuel applied worldwide are as follows:

1. **Waiting solution (temporary storage) in the spent fuel pool**
   When there is no urgent need to evacuate defective fuel, very often the option is to keep them in the spent fuel pool at the Nuclear Power Plant (NPP) while activity is decreasing until the best management solution has been decided. Depending on the safety requirements specific to the site, underwater conditioning can be implemented directly in the spent fuel pool thanks to robust, flexible and qualified canning technologies (see point 4). This has the advantage of ensuring that neither material nor gas will be released uncontrollably in the spent fuel.
2. **Pin replacement**
   Pin replacement can be used if single pins of a fuel assembly are damaged and hence fail to meet the safety functions. Many facilities are able to remove selected pins from fuel assemblies. Replacement of the damaged pins with steel-only pins could render the assembly 'undamaged.' The removed damaged pin can then be managed separately, e.g. reprocessed, kept in the spent fuel pool or stored in pending disposal.
3. **Reprocessing**
   Reprocessing remains the most decisive, least risky way to dispose of defective fuel as this specific type of fuel is replaced by final produced residues stored in the safetiest way in the dry storage facility or geological disposal, residue packages being designed for long-term storage or disposal. Therefore, preparation and/or conditioning operations before transport to the reprocessing plant can be required. One of the alternative methods to avoid any conditioning, such as canning during interim storage before transportation to reprocessing facility, is the use of hydrogen absorbers such as Orano TN's oxide getters (see chapter 4) in the cask cavity which prevent the undesirable build-up of hydrogen and avoids the risk of radiolysis. Orano TN's TN®12, TN®13, TN®17/2 & TN®117 casks have been licensed in various European countries for the transportation of defective fuel rods/assemblies, encapsulated or not, or loaded in quivers, from all around the world to the La Hague plant in France.
4. **Canning/Encapsulation**
   Canning covers a large range of solutions for managing damaged spent fuel during operations and transport. The terminology "canning defective fuel" may include simple cans (which are not sealed) or sealed capsules, quivers, and so on, and may concern also fuel rods as well as fuel assemblies, and subsequently several sizes and designs. Canning can be used for fuel that has difficulty meeting criticality, confinement and operational functions (i.e. retrievability during operations or damage after accident). The can confines the fuel

(e.g. anything from an entire fuel assembly to a few damaged rods) to a known geometry within a storage or transport cask. The sealed-can may include mechanisms to dry the fuel, to reduce radiolytic generation of gases, and may necessitate the evacuation of the residual water prior to sealing.

3. Conditioning, transport & storage approaches

As an alternative or complementary solution to reprocessing, for the management of defective fuel, existing proven and robust solutions (with regard to specific constraints, dry or wet conditions, etc.) can be proposed for short, mid and/or long-term management, depending on customer needs and site requirements, which combine Orano transport or Dual-Purpose Cask (DPC) solutions such as the TN®24 family and getters with different canning technologies (Framatome, Westinghouse and Daher ones) depending on customer needs and/or site specific requirements.

As for transport or storage applications, the main safety difficulties concerning defective fuel are twofold: residual water inside rods that are not leak tight and the feasibility of completely drying the cavity and the potential risk of radioactive material dispersion (also called "fissile material release").

- **Bottles or quivers for fuel assembles leaking material**
  Bottles shown in Figure 4 are used by Orano mainly for domestic transport of gas-leaking fuel rods in France, but only a limited number of defective fuel rods are authorized in one package. A remaining issue is the potential clogging of the filters due to released fissile material powders or fragments.

Figure 4 Orano bottle concept

In the safety justification of such technologies, Orano TN uses the most penalizing assumption for: fissile material release and location, for radiolysis evaluation, and for the amount of free residual water.

An alternative solution to bottles, and much more adapted to long-term storage applications and retrievability function, consists of conditioning several defective rods under water in Westinghouse leak-tight quivers (Figure 5) which are closed at the top with a lid screwed with metal seals. After vacuum drying, the loaded quiver is then put in a basket lodgment of the cask. The quiver can be transported in the same dry shielded cask as a normal fuel assembly.

Figure 5 Westinghouse Quiver (Left: PWR version - Right: BWR version)

In the past few years, NPPs in Sweden and Switzerland have already successfully used the Westinghouse quiver, either for transportation or for storage applications in the pool. Significantly, it has been verified that such quivers can be loaded in combination with undamaged fuel assemblies in an already licensed TN 24®BH package used in Switzerland.

- **Single rod capsule or can**
  To be more flexible in further handling of reconditioned fuel and to be adaptable to the requirements of on-site packaging in a NPP, the single rod encapsulation solution gives more flexibility for each nuclear utility.

This concept is based on placing individual fuel rods separately in gas-tightened capsules consisting of a tube and two end plugs. After being welded together safely, no fission product will be released over time. The capsules provide the first protective shell and ensure safe confinement of radioactive substances and, at the same time, adequate heat removal, as well as radiation shielding. The capsules are specially designed for long-term dry storage using specific durable corrosion-resistant materials. This concept has been deployed for more than ten years for underwater storage and transportation.

The approach consists of:

- Encapsulating each DFR once the fuel rod has been dried, using a qualified process to physically verify with high accuracy the residual water content inside the DFR.
- Closing the capsule with brazed, welded or screwed plugs depending on the storage time and conditions.
- Assembling the capsules in a capsule canister for PWR or BWR versions.
- Transferring it along with intact fuel assemblies in an associated DPC.

The gas-tight closure technologies of a single fuel rod that can be loaded into an Orano TN DPC, are the following:

- A **welded capsule**, developed and licensed by Framatome, that has been qualified and implemented underwater in 2018 during a first encapsulation campaign at the Doel site [2]. In the meantime, Orano TN has obtained an extended license to load such capsules in the TN®24 SH dual purpose cask in France and Belgium.
- A **brazed can,** developed by Daher Nuclear Technologies GmbH, and qualified by the German Safety Authority in 2018. The characteristics of the brazed cans and the encapsulation equipment were presented during the PATRAM conference in 2016 [5].

Figure 6 TN®24 SH DPC

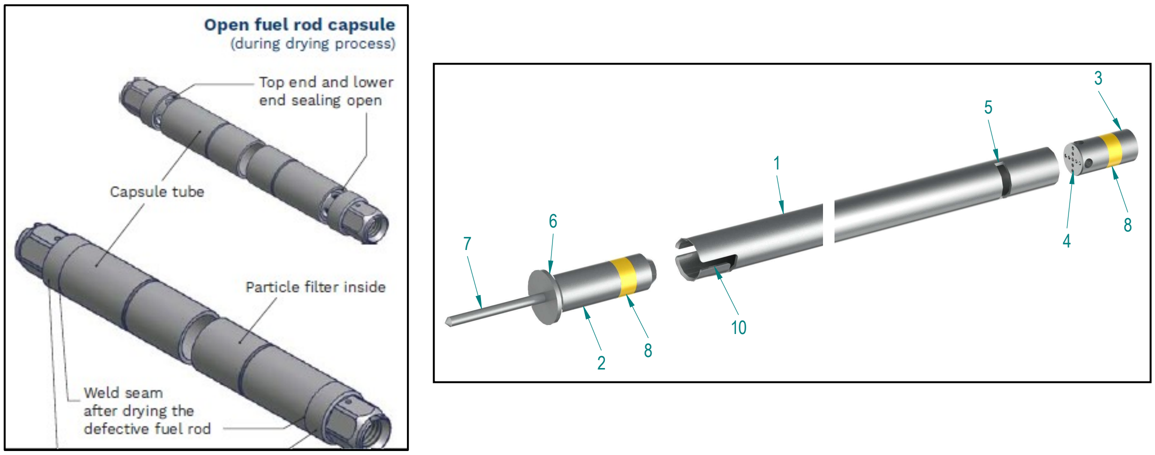

Figure 7 Framatome welded capsule (on the left); Daher brazed can (on the right)

Both canning solutions that can be loaded into Orano TN casks, such as the TN24®DPC family, require the implementation of an encapsulation facility operated in the NPP, either by a mobile set of equipment (rented), or by an investment for a permanent installation of such equipment.

For the different abovementioned canning solutions with varying mechanical resistance in the long term, considering the application of different drying methodologies and effectiveness, Orano TN metallic casks are flexible and robust complying with existing safety margins for the transport and/or the intermediate storage of a mixed content including quivers, cans or bottles and intact fuel assemblies.

- **Others devices and solutions (sealed cans, end caps, etc.)**

  In the USA, historically, damaged used fuel assemblies (ruptured rods, gross breached rods, fuel debris) have been placed directly into adapted cans, according to NRC requirements [6]. For dry storage, these cans for fuel assemblies must be dried and then placed inside a dry cask canister for damaged used fuel.

  Up to 61 damaged fuel assemblies are authorized to be loaded into the Orano TN NUHOMS®-61BTH DSC. The DSC basket cells that store damaged fuel assemblies are provided with top and bottom end caps, as shown in Figure 8, to ensure retrievability. Exelon's Oyster Creek facility was the first site to use the 61BT in 2004 for intermediate storage of damaged fuel assemblies.

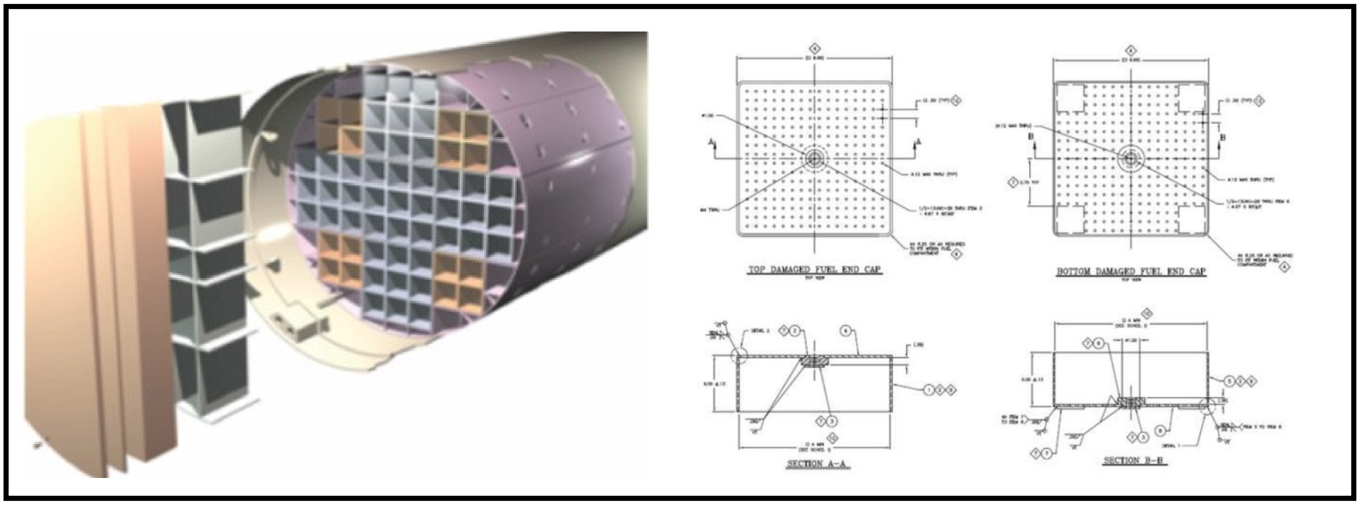

Figure 8 NUHOMS®-61BTH DSC with end caps (Orano TN solution)

As for DFA, up to 4 failed fuel assemblies (fuel that cannot be handled with normal means) can be placed in the dry cask canister. Each failed fuel assembly is to be encapsulated in an individual Failed Fuel Can (FFC) provided with a welded bottom closure and a removable top closure (Figure 9).

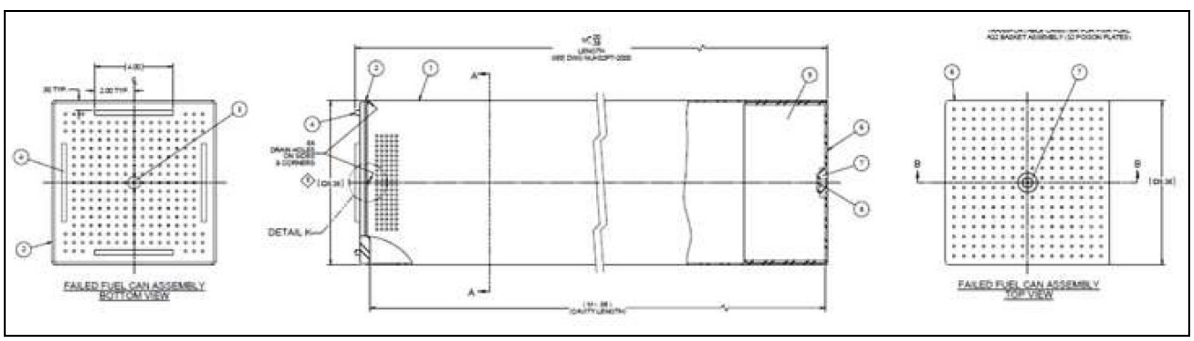

Figure 9 Orano Failed fuel can

Presently, the NUHOMS® Extended Optimized Storage (EOS) basket can accommodate up to 8 damaged assemblies in combination with other intact fuel, or 4 failed plus other intact fuel assemblies. In addition, smaller dry cask canisters with lower heat loads can fit up to 16 DFA.

4. Radiolysis risk management

The main risk when transporting and/or storing damaged and/or failed used fuel, conditioned or not, for a temporary or long-term period, is linked to the H_2 concentration build-up inside the cavity due to the gas generation from water decomposition.

An evaluation/mitigation of hydrogen generation in transportation packages is necessary to ensure that a flammable mixture will not be formed and to verify that packages do not accumulate an unsafe concentration of hydrogen (lower flammable limit (LFL) for $H_2 < 4\%$ vol. at room temperature in air).

From the storage pool at the reactor, used fuel is conditioned, and prior to transportation, a drying operation is carried out to ensure that the minimal dryness criterion is met; then the cavity is backfilled with inert gas. However, such drying technologies may not be sufficient enough in regard to the site and time constraints for the long-term storage of leaking rods in a storage cask cavity.

In that sense, to prevent/limit/manage this risk and reduce the significant time dedicated to drying operations as much as possible, Orano TN and the CEA have developed specific getters, used to trap hydrogen through chemisorption [7]. They are compatible with the trapping of hydrogen released by radiolysis of residual water for used fuel and radiolysis or thermolysis of polymers, and they are efficient in multiple gaseous environments, even in the event of a lack of oxygen. This solution offers great versatility as it is compact, **suitable for encapsulated or not DFR** , suitable for low volumes and can be used for dry/wet transport and interim storage, even in extreme temperature conditions (+450°C). It can be conditioned in a wide range of packages to bring a cost-effective answer to safety issues (i.e. flammability concerns).

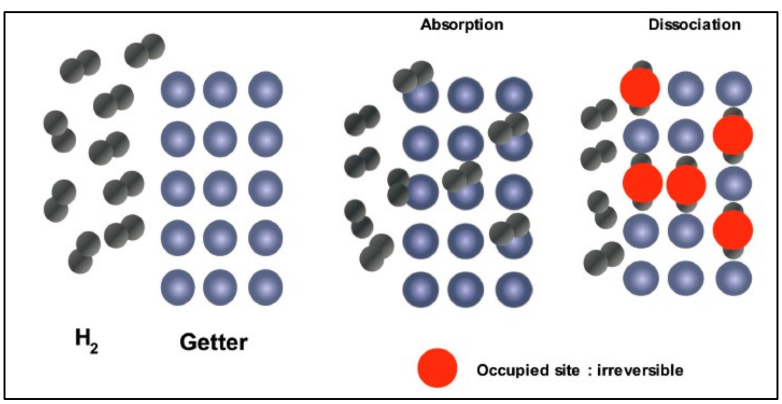

Figure 10 Mechanism of H2 absorption

The Getter solution is already available and can be applied in Orano TN transport and/or DPCs solutions, along with associated services such as design, licensing support, and maintenance.

5. Conclusions

The range of available Orano TN options for managing defective fuel rods or assemblies includes:

- Treatment of fuel rods as if they were undamaged with eventually specific restrictions.
- Use of specific intermediate capsules/cans that allow damaged fuel rods to be reassembled. as a “dummy” fuel assembly after drying and placed into a storage or transport dry cask, as for undamaged used fuel.
- Use of specific intermediate bottles or quivers that allow several defective fuel rods from damaged used fuel assemblies to be placed after drying into a transport dry storage cask that could then be handled as if it contained undamaged used fuel facilitating the retrievability of the fuel.
- Adoption of a completely different strategy, e.g. fuel assembly reprocessing.

By combining Orano TN flexible and robust casks and getters with robust canning solutions for damaged fuel rods proposed by specialized companies (Framatome, Westinghouse and Daher), a myriad of possible scenarios for transportation or short, mid and/or long-term storage applications can be adapted and implemented to customer needs and to the requirements of the Competent Safety Authority.

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