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Packaging Strategies to Ensure Safe and Reliable Intermediate and Final Storage of Damaged Irradiated Nuclear Fuel

*Anna. Wikmark**

[*] Studsvik Nuclear AB, Nyköping, Sweden

Abstract

Despite today's increasingly more reliable operation of nuclear power plants, damaged fuel rods exist in many nuclear power plants. Managing preparations for disposal or intermediate storage of such rods has been a growing problem. For instance, most of the dry storage systems for used irradiated nuclear fuel do not allow storage of damaged fuel rods together with intact fuel. Also final repositories have limitations on presence of moisture, which present difficulties in accepting failed or broken fuel rods. Consequently, more data is required to enable both intermediate and final disposal of damaged irradiated fuel. Transport solutions, as well as intermediate storage solutions, for damaged fuel also have to be developed to fulfil national and international expectations.

Investigations in a hot-cell laboratory, with methods for mechanical testing and advanced microscopy together with its inherent knowledge of materials integrity, fuel reliability and activity build-up, is an important vehicle to deliver the necessary data to ensure a safe and reliable intermediate and final storage of damaged spent fuel. It is, however, then also necessary that damaged fuel stored a long time in pond is available for the investigations. Safe and efficient handling of the package at the plant and the hot-cell laboratory as well as safe transportation are crucial elements. A hot-cell can also develop methods for conditioning of damaged fuel for acceptance in available intermediate and final storages for non-failed fuel. To perform the necessary investigations or conditioning, it is hence a key to transport the damaged fuel to the hot-cell and to have ability to manage the disposal of the fuel after examination in a manner suitable to national and international requirements.

The transport of damaged fuel requires packages designed and licensed for this kind of material. The packages that brings irradiated fuel to a hot-cell for examination does not take larger quantities and can only be used for bringing material for investigation. Even so, it is currently very few packages able to transport damaged fuel rods of any quantity .The packages for loading spent fuel in a nuclear power plant are too heavy and bulky for most hot-cells.

The Studsvik strategy to enable a solution for future storage of damaged spent fuel hence includes

- Update/upgrade of the PDSR prolonging the life of existing older B(U)F packages
- Investment in a new package, NCS 45, certified to transport damaged fuel
- Preparations for a new pool facility with functional requirements enabling also the reception of the nuclear power plant spent fuel packages

1. Introduction

The behaviour of spent nuclear fuel during intermediate and final storage has been subject to studies for many years. Intermediate storage in wet or dry conditions is used in various countries[1] and is necessary, while options for final disposal are currently developed. To maintain safe storage and allow for safe retrieval and disposal of the fuel, no significant degradation of the fuel cladding or fuel assembly should occur during intermediate storage. Extended storage times are today considered, up to 300 years, emphasizing the importance of cladding integrity. Therefore all potential fuel degradation mechanisms need to be considered when evaluating the safety of long term storage. Fuel rods that have failed during operation are of special concern. In cases with an open cladding failure, any air or moisture ingress into a dry storage container can give rise to fuel pellet oxidation at the failure. Regulations consequently typically do not accept fuel rods with large open failures for dry storage and such fuel should be safely encapsulated before being stored. Fuel rods with small cladding failures, such as small pin-hole failures, can be accepted for dry storage without encapsulation. However, such fuel rods can also have residual internal moisture and the vacuum-drying is most generally not sufficient to remove the remaining moisture. Any remaining moisture can result in fuel and cladding oxidation during storage at elevated temperature and since the oxidation of irradiated fuel is associated with a volume increase and disintegration of the fuel, the failure may potentially open and promote crack propagation. In addition, moisture reaction with cladding will affect the cladding and produce hydrogen.

Studsvik Nuclear, in the following called Studsvik, has 60 years of experience on fuel examination with a wide range of methods, enabling reliable determination of the fuel and cladding condition. In addition to that, Studsvik has an already established and approved procedure to send cut pieces of irradiated fuel to the Swedish intermediate storage, CLAB, after investigation. The Studsvik hot-cell and mechanical testing laboratories have also been involved in work related to fuel storage issues for a long time. However, so far no studies have been made on residual moisture for different degrees of failure, or methods for drying or the drying efficiency. A research program with this purpose is on-going at Studsvik. Damaged fuel rods from one of the Swedish NPPs which have been stored for a long time in the fuel storage pool at the nuclear plant will be shipped to the Studsvik hot-cell.

The Studsvik Materials Technology Department is already today transporting failed fuel to its hot cells for PIE (Post Irradiation Examination) and has a number of packages for both irradiated fuel and core components. Extensive work to update the Package Design Safety Reports also for older packages has been on-going for a number of years with the purpose of enabling maximum flexibility for failed fuel rod shipments.

2. Transportation and Reception

The planning and performance of a shipment of failed fuel, especially fuel with large open failures is demanding. Not many packages are licensed to transport reasonable quantities of failed fuel. The NCS 45 (licensed according to the most modern B(U)F-96 regulations) package, of which Studsvik has one, can transport a certain amount of failed fuel rods without encapsulation and has in addition to that an encapsulation procedure for pool encapsulation in its license. Encapsulation of the fuel in the nuclear power plant enables a safe transport but might challenge the radiological safety of the personnel in the power plant when it comes to handling of larger quantities of failed fuel rods.

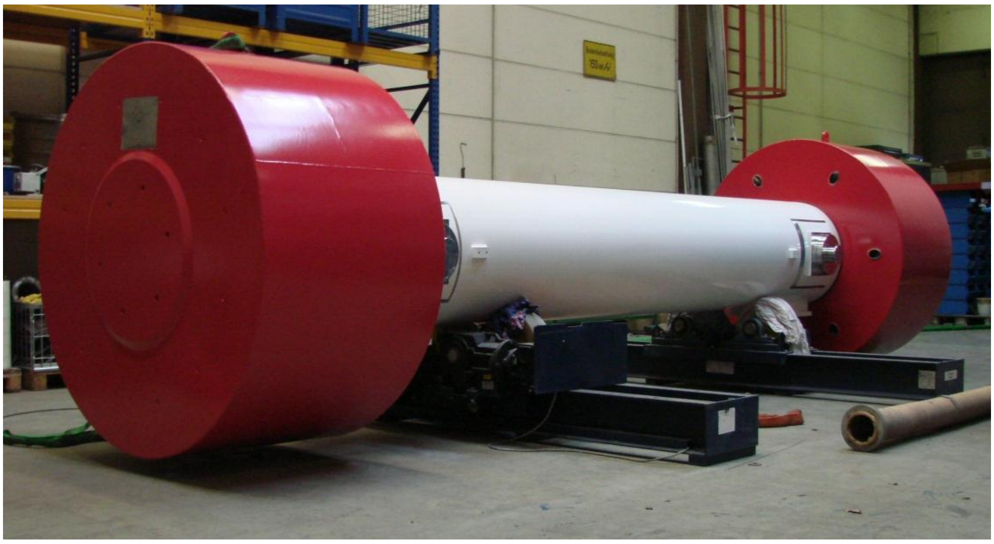

Figure 1
The Studsvik NCS 45 package

All leakage from failed fuel of fission products with long half-lives and transuranium elements in a nuclear power plant gives unnecessary radiological doses to the personnel, risks with distribution of alpha contamination in systems and facilities, increased volumes of waste with long half-lives and transuranium elements, as well as an increased need of protection measures, personal protection equipment and cleaning. Handling of damaged fuel should thus be reduced to a minimum. Transports under *special arrangement*, optimising ALARA (As Low As Reasonably Achievable) for the whole process of dealing with the failed fuel, from the removal from core to the final disposal, is recommended in some cases. Studsvik is maintaining an older B(U)F package, designed to take available failed fuel baskets in the fuel storage pool. Continued operation of B(U)F packages licenced according to older regulations requires a maintained and upgraded package design safety report according to the latest regulations, even for transports under special arrangements.. Calculations according to the latest methods could be necessary to validate older assessments.

Figure 2
The Studsvik 29- tons package

Another alternative is to use nuclear power plant spent fuel packages designed to transport larger quantities of fuel. The Studsvik hot-cell and mechanical testing laboratories can already today handle most of the packages on the market intended for shipment of irradiated nuclear fuel to a hot-cell. Together with the existing pool facility in Studsvik, also wet loading and unloading is an option. However, nor the laboratories or this existing pool facility has the capacity to take the weight of the nuclear power plant spent fuel packages. Since the handling and loading of these packages are already implemented and approved at most nuclear power plants, the alternative to use them also for the shipment to a hot cell would enable an easier solution for the failed fuel issue. Larger quantities of failed fuel could be loaded, shipped to Studsvik for characterisation and conditioning. A very valuable spin-off will be that the fuel can be repacked for intermediate or final storage in the same cask. Studsvik is preparing for a new pool facility[2] with functional requirements enabling also the reception these packages. This will also make it possible to load fuel, directly after treatment, in packages for dry intermediate storage instead of sending it back to the nuclear power plant for cumbersome shuffling and reloading.

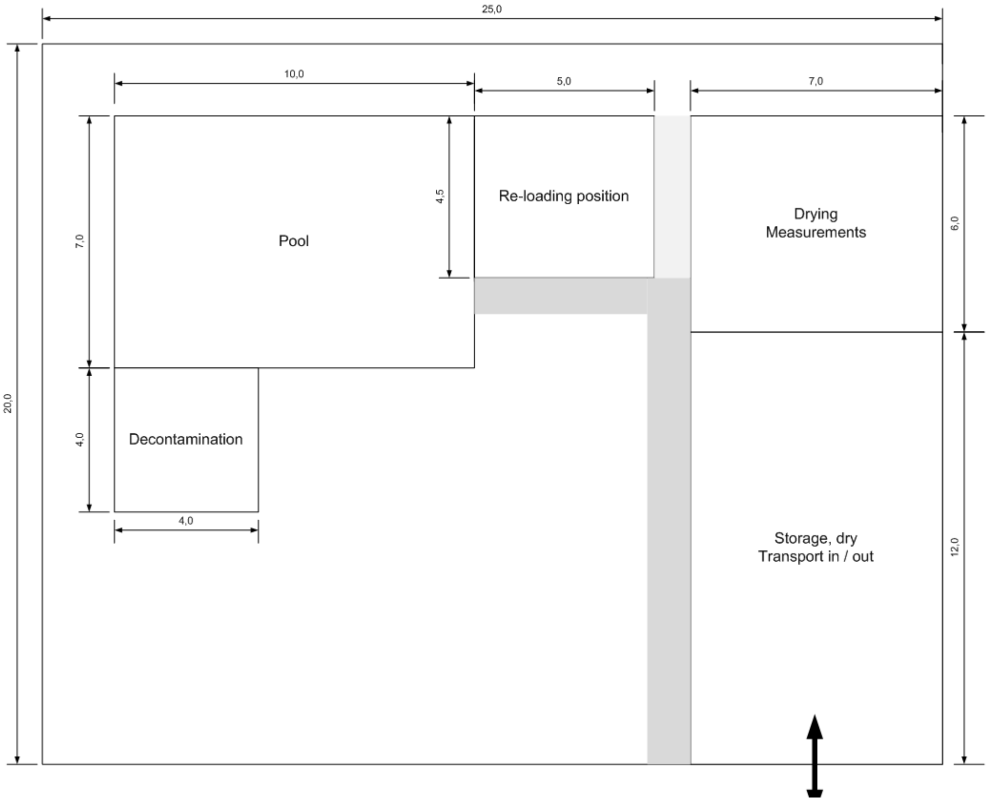

Figure 3
The Studsvik project for a new pool facility for large and heavy casks

3. Characterisation[3]

Cladding Creep. The cladding material creeps under internal stress at elevated temperature. In the dry storage safety evaluation it should be ensured that the cladding has no risk of failure by creep for the storage period. At Studsvik, creep measurements are performed at actual temperature and pressure on defueled and refabricated cladding specimens cut from irradiated fuel rods.

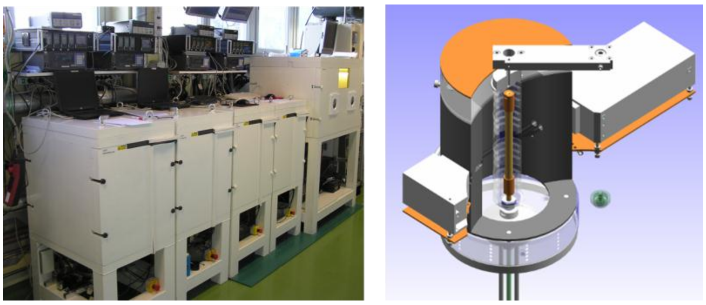

Figure 4
Creep cells in the mechanical testing laboratory (left), a cut-away drawing of a furnace with a mounted cladding specimen (right).

Hydride embrittlement. Hydrides lower the ductility of the cladding and this is more pronounced with radially oriented hydrides. As the temperature decreases over time in a dry storage cask (the temperature drops from about 350°C to 150°C over tens of years of dry storage) dissolved hydrogen will precipitate forming hydrides in addition to hydrides already present. Together with lost ductility, Delayed Hydride Cracking (DHC) could be a potential mechanism for rod failure. Studsvik simulates the production of radial hydrides in dry storage situations and have a number of methods to determine the ductility of the cladding. There is also a test technique present to quantify the critical parameters for DHC.

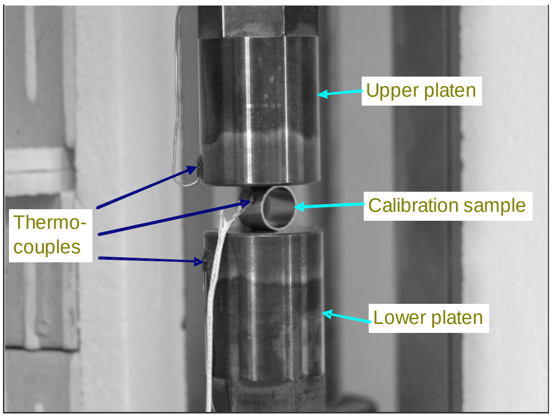

Figure 5
Calibration set-up for ring compression testing, a test method to determine the ductility of the cladding.

Oxidation, swelling and fragmentation. Any moisture in a dry storage cask during storage, either from ingress into the cask or from residual moisture inside the fuel rods with small cladding failures, can potentially generate hydrogen through radiolysis. The hydrogen could be picked up by the cladding and hence add to existing cladding hydride contents. Remaining moisture will result in fuel oxidation and associated volume increase and disintegration during storage at elevated temperature. To avoid any risk of such a scenario failed fuel needs to be treated by a drying procedure and encapsulated such that the moisture content is controlled within acceptable limits. A research program with this purpose is also planned at Studsvik. A furnace has recently been installed in the Studsvik hot-cell to study oxidation, drying and fragmentation of fuel rod samples.

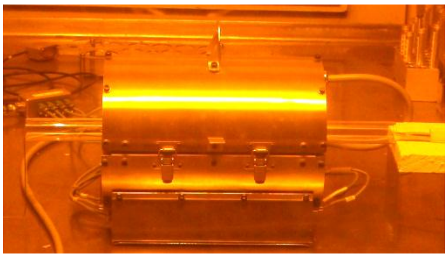

Figure 6
The furnace used for oxidation, drying and fuel annealing studies

Transport and handling accidents. In case the storage cask is dropped the fuel rods would be subject to bending between the spacer grids. Bending test equipment is available in the Studsvik hot-cell and the tests are made on irradiated fuel rods with fuel pellets inside to represent the actual situation.

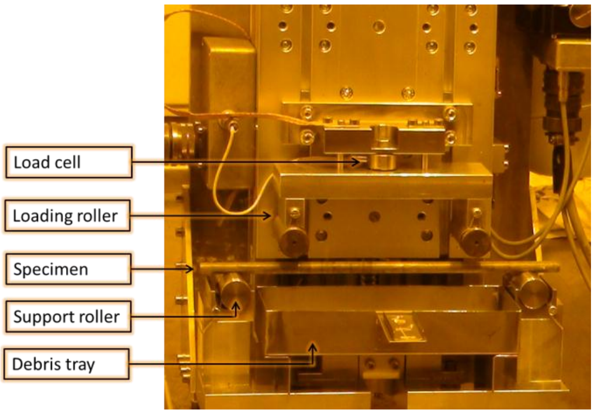

Figure 7
The 4-point bending machine in the hot-cell.

4. Treatment – method development and performance

Methods to dry and encapsulate damaged fuel rods can be developed and evaluated with the planned research program in the Studsvik hot-cell. Vacuum drying efficiency or heat treatment as a function of time, and also other methods, can be tested and evaluated with sensitive moisture measurements in combination with simulation of dry storage conditions.

In addition to the program for development of an efficient and reliable drying method a concept idea has been developed at Studsvik for a new pool facility with functional requirements enabling also the reception of nuclear power plant spent fuel packages, as mentioned above. These packages are in weight ranges up to 150 tons and are designed to transport much larger quantities of fuel than packages that normally bring fuel to a hot-cell for PIE. This would allow also treatment of damaged fuel elements, which could include drying and encapsulation. After treatment and verification, the fuel can be loaded and sent back directly to the intermediate storage facility of the concerned nuclear power plant, instead of back to the fuel storage pool. In the case of dry intermediate storage this possibility would also allow loading of several fuel elements together in one dry storage cask in Studsvik. Since most of the dry storage systems for used irradiated nuclear fuel do not allow storage of damaged fuel rods together with intact fuel, this opportunity will reduce the number of required dry storage casks and hence minimise the required storage volume and the costs for casks. Wet intermediate storage, like in Sweden, has the same risk with storage of damaged fuel as in the nuclear power plant fuel storage pool and has limitations in acceptance of damaged fuel. Encapsulation is today necessary to allow further storage according to regulations in most countries.

5. Recent experience

The NCS 45 cask has a license for shipment of larger amount of encapsulated fuel rods. However, with the NCS 45 encapsulation equipment, Studsvik has experienced the difficulties a nuclear power plant is facing when it comes to implementation and performance of fuel rod encapsulation in its pool. In the on-going Swedish research program, with the purpose to stydy damaged fuel rods which have been stored for a long time in the fuel storage pool,this difficulties were challenging. Many fuel rods were so damaged that extensive handling in the fuel storage pool would imply a high radiological risk. Alternatives to encapsulation have consequently been developed. This includes transportations with older packages or packages not licensed for the transportation of failed fuel. To enable such shipments also the authorities plays an important role in setting up the conditions for a transport under special arrangement.

6. Summary and Conclusions

Interim storage of spent nuclear fuel is widely utilized and is in many countries the preferred solution for the foreseeable future while developing or designing final disposal facilities. The behaviour of the fuel under storage and the criteria for safe storage are established for existing licensed facilities. However, the expected storage times and the requirements on transportability and retrievability after storage have increased. New fuel materials and designs also continue to be developed and utilized to higher burn-ups. These developments require new tests and examinations to be performed to verify that the spent fuel can be stored safely without any risk for fuel degradation.

New tests and examinations require shipments of failed fuel to a hot-cell and a shipment is dependent on the availability of packages licensed for the content. With the competence in transportation, hot-cell reception and PIE, Studsvik is actively working to deliver turn-key solutions and the ability to transport has turned out to be a most crucial parameter for a successful result. It is clear that the packaging and transportation alternatives have to be developed further to keep up with more demanding regulations regarding failed fuel transportations.

7. References

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, “Long Term Storage of Spent Nuclear Fuel — Survey and Recommendations”, IAEA-TECDOC-1293, IAEA, Vienna (2002).

[2] Per Lidar, ndcon Nuclear Decomissioning Consortium formed by Studsvik & Westinghouse

[3] J K.-H. Karlsson A-M. Alvarez-Holston, “Post-Irradiation Examinations for Resolving Fuel Issues in Long Term Storage.“, OECD/NEA International workshop on Safety of long term interim storage facilities, Munich 20-13 May, 2013