Nuclear Plant Shutdown: a Challenge for the Competent Authority

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In Sweden in recent years, it has been decided that certain old reactors will be shut down in the near future. To enable the nuclear power plants to enter decommissioning, all nuclear fuel and other nuclear materials must first be removed from the plant. Nuclear materials include damaged nuclear fuel from BWR and PWR, as well as used nuclear core detectors containing far less than gram quantities of U-235.

Depending on the type of damage etc., there are two methods for encapsulation for intermediate storage at SKB's Clab facility and for later final storage: the "Westinghouse Quiver method" adapted for final storage, and the "Studsvik method", where encapsulation takes place at the Studsvik site before further transportation to final handling. In addition, logistical differences regarding the types of transport packages that can be handled by both consignor and consignee also necessitate different solutions for safe transportation within the terms of transport regulations.

The below are solutions approved by the Swedish Radiation Safety Authority, the competent authority in Sweden for shipments of radioactive materials regardless of the mode of transport:

- Using “Quivers” as a method to encapsulate damaged fuel on site to replace the function of the cladding. The quivers can therefore be implemented for use in new revisions of package designs already used for shipments of irradiated fuel. Likewise if necessary, for Special Arrangement Transport.
- Regarding the “Studsvik method”, a package design specially made for damaged nuclear fuel may be used. This method is preferable for severely damaged nuclear fuel. However, since this solution cannot be used for one of the Swedish NPPs, Special Arrangement Transport using an old package design had to be used for a few transports, e.g. to prevent static and kinetic energy buildup during shipment.
- In order to transport used core detectors (containing U-235) in a package designed for non-fissile internal parts together on the same marine vessel with (fissile) packages containing spent fuel (thus “excepted fissile” cannot be used), the use of exception 6.4.11.2 (b) per the IMDG Code 2018 edition was implemented in the new revision of the package design certificate (total CSI less than 10).

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Swedish Nuclear Power Plant Shutdown

In Sweden in recent years, it has been decided that certain old reactors will be shut down in the near future. Sweden once had 12 nuclear power reactors located at four sites, where one site having two reactors already entered decommissioning about three years ago. The new shutdown plans concern four Swedish reactors, at two different nuclear sites, that will be shut down and enter decommissioning. A prerequisite for allowing the nuclear power plants (reactors) to enter the decommissioning phase is to first have all the nuclear fuel and other nuclear materials removed from the plant. This nuclear fuel includes damaged nuclear fuel. The “other nuclear materials” include used nuclear core detectors containing very small quantities of uranium-235 (U-235), so the total amount within a shipment will at the most be measured in gram quantities. If the above-mentioned nuclear materials cannot be removed from the plants, the reactor plants will be required to remain in the shutdown state and cannot proceed to the decommissioning phase. Because of this, the transports, as well as the methods for encapsulation of the damaged nuclear fuel, are both attributed very high priority: not only for the owners of the nuclear facilities where these reactors are located, but also on the part of Sweden from a national perspective. Since many of the necessary transports can be considered as “one of a kind”, as well as an important part of decommissioning, they may represent a challenge for the competent authority. In Sweden, the competent authority as far as concerns transport of radioactive materials (class 7), regardless of the mode of transportation, is the Swedish Radiation Safety Authority.

Encapsulation and Transport Methods for Damaged Nuclear Fuel

Damaged nuclear fuel comes from BWR (Boiling Water Reactors) as well as PWR (Pressure Water Reactors). There are two Swedish methods chosen for taking care of nuclear fuel with damaged cladding. These methods are mainly intended to replace the encapsulation function of the cladding during intermediate storage at SKB's Clab facility, as well as for later final disposal. The two Swedish methods for encapsulation are the "Quiver method", developed by Westinghouse, which is adapted for intermediate storage and final disposal, and the "Studsvik method", where encapsulation first takes place at the Studsvik site before any further transport to intermediate storage, and once again later to the final disposal facility. In addition, logistical differences regarding the types of transport packages that can be handled by both consignors (the shut down reactors) and consignees (Studsvik facility or storage facilities) necessitate different solutions for safe transportation within the terms of the transport regulations.

Using Quivers for Encapsulation

Using "Quivers" is a method to encapsulate damaged fuel on site to replace the function of the cladding. Quivers have the external form and dimensions of a nuclear fuel bundle, as used in the reactor. The quivers can therefore be implemented for use in a new revision of the certificate for package design approval, regarding the transport packaging already used for shipments of irradiated fuel, or if needed, for a Special Arrangement Transport. In a few years, a new transport packaging is planned to replace the old transport packaging now being used for shipping irradiated fuel in the Swedish transport system. In other words, both package designs will be used in parallel over a few years. From a transport point of view, the same methods for transport can mainly be used for the new transport package design. The Quiver method will continue to be used for damaged nuclear fuel from seven Swedish reactors, BWR as well as PWR.

Encapsulation at the Studsvik Site

Regarding severely damaged fuel, the "Studsvik method" is preferable. In addition, if the nuclear plant cannot for any other reason use the new Quiver method mentioned above, the Studsvik method has to be used. For reactors where the Studsvik method is the best solution, a package design tailored for damaged nuclear fuel may be used for shipments from the reactor to the Studsvik site. However, since this transport solution could not be used for one of the Swedish NPPs that had damaged nuclear fuel on site (requiring treatment using the Studsvik method), Special Arrangement Transport using an old packaging was applied to a few shipments. The mentioned packaging was formerly a package design intended for transporting damaged nuclear fuel as a B(U)F package.

Special Arrangement Transports

In the case of Special Arrangement Transport, the shipment must fulfill two key conditions: 1) the transport needs to be justified, and 2) compensatory arrangements must be in place ensuring equivalent transport safety; or preferably, at a higher level of safety than compared with using a standard method with a UN number other than "UN 3331" for the shipments.

Justification for shipping as Special Arrangement Transport

Any delay in shipping the damaged fuel prevents the reactors from entering the decommissioning phase. This aspect is also a matter of national interests. The transports usually regard final shipments that need to be made from facilities intended to enter into decommissioning. For this reason, it cannot be considered justifiable to rebuild the facilities, or to develop a system or new package designs, as would be the case involving a newly built nuclear power plant intended to be used many years into the future.

Compensatory Arrangements regarding Special Arrangement Transport

Put briefly, the aim of compensatory arrangements in this situation can be expressed as the two main conditions shown below:

1. The packages are required to be as leak tight as any other shipment containing irradiated nuclear fuel without damaged fuel cladding.

2. If the package design intended to be used for shipping the temporary load is deemed to have any risk of failing the fall or puncture tests, etc., prevention must be ensured in the form of compensatory arrangements. This is for example intended to prevent static energy buildup and high kinetic energy during shipment.

In other words, in a case of a compensatory arrangement when using the old package design mentioned above, for the prevention of static energy buildup and high kinetic energy during shipment, the main rationale was that the shipments were performed exclusively by the special-purpose Swedish INF vessel ordinarily used for transports of irradiated nuclear fuel. An additional factor was that the brief duration of road transport, from the plant to the harbor, was performed very slowly using a purpose-built vehicle as well as escorted by guards. Here, the rationale was that the package design was considered inappropriate and incapable of withstanding the applicable test requirements taken altogether, when simulated using modern software. However, individually, the test requirements were no problem to fulfill.

When it comes to shipments of damaged nuclear fuel, it is largely a complex matter for a competent authority, involving evaluations of all shipments in terms of identifying the best solution within the parameters of the transport regulations, in addition to the means at hand. The shipments are required to comply with the modal regulations, road transports (from the site to the harbor, and vice versa) covered by the ADR regulations used on the European continent, and marine transports covered by the IMDG Code.

Transport of Used Nuclear Core Neutron Detectors

In the case of used nuclear core neutron detectors containing very small quantities of U-235, the situation is rather different. The intended packaging for shipments of these detectors is a packaging designed for transporting non-fissile internal reactor parts, a package of type B, referred to as the TN17/CC [approved design as B(M)-96]. In addition, the mode of transportation is by sea using the Swedish vessel mentioned above for marine transports of irradiated spent nuclear fuel. The above-mentioned transport packaging is a similar version of the transport packaging used for spent fuel, though without having any cooling fins or neutron shielding built in.

Shipping as Excepted Fissile Materials

In order to transport used core detectors in a package designed for non-fissile material, there is a possibility to have them shipped as excepted fissile. The best exception alternative for this situation would be according to the alternative "(e)" of paragraph 417, regarding excepted fissile materials as per Regulations for the Safe Transport of Radioactive Material, SSR-6 (and corresponding regulations in the ADR and IMDG Code). The alternative "e)" as per SSR-6 allows up to 45 grams of U-235 contained in a package, as well as for the total amount shipped under exclusive use.

Shipping Used Core Neutron Detectors together with Spent Nuclear Fuel

The best option is to have the package containing the used core detectors shipped together with packages containing spent nuclear fuel on board the same marine INF vessel. However, it is not allowed to ship excepted fissile materials together with regular fissile materials, implying shipping of only one package on board an INF vessel.

Is there any possibility to have the intended type B package containing the core detectors shipped together with the regular packages containing spent irradiated fuel? (However, shipping the core detectors in the same B(U)F package as irradiated fuel is not a good solution.)Yes, there actually is a possibility in compliance with the transport regulations to have the core detectors shipped together on board the same marine vessel being used to ship packages containing spent fuel.

The solution is to apply the exceptions for transport of fissile materials according to paragraph 674 (b) as per the IAEA Regulations for the Safe Transport of Radioactive Material, SSR-6, which correspond to exception 6.4.11.2 (b) as per the IMDG Code, 2018 edition (also as per the ADR regulations covering road transport).

Conditions

Important conditions, e.g. from the transport regulations as well as regarding the certificate for approval of the package design:

- 674 (d) of SSR-6: “the total mass of beryllium, hydrogenous material enriched in deuterium, graphite and other allotropic forms of carbon in an individual package except where the total concentration of these materials does not exceed 1 g in any 1000 g of material. Beryllium incorporated in copper alloys up to 4% by weight of the alloy does not need to be considered.”
- Since the packaging intended is a 67 ton steel container used as a package of type B, it is very likely to preserve the dimensions to a minimum of 30 cm and to prevent the entry of a 10 cm cube, etc. (It is irrelevant in this paper to further discuss conditions that are clearly considered by design. However, these conditions are nevertheless taken into account.)
- The CSI (Criticality Safety Index) for each package in the shipment is required to be below 10. (Since the regular package design used for shipments of spent fuel has a CSI equal to zero, the total CSI for the shipment depends solely on the package containing the used core detectors.)
- The CSI for the package is to be calculated as mentioned in 674 (b) (iii) of SSR-6:

  CSI = 50 x 2 x {[mass of U-235 in package (g)]/Z* + [mass of other fissile nuclides** in package (g)]/280}

  *Z = 450, since the uranium in the detectors is enriched > 20%

  **Plutonium may be any isotopic composition provided that the amount of plutonium-241 is less than that of plutonium-240 in the package.

- To prevent neutron radiation from the package, internal and modulated neutron shielding must be used. (The type B packaging has no neutron shielding built in by design.)
- The core detectors are a new kind of radioactive material that needs to be implemented and approved in the certificate for approval of the package design. (Since the package is of type B, it must be approved by the competent authority in the country of origin.)

Advantages

Implementing the exceptions as per paragraph 674 (b) of SSR-6, and conditions thereof in a new revision of the certificate of package design approval regarding the transport packaging TN17/CC, implies some advantages compared to shipping as fissile excepted as per paragraph 417 (e) of SSR-6.

There were also some benefits for the Swedish competent authority regarding the implementation itself, e.g. that the package design has a Swedish origin certificate:

- The core neutron detectors can be shipped together with packages containing spent fuel on board the marine vessel, which saves a great deal of time and resources.
- The core neutron detectors can be shipped safely in compliance with the regulations governing transport of dangerous goods as far as concerns radioactive materials (class 7), without using a Special Arrangement Transport.
- When applying exception 674 (b) as per SSR-6, the small amount of fissile material must be declared as “Fissile”; however, there is still the option of using a type B package designed for non-fissile material, as otherwise when being shipped as “Excepted Fissile”.

- Since the regular package design used for shipping spent fuel has a CSI equal to zero, the total CSI for the shipment will solely depend on the package containing the used core neutron detectors.
- From the mathematical equation above, and at a maximum CSI = 10, it is straightforward to determine that core detectors can be shipped with the total amount of U-235 up to nearly 45 g, similar to being shipped as excepted fissile according to alternative 417 e) as per SSR-6, as mentioned above. (The amount of other fissile nuclides is much smaller than the amount of U-235.)
- The country of origin in terms of the certificate regarding approval of the TN17/CC package design is Sweden, which makes it rather straightforward to approve and implement the new material (core neutron detectors containing small amounts of U-235), as well as application of the 674 (b) SSR-6 exception in a new revision of the certificate of approval of the package design.

Conclusions

Damaged nuclear fuel from Swedish nuclear power plants may be taken care of by either using the Quiver method or the Studsvik method. By e.g. using Special Arrangement Transport, all shipments can be performed safely on board the Swedish Marine INF Vessel MS Sigrid.

By applying the exception as per paragraph 674 (b) as per the IAEA Regulations for the Safe Transport of Radioactive Material, SSR-6, shipping used core neutron detectors containing small amounts of U-235 together with packages containing spent nuclear fuel on board MS Sigrid is made possible.