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Licensing U.K's First Multiple Water Barrier Package

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Abstract

The U.K Government has a strategic objective to consolidate fissile materials onto a single site. Inventory includes unused and spent Fast Reactor fuel and an assortment of fissile material from mainly UK nuclear establishments. The nuclear material was originally destined for reprocessing; the material had been put into short term storage in the 1980s/90, however following the closure of certain facilities in the 2000s a longer term storage solution was required.

Difficulty inspecting the materials together with decades in storage had raised questions over the integrity of components (including mixed oxide fuel pins and mixed carbide sub-assemblies) following a decision not to re-package the materials for transport or leave in further longer term storage at the original site. It was decided a High Standard Multiple Water Barrier (MWB) Package will be required for the transport of the material to the new site.

To enable the transport of high quantities of the radioactive materials with adequate margins of sub-criticality, it was necessary to demonstrate the exclusion of water from the proximity of the contents under all conditions of transport. International Nuclear Services proposed enhancing the design of an existing flask, the M4/12 into a High Quality MWB transport package.

International Nuclear Services' package justification was based on the M4/12 transport package providing the first line of protection with a newly designed inner container dubbed the Un-irradiated Fuel Container (UFC) providing the second water barrier.

This newly designed UFC coupled with the M4/12 was approved by the Office for Nuclear Regulation (ONR) for use as U.K's first High MWB package for transport under Special Arrangement.

The paper will set out the process and approach that was taken by International Nuclear Services (INS) during recent application to the ONR the UK safety regulator for the civil nuclear industry, for the package approval. This paper will include details on the key aspects of the licensing process used, interpretation of the transport regulations, the difficulties encountered, how they were overcome and ultimately how INS achieved a right first time safety case.

Two other papers [1] [2] have been produced discussing the engineering challenges behind the UK's first multiple water barrier package and demonstration of criticality safety of the design.

Introduction

The U.K Government has a strategic objective to consolidate fissile materials onto a single site. Inventory includes unused, spent Fast Reactor fuel and an assortment of fissile material from mainly UK nuclear establishments. The nuclear material was originally destined for reprocessing, however following the closure of certain facility in the 2000s the material had been put into short term storage.

Difficulty inspecting the materials together with decades in storage had raised questions over the integrity of the material. A decision was also made not to re-package materials from the original storage containers for transport.

To enable the transport of high quantities of these materials with adequate margins of sub-criticality, it was necessary for International Nuclear Services (INS) to demonstrate the exclusion of water from the proximity of the contents under all conditions of transport. INS proposed enhancing the design of an existing flask, the M4/12 into a High Standard Multiple Water Barrier (MWB) transport package.

INS' MWB justification was based on the M4/12 transport package providing the first line of protection with a newly designed inner container dubbed the Un-irradiated Fuel Container (UFC) providing the second water barrier.

INS produced Package Design Safety report (PDSR) was compliant with the relevant IAEA Transport Regulations [3]. However subsequent development of a new INS package highlighted an issue over the performance of a neutron shielding cross-linked polymer when under thermal accident scenario. The same shielding material is also used in the M4/12 package. This raised a question over the M4/12 which, pending resolution led the package safety case to become a Special Arrangement application.

This newly designed UFC coupled with the M4/12 was approved by ONR for use as U.K's first High Quality Multiple Water barrier package for transport under Special Arrangement.

Rationale for a MWB Package

Fissile materials i.e. material comprising of Plutonium Pu_{239}/Pu_{241} and or Uranium U_{233}/U_{235} nuclides are capable of supporting a 'nuclear chain reaction' which may lead to a criticality accident and consequential high radiation level/dose rates.

Criticality safety is based on the control of one or more key factors, for example: the total mass of fissile material, the proportion of fissile nuclides in the material, the proportion of water present, the geometry the fissile material can accumulate in, the presence of poison materials which can control/prevent the 'chain reaction'.

If water is present the mass of fissile material needed for criticality is reduced for example, a sphere of less than 10 kg of dry plutonium will not be critical, if water is added the "critical mass" reduces to around 0.5 kg.

The geometry in which the fissile material can accumulate also affects the potential for criticality (e.g. fissile material which is safe with cylindrical geometry may be unsafe with spherical geometry) IAEA Transport Regulation [3] requirements for fissile packages necessitate the design and transport to be in such a way that an accidental criticality is avoided.

The radioactive materials (RAM) containing fissile materials must comply with regulatory criticality safety standards under both normal and accident conditions of transport. Although the material identified for transport was old and the physical state was unknown, a possibility existed that the RAM may be in poor condition therefore the RAM could break up, releasing "free" fissile material which could lead to a criticality.

Inspection of the radioactive material and fuel identified for transport had either failed to provide sufficient evidence to the integrity of the fuel pins or it had been impossible due to an operational decision not to re-pack the RAM into more suitable containers. This decision has rendered any Finite Element Analysis (FEA) work to prove material integrity in accident conditions unfeasible. Consequently the criticality assessment has had to consider the potential for fuel breakup in Accident Conditions. Safe margins of sub-criticality have not been demonstrated for all fuel types under conditions of full water ingress. Consequently a decision was made to contain the RAM within an internal vessel that demonstrated to provide a high-standard water barrier, such that the complete package could be considered as a MWB system.

If the RAM was transported under dry conditions without a multiple water barrier package, an initial assessment identified that the payload for each package would be reduced from 600 kg for example MOX to 8 kg or less.

Interpretation of the Transport Regulations

Right at the start of the project, INS established what constituted a "High Standard Multiple Water Barrier" (MWB) and the leak test criteria. Before a leak tightness criterion could be established for a MWB feature for the M4/12, INS established that at least two independently testable containers were required. Consideration was also given to the relevant IAEA regulatory position as currently given in Para 680 of [3] and the additional advisory information given in [4] with regards to the leak test criteria.

Para 680 of the IAEA Transport Regulations [3] states:

- For a package in isolation, it shall be assumed that water can leak into or out of all void spaces of the package, including those within the containment system. However, if the design incorporates special features to prevent such leakage of water into or out of certain void spaces, even as a result of error, absence of leakage may be assumed in respect of those void spaces. Special features shall include the following:

  (a) Multiple high standard water barriers, not less than two of which would remain watertight if the package were subject to the tests prescribed on para 685(b), a high degree of quality control in the manufacture, maintenance and repair of packagings, and tests to demonstrate the closure of each package before each shipment; or

Para 685(b) gives the prescribed tests:

(a) Hydrogenous moderation between the packages and package arrangement reflected on all sides by at least 20 cm of water.

(b) The tests specified in paras 719-724 (tests for normal conditions of transport) followed by whichever of the following is the more limiting:

(i) The tests specified in para 727(b), and either para. 727(c) for packages having a mass not greater than 500kg and an overall density not greater than 1000kg/m3 based on the external dimensions, or para 727(a) for all other packages: followed by the test specified in para 728 and completed by the tests specified in para 731-733: or

(ii) the test specified in para 729; and

(c) Where any part of the fissile material escapes from the containment system following the tests specified in para. 682(b), it shall be assumed that fissile material escapes from each package in the array, and all of the fissile material shall be arranged in the configuration and moderation that results in the maximum neutron multiplication with close reflection by at least 20cm of water.

The tests referenced in para 685(b) cover both normal and accident conditions of transport. Tests for accident conditions of transport (ACT) bound those for normal conditions of transport (NCT). ACT tests applicable to the M4/12 are given in paras [3]:- 727(a), 727(b), 727(c), 728 and 729.

However para 730 was applied instead of 729 which denotes the enhanced water immersion test i.e.:

- Enhanced water immersion test: The specimen shall be immersed under a head of water of at least 200 m for a period of not less than 1 h. For demonstration purposes, an external gauge pressure of at least 2 MPa shall be considered to meet these conditions.

Test described in para 730 is more stringent than the one in para 729 however it should be noted that the test described in para 730 is not required in the demonstration of MWB feature as the test described in para 729 provides sufficient demonstration.

The IAEA Advisory material [4] provides the following advice relating to MWB features, Para 680.1 states;

- Owning to the significant effect water can have on the neutron multiplication of fissile materials; the criticality assessment of a package requires the consideration of water being present in all void spaces within a package to the extent causing maximum neutron multiplication. The presence of water may be excepted from void spaces protected by special features that must remain watertight under accident conditions of transport. Credible conditions of transport that might provide preferential flooding of packages leading to an increase in neutron multiplication should be considered.

Para 680.2;

- To be considered ''watertight'' for the purpose of preventing in-leakage or out-leakage of water related to criticality safety, the effect of both the normal and accident condition test need to be considered. Definitive leakage criteria for water tightness should be set in the safety assessment report (SAR) for each package, and accepted by the competent authority. These criteria should be demonstrated to be achieved in the tests, and achievable in the production models.

Para 680 [3] refers to water leaking in to and out of void spaces including those within the containment system. Significant consideration was given to this because flooding could lead to a potential criticality incident. This consideration became irrelevant for the M4/12 package when configured as a high standard MWB version. However engineering development emphasised that all MWB features must function under normal and accident conditions and there must not allow significant water leakage past any water barrier feature into or out of a void, irrespective of the potential influence on criticality safety.

The most important statement in the IAEA regulations is given in Para 680.2 of the advisory material [4] which states;

- Definitive leakage criteria for water tightness should be set in the safety assessment report (SAR) for each package, and accepted by the competent authority. These criteria should be demonstrated to be achieved in the tests, and achievable in the production models.

In the absence of more specific criteria, this statement effectively says it is the responsibility of the package design authority to set out their leakage criteria for water tightness in the package SAR and then demonstrate this by testing to the satisfaction of the Competent Authority. This implies there are no definitive criteria for water tightness applicable to all packages with MWB features and in practice, criteria for water tightness are dependent on the package design and duty.

INS defined what constitutes 'leak-tightness' relating to the in leakage of water i.e. specified a test criteria expressed in Standardised Leakage Rate (SLR) below which it was known water cannot leak. An acknowledged leak tightness criterion below which water leakage was assumed not to take place was 1 x 10^{-5} Pa.m^3.s^{-1}. This value is supported by experimental results in [5] and theoretical data in [6]. INS however placed a more stringent leak rate pass rate of 1 x 10^{-6} Pa.m^3.s^{-1}.

M4/12 the High Standard Multiple Water Barrier Package

The Original M4/12 Package

The M4/12 Package was originally envisaged as a Multiple Water Barrier package however during the design process in the late 1990s the MWB application was not taken forward to a conclusion. At the time of design due to no direct comparable precedent for a MWB package, it was therefore assumed this design feature was a high risk and not required for the project. Consequently the M4/12 package was licensed in the early 2000s for the transport of Unirradiated Pressurised Water Reactor (PWR) Mixed Oxide (MOX) fuel. After the completion of original design intent missions, it was identified the internal geometry of the M4/12 PWR basket is adaptable for many different materials types.

Package Specification:	
Size	6,083mm overall length with shock absorbers 1,530mm overall width across trunnions 5,365mm overall length with shock absorbers removed 1,430mm diameter of shock absorbers
Weights	13,700 kg maximum gross weight loaded package (excludes transport frame) 624 kg lid end shock absorber and attachment bolts 560 kg base end shock absorber and attachment bolts
Package Thermal Rating	3.2 kW

Figure 1: M4/12 Package and Specifications.

The First Water Barrier

The M4/12 package body which provides the first water barrier was not modified from the original design [7]. The M4/12 is in the form of a composite high strength duplex stainless steel vessel, comprising three concentric cylindrical shells. The inner shell is directly welded to a forged base at the base end and a forging at the lid end. The outer and intermediate shells are welded to a base pad at the base end and a forging at the lid end. The annular spaces between the shells are filled with neutron shielding segments contained within aluminium extrusions. The base end construction contains a bare neutron shielding section held in place by a welded-in capping plate.

The lid end forging has a seal face to accommodate a pair of face type ‘O’ ring seals in the lid. Incorporated in the forging are castellation features to capture a bayonet type lid and a bayonet type fuel retainer. The inner seal is the containment boundary whilst the outer seal forms a testable interspace between the two.

Stainless steel clad, balsa wood filled, permanent shock absorbers are welded near to each end of the body. For transport, stainless steel clad, balsa wood filled, removable shock absorbers are bolted to the permanent shock absorbers.

The lid is fabricated from a duplex stainless steel forging and a spun austenitic stainless steel centre membrane. The lid contains two elastomer ‘O’ ring seals, which seals the lid end forging. The inner seal is the containment boundary whilst the outer seal forms a testable interspace between the two.

The Second Water Barrier

The second water barrier is provided by the Unirradiated Fuel Container (UFC). The UFC is a 4m long 0.22m diameter stainless steel cylinder with a thick chamfered base with an inner step, welded (base weld) to the main tube body. Above the main body is a throat transition section, to which the lid is welded on following inventory loading. The UFC has several different inner furniture arrangements, which facilitated the shipment of different content containers. The UFC has also been designed for long term storage minimum of 100 years before final disposal.

The High Standard Multiple Water Barrier Package System

The M4/12 Package had no modifications made to the safety design of the package to accommodate the UFC containing unirradiated fuel contents, other than those inherent to the MWB system. Additional lodgement ‘furniture’ was designed to enable the UFC to be carried within the lodgements of the basket designed for PWR fuel. This furniture also incorporates devices to reduce the effect of impact loads in the event of an accident. The M4/12 can carry up to four loaded UFCs, in cases where less than four loaded UFCs are available, substitute dummy UFC are utilised.

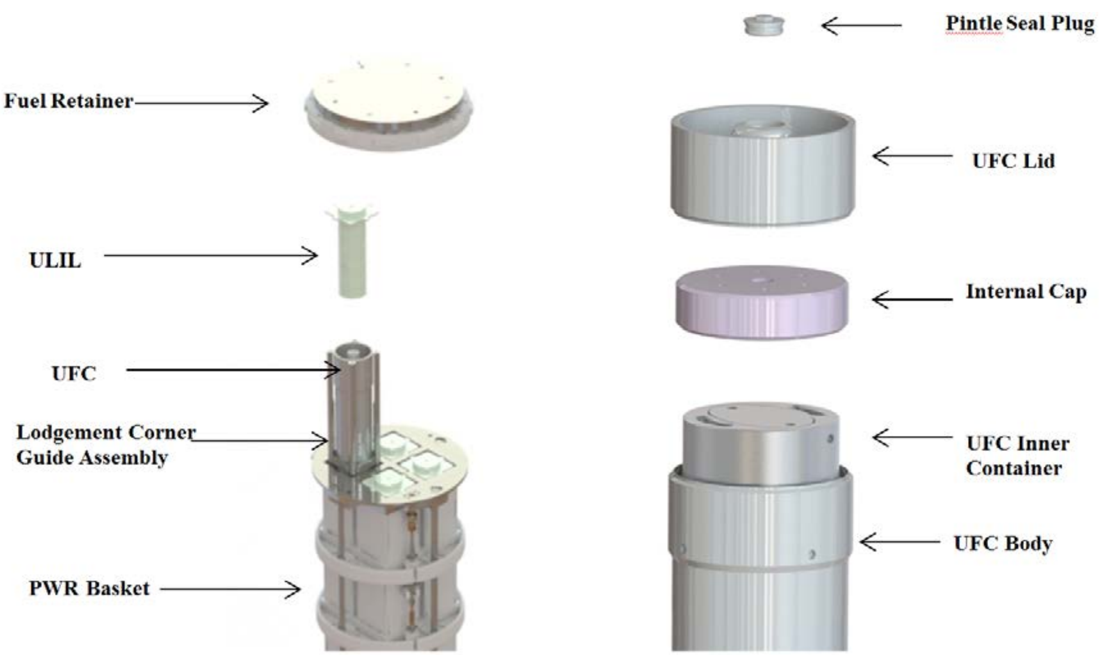

Figure 2: MWB Package Internals

Illustration on the left of figure 2 shows the top end detail of the PWR Basket, Fuel Retainer, Lodgement Corner Guide Assemblies and Upper Lodgement Impact Limiter (ULIL). Illustration on the right shows top end detail of the Unirradiated Fuel Container (UFC)

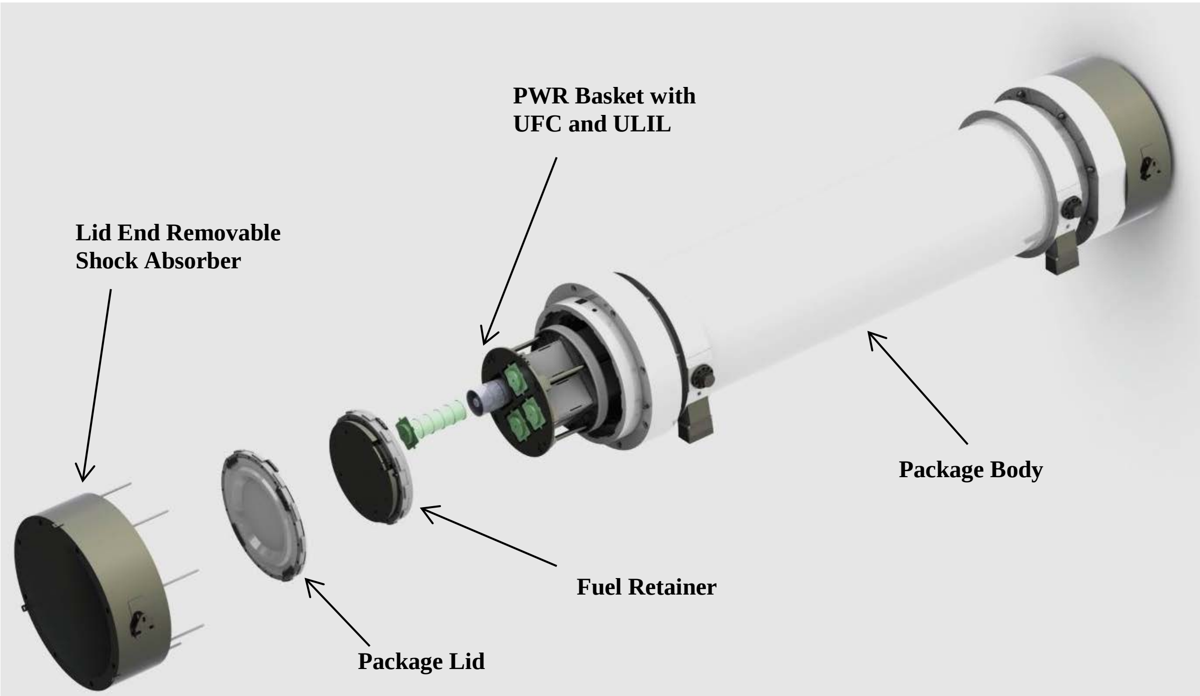

Figure 3: M4/12 MWB Package

Figure 3 illustrates the main components of the M4/12 flask when configured as a High Standard Multiple Water Barrier package for transport.

Competent Authority Interaction

It was essential INS engaged with the Office for Nuclear Regulation (ONR) the U.K. Competent Authority (CA) at the earliest possible opportunity. This gave ONR the option to provide guidance on general expectations and to gain familiarity with important elements of the development of the MWB package.

There was some early engagement between the applicant and the CA before the submission was made as recommended in the applicant guide [8]. This was particularly important because INS' safety case was not only novel but also complex. As the applicant INS held regular meetings with the ONR to discuss design intent/project updates and any clarification required while acknowledging ONR's independence from the design process. ONR also agreed with INS' interpretation of the transport regulations [3]. ONR attended site meeting to witness testing, and inspect manufacturing processes, giving them the opportunity to raise concerns.

Complexities Encountered

The original intention was to achieve a Type B licence for the MWB package. However during the development of a new INS package design, evidence came to light that raised questions over the assumptions used in a previously licensed M4/12 Package Design Safety Report (PDSR). The issue was over the performance of a neutron shielding cross-linked polymer when under thermal accident scenario, this very same material used in the M4/12. The M4/12 package was previously judged to be compliant with the regulations for a Type B(U)F approval. However due to this new information and the project being declared a National Imperative, led to timescale and schedule related challenges. Due to time constraints placed by the UK Government, INS could not conclusively demonstrate technically the package performance in respect to the thermal test as part of the accident scenario specified in paragraph 728 of [3].

It should be noted that further work since has been carried out, the M4/12 package has been modelled with Finite Element Analysis (FEA) to assess the structural integrity of the inner shell when subjected to an internal pressure due to off-gassing of degrading neutron shielding material during a regulatory thermal accident [3]. INS now believes the thermal accident scenario could now be demonstrated successfully.

However in order to secure the full benefits of the relocation programme in a timely manner as it was concluded following discussions with ONR that INS would commence with a Special Arrangement application, as per paragraph 830 of [3].

At the time, it was judged that there was a gap in the demonstration of performance of the package during the thermal accident. There was now a requirement to show that special precautionary, special administrative and operational control measures could be put in place to ensure that when operated under 'Special Arrangement', package safety would be maintained at a level of at least equivalent to that required of the IAEA regulations [3].

To make further use of the package, a Special Arrangement was required to satisfy the legal provisions laid down in the following transport legislation, [9], [10], [11] and [12].

The application produced required input from several third party contributors. INS as the author of the PDSR and the Special Arrangement application had to ensure not only we met the design requirements for a High Standard Multiple Water Barrier package but also the special arrangement requirements.

INS had to ensure that the special precautionary, special administrative and operational control measures employed by individual contributors during the transport did not counteract any of the other measures in place or impact the design integrity of the M4/12 package. This demonstration required considerable effort and demanded consultation, table top workshops, risk assessments and the production of scenario tables with all relevant parties

The entirety of the shipment was considered and the presence of other cargos had to be reviewed and deliberated to see if their presence influenced the safety demonstration. The effect of these packages on the packages under Special Arrangement during transport had to be investigated to ensure they had no effect on the measures in place.

Right First Time Safety Case

As a part of INS' procedures, a holistic transport risk assessment was carried out to review the risk levels associated with the activities involved in the proposed transports. The process undertaken mapped out the transport route. A workshop was held for the transport risk assessment, which involved participation from representatives of each process owner(s) for the phases of transport and intermodal transfer. Essentially the transport of the loaded packages was broken down into five different modal and intermodal transport phases.

This transport risk assessment encompassed all transport related activity including ones that fell outside the package safety case. Each transport mode and intermodal transfer process owners walked through the transport route to assist in the hazard identification along the route of transport. For each phase of transport and intermodal transfer analysed, the significant credible hazards and risks identified were all scored.

The Special Arrangement submission was based on this risk assessment as it highlighted the hazards at each stage of the transport including the risk of fire scenarios.

The Special Arrangement report coupled with engineering assessment as required formed a part of the package safety case which was submitted to the ONR.

Conclusions

The suitability of the M4/12 package was identified at an early stage, the flask and fuel baskets were originally designed for the transport of unirradiated Mixed Oxide (MOX) fuel. However ingenious repurposing of the M4/12 package and engineering of new internal components resulted in a MWB transport package. This gave the flask a new lease of life which facilitated and expedited the consolidation of radioactive material.

The IAEA regulations [3] requires the package designers to follow a prescribed series of impact and thermal test conditions, the package (i.e. the water barriers) must remain watertight under a head of at least 15m of water. With discussion with the ONR, the intent of the regulations was confirmed that no water in-leakage under these conditions is acceptable.

INS established that a leak tightness standard of 1 x 10^{-6} $Pa.m^3.s^{-1}$ SLR demonstrates the MWB features are watertight, although this must apply following both the impact accident and thermal test sequence.

INS produced PDSR was compliant with the relevant IAEA Transport Regulations [3] however subsequent development of a new INS package highlighted an issue over the performance of a neutron shielding cross-linked polymer when under thermal accident scenario which is also used in the M4/12 package. This led the package safety case to be become a Special Arrangement application. Nevertheless INS now believes we can successfully demonstrate compliance against this regulatory requirement through FEA Analysis.

The special precautionary, special administrative and operational control measures devised and highlighted in the application were as least equivalent or where possible above and beyond of what was required to ensure the highest level of safety was maintained during any phase of the transport. This gave the approving Competent Authority additional assurance required to approve the Special Arrangement.

INS were able to demonstrate a continuous level of safety at least equivalent to the package design fully satisfying the regulations [3].

With successful demonstration of the newly developed inner containers (UFCs) coupled with the M4/12 package, INS was granted approval to use the M4/12 package as a High Standard Multiple Water Barrier package for several transports.

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