Experience in Wet Transport of Irradiated LWR Fuels

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INTRODUCTION

Between 1973 and 1988 British Nuclear Fuels plc and its subsidiary company Pacific Nuclear Transport Limited have transported more than 570 flask loads of LWR fuel comprising over 7,000 assemblies, in water-filled "Excellox" flasks on 79 sea voyages from Japan to the United Kingdom. During these shipments no incident has adversely affected a flask or its contents, and in every shipment the package has performed well within its design margins. The object of this paper is to describe how the design margins for these flask packages have been met and how the designs have been developed to meet new requirements and advancing experience.

THE FLASKS AND THEIR USAGE

Excellox flasks at present in service with PNTL comprise 3 - 72 ton gross Excellox 3 carrying 14 BWR assemblies, 51 - 74 ton gross Excellox 3B flasks carrying 14 BWR assemblies and capable of carrying 5 PWR assemblies, and 26 - 92 ton gross Excellox 4 carrying 7 PWR assemblies and capable of carrying 15 BWR assemblies. The Excellox 3 was introduced in 1973 to service Japan's first commercial-scale BWR and has since (to the end of 1988) delivered 67 flask-loads containing 895 assemblies to Sellafield. The Excellox 3B, a slightly longer development of the EXL-3, was introduced in 1978 and has delivered 357 flask-loads totalling 4,998 BWR assemblies to Sellafield, as well as 53 loads comprising 265 PWR assemblies to COGEMA at Cap la Hague. Like the Excellox 3, the size and weight of the EXL-3B are within the handling capacity of earlier power stations.

The Excellox 4 is an expanded design, built to the maximum weight and dimensions which can be handled at the more modern plants and carried on the transport system, and this has so far delivered 32 flask-loads of 448 BWR assemblies and 116 loads totalling 812 PWR assemblies to Sellafield.

THE FLASKS: THEIR DESIGN

The main design features of the Excellox flasks are illustrated in the cutaway view of EXL-3B in Figure 1. EXL-4 is of similar appearance.

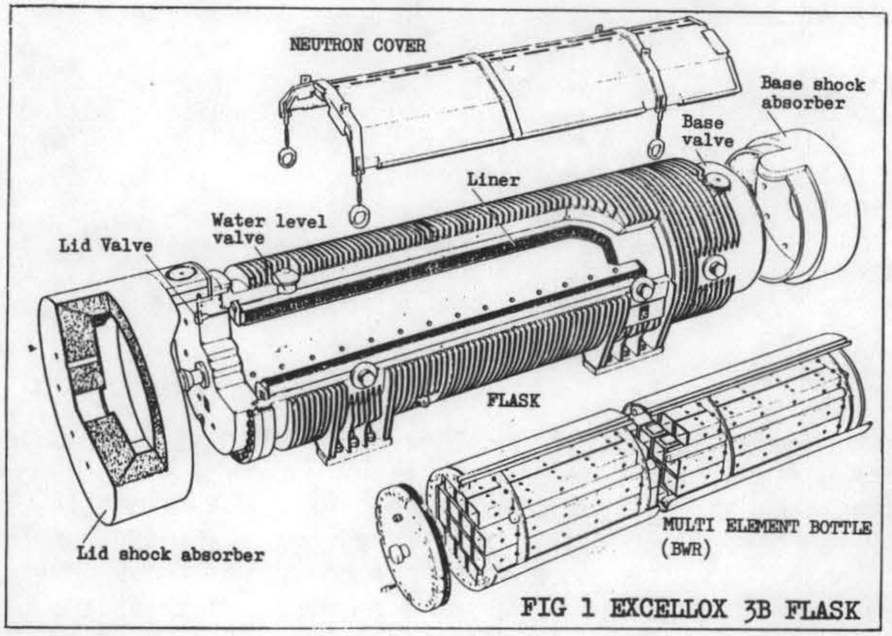

FIG 1 EXCELLOX 3B FLASK

Individual design features and parameters are listed in the table.

EXCELLOX FLASKS: DESIGN PARAMETERS

	EXL-3B		EXL-4	
	BWR	PWR	PWR	BWR
Gross weight tonne	75.2	73.7	93.4	92.6
Gross weight with transport frame	77.9	76.3	96.3	95.5
Crane hook weight (inc lifting beam)	87.4	85.8	105.8	105.0
Flask length mm	5994	5994	6269	6269
Flask max dia mm	2114	2114	2362	2362
No. of fuel assemblies	14	5	7	15
Maximum heat load kW	24	30	40	40
Average fuel assembly burnup GWd/tU	30	40	40	30
Average fuel core rating MW/tU	25.2	39	39	25.2
Enrichment (pre-irradiation)	3.04	3.5	3.5	3.04
Cooling time days	300	400	400	180

The body shell is fabricated from a rolled carbon steel cylinder which is welded along the longitudinal seam and to base and lid flange forgings of the same material. Fins are welded circumferentially to the outside of the shell to dissipate decay heat and to absorb impact energy. The lid is a carbon steel forging which is bolted to the body flange by up to 40 forged steel bolts and sealed by two concentric Viton O-rings. The body shell contains a separate stainless steel clad lead liner to provide lengthwise gamma shielding, with angled or staggered holes for water circulation. The body, lid and base have valves, some of which can be operated remotely, for venting, establishing ullage, flushing and draining. These orifices, as well as the lid seals, have access to the seal interspaces for leak testing as described in our paper on that topic (Hunter et al, 1989). Sealing and wearing surfaces are clad in stainless steel, and all orifices and bolt holes are lined with this material. Other surfaces are coated with a multi-layer, contamination resistant paint system. Stainless steel clad balsa shock absorbers provide impact protection to the lid and base and contents as well as thermal protection to the lid seals. Extensions to the shock absorbers protect the valves against impact.

MULTI-ELEMENT BOTTLES

The fuel is supported in the flask in a frame with dividing walls consisting of stainless steel pockets holding sheets of Boral for criticality control, with aligned holes to allow water circulation.

When the first shipment of Excellox 3 flasks each carrying 15 BWR assemblies in an open frame was opened up in the receipt pond at Sellafield, clouds of brown highly gamma-active crud emerged and contaminated the pond. In addition, in transit this crud settled between the lead liner and the flask wall, causing high levels of external radiation from the flask. To overcome this problem the frame was enclosed in a bottle with a bolt-on lid and arrangements for ullaging and flushing. This container is known as a multi-element bottle or MEB. It can be removed with its contents from the flask in a single operation and used to store the fuel in the pond pending reprocessing. The type used for BWR fuel is shown in Figure 1.

The effectiveness of the MEB in containing crud has been demonstrated by the activity levels measured in empty used EXL-3B and 4 flasks entering the maintenance facility at Sellafield. These are up to a maximum of 10^8 Bq beta-gamma, 10^6 Bq alpha, as compared to the 1973 IAEA A_2 limit for a Type A package of 1.5 x 10^{10} Bq beta-gamma, 7.4 x 10^7 Bq alpha for the mixture of radionuclides concerned.

RADIATION SHIELDING

LWR fuel assemblies extend the full length of the reactor core, so that neutron emission due to spontaneous fission of higher actinides falls off significantly towards the end of the fuel and is absent from the non-fuel bearing end fittings of the assembly. Gamma emission, while following the neutron emission in the fuelled part of the assembly, peaks again at the ends due to high induced activity in the massive end fittings.

Neutron shielding is provided by the water surrounding the fuel in the bottle, and in the annuli between bottle and liner and between liner and flask. Ullage space to allow for water expansion and gas generation is needed both inside the bottle and in the flask volume enclosing the bottle, and this results in reduced neutron shielding over the top of the fuel, in the normal horizontal transport attitude. To compensate for this a supplementary external neutron shield made of neutron absorbing resin impregnated wood is attached to the top of Excellox 3 and 3B flasks when carrying BWR fuel. This is shown in Figure 1. Slots in the top, staggered to avoid a direct shine path, allow the escape of convective cooling air which has risen between the fins under the cover. Addition of this cover reduces the maximum heat loading of the flask from 30 to 24 kW, a restriction which has not so far proved onerous in planning shipments. The IAEA regulations allow an increase in radiation by a factor of 100 in the event of an accident. The shielding calculations show a maximum neutron attenuation by the shield of about 20, so its loss in impact or thermal accident would be immaterial. Type A tests carried out with $^{1}/4$-scale models have demonstrated the survival of the shield and its attachment to the flask under normal conditions of transport.

To allow for the passage of cooling water, the lead liner is separated from the flask base by 1.5 in pads, leaving a shine path for gamma radiation from the fuel assembly bottom nozzles. This is reduced by inserting 3.5 in high stainless steel stools at the bottom of each channel in the MEB, which take up the free length between the fuel assembly and the MEB channel.

PWR fuel is about 15 inches shorter than BWR fuel. This enables the PWR bottle to be designed with a fuel chamber completely filled with water and a separate ullage chamber at the base end, into which the water can expand by way of a suitable arrangement of connecting and sealing pipes. Elimination of the external neutron shielding allows the full design heat load of PWR fuel to be carried in the flasks, 30 kW in the EXL-3B and 40 kW in EXL-4. At the same time the highly gamma active bottom nozzles of the fuel assemblies are supported well up inside the flask, well clear of the potential shine path past the lead liner. This MEB is shown in Figure 2.

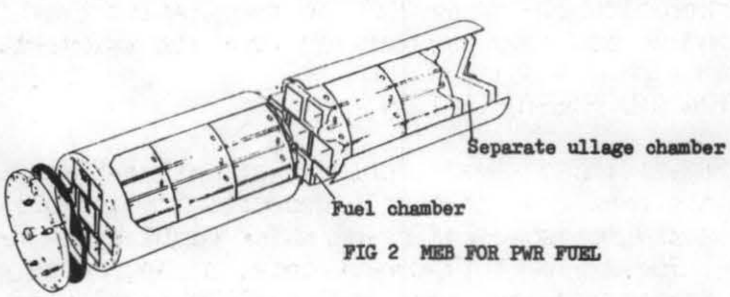

FIG 2 MEB FOR PWR FUEL

Bottles of this kind have been used successfully for all the PWR fuel transported in EXL-4, and a similar design exists for carrying

PWR fuel in EXL-3B flasks.

The effectiveness of the shielding has been confirmed in practice, with maximum transport index recorded 5.7 but usually around 3 for the EXL-3B BWR package, maximum 2.1 but usually less then 1 for the EXL-4 PWR package.

IMPACT RESISTANCE

The resistance of the Excellox flasks and multi-element bottles to the IAEA impact tests has been proved in over 160 drop tests on 1/4-scale models. In the course of these tests the lid and base impact limiters and their attachment to the flasks were developed and protection for the orifices added as the most severe angles and points of attack were sought out. Many of the tests were duplicated, with consistent results. Details such as the complex structure of the water level valve and sections of irradiated fuel pin (Clemson, 1989) have been tested at full scale. These tests have given great confidence in the robustness of the flasks and experience towards the design of further flasks.

NUCLEAR (CRITICALITY) SAFETY

The flasks have been used to carry a wide range of BWR and PWR assemblies from the various reactors in Japan. The assemblies offered for transport were analysed and the most reactive BWR and PWR assemblies selected for criticality clearance of the flask packages. To increase the initial enrichment that can be cleared, burnup credit will be required. Although this is not at present used in BNFL's criticality assessments, it is certainly an option which will be exercised in the future, as indicated in a BNFL paper at this Symposium (Clemson and Thorne, 1989).

The packages are cleared for undamaged and damaged package conditions. Criticality assessment sets a limit on the number of leaky fuel assemblies which can be carried, since cladding defects can initiate pin breakup on flask impact. This limit amounts to 1 ordinary leaky PWR assembly or 2 BWR assemblies per flask. There is no other restriction placed by BNFL on the transport of ordinary leaky fuel and no problems have arisen from its shipment.

GAS GENERATION AND PRESSURIZATION

One of the greatest perceived problems with water-filled irradiated fuel flasks has been the radiolytic decomposition of the water to produce uncertain pressures of gases which might be in explosive proportions. Because of this uncertainty, arrangements were made for regular pressure measurement and possible venting of the flasks during the 6 week sea voyages from Japan. MEB pressures and gas compositions have been measured on receipt at Sellafield, and at an early stage an extensive programme of experimental irradiations of water in flask and MEB environments was undertaken. Although this research showed the difficulity, with so many variables, of predicting the results of over 30 simultaneous chemical reactions between the water, its breakdown components and the materials in contact with or in solution in the water, it did result in a fair understanding of the processes involved and indicated certain alleviating measures that could be taken, and these were adopted at an early stage of the transport programme.

Radiolysis can be regarded as essentially the breakdown of water into hydrogen and oxygen. To avoid the risk of explosive mixtures of these two gases, two approaches are used: gettering and inerting. It has been found that the exposed Boral on the edges of the criticality control plates removes (getters) the oxygen as it is formed in the water and prevents it from reaching the ullage space. The amount of Boral consumed in this process is too trivial to adversely affect its primary function. To prevent the hydrogen released to the ullage space from forming an explosive mixture with air in the ullage, this space can be filled with a chemically inert gas such as argon or nitrogen. Tests showed that argon could actively promote hydrogen generation, and while they indicated a very slight tendency for nitrogen to form nitric acid under the influence of radiolysis, this effect was not sufficient to deter its choice as a cheaper gas and better radiolysis suppressant, so it was adopted as ullage gas for the multi-element bottles.

Complete filling of the ullage space in the MEB by nitrogen is guaranteed by the operational procedure for loading in which the bottle is completely filled with water on immersion in the power station pond and, after loading with fuel and attaching the lid, ullage is established by pumping in nitrogen and expelling water. The nitrogen in the ullage is allowed to equilibrate to atmospheric pressure before the MEB is finally sealed.

Radiolysis in the flask water outside the MEB is less of a problem than within the MEB where the water is in intimate contact with the radiation source, much of the radiolytic action being effected by short-range beta radiation, and a high proportion of the flask water is effectively shielded by the lead liner. Radiolytic gas production in this water may be taken to be a tenth of that in the MEB water. Oxygen in the flask water is effectively gettered by the painted inner surface of the flask. Experience has shown that with the flask ullaged with air, radiolytic hydrogen production is not enough to produce explosive mixtures, and ullaging is effected by the simple process of air being drawn into the flask through the lid vent valve as the surplus water drains from the water-level valve.

The results obtained from the extensive monitoring programme, particularly since gettering and inerting were instituted, show that almost invariably the flasks have remained at or slightly below atmospheric pressure, and the highest pressure measured in a PWR MEB has been 17 psi (117kPa) gauge, consisting almost entirely of hydrogen and the nitrogen with which the bottle was ullaged. Using the pessimistic assumption that gas generation is directly proportional to the radiation energy input (in fact experiments have shown that it quite soon reaches an equilibrium due to recombination), allowing for the fall in activity of the fuel due to radioactive decay and correcting for full IAEA normal transport thermal conditions, a hydrogen partial pressure for the EXL-4 flask and bottle combined of 35 psi (240 kPa) at the end of the regulatory year has been derived. This, when added to the pressure of the ullage gas and the water vapour, gives a maximum normal operating pressure of 60 psi (400 kPa) gauge, which is well within the type B (U) limit of 100 psi (700 kPa) gauge. This MNOP and its derivation have been accepted in principle by the UK Competent Authority, and when formally approved will allow the elimination of the breaking of containment and exposure to flask radiation inherent in pressure measurement in transit.

Experience with the EXL-3 and 3B BWR packages has been similar and the indications from the data are that acceptable MNOPs will be obtained by the same reasoning.

OPERATION AND MAINTENANCE

Operation of the flasks was described at the 1988 Stratford Conference (Middleton and Blackburn, 1988). Loading and discharge of Excellox flasks takes place under water in ponds at the reactors and the reprocessing plant. Thus the fuel remains in the water environment for which it was designed and avoids the thermal shock of being placed when dry and hot into cold water, as well as the embarrassing generation of steam in the pond. Lengthy periods of drying out the package interior in preparation for shipment are avoided.

The finned surface may be protected from contamination by pond water by covering it with a plastic bag when immersing the flask in the pond. However, the simple finned surface is coated with a hardwearing, contamination resistant paint finish and with gaps of 1.5 in (38 mm) between the fins is readily decontaminated by water sprays over the pond or by hand if necessary.

Orifices and lid seal, a total of 5 points, are leak tested before despatch by the pressure drop method. This assembly verification check is backed up by full definitive leak tests at the 3 yearly maintenance period, as described in our paper (Hunter et al, 1989).

Most routine maintenance operations such as checking seals and sealing surfaces, trunnions, bolts and threaded holes for wear are carried out in the flask receipt facility at Sellafield every time the flask is turned round. At three yearly intervals the flask enters the maintenance facility for more detailed gauging checks on screw threads, visual and dye penetrant checks on trunnions and the full leak tests required to back up the assembly verification tests. At six yearly intervals the flask is completely stripped down, repainted, reassembled and subjected to pressure tests, definitive leak tests and trunnion tests, restoring it to as-new condition. All operational and maintenance procedures are fully quality-assured.

APPROVAL STATUS

The Excellox 3B BWR and Excellox 4 PWR packages described here are approved Type B(M) Fissile I against the 1973 IAEA Regulations by the UK and Japanese Competent Authorities and application has been made to DTp for approval of the EXL-3B PWR and EXL-4 BWR package designs. Although, to avoid the onus of proof, the flasks have been transported empty of fuel under their B(M) approvals, it is now clear that they can be transported empty as type A packages.

Before the 1985 IAEA Regulations came into force in January 1990 these 1973 approvals are being updated to benefit from our long experience of their operation, and these updated approvals will be "grandfathered" for continuing 1973 approval under the terms of the 1985 regulations.

CONCLUSIONS

Experience of over 16 years has shown, especially when compared with alternative flask concepts, that these Excellox flasks with their simple construction using conventional materials are easy to operate and maintain, reliable and effective for the safe transport of irradiated fuel. Their continuing availability for use will be ensured by their "grandfathered" 1973 approval against the 1985 regulations, offering potential customers a well proven route for transport of irradiated material when the commitment of the flasks to present contracts comes to an end.

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