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NTL 11 Spent Fuel Flask – Meeting the Challenge of Regulatory and Technological Change

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Abstract

By June 2005, when shipments of spent fuel for reprocessing from Germany are concluded, the NTL11 flask type will have been responsible for transporting a total of 1500 tonnes of heavy metal in the form of spent fuel. Excluding domestic transports in France and the UK, this represents 25% of the total European spent fuel transported for reprocessing since the flasks came into service in 1977.

Approximately 40% of the total for the flask type will have been transported to BNFL's Sellafield facility, the remainder to Cogema at La Hague. The NTL11 flask can justifiably be described as being the workhorse of BNFL's European spent fuel transport business.

The NTL11 flask started life under the ownership of Nuclear Transport Limited, an associate company of BNFL, and in recent years the original fleet of five flasks has been absorbed into the BNFL inventory. A recent build programme has seen a further four flasks added to the fleet, an expedient measure to cope with the additional transport requirements imposed by the need to meet the June 2005 deadline for the removal of contracted fuels from Germany.

While there have been certain evolutionary changes affecting the package design, there have also been more significant changes in the Design Safety Case. These have sometimes been necessary to meet regulatory changes, or the challenges posed by the regulators. In other cases advantage has been taken of improvements in analytical techniques to demonstrate increased margins of operational safety. Where possible those margins have also been increased by other means, such as taking advantage of commercial trends to reduce package thermal loads.

The NTL11 flask was designed around the reactor and fuel characteristics prevailing in the 1970's. Over the lifetime of the flask the responsible engineering teams have faced and met the successive challenges to develop the capability of the Package to face the changing requirements of the industry and the Transport Regulations. Both Package design and Safety Case have been revised such that it has continued to service the needs of the industry more than a quarter of a century after first use.

Introduction

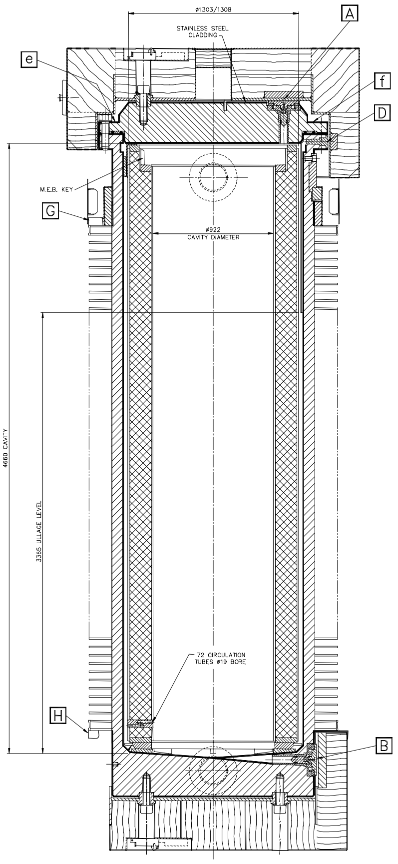
The NTL11 cask has a long history in European spent fuel transport, a history of largely successful adaptation to meet the changing needs of spent fuel specifications. The key design and development stages are described against a framework of changing fuel trends and increasing expectations from the transport regulators.

Design basis

In 1972 Nuclear Transport Limited (NTL) was formed as an associate company of British Nuclear Fuels Ltd, itself recently established from the fuel manufacturing and reprocessing arm of the UKAEA. Nuclear Transport Ltd was a truly international business, with equal French and German shareholdings. The business remit was to manage the rapidly growing need for spent fuel transports across Europe from the new LWR power stations to the reprocessing facilities in France and the UK.

To facilitate the business, NTL acquired various packages of British and French origin, such as the NTL1, NTL2 and NTL3. The latter design began life as the Excellox 1 around 1960, the former two were French-designed and manufactured. However, developments in reactor core design led quickly to the need to transport longer fuel assemblies than could be accommodated by these early packages, and by the mid-70s a design for a larger flask that would become known as the NTL11, had commenced.

During the design phase, it became clear that even larger fuel assemblies from anew generation of West German power plant would need to be accommodated, and the design was modified to accept a detachable extension to allow fuels of up to 5 metres in length to be transported. In this guise the flask became known as the NTL14 and was used at the Biblis and Unterweser power plants. Five flasks of the NTL11 design were initially manufactured, entering service between 1977 and 1979. Two flasks were manufactured by British Steel Engineering at Workington in Cumbria, the remainder by Whessoe in Darlington.



Arrangement of the NTL11 Flask

This detail shows the flask in its latest form, flask numbers 06-09, with steel-encased balsa shock absorbers. The lead liner, providing gamma shielding, and the extent of the cooling fins are clearly indicated.

The recess at the top of the lead liner locates the flange of the Multi-Element Bottle. A typical detail of the water circulation holes in the lead liner is also indicated.

The location of the various orifice plugs is indicated thus:

A = vent orifice in lid
B = drain orifice
D = ullage orifice (earlier flasks had an additional ullage orifice 'C' for use with extension as NTL14)
e, f = two lid seal interspace test points (earlier flasks had one test point)
G,H = water connections to 'bagging' ring – to prevent contamination in reactor ponds, the finned area is encapsulated in a steel or plastic tube, or 'skirt', in which uncontaminated water is circulated at a slight overpressure

The flask design was validated by a research programme which included both non-destructive and destructive testing. An extensive impact test programme examined the behaviour of the package in both NTL11 and NTL14 configurations, and under both regulatory and, in the early 1980s, extra-regulatory conditions. This programme gained valuable information on various impacts against 'realistic' structures - simulating bridge abutments, for example - at speeds of up to 100 kph. At the time this was perceived as a very effective public relations exercise.

Short-cooled fuel

Some of the older nuclear plant in Germany have limited space in their small fuel storage ponds. This means fuel has to be transported with a short cooling time. In the case of the Neckarwestheim-1 plant, a requirement to transport fuel with cooling times in the 6-9 month region was met with the introduction of the NTL11. The flask was at one time regularly used with thermal loads of up to 35kW, having a design limit at that time of 40kW. Subsequent changes, both physical and to the Safety Case, have meant the flask is no longer used for such high thermal loads. This is discussed later in the text.

Receipt of fuel in warm ambient conditions with thermal loads of this magnitude imposed problems at Sellafield, as the package water temperature would sometimes exceed 100°C. The flask was required to be immersed for a period of time to reduce the internal temperatures before the lid could safely be removed, without release of contaminated steam.

Modification for Convoy reactor fuels

The NTL11 was designed to be adapted for use for the Biblis and Unterweser reactors in Germany before the advent of packages specifically designed to carry 5-metre long fuel. A flanged cylindrical spool piece was added to the top of the body, attaching to the body flange, and the lid in turn attached to this. Internally a cylindrical extension was used for the lead liner. The flask body flange was fitted with two separate ullage valves so that the correct level could be obtained in either NTL11 or NTL14 guise.

A full validation of the flask as NTL14 was carried out as part of the impact test programme. The NTL14 was rated at 45kW thermal capacity.

Modification for high-burnup fuels

In order to cope with the trend towards higher burnup fuels in the late 1980s, it became obvious that neutron dose was a significant problem for this type of design. The upper part of the flask contains an ullage volume necessary to allow for expansion of the water content, and consequently the shielding provided by the water is absent in this region. However, some partial exposure of fuel assemblies above the water level is a feature of the internal design, leading to high neutron doses above the flask, and on the flask’s upper surface.

In order to address this problem, the flask finned area was provided with an enveloping cover manufactured from a compressed wood-based material (Permali) with a high hydrogen content. This cover was vented to allow passage of cooling air around the flask fins, but nevertheless had a restrictive effect on the ability of the package to dissipate heat. With the cover fitted, the design thermal capacity was restricted to 34kW.

Initially the cover was used as ‘supplementary shielding’, but a later development, supported by an impact test programme, saw the cover become part of the Package, and credit could be fully taken for its shielding effect in the Safety Case. Further supporting analysis at this stage, coupled with some minor modifications to the cover, saw the thermal capacity of the package re-rated at 35kW.

Changes in thermal rating

When the neutron shield cover was introduced to take account of higher burnup fuels, the flask thermal capacity was re-assessed and reduced to 34kW. During the major revalidation exercise in the late 1990s this was ratified at 35kW. The four newly-built flasks meeting 1996 B(U)F criteria are rated at 20kW. This takes account of different seal materials, and the absence of a commercial incentive to ship short-cooled fuel. Subsequently flasks 03-05 have been revised to meet 1996 B(M)F with EPDM seal material and a reduced thermal capacity of 20kW. The benefit in reducing the thermal capacity is that package temperatures and pressures are lowered throughout, and design margins of safety improved.

Design revalidation 1998-2000 – new shock absorbers

Increasing focus on package structural integrity in the late 1990s questioned the ability of the internals to maintain a safe array under severe impact accident conditions. During a major revalidation of the package at this time, in addition to revising the design of the internal multi-element bottle (MEB) it was necessary to improve the design and attachment of the shock absorbers/impact limiters.

In place of the open aluminium structure, an encased wood shock absorber was employed. This had superior impact and thermal insulation properties, and was validated in both these respects. A full scale fire test yielded valuable specific and generic information, which has been used in the validation of other similar designs. The attachment of the shock absorbers to the flask lid and base was improved by using greater numbers of larger bolts, which required major machining work to be carried out in BNFL’s flask maintenance facility.

KTA 3905 requirements and trunnion attachment issues

Since around 1990 flasks used in Germany have had to demonstrate compliance with the German standard KTA3905 where load attachment points are used for lifting in reactor buildings. Initially this entailed a substantial increase in the torque applied to the trunnion attachment bolts before the calculations could be accepted by TÜV. After some years service, unacceptable deterioration in the bolting integrity was experienced.

This phenomenon was thoroughly investigated and eventually ascribed to stress corrosion cracking, the effect of high stress in the presence of water. The exposure to water was due principally to immersion of the flask in the reactor ponds. No attempt to prevent water reaching the bolts with this type of design has been entirely successful. A research programme commenced to investigate the torque-tension relationship in this specific application, at the same time as improved and more comprehensive ultrasonic monitoring techniques were applied during turnaround maintenance.

It was found that conventional theory suggested too high a friction factor for this bolted connection, and when an experimentally-determined friction factor was applied, it was demonstrated that substantially lower bolt torques could be used. The development programme to satisfy TÜV Nord was extensive. Agreement was reached in time to incorporate lower torques into the recent new build programme for NTL11 flasks, and to refit existing flasks with new bolts at lower torques.

Increase in fleet size to meet challenging fuel shipment timescales

Early in 2001 it became clear that to meet the challenging requirement to complete contracted fuel business in Germany before the end of June 2005(this date being incorporated into German Atomic Law), it would be necessary to increase the flask fleet size considerably. Consequently an order for four further NTL11 flasks was placed in June 2001 with Corus Process Engineering (Workington).

Opportunity was taken to incorporate minor design improvements while keeping within the general envelope of validation. It was also decided to ensure the new packages met the full requirements of the latest regulations. This required significant new analytical justification, particularly in the area of brittle fracture. Design approval was gained in September 2003 as B(U)-96.

Licensing challenges and 1996 Regulations

The decision to apply for a B(U)-96 licence for the new flasks was taken after some debate. The NTL11 is acknowledged as a well-proven but dated design, more recent designs being of ‘monolithic’ or thick-walled construction, where the steel wall of the cavity provides both structural integrity and all of the gamma shielding requirement. Strictly speaking, from the viewpoint of capacity per tonne of material used, the composite steel-and-lead design of the NTL11 is superior, and there are advantages in thermal performance, the rejection of heat from spent fuel carried being achieved more efficiently with the water circulation around and behind the lead liner.

In order to meet the new regulations and achieve a B(U) Type Approval, certain detail changes were made to the material specification to achieve better low-temperature properties, and to the sealing system to benefit containment.

The fluorocarbon seals originally fitted to the design were considered inadequate below -20°C, and were replaced with EPDM material. In conjunction with RAPRA, BNFL has developed a specific grade of EPDM to suit applications with significant radiation, designated EPDM-30H. Extensive analysis, including pioneering FE work, was undertaken to establish the dynamic performance of the seals and demonstrate they satisfied newly defined regulatory criteria relating to residual compression requirements.

Ageing trials have been carried out on EPDM seals, to establish that containment performance is maintained after at least 12 months at conditions of maximum normal temperature and pressure. In addition to this, the ability of the seal to maintain containment integrity in the event of a thermal accident occurring after 12 months, causing a major pressure excursion and thermal distortion of the flange faces.

Further to proving the integrity of the seals under conditions of continuous high temperature and pressure, the expansion characteristics of the material itself have been investigated, together with the available volume contained in the seal grooves, to ensure sufficient room for thermal expansion exists. This has led to the reduction of seal section size in the older NTL11 flasks numbers 03-05, and a redesign of the seal grooves used to house the primary seals in the orifice plugs.

Brittle fracture requirements

The recent build of four NTL11 flasks has been licensed against the 1996 TS R-1 regulations as Type B(U)F. This has demanded some changes compared with the construction of the original flasks, although visually they remain identical. One of the most important changes is the selection of material for the construction of the main body and lid, forming the containment boundary. This is necessary to achieve the necessary toughness at -40°C. The material for the original build programme of five flasks had impact, or toughness properties at no less than -35°C, which meant only a multilateral approval could be obtained.

The material specification for the new-build flasks was written specifically to require a rigorous demonstration of the low-temperature impact resistance of the material. The base and lid are manufactured from forgings, the shell from rolled plate. The plate material is a relatively low-tensile boiler plate, the low temperature toughness properties being much more important than tensile strength at temperature.

MEB and basket development

The majority of spent fuel shipments in NTL11 have been carried out to Cogema's La Hague reprocessing facility near Cherbourg. The fuel payload was not separately bottled for these shipments, being carried in 'fuel assembly frames' (FAFs). The structure of a FAF is similar to the internals of an MEB, but without the base or lid closures. Although no claim is made for the containment provided by an MEB, a practical advantage is that crud deposits from the fuel are prevented from circulating in the cavity water, where they may lodge between the lead liner and the outer steel shell and possibly create a dose 'hot-spot' on the outside of the flask. This occurred on several occasions with FAFs, and the NTL11 flasks used most at La Hague have been modified to incorporate additional lead shielding where hot-spots have been detected.

Spent fuel received in the NTL 11 flasks at Sellafield has been contained in MEBs. In addition to keeping the cavity of the flasks relatively free from contamination, the use of MEBs ensures the water quality in the Thorp receipt ponds is maintained at a high level. The MEBs are removed from the flasks in the receipt pond and stored in racks for later removal of the contained fuel. MEBs are almost without exception single-use pieces of equipment, but this addition to the cost of reprocessing is considered by BNFL to be justified by the benefits offered to pond management.

The design of MEBs, and to some extent FAFs, has evolved over the years. In the early days, late 1970s and early 1980s, the over-riding design ethos was to maximise capacity with respect to criticality safety in normal conditions. There was a greater Regulatory acceptance of reasoned argument to support the case where packages underwent accidents, including the nine-metre drop impact. Typical of the designs of MEB from this era was the 1190-type, used until the late 1990s. This orthogonal design held seven PWR assemblies within lodgements fabricated from relatively thin stainless steel, the neutron poison being in the form of encapsulated Boral sheets. During a revalidation programme in the late 1990s, impact testing with simulated fuel revealed considerable distortion of the lodgement walls. It must be emphasised that this MEB was never proved unsafe, or that criticality margins had been eroded below the norm. The decision to withdraw was based on the availability of a superior radial design, and the difficulties of applying adequate metrology techniques.

The next phase of development was in response to concern at the prospect of eventual disposal, and to maximise the benefits resulting from the use of boronated stainless steel (BSS). This generation of MEBs were characterised by lodgements formed from BSS plates located together by slots and tabs, the whole group of assemblies being held together by stainless steel straps and wedges before being enclosed in a cylindrical shell. Both orthogonal and radial arrays have been produced, depending on the requirements of the application. To aid disposal, cutting the straps allows the internal structure to be collapsed.

In recent years, a greater requirement has been placed on the Applicant to support any reasoned argument for the accident case with either analytical techniques or practical testing, often both. As a result the MEBs in current service have been drop tested in fully-detailed model form, with simulated fuel loads, under circumstances representing the most severe impact attitude. The deformed shape of the lodgements and any inter-lodgement spaces (flux gaps) is measured accurately and the results used in criticality analysis to demonstrate adequate margins of sub-criticality.

The most recent MEB types to be used in NTL11 are the 3346-type 'radial' MEB for seven PWR fuel assemblies, and the 3184 'orthogonal' MEB for 16 BWR assemblies. Both these designs have been validated by testing at one-third scale.

Future developments

It may be concluded that demonstration of integrity in impact has entirely superseded the requirement for ease of disposal, at the same time that new techniques in compaction have reduced the need for special design measures. A new generation of basket design, applicable to both MEBs and FAFs, addresses the needs of maintaining sub-criticality as a fundamental maxim, employing a cellular construction with great resistance to collapse of the flux gaps. This has now progressed beyond the drawing board to the drop-test model stage, with impressive results.

Radiolysis solutions

Combination of high temperatures and high gamma radiation field are known to divide the water molecule into its constituents of hydrogen and oxygen. These circumstances occur inside the MEB or FAF lodgements, allowing a buildup of hydrogen and oxygen in the ullage space within the flask or MEB. In certain concentrations, an inflammable or detonable mixture of these gases can form. Although there is no really credible source of ignition within the flask to spark a conflagration, there is the theoretical possibility that sufficient energy could be introduced to detonate the gas mixture, for example by impact.
Studies have shown that insufficient energy exists to breach package containment, but concerns on the integrity of the internal components and contents required a complete solution to be sought. A particular concern was that generation of radiolysis pressures with some flask designs could exceed B(U) limits.

The subject of radiolysis and its suppression has occupied scientists for many years. In terms of transport flasks such as NTL11, early steps taken involved the use of Boral as a sacrificial corroding material, or 'oxygen getter'. This proved successful in certain applications, the resultant ullage gas mixture having too little oxygen content to be dangerous. The introduction of MEBs fabricated with BSS, despite the provision of sacrificial auxiliary Boral sheets, did not demonstrate the same effective suppression. Improvements were made by purging the ullage volume with nitrogen prior to shipment, but despite this there were instances where high partial pressures of ullage gas were recorded.

BNFLs Radiolysis Working Party, a group of scientists working to understand and solve the vagaries of radiolysis, proposed the use of catalytic recombiner material incorporated in the build of the MEB, or FAF. An extensive programme of testing was undertaken between 1999 and 2002. This involved the building of model MEB structures, investigation of the effects of water, temperature and radiation on the catalyst. Results allowed the quantity of catalyst to be established, contained in a stainless steel mesh cylinder. A number of these units are incorporated in the latest generation of MEBs (since 2003) to ensure a high redundancy factor, and allow for change in attitude of the MEB. The catalytic recombiners are suspended in the ullage space of the MEB.

Validation of performance has been achieved by sampling the ullage gas after receipt at Sellafield. This has shown that free radicals of hydrogen and oxygen are effectively recombined. Under some circumstances relatively high levels of hydrogen have been seen – but have been attributed to corrosion of the oxygen getters. During a 12-month proving period, during 2003, oxygen getters were used in addition to catalytic recombiners. Shipments without oxygen getters have shown significant levels of uncombined oxygen, attributed to release of dissolved oxygen from the water in the MEB. In either case, the concentration of the partner gas has been insignificant.

Shipments of fuel in NTL11 have used catalytic recombiners since January 2002, with type 3346 and 3184 MEBs, with complete success. Gas sampling techniques have advanced during this time, overcoming initial quality control problems to give consistent results.

End of shipments to Cogema, and end of open baskets

NTL11 has not been used with FAFs, or for shipments to Cogema La Hague since 1996. Since that date, all shipments have been to Sellafield from German and Swiss NPPs. However, the changing demands of the nuclear transport business mean that future use may see a return to the use of open frames, and a return to La Hague – though there the similarity will end!

MEB types

The radial design of MEB replacing the earlier orthogonal type 1190 in the NTL11 was derived from the Type 3324, a design originally developed for the Excellox 7 flask. This flask was designed to replace the Excellox 4 types formerly shipping Japanese spent fuel arisings, but in the event was never licensed or manufactured. The 3346 design is virtually identical to the 3349 type used in another BNFL spent fuel flask, Excellox 6, changes being limited to the external location feature.

Recent modifications have involved extending the length of the boronated steel plates forming the lodgement structure. The lodgement structure was until this point a legacy from the 3324 design, and additional length has increased the margins of safety from the criticality perspective, by reducing the volume of the unpoisoned region below the boronated stainless steel.

Conclusions

The NTL11 flask has survived for 27 years of service, demonstrating the benefits of a straightforward and flexible design. It has a proven ability to be upgraded, both in terms of the parameters of its contents, and its safety performance and Approval category. This has not been accomplished without great efforts of analytical support and effective management of test programmes, but such work has added greatly to our knowledge and understanding of package behaviour under extreme conditions.

While the future of spent fuel transports is currently uncertain, nuclear materials in general continue to require to be transported, and there is every expectation that the NTL11 flasks will find a new lease of life to take the design into its fourth decade.

DEVELOPMENT AND LICENSING MILESTONES

1977 – Introduction of type into service, as B(M)F-73. Adaptable to NTL14 with extension. 40/45 kW

1979 – five flasks in service. Fuel shipped to Cogema La Hague in fuel assembly frames (FAFs), and to Sellafield in multi-element bottles (MEBs)

1991 – introduction of neutron shield detachable cover for high burn-up fuels – 34 kW

1998 – during impact tests to support validation of 1190 MEB performance, lid shock absorber detached. Package Approval suspended.

1998-2000 – modification to accept encased wood shock absorbers in place of aluminium, with improved attachment. Neutron shield cover validated as part of Package. New impact validation programme. Major thermal revalidation work.

1999 – impact tests with new shock absorbers and detailed MEBs. Thermal test on full-size shock absorber

2001 – New Approval to B(M)F-73 (flasks 01 and 02), B(M)F-85 (flasks 03-05) – 35 kW

2002-2003 – new build programme of four flasks, 06-09. Incorporating new seal material and improved impact properties of body material.

2003 – Catalytic recombiners incorporated in all MEBs from January

2003 – flasks 06-09 licensed to B(U)F-96 - 20 kW

2004 – renewal of Approval for flasks 03-05, as B(M)F-96 (20 kW). Withdrawal of flasks 01 and 02 from service

NTL11/14 FLASK OPERATIONAL HISTORY

				NTL11- 01	NTL 11-02	NTL 11-03	NTL 11-04	NTL 11-05
			Built	1976/7	1976/7	1976/7	1977/8	1976/7
			First use	1977	1977	1977	1978	1977
Transports to Sellafield: Reactors serviced	year	Internals	Capacity, assemblies	NUMBERS OF SHIPMENTS				
Biblis (as NTL 14) - D	1977-1980	1177 MEB	5 PWR	8	7			
Oskarshamn - S	1979-1982	1160 FAF 1185 MEB	17 BWR 17 BWR	10	4	3	6	7
Beznau - CH	1979-2003	1184 MEB 1190 MEB 3346 MEB	7 PWR 7 PWR 7 PWR	22	29	10	2	7
Santa Maria - E	1978-1981	1160 FAF	17 BWR	3	2	3	3	6
Gösgen - CH	1989-1996	1190 MEB	7 PWR	18	3	12	2	1
Neckarwestheim-1 - D	1997	1190 MEB	7 PWR	3	4	3		
Krümmel - D	1996-2003	1185 MEB 3184 MEB	17 BWR 16 BWR	6	11	3	5	5
Stade - D	1982	1190 MEB	7 PWR					2
		Total transports to Sellafield:	**210**	70	60	34	18	28
Transports to La Hague: Reactors serviced				NUMBERS OF SHIPMENTS				
Würgassen - D	1977-1995	1160 FAF	17 BWR	9	14	17	21	32
Stade - D	1980-1996	1173 FAF	7 PWR	3	5	22	40	28
Neckarwestheim-1 - D	1978-1996	1173 FAF	7 PWR	0	0	37	42	35
Isar - D	1981	1160 FAF	17 BWR	0	0	1	1	0
Beznau - CH	1991	1173 FAF	7 PWR	0	0	1	1	0
		Total transports to La Hague:	**309**	12	19	78	105	95

D = Germany; S = Sweden; CH = Switzerland; E = Spain