The Use of Computer Analyses in the Impact Design of the Used Fuel Flask

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Introduction

This paper presents the use of advanced structural analysis programs in the design of a spent fuel transport flask. Conflicting requirements that took cognisance of the Transport Regulations and the obligation to meet ALARP principles for on-site handing, led to a complex design that could not have been engineered without the use of these structural analysis techniques. Furthermore, the use of these techniques also reduced the scope of physical testing needed to demonstrate compliance with the IAEA Transport Regulations.

Requirements for New Flask

A requirement for a new flask for the transport of spent fuel was identified in the early 1990s to replace an existing flask design that had reached the end of its useful life. At the start of the programme, reviews of currently operating flasks were carried out to determine whether an existing design could be used. The review concluded that existing designs could be easily adapted for the transportation role. However, there were, in all cases, major difficulties with respect to on-site handing. In order to comply with modern safety case requirements, in particular meeting the As Low As Reasonably Practical (ALARP) principles, it was decided that a new flask would be designed and procured. The new spent fuel flask was designated the Used Fuel Flask (UFF).

The sites where the UFF would be used were existing facilities, undergoing staged improvement programmes, and a new modern standards facility, which was at the concept design phase. A comprehensive statement of requirements was produced, which met the safety case demands of the existing sites and would also result in a flask that was suitable for use in a modern standards facility. Those requirements most pertinent to the subject of this paper are discussed below.

The maximum all up weight of the UFF and lifting arrangements was limited by the safe working load (SWL) crane capacity of 80 Te, at the existing facilities.

The maximum lift height at one site was 13.5m. Although the target at this site was concrete, it was decided that the flask and contents should be capable of withstanding a drop of 13.5m on to a flat rigid target. The physical drop testing was to be carried out in accordance with the IAEA regulations, i.e. a nominal 9m impact, and the structural integrity of the flask and contents, for the 13.5m impact, demonstrated by finite element analysis.

To maintain the structural integrity of the spent fuel payload, a maximum flask deceleration for all impact attitudes was specified. This was a major constraint on the design of the flask shock absorbing features.
A further requirement was the ability to carry out fuel loading and unloading in both dry pits and underwater in storage ponds.

Further major constraints on the design were driven by the required payload of spent fuel to minimise the number of fuel shipments required to maintain the spent fuel shipment programme.

Various concept designs were proposed and reviewed. All the designs were considered viable with respect to licensing the flask to the IAEA regulations. However, on-site constraints posed major difficulties to those design options that had removable impact limiters. For example, at one facility, it was necessary to remove the impact limiters before a high lift was performed. Justification of the basic flask design for impact capability, with no additional engineered shock absorbing capability, posed major concerns for the site safety case. Similarly, conventional impact limiters would have to be removed before the flask was lowered in to fuel loading pits or the underwater spent fuel storage ponds.

After a comprehensive review, it was concluded that a design with integral impact limiters, rather than one with conventional detachable impact limiters, should form the basis of the new design. It was recognised that the design with integral impact limiters, although ALARP for the on site safety cases, would pose an increased project risk with respect to justifying the flask against the transport regulations. In order to reduce this project risk to acceptable levels it was recognised that use would have to be made of advanced finite element impact analysis techniques to carry out the design optimisation process. The code chosen for the structural optimisation process was LS-DYNA, Reference 1, which is internationally accepted by the nuclear industry for explicit finite element impact analysis.

The design that was selected is shown in Figure 1. The flask mass is 74Te, is 4m high and has a diameter of 2.4m. The flask body and lid is manufactured from carbon steel and the internal surfaces are clad with stainless steel. Carbon steel fins fulfil both cooling and impact limitation functions. The lid is retained by 15 high tensile steel bolts. Tie down to the transport frame is by four feet welded to the flask body. The internal basket is manufactured from boronated stainless steel.

Impact Limiter Design

The integral impact limiting fins were designed to collapse on impact, thus absorbing the impact energy by the formation of plastic hinges. It was essential to design fins that produced flask impact limiter knock back, within acceptable limits. The flask knock back is a true measure of the average deceleration. Too little knock back would result in a deceleration that exceeded the allowable limits for irradiated fuel and internal basket integrity. However, if excessive knock back occurred, lock up of the integral limiters with the flask body would result in high deceleration at the end of the impact, giving similar fuel and basket justification problems

The main impact attitudes chosen for the design optimisation process were,

1) Axial lid impact
2) Axial base impact
3) Flat side impact on to lifting trunnions
4) Flat side impact on to fins
5) Centre of gravity over base corner impact
6) Centre of gravity over lid corner impact

To speed up the structural optimisation process, simplified models were generated to characterise the fin behaviour for horizontal impact attitudes. Figure 2 shows a typical model used in the optimisation process. The simplified model represents a slice of the flask body and includes representations of the longitudinal and circumferential fins.

Vertical impacts on to the flask lid and base gave high decelerations due to the large plan area of the support ring in contact with the target. To reduce the flask deceleration, the fins attaching the support ring to the flask lid and body had to be reduced in thickness. However, this was problematic for centre of gravity over lid and base corner impacts since the reduced impact projected area resulted in excessive knock back and locking up of the deformed fins with the flask body. This gave unacceptably high decelerations at the end of the impact transient. Various designs of fin were assessed using a full-scale finite element model but without success.

The solution was the adoption of a two-stage fin design. The support ring is joined to the flask through long thin fins. Thicker, shorter fins protrude from the flask and lid body with a gap between the free edge of the fin and the support ring. The load is initially taken by the long thin fins, and after a predetermined knock back, the thicker fins make contact and provide a stiffer load path. Since the flask velocity has been reduced substantially before the thicker fins make contact, the flask peak and average deceleration is maintained within acceptable limits.

A full three-dimensional finite element model of the UFF was constructed using PATRAN, Reference 2, and is shown in Figure 3. The model comprised 201086 nodes and 157142 elements. The 15 bolts retaining the lid are explicitly modelled. Contact surfaces on the lid and body model the interface gap. Bi-linear material models based on true stress/true strain curves were used to represent the flask components.

The thickness and length of the thin and thick fins were optimised by successive runs of the full 3D finite element model. The optimisation process produced a solution that achieved acceptable flask decelerations and knock back for both end on and centre of gravity drops on the lid and flask corners. Further sensitivity studies were carried out to ensure that the design solution chosen was robust to possible uncertainties in the analysis.

Similarly, the full 3D finite element model was used to optimise the fin design for horizontal impacts. This included horizontal impacts on to the trunnion region and the flask tie down feet. Analyses were also carried out with the flask at shallow angle attitudes to model the slap down impact scenario.

In addition to optimising the flask deceleration and knock back of the fins, the finite element analyses also gave predictions for lid bolt strain and seal face opening. Figure 4 shows the predicted deformation at the seal face region. Figure 5 shows the deformation at the base of the flask and demonstrates the function of the two-stage impact absorbing fin design.

Impact Testing

Impact testing of the flask was carried out at the AEA Technology drop test facility, Winfrith, England. A 1/3-scale model of the flask was used and a series of drop tests carried out. Due to the complex nature of the integral impact limiter design, the number of drop tests required to demonstrate compliance with the regulations would have been large, if no detailed analytical data were available to assist in the drop test critical case selection. However, by taking advantage of the sophisticated impact modelling carried out using the LS-DYNA code, the actual number of impact tests carried out was reduced to an acceptable level.

A pre-drop test report was prepared that summarised the results of the impact analyses. A critical case selection exercise was carried out which ranked the impact attitudes, based on the impact analysis results. From the ranking exercise, a subset of impact attitudes was selected for physical drop testing. These were chosen as worst case scenarios to test the critical parameters of the flask, namely, containment, loss of shielding and basket integrity fuel integrity. Although the drop test is the final arbiter in demonstrating the impact withstand of the flask, it is also necessary to show that the impact analyses correctly characterised the impact performance, in order to give credence to the selection of the critical drop test attitudes.

The flask was successfully drop tested with all major parameters meeting or exceeding the design requirements. The post drop leak tests showed that the flask was well within the allowable leakage rate. The lid bolt elongations were minimal, as predicted by the finite element analysis.

Table 1 presents the measured and predicted knock backs for the three impact attitudes tested along with the predicted and measured flask accelerations. Good agreement between drop test and finite element prediction was achieved for the centre of gravity over lid corner impact. For the axial lid impact and side impact on to the trunnions, the knock backs were over predicted in the finite element analysis.

A review of the finite element analysis modelling assumptions was carried out to investigate the possible reasons for the differences between analysis and test. The parameters investigated were as-built fin thickness, material properties, strain rate effects, target friction and mesh density. The only significant parameter was found to be target friction. A coefficient of friction of zero had been used to provide an upper bound to the knockback in order to ensure that lock up would not occur. The analysis was repeated with a coefficient of friction of 0.2 and a better correlation between test and analysis was achieved. The critical case ranking of impact attitudes was shown to remain valid with this modified contact friction data. This result is shown in Table 1. Very similar results were obtained using coefficients of friction of 0.15, 0.3, 0.5 and full stiction. Thus, only a small friction coefficient is needed to suppress lateral movement at the target and induce bending at mid height of the fin. The UFF was fully licensed in 2000 as a Type B(M) Fissile package.

Summary

A new flask has been designed and fully licensed as a Type B(M) Fissile package, which meets the requirements of the transport regulations and recognises the ALARP principle for on-site use.

The basic flask design and the complex integral impact limiter design features were optimised by the use of advanced structural analysis techniques. This design process also reduced the scope of the drop testing required to demonstrate the compliance of the flask against the IAEA regulations.

Table 1 Comparison Between Predicted and Measured Knockback and Acceleration

Drop attitude	Predicted knock back (mm)	Measured knock back (mm) - see note (1)	Predicted acceleration average/peak 'g'	Measured acceleration average/peak 'g' - see note (1)
Axial lid impact	75	58	136/142	176/NR
C of G over lid corner	318	300	32/130	34/117
Flat side impact on trunnions (smooth target)	84	64.5	116/290	152/NR
Flat side impact on trunnions (rough target)	69	64.5	142/340	152/NR

Notes: (1) Scaled to full size flask, and (NR) Not recorded

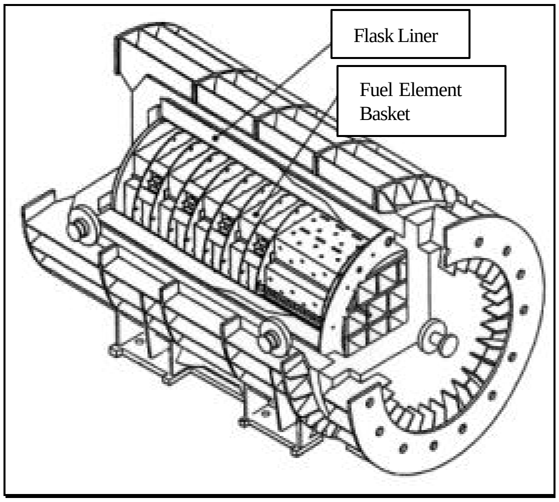

Fig. 1 Schematic of New Spent Fuel Flask designated the Used Fuel Flask (UFF)

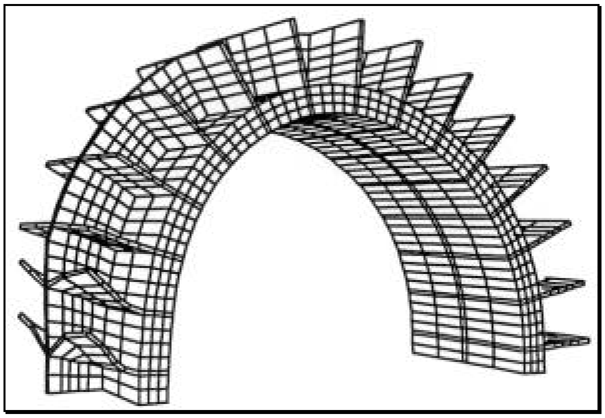

Fig. 2 Simplified Fin Model for Horizontal Impact Attitudes

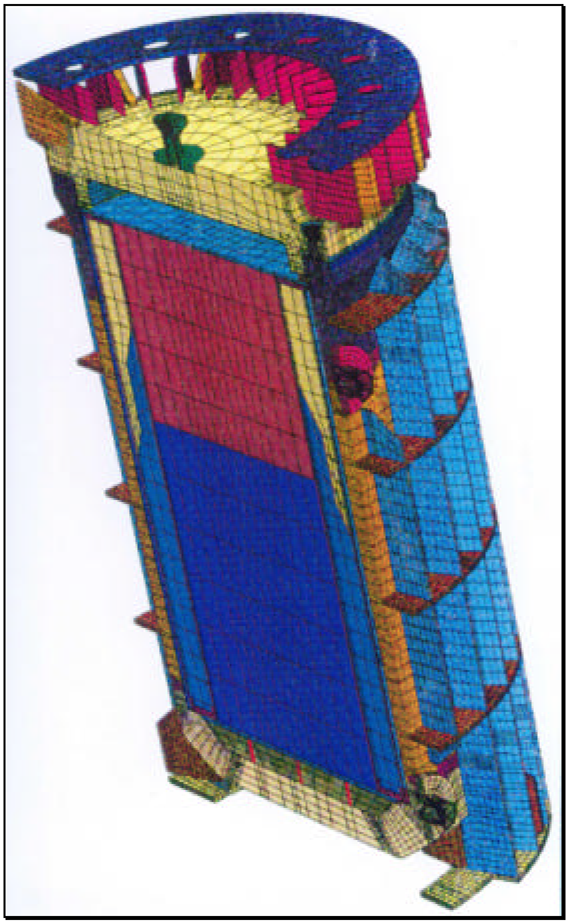

Fig. 3 LS-DYNA Finite Element Model of UFF

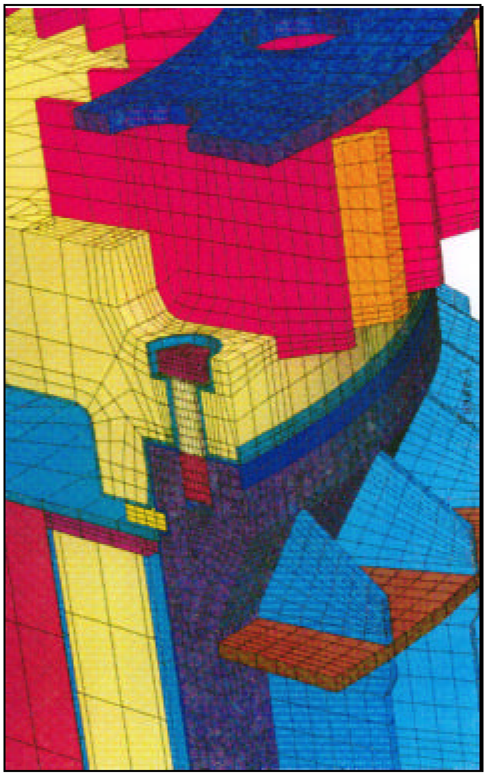

Fig. 4 LS-DYNA - Deformation of Lid Bolt and Seal face Opening

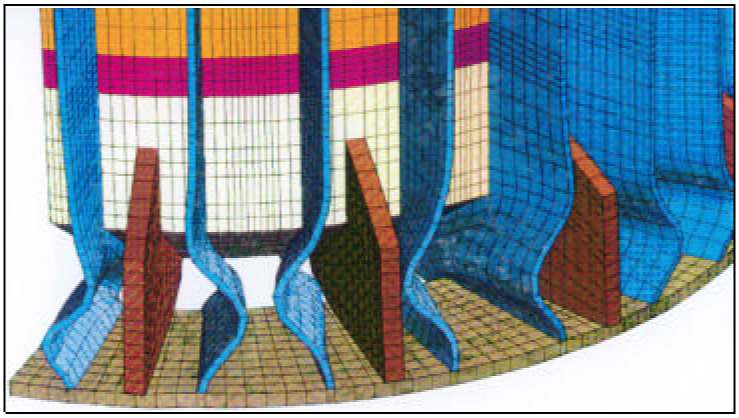

Fig. 5 LS-DYNA - Deformation of the UFF Impact Limiters

References

1 LS-DYNA Version 940_2a Software, 1999, Livermore Software Technology Corporation (LSTC), USA.

2 PATRAN Version 7.5, MSC Corporation, USA.