DESIGN AND DEVELOPMENT OF BI-TL-300 EQUIPMENT AS A TYPE B (U) TRANSPORTATION CASK

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ABSTRACT

BI-TL-300 equipment, designed to irradiate blood and its components to prevent Graft Versus Host Disease in immune deficient patient, is a Type B (U) transportation cask. This is designed as an innovative package consisting of main body and outer enclosure as its impact limiter. The package is made compact in its overall size and mass by suitably placing tungsten and lead as shielding material. The blood bag moves in an elliptical bent pipe by gravity. The design of the irradiator ensures dose uniformity ratio within the specified band. The package is designed to meet the national and international regulations of radioactive material transportation by road and sea and it conforms to the requirements of “Type B (U)” Package as specified therein.

In this paper design features of the package are presented along with the demonstration of accident condition test by numerical simulation. The structural integrity and performance optimization under 9m drop is carried out by numerical simulation using commercial F.E.M software PAM-CRASH. Performance under thermal test assessed by numerical simulation is also presented.

Keywords: Irradiator, Dose Uniformity, Structural Integrity

INTRODUCTION

BRIT has designed equipment “BI-TL-300” which can irradiate blood and its components to prevent Graft Vs Host Disease in immune deficient patient. A dose of 25-30Gy is required to irradiate blood and its components. The equipment is designed for a source strength of 10.31 TBq (275 Ci) of Co^{60} in three pencils. This equipment is a Category – I Irradiator according to IAEA Safety Series 107, 1992 [1]. Here, the source is stationary and the product is movable. The equipment has been designed to meet ANSI-N 433.1,1977 [2] as Category-I Irradiator. Since the equipment needs transportation, it is also designed as a Type B (U) transportation cask as per IAEA Code TS-R-1, 2009, [3], Safety guide TS-G-1.1(Rev 1)2008 [4] and AERB/ SC/TR-1 [5] for Safe Transportation of Radioactive Material. The equipment is analysed for 9 meter drop test and 800^0C fire test to meet these regulations.

DESIGN

The design has been made utilizing three Co^{60} pencils put in a triangular fashion. The blood bag moves in an elliptical passage. The placement of the source pencil and the elliptical passage has been done in such a way that the dose uniformity ratio (DUR) remains within as small a limit as possible. Control of DUR within acceptable limits is the main criteria of this design since there is no rotation of blood bag. The design gets more complicated when it is required to qualify the equipment as a Type B (U) Transportation cask.

The equipment consists of the transportation cask, control panel, trolley and conveyor. The general features of the Blood Irradiator are shown in fig-1. The transportation cask comprises of main housing and outer enclosure. The main housing consists of main body, shield plug, source cage and guide plate cum plug. An elliptical bent pipe is used for smooth flow of product. It is designed in such a way that there is no radiation streaming.

The main housing consists of inner shell and outer shell filled with lead as primary shielding material. The design of outer and inner shells and the lead shielding provided inside the encasement takes care to maintain the structural integrity of flask under all expected internal and external loads during its service as well as transport regulation requirement. The main housing houses the radiation sources in sealed capsule/ pencil. An annular cylindrical cavity of 196 x 218(h) mm in the main housing provides for accommodating for three cylindrical source pencils in the source cage. The three pencils are positioned around the blood bag in such a way that there is no radiation streaming through the bent pipe.

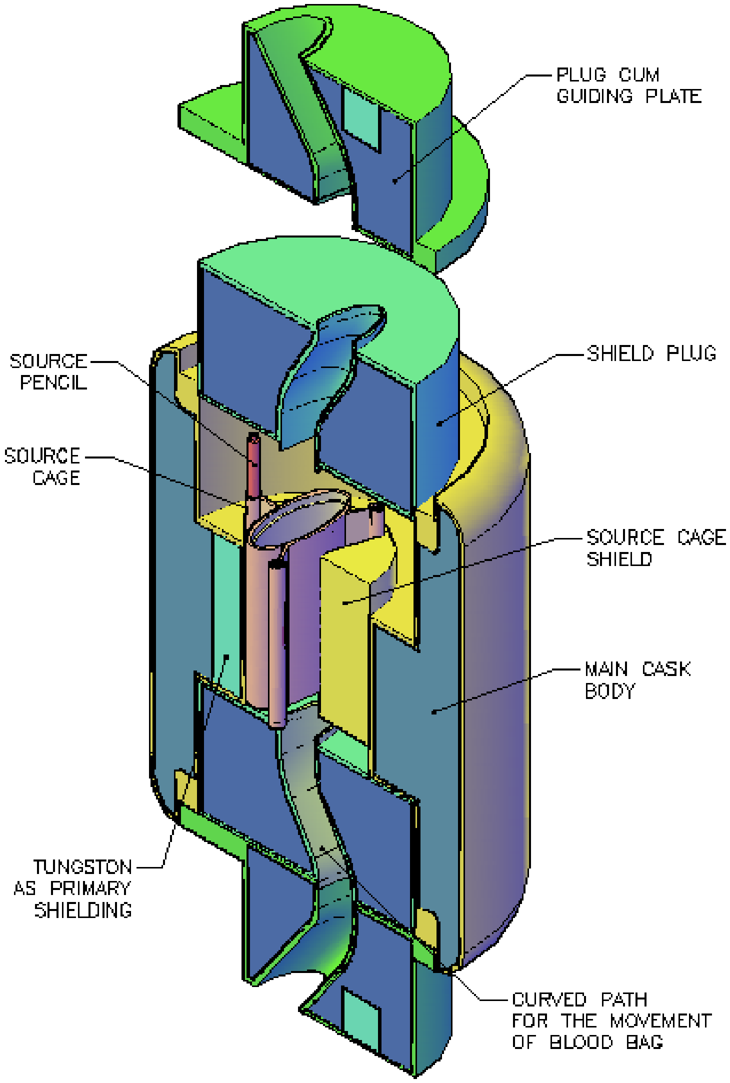


Fig. 1: General Feature of the Blood Irradiator

The source cage is in between the lower and upper shield plug. The shield plugs along with the main housing keeps the source cage in position. The plate cum plug is then put on the main housing and the whole assembly is bolted by socket head screw. The outer enclosure, which houses the main cask, is made of SS 304L. This consists of outer and inner shell and is a part of the Irradiator. Pipes of NB 3 ½" Sch 40 are placed suitably inside the enclosure as shock absorber.

The cask is designed to provide adequate shielding to 10.31 TBq (275 Ci) of Cobalt-60 source such that it satisfies the dose limits of Category –I Irradiator as well as Transportation cask. According to ANSI-N 433.1,1977, maximum exposure rate at 5 cm from the accessible surface of Category I Irradiator should be less than 20mR/hr and maximum exposure rate at 1 m from the accessible surface of Category I Irradiator should be less than 2mR/hr. According to IAEA Code TSR-1, 2009, the surface dose rate on the surface of the cask unit should be less than 2mSv/hr. (200mR/hr). The dose limits are achieved with a minimum of 135 mm of lead encased in steel shells of total thickness of 16.5 mm. In order to make the cask compact, three tungsten pieces in form of half moon shape are placed suitably in front of the source pencil as primary shield.

The transportation cask has been designed to meet national & international regulations of radioactive material transportation by road and sea. The cask is designed for a loading of 2G, 2G, and 3G in longitudinal, lateral and vertical direction respectively to meet tie-down requirements.

Specification of the Equipment

Cask Overall Dimensions	ϕ 717 x 1185 (h) mm.
Weight of Package	1,760 Kg.
Weight of Lead in Package	1100 Kg.
Size of cavity of source	ϕ 196 x 218 (h) mm.
Cobalt-60 content	275 Ci (10.31 TBq)

Structural Analysis

The structural analysis of the cask is required to show its conformance to the regulatory requirements for it to be suitable as a Type B (U) package. The cask has to drop from 9m on an unyielding target such that the integrity of the cask is retained to the extents specified by the standard. Orientations considered for drop analysis are Corner, End, and Horizontal.

Impact of cask on an unyielding target is a dynamic phenomenon featuring complex interaction between structural and internal forces. In the event of impact, the cask is subjected to loadings of high intensity, which induces transient deformations ranging from small deflections to large strains resulting in geometrically nonlinear behavior. This is further complicated by a nonlinear material behavior resulting from plastic flow of materials. To simulate these large deformation and inelastic material response, the cask was analyzed by a non linear FE code PAM-CRASH [6]. The code is formulated on Langrangian mechanics. The resulting second order equations are then solved by an explicit central difference technique.

The Finite Element model of the cask was constructed using FEMAP v-8.0. Fig. 2 schematically depicts the finite element mesh plots of the cask with shock absorber. All the plates of the cask are modeled using 3D, 4 noded bilinear Belytchko-Tsay shell elements. Lead material, which is more likely to flow under pressure, is modeled using 8 noded 3D brick elements. Tungsten blocks, which act as primary shielding, are modeled as 8 noded 3D brick elements. Pipes used as shock absorber are modeled as shell elements. The bolts are modeled using one dimensional beam elements. All nodes of bolts are merged with coincident nodes of corresponding part. All nodes are merged at all welding locations. Element size is varied from region to region, but sufficiently fine mesh was taken to correctly represent the physics of the problem. The cask model consists of 45420 nodes, 13692 solid elements, 26910 shell elements and 40 beam elements in total. Self-contact with edge treatment with a contact thickness of 10µm is used to describe the contact between the mating surfaces of the transportation cask and its enclosure. The material properties used in the analysis are shown in Table1.

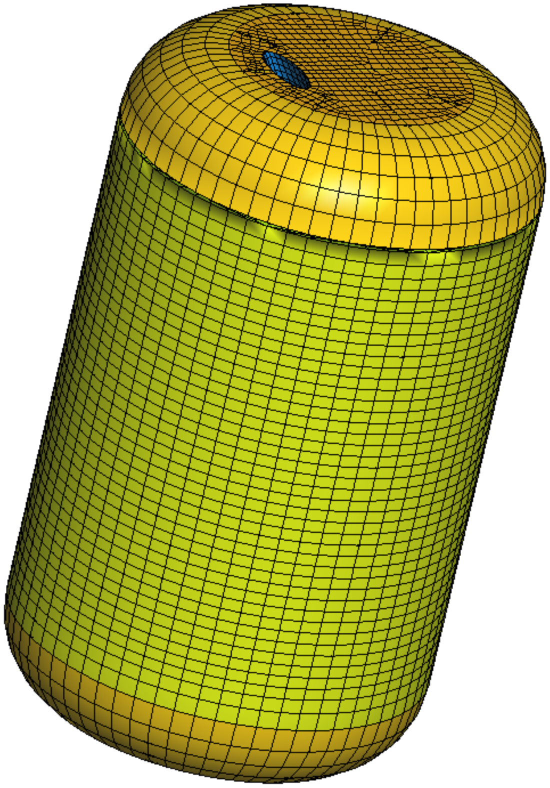


Fig.2: F.E. Model of cask with shock absorber

Some of the assumptions made include: the structural welds are not considered in the model and uniform base material is modelled across any surface, the material properties for the analysis is considered at room temperature, the unyielding target is assumed to be a perfectly rigid wall without friction, the interfaces such as steel-steel & steel-lead are frictionless, the bolt response is assumed to be elastic & 1% plastic & second impact on rebound is ignored.

Design Optimization

Preliminary numerical simulation of this cask was carried out under 9m drop on unyielding target in different orientations. Results of the simulation revealed that stresses generated in guide plug, bend pipe and bolts were not meeting the structural integrity criteria. This was because the guide plug cum plate was not fully protected by Outer Enclosure. Bolts connecting guide plug and cask main body failed due to shear load. Therefore, design modifications were required in the initial cask design to meet the structural integrity.

The shock absorber was extended in such a way that it covers complete cask. The thickness of shock absorber pipes was increased to 8.1mm. The bent pipe thickness was increased to 8mm from 4mm.

The bent pipe was made in different pieces. The top plug cum guide plate thickness was increased to 12 mm from 6 mm. The outer shell of the cask body was modified in such a way that there is a male-female joint between the cask body and guide plug cum plate.

Table 1

Sr. No.	Properties	Steel (SS 304L)	Tungsten	Lead	Bolt SA 540 Gr B24
1	Material law	Bilinear Elastic-Plastic	Bilinear Elastic-Plastic	Bilinear Elastic-Plastic	Bilinear Elastic-Plastic with1%plastic strain
2	Density	7800 kg/m³	18500 kg/m³	11350 kg/m³	7800 kg/m³
3	Young's modulus	200E9 N/m²	310 E9 N/m²	Not Used	200E9 N/m²
4	Poisson's ratio	0.3	0.28	Not Used	0.3
5	Yield stress	170 E6 N/m²	586 E6 N/m²	3.2 E6 N/m²	1035E6 N/m²
7	Ultimate stress	485 E6 N/m²	758 E6 N/m²	Not Used	1140E6N/m²
8	Strain – rate Cowper Symond's model parameters	C=100 P=10	None	None	None

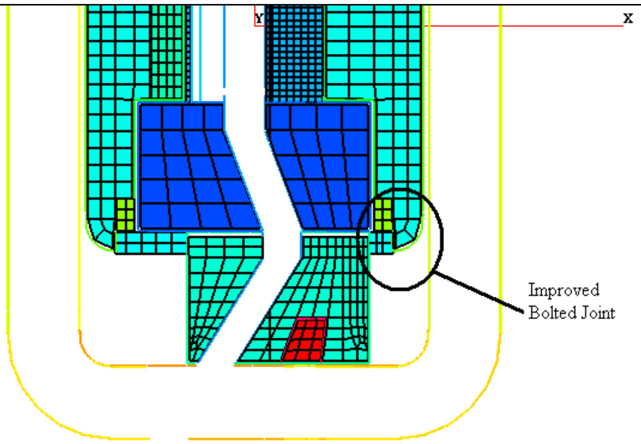
After the modification, the deformation in the guide plug was reduced. The maximum stresses induced before and after modification are 720 MPa and 402.5 MPa respectively. The stress intensity over impact duration in the bent pipe before and after modification is 993.5 MPa and 424.2 MPa respectively. The stresses in the bent pipe are largely reduced because the pipe has been made into pieces. The bent pipe does not face any resistive force during the slide of guide plug, if any.

Under the 9m drop test, the closure bolts failed because of the displacement of the guide plug (Fig 3). This sliding movement of the guide plug was arrested by modified structural design as shown in Fig 4. The stresses induced in the cask body and bolts are lower because of the male female joint between the guide plug and cask body. This has restricted the relative movement by providing larger shear area.


Bolts Failure

Sliding movement of Guide plug has to be arrested by suitable structural design instead of bolts.

Fig. 3 Failure of bolt due to sliding movement of Guide Plug



Improved Bolted Joint

Fig. 4 Improved structural design

Results & Discussion of Optimised Cask Design

Numerical simulation of the modified cask is carried out under 9m drop in different orientations on the rigid wall. Results of the simulations are presented in form of geometrical deformation & stress values in cask components.

Figure 5 shows the internal, kinetic and total energy plot with time for corner drop. The initial kinetic energy is 1.65 MJ and approaches the minimum value in 12 Milliseconds (ms). The initial internal energy is zero and this approaches a maximum value, 1.5 MJ, at the same time. Also some hourglass, contact, and rigid wall energy exists but it is very negligible. The total energy remains constant with time and is addition of internal and kinetic energy.

The maximum deceleration observed is 184 g in the horizontal drop at 12 ms. Figure 6 shows plot of deceleration and time history. Figure (7, 8, and 9) shows the final deformation of the cask under 9m drop test. It can be seen that the Outer Enclosure which is acting as a shock absorber is completely deformed and there is a small deformation in the main cask.

Structural qualification is carried out as per ASME Sec III Div 1, Appendix F [7]. For containment structure, stress limit is lesser of 0.9 S_u and for non containment structure stress limit is lesser of 3.6 S_y, or S_u. Stress values of some of the critical components are shown in Table 2.

Table 2

Component / Material	Stress Limit(MPa)	Observed Maximum S.I. **(MPa)**		
		End Drop	Horizontal Drop	Corner Drop
Outer shell of main cask	485	398.6	440.0	392.4
Inner shell of main cask	485	386.2	379.4	377.7
Steel casing of guiding plug	485	391.8	439.0	402.5
Steel casing of shield plug	485	383.8	383.8	384.6
Bent pipe	485	424.2	436.4	415.3

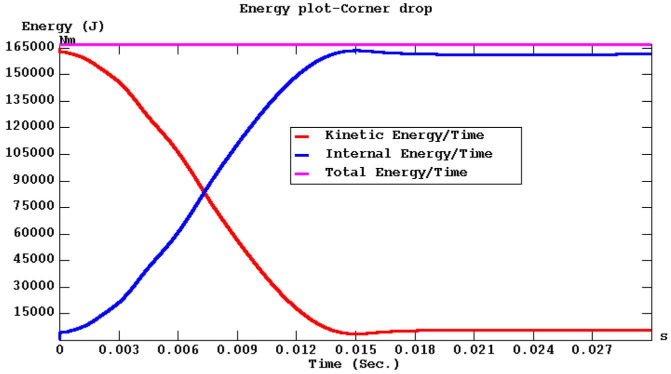


Fig. 5 Energy plot under 9m corner drop

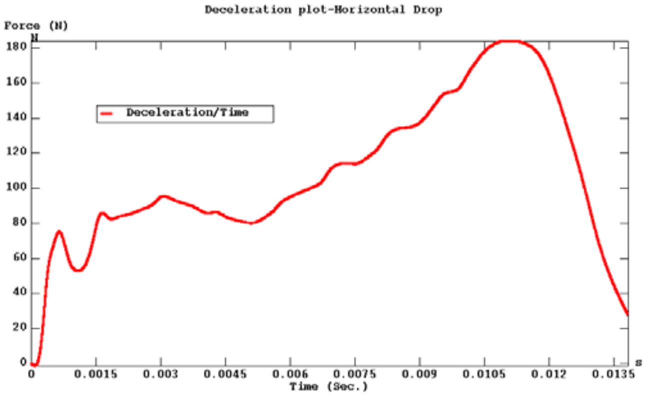
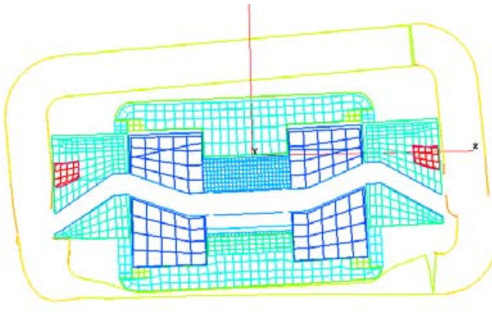
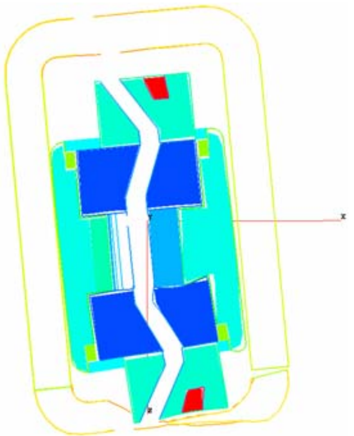


Fig. 6 Deceleration plot under 9m horizontal drop

 Fig.7 Final deformation under 9m horizontal drop	 Fig.8 Final deformation under 9m end drop	 Fig.9 Final deformation under 9m corner drop

Thermal Analysis

Thermal analysis of the transportation cask has been carried out under steady state and accident conditions of transport using CFD code STAR CD 3.2 [8]. Axisymmetric model has been assumed. Guide plates at top and bottom are assumed to be of same shape and curved pipe details are not modelled. Centre pipe which is elliptical in shape is assumed as a circular pipe. Pipes in the enclosure are not modelled. Analysis has been carried out to meet IAEA Code TS-R-1, 2009 for normal as well as accident conditions including fire test.

Normal Transport Condition

The cask contains 275Ci of Co^{60} which will generate 5 Watt of heat in the cask. In addition a solar heat flux of 800 W/m^2 and 400 W/m^2 is considered in the top and on the side surface of the cask respectively. The cask was analysed considering an ambient temperature of 42° C. For steady state analysis, the surface emissivity is assumed to be 0.3. The temperature contours in the cask under normal conditions are shown in Fig. 10. It can be observed from the figure that the maximum temperature at outer surface is 342 K (69° C), which occurs at top surface.

Accident Condition

Fire test analysis has been carried out by taking the temperature distribution of steady state analysis as the initial condition. The flame emissivity is taken as 0.9 and surface absorptive is taken as 0.8 for cask outer surface. The convective heat transfer coefficient is taken as per regulatory guidelines. The test duration is 30 minutes. In order to analyse the post fire condition, analysis continued after the fire test till the temperatures at all points started reducing. The cask was analysed considering surface emissivity of 0.8 and ambient temperature of 315K (42°C) and the convective heat transfer co-efficient based on natural convection.

The temperature contours in the cask at the end of fire test are shown in Fig. 11. Partial lead melting has been observed in the outer periphery of the cask. The molten thickness of lead is about 6mm out of the available thickness of 112mm. Top and Bottom plug cum guide plates are fully molten but solid thickness at the top is still higher than that at the centre. Total lead melting is about 25 % (V/V) including top and bottom plug at the end of fire test.

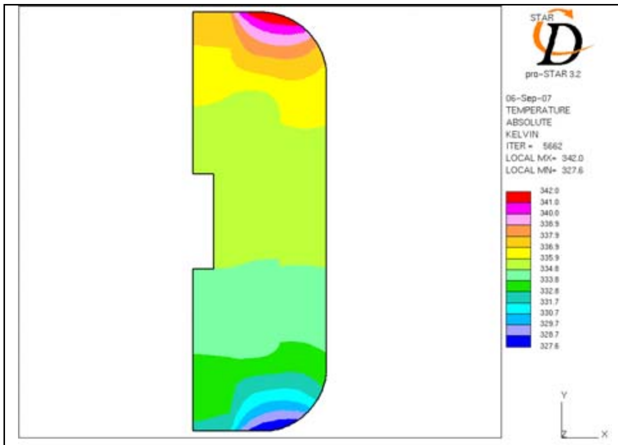


Fig.10. Temperature contours in the cask under normal conditions

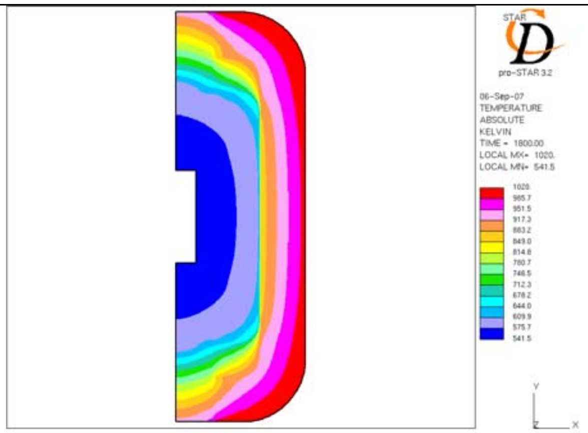


Fig11. Temperature contours in the cask at the end of the fire test (30 minutes)

Conclusion

The initial design of BI-TL-300 equipment was not meeting the regulatory criteria fully. Design optimization was carried out using PAM Crash FE Analysis. By suitably modification in the design of the cask structure, stresses in the closure bolts were reduced and are well within the limits. The outer enclosure gets completely deformed implying that the impact limiter is fully comes into action. Deformations observed in the main cask are minor.

During normal conditions of transport, cask outer surface maximum temperature is found to be 69^o C. During accident conditions, partial lead melting (i.e. 6 mm) occurred in the outer periphery which is insignificant. The analysis shows that the cask maintains its structural integrity in the 9m drop and 800^o C fire test. Experimental testing of the cask is also planned to be carried out.

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