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Postulated Accident Scenarios For The On-Site Transport of Spent Nuclear Fuel

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1. ABSTRACT

Once a spent fuel container is loaded with spent fuel it typically travels on-site to a processing building for permanent lid attachment. During on-site transport a lid clamp is utilized to ensure the container lid remains in place. The safe on-site transport of spent nuclear fuel must rely on the structural integrity of the transport container and system of transport. Regard for on-site traffic and safe, efficient travel routes are important and manageable with well thought-out planning. Non-manageable incidences, such as flying debris from tornado force winds or postulated blasts in proximity to the transport container, that may result in high velocity impact and shock loading on the transport system must be considered. This paper consists of simulations that consider these types of postulated accident scenarios using detailed nonlinear finite element techniques.

Specifically, a blast analysis is considered that simulates a blast shock load impacting a transport container and transport vehicle while in transit. It is imperative that the lid/container interface is preserved and no damage to the contents occurs. The results of the simulation show that the lid clamp retains the lid/body interface and the transport vehicle does not overturn due to the pressure pulse from the blast.

The second part of this paper deals with possible damage due to flying debris resulting from tornado force winds. There are two projectile impact scenarios:

1. Large object impact (large poles, pipes, vehicles) in the vicinity of the lid/container interface that potentially result in damage to the lid clamp and dislodging of the lid.
2. Small object impact (slender solid rods) that potentially results in through-wall penetration and loss of shielding.

Impact simulation results of these two types of objects show that for large projectiles the lid clamp retains the lid/body interface and for small projectiles there is no penetration of the container wall. This paper will only present the results of a pipe impact.

2. FINITE ELEMENT MODELS

2.1 SFC and Transfer Clamp Model

In order to assess the possible damage to the spent fuel container (SFC) during the postulated accident scenarios, a full-scale three-dimensional finite element model was developed with refinement in key areas (Fig.1). The SFC model is comprised of a high-density concrete body and lid encased in a shell fabricated from CSA G40.21M grade 300WT steel. The lid and body are attached through two flange plates made of the 300WT material. In order to allow for movement between the two flanges, a contact surface is modelled at the flange interface. The body flange plate has a raised lip around the periphery, which is used for welding the two plates together when completing the final seal.

The transfer clamp model (Fig. 3) consists of a C-shaped channel section, structurally reinforced with vertical web plates, attached to a solid shear skirt. The clamp sits around the periphery of the lid plate. The shear skirt houses a total of 26 cam pivoted clamping dogs (Fig. 2) situated along each side of the clamp (6 along each short side and 7 along each long side). When the dogs are engaged they swing under the body flange plate, containing the flange plates between the C-frame and the dogs. Attached to the bottom of the shear skirt are 8 tapered channel sections that act as lead-ins for assembly with the SFC and there is a lifting plate attached to the clamp frame in each corner.

Contact surfaces, including a stick/slip formulation are specified between each separate component [1]. In all there are 31 contact surfaces.

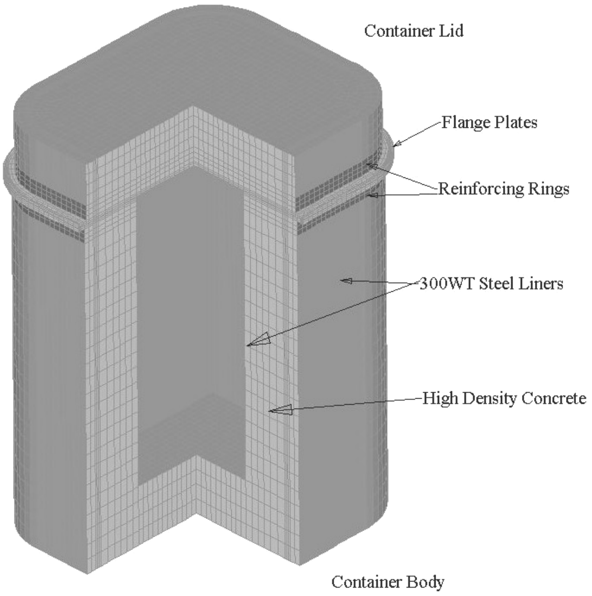

Fig. 1 – Spent Fuel Container Model

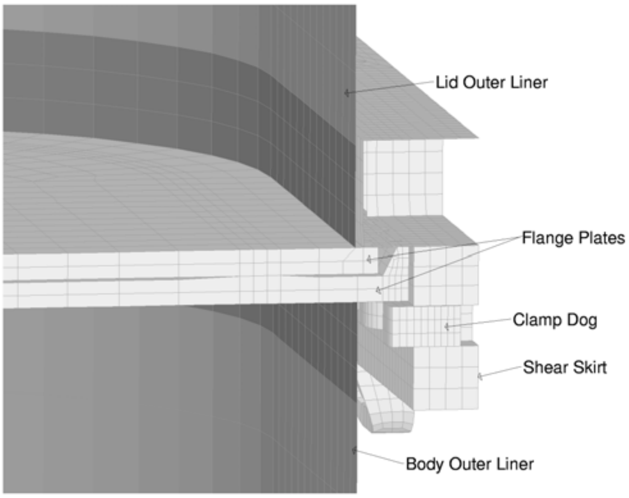

Fig. 2 - Section View of Clamp/SFC Assembly

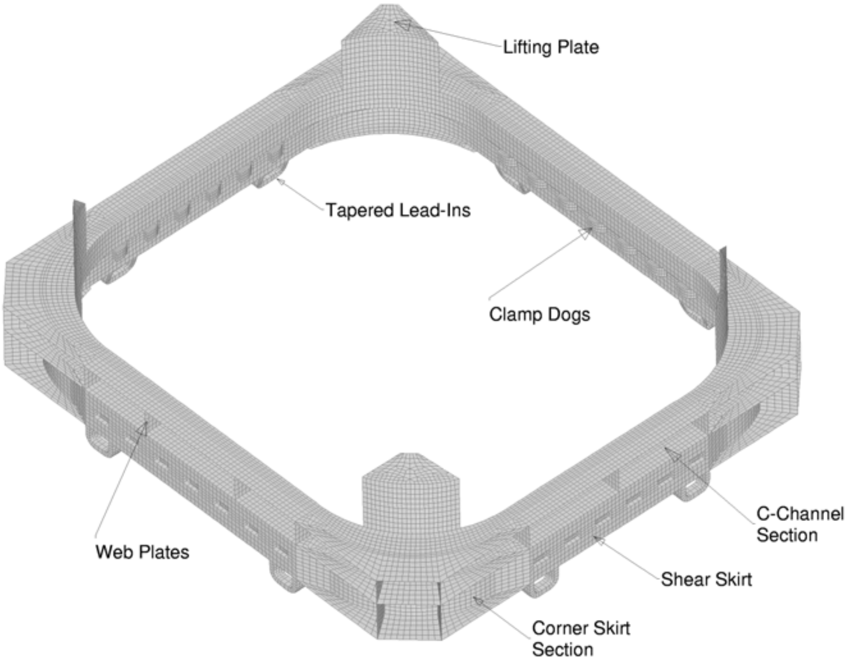

Fig. 3 – Spent Fuel Container Transfer Clamp Model

2.2 Transporter Model

The SFC transporter model shown in Fig. 4 is a custom built vehicle for transporting empty SFCs to the spent fuel bays and loaded SFCs from the fuel bays to the spent fuel storage building. The vehicle consists of a main box section frame measuring approximately 6.8 m long by 3.3 m wide. The outer box section is 0.53 m by 0.46 m and is built from 25.4 mm ASTM A709 grade 50W mild steel plate. The cross member sections are 0.30 m by 0.46 m and run between the outer frames at three locations. Located on the top of the main frame at the front of the vehicle is the drive cab. The approximate dimensions of the cab are 2.0 m by 1.6 m by 2.0 m high. Directly below the cab is the front drive assembly. The drive assembly consists of a turntable, which is attached to the steering column and a hydraulic lift arm assembly that connects to the front drive train. The two front tires are 1.27 m diameter solid rubber tires. Below the main frame just behind the cab is a steel frame cage that houses the transporter engine. On either side at the rear of the transporter is an axle assembly. Each axle houses two 1.27 m diameter solid rubber tires and is attached to the main frame through a hydraulic arm. Attached to the top of the transporter main frame near the rear of the vehicle are two lifting pins. The transporter lifts the SFC at the lifting trunnions located on either side of the container.

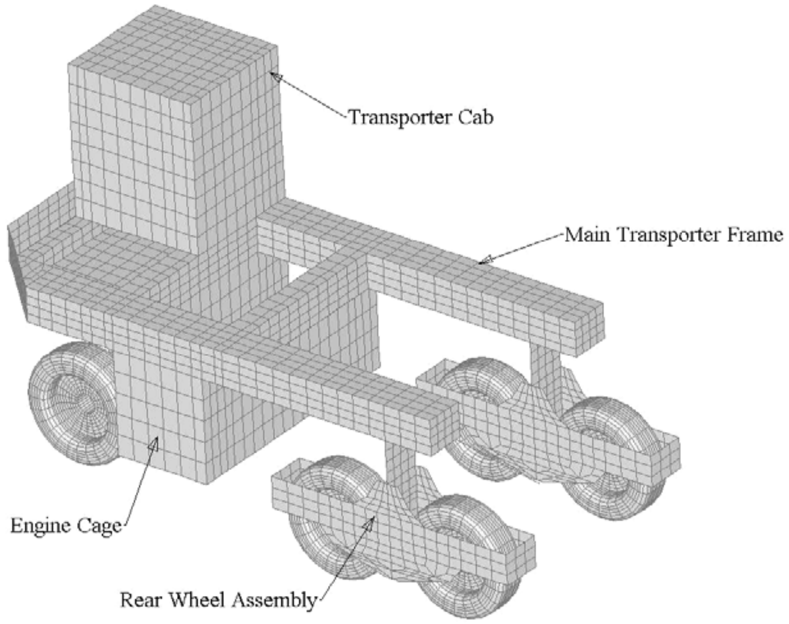

Fig. 4 – Transporter Finite Element Model

2.3 Projectile Models -Tornado Simulation

Seven tornado generated missiles are considered. Each projectile and the respective velocities are listed in Table 1. The three worst cases analysed (a utility pole, a schedule 40 pipe, and a solid rod) envelope all seven projectiles based on projectile type and the kinetic energy at impact. Table 1 outlines all seven cases and the analytical case that covers those projectiles not analysed. It is evident from Table 1 that the wood plank and automobile have lower kinetic energy at impact than the wood pole. Given that the wood pole analysis does not account for damage to the pole, these two cases are covered by the wood pole analysis. Similarly, the 3 inch and 6 inch diameter pipes having a smaller wall thickness and size than the 12 inch pipe with the same velocities and therefore are covered by the 12-inch pipe analysis.

The impact scenarios considered for the wood pole and the schedule 40 pipe are the possibility of dislodging the SFC lid and therefore the initial impact for both cases is on the side of the lid. The impact scenario considered for the solid rod is a possible penetration through the container wall. This paper will only present the results of the pipe impact.

The pipe is modelled using a total of 7,200, 4-noded shell elements with elastic-plastic carbon steel material properties. Refinement of the topology at the end undergoing impact is made in order accurately track the evolution of contact. A three dimensional single surface contact model is used in conjunction with the general arbitrary contact model to account for the possibility that the shell folds on itself during the expected severe deformation. This ensures that the correct momentum/energy transfer from the pipe projectile to the SFC/Lid Clamp assembly is achieved.

Table 1 – Tornado Generated Missile Cases

Description	Missile Mass (Kg)	Missile Velocity (m/s)	Kinetic Energy (N·m)	Covered By
Wood Plank (4” × 12” × 12’)	90.5	93.0	391,835	Wood Pole
Automobile	1810.0	23.3	492,722	Wood Pole
Wood Pole (13.5” Dia. by 35’ long)	674.0	46.7	734,960	
Steel Pipe (3” Dia. Sch. 40 by 10’ long)	35.0	46.7	38,166	12” Steel Pipe
Steel Pipe (6” Dia. Sch. 40 by 15’ long)	129.0	46.7	140,667	12” Steel Pipe
Steel Pipe (12” Dia. Sch. 40 by 15’ long)	336.0	46.7	366,390	
Steel Rod (1” Dia. by 3’ long)	3.6	69.7	8,745	

3. SIMULATION CASES

3.1 Blast Loading of SFC and Transporter

A pressure time history loading as a result of the blast is determined using the methods outlined in references [2], [3], and [4]. The blast pressure time history is determined using a surface burst type blast charge equivalent to a specified charge of TNT at a specified distance from the blast source. The characteristic shape of the blast pressure wave is shown in Fig. 5. The SFC/Transporter model, presented in Fig. 7, is treated as a rectangular structure based on the overall dimensions with the side of the transporter normal to the blast wave. The blast procedure defines a pressure time history curve for each side of the structure. Due to the relatively small width of the Transporter, the determined pressure pulse on the sides and top of the SFC/Transporter are neglected. As a conservative assumption the pressure on the backside is also neglected. The blast loading is applied to all front faces of the SFC and Transporter as a time history of element pressures. The pressure time history curved used for this load case is shown in Fig. 6.

The blast simulation on the SFC/transporter model is run to 800 ms. The overall deformation of the SFC and transporter is shown in Fig. 8. The pressure pulse impacts the facing side of the SFC and transporter resulting in a rotation of the front of the transporter. There is some rotation of the rear tire, which is pinned in the simulation but there is no evidence of the transporter tipping.

The relative displacement between the lid and body flange plates is evident in Fig. 9. The lateral clearance between the two plates is reduced and the lid flange starts to travel up the body flange lip. Inspection of the SFC and transfer clamp components indicates that there is no permanent damage to the SFC or transfer clamp.

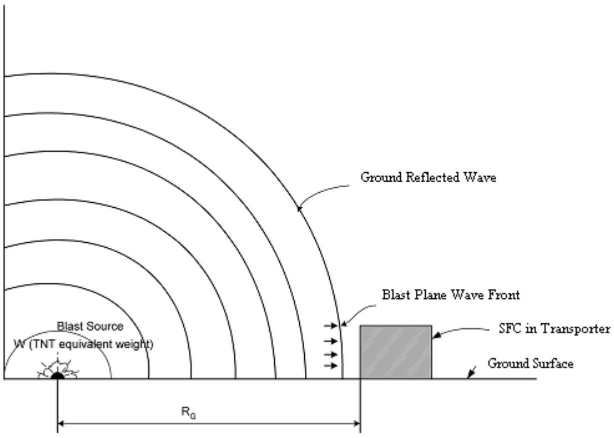

Fig. 5 – Characteristic Shape of Pressure Pulse Wave

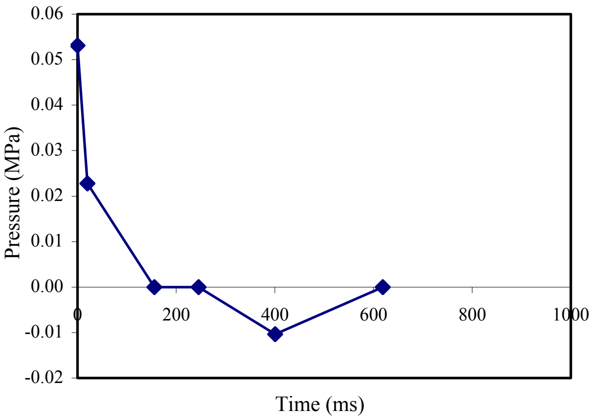

Fig. 6 – Blast Pressure Time History Load

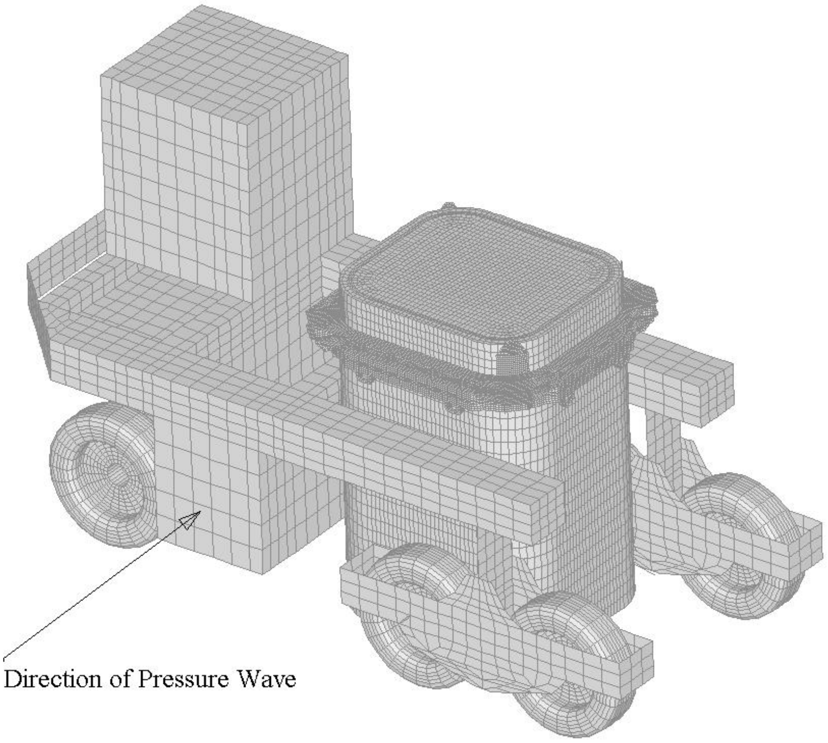

Fig. 7 – SFC/Transporter Finite Element Model

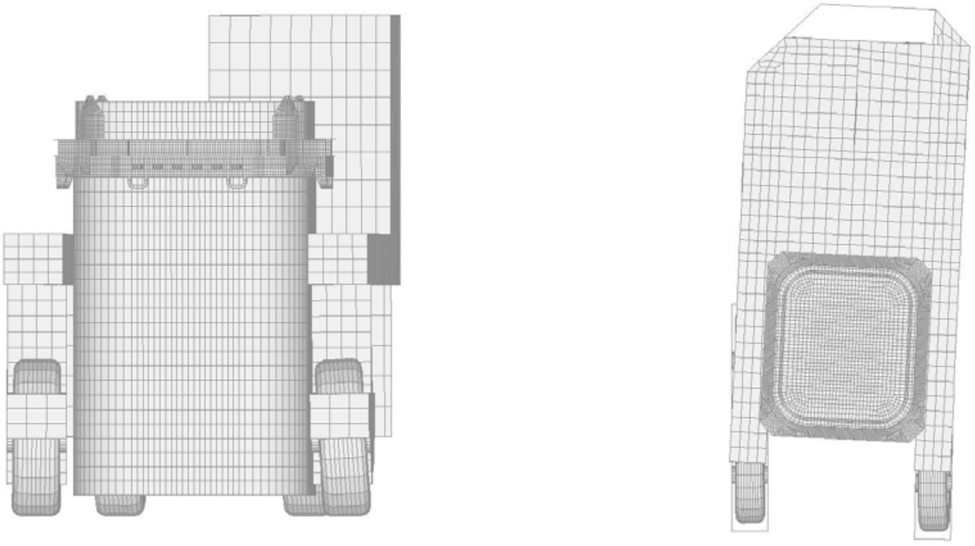

Fig. 8 – Overall Deformation of SFC/Transporter – Blast Pressure Case 1

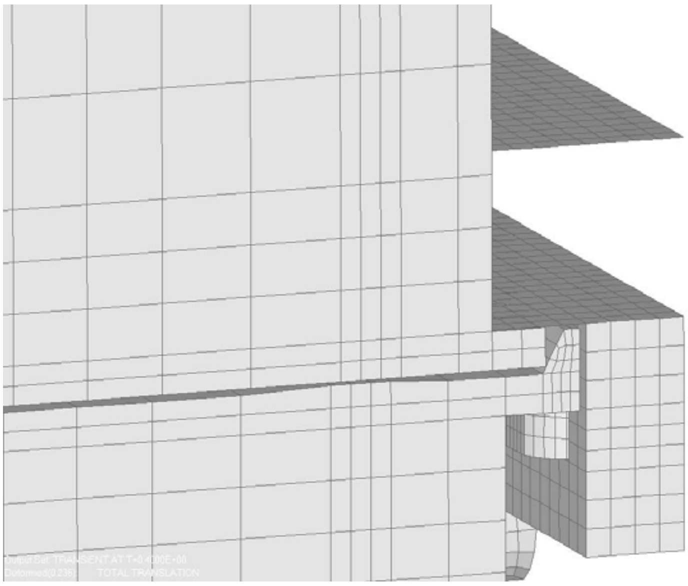

Fig. 9 - Relative Deformation of Flange Plates at Maximum Travel

3.2 Tornado Debris Impact of Steel Pipe

Two impact cases are considered. The first case scenario is the pipe's normal impact onto the SFC lid. This impact scenario concentrates the entire pipe mass onto the lid, which will try to move the lid off the container body exposing the contents. To achieve this the transfer clamp must fail. This is a conservative analysis as it is highly unlikely that a pipe in a tornado would strike the lid in this orientation. Given the length of the pipe, even a slight relative angle between the pipe and the SFC would cause the pipe to rotate on impact and reduce the energy input into the container. The second impact case scenario is the pipe impacting the SFC lid at 5° normal to the lid. For these analyses the pipe is modelled as an elastic-plastic deformable object. The impact orientation for the 5° scenarios is presented in Fig. 10. Due to the large cross section of the pipe there is no concern of penetration of the container wall, therefore this scenario is not considered.

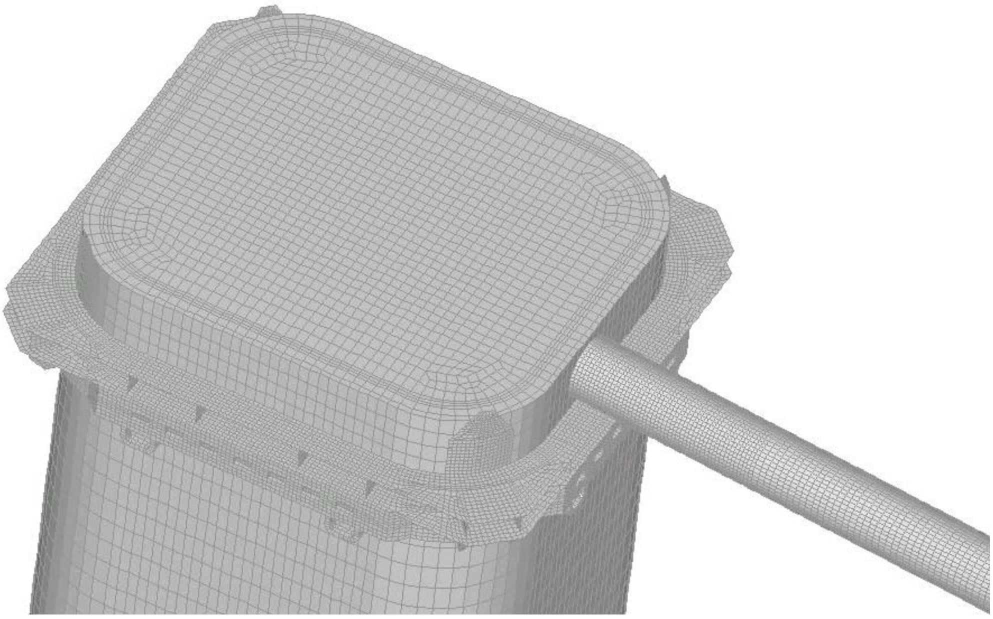

Fig. 10 – SFC/Steel Pipe Impact Scenario

The impact force time history curves for the normal impact case and the 5° impact case are shown in Fig. 11. A maximum impact force of 3.75 MN occurs at 0.5 ms for the normal impact case, which equates to a g load of 1,138. A maximum impact force of 2.55 MN occurs at 1.9 ms for the 5° impact case, which equates to a g load of 774. Comparison of the total energy input into the SFC lid for both cases is very close. The normal impact case results in a higher peak force and a lower duration compared to the 5° case. Due to the similarity in the results only the 5° case is presented.

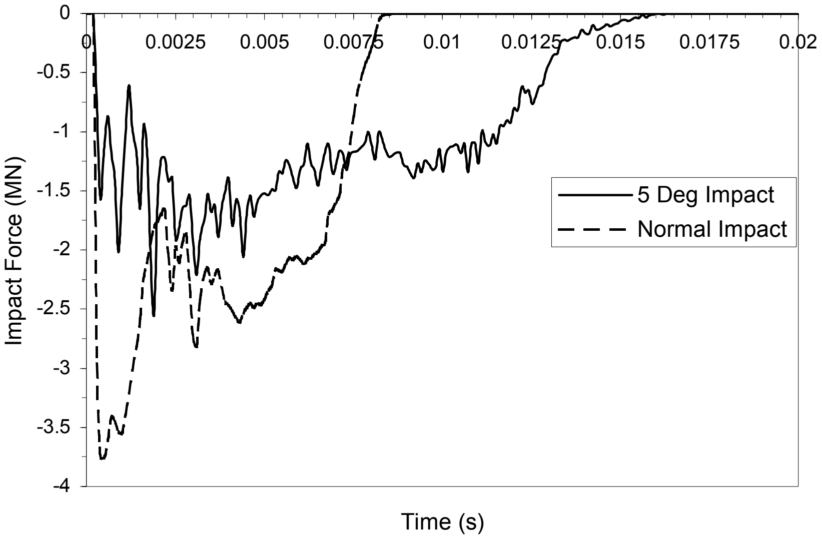

Fig. 11 – Impact Force Time History for Steel Pipe Impact

The overall deformation of the steel pipe impacting the SFC is evident in Fig. 12. The pipe impacts the SFC lid initially at a 5° angle. The impact causes the end of the pipe to deform and slide across the lid, and then rebound off the lid. The pipe end folds back onto itself to produce a flared end. The impact force pushes the lid across the body flange plate and the lid begins to separate from the container by travelling up the body flange plate lip. When all the free clearances between the lid and body flanges are reduced, the transfer clamp gets loaded. Fig. 13 shows the maximum separation of the two flange plates as the lid flange rides up the body flange lip.

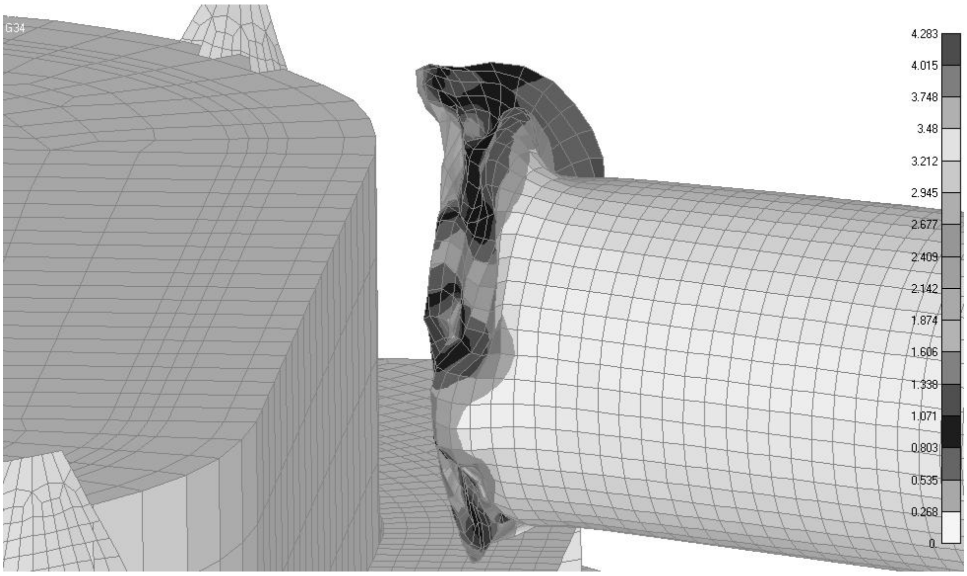

Fig. 12 – Predicted Damage to Steel Pipe

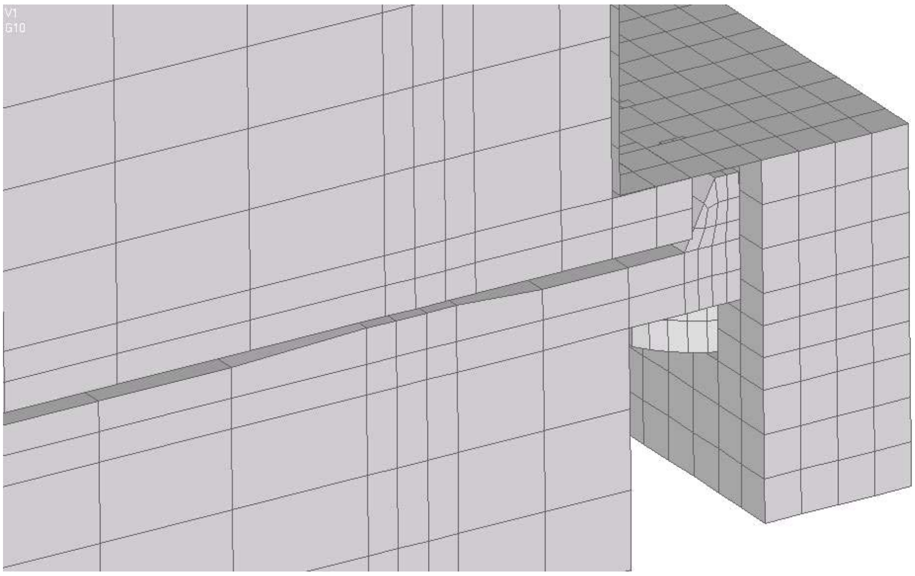

Fig. 13 – Relative Deformation of Flange Plates

4. Conclusions

The safe on-site transport of spent nuclear fuel must rely on the structural integrity of the transport container and system of transport. Non-manageable incidences, such as flying debris from tornado force winds or blast accidents in proximity to the transport container may result in high velocity impact and shock loading on the transport system.

This work shows that a simulated blast analysis resulting from the shock wave of a prescribed quantity of TNT impacting a spent fuel container and transport vehicle while in transit does not breach the lid/body interface and the transport vehicle does not overturn.

There are two scenarios resulting from projectiles due to tornado force winds:

1. Large object impact (large poles, pipes, vehicles) in the vicinity of the lid/container interface that potentially result in damage to the lid clamp and dislodging of the lid.
2. Small object impact (slender solid rods) that potentially results in through-wall penetration and loss of shielding.

Although only the pipe impact simulation is presented, results of these two types of objects show that for large projectiles the lid clamp retains the lid/body interface and for small projectiles there is no penetration of the container wall.

5. References

[1] Sauvé Richard G, et al. Contact simulation in finite deformation - algorithm and modelling issues. In: Badie, Navid, editor. Computational mechanics: developments and applications--2002: presented at the 2002 ASME Pressure Vessels and Piping Conference; 2002 Aug 5-9; Vancouver, BC, Canada. ASME PVP-441; p.3-14.

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