LS-DYNA Calculation of Blast Load on the Micro Molten Salt Reactor Designed to Fit on a Truck

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1. Introduction

Currently, large R&D efforts in Korea are performed in the framework of the Generation IV reactors that significantly improve stability and capacity to dispose of nuclear waste while maintaining the utility of existing nuclear power plants. Among them, the most popular for the micro-scale reactor is the Molten Salt Reactor (MSR) [1]. MSRs use molten salt in both nuclear fuel and coolant. MSRs have the advantage of low risk of radiation leakage as the probability of meltdown (core meltdown) accident is significantly lower than that of conventional nuclear power plants.

However, not only the safety of this engineering design but also the vulnerability of nuclear plants to deliberate attack is of concern in the area of nuclear safety. In this paper, a numerical analysis was conducted to prepare for an external missile attack, one of the threats of attack on nuclear power plants. For this purpose, a certain amount of TNT (trinitro-toluene) explosion was assumed inside the reactor, and the scattering distance of molten salt inside the MSR was evaluated through the finite element software, called LS-DYNA [2].

2. Modeling Methods

2.1 The Microreactor of MSR inside a Truck

MSRs can be applied at any scale, from small microreactors to large commercial nuclear power plants. Among them, the micro molten salt reactor can deliver power to a specific site for a set amount of time and then can be transported on a truck in a standard shipping container to another location when an energy need arises. Therefore, this microreactor technology has the potential to provide benefits to the military operations [3].

In this study a blast load on the micro MSR for military use is calculated by LS-DYNA code. This microscale of MSR is truck-transportable (see Fig. 1), with a reactor vessel inside 12.2 m length and 2.6 m height of container.

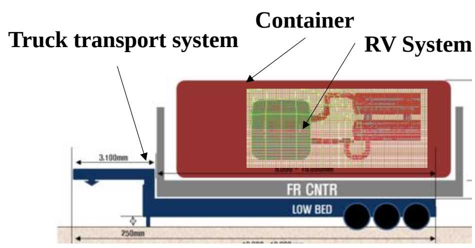


Fig. 1. A conceptual design of the micro MSR inside a truck.

2.1 SPH model

This study uses the Smoothed Particle Hydrodynamics (SPH) method available in LS-DYNA code to predict the structural response and estimate the scattering distance of the molten salt of the micro MSR.

The SPH method was initially developed by Lucy [4], Gingold and Monaghan [5] to solve problems in astrophysics [6]. Lacome [7] has implemented this method in LS-DYNA code to avoid problems associated with large mesh deformations and tangling that occurred in high velocity impact problems. In SPH method, the mesh is represented by a set of particles moving like a fluid. The main difference between classical methods and SPH is the absence of a grid. Therefore, the particles are the computational framework on which the governing equations are resolved [8].

2.2 Simulation Scenarios

Assuming the missile bombardment of MSR, a scenario according to the path of external explosives was selected (Fig. 2). Considering the TNT mass, the separation distance from the floor, and the material properties of the surrounding structures including container, a reference analysis model was developed so that it can be changed later. The penetration by attack of missile is considered through the path from external structure to molten salt inside the reactor. The diameter of the penetration is assumed to be 720 mm.

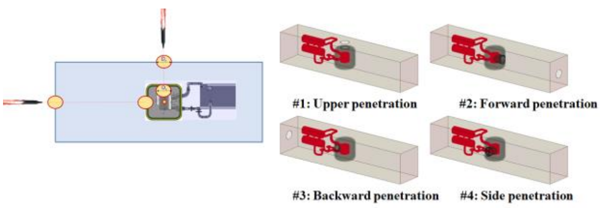
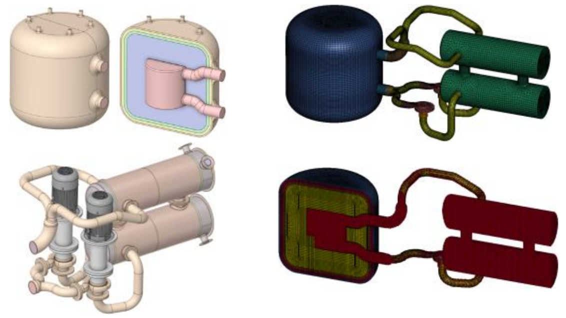


Fig. 2. Classification of the analysis scenario by penetration paths of missile attack.

2.3 Finite Element Modeling and Material Properties

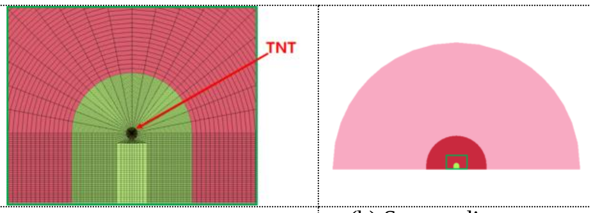
The preliminary CAD design of MSR system is applied to construct the finite element model (FEM) for LS-DYNA analysis as shown in Fig. 3. The FEM consists of shell, solid, and SPH particle models. For the initial grid of FEM, the number of node is 698,345. The number of shell, solid, and SPH is 36,504, 326,468, and 323,566, respectively.



(a) CAD model (b) FEM model

Fig. 3. Conversion from CAD to FEM model.

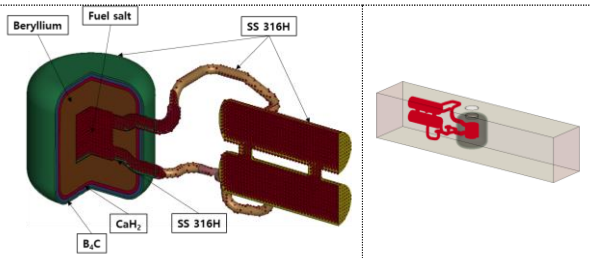
Fig. 4 shows the fluid domain for analysis of blast propagation. For the explosive model of TNT, the spherical region of the TNT mass (50kg for the present study) is assigned at the location offset from the bottom of the containment structure. The shock wave by the blast of TNT is propagated in a hemispherical space.



(a) Grid for fluid analysis (b) Surrounding space for blast propagation

Fig. 4. Fluid model for explosion of TNT

The different materials are used for the structures for FEM analysis as shown in Fig. 5. Shell models are applied for the thin walls of inner reactor vessel, coolant loop, and container. Other solid regions are treated as the solid element models.



(a) Reactor vessel and heat exchanger (b) Container: steel

Fig. 5. Materials consisting of the reactor system.

Table 1: Material properties used for structural analysis

Material	Density (g/cm³)	Modulus of elasticity (GPa)	Poisson's ratio(ν)	Yield strength (MPa)	Elongation (%)
Beryllium	1.844	303	0.07~0.18	240	3
CaH_2	1.96	-	0.22	-	-
B4C	2.3~2.55	362~472	0.18~0.21	350	-
SUS316H	8.0	200	0.3	205	30
Steel	7.85	200	0.3	250	10

Table 1 shows the material properties used for the structures of MSR. Since all property data are not obtained for LS-DYNA simulations, the missing data are replaced with other secured physical property data keeping the conservative results.

2.4 Blast Load in a Sphere

The blast of an explosive TNT liberates energy causing pressure disturbances in the surrounding space which develop into a blast wave system led by an incident shock wave.

The explosive is set with the card named *INITIAL_VOLUME_FRACTION_GEOMETRY, defining the container geometry by a sphere and following similar previous works [9,10]. As the data is required by volume, knowing the TNT equivalent and the density of the TNT introduced into the model (Table 2), the explosive volume (m^3) is calculated. The necessary data for the EOS used in this case, the traditional JonesWilkinsLee [11], are shown in Table 2.

The pressure (P) due to blast of TNT is calculated by following Eq. (1) [12]:

$$P = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

where V is the relative volume, E the internal energy, and the Grüneisen coefficient.

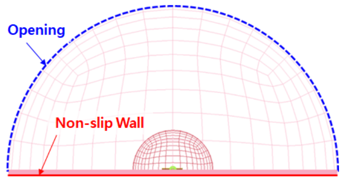
Table 2: LS-DYNA inputs for the cards *MAT_HIGH_EXPLOSIVE_BURN and *EOS_JWL

*MAT_HIGH_EXPLOSIVE_BURN					
Density [kg/m³]		Detonation velocity [m/s]		Chapman-Jouguet Pressure [GPa]	
1,600		6,730		21	
*EOS_JWL					
A	B	R_1	R_2	ω	E_0
3.738e+11	3.747e+09	4.15	0.9	0.35	6.0e+09

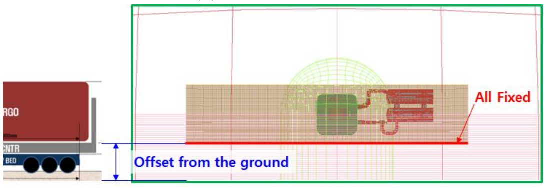
The air was modelled as a perfect gas using the material *MAT_NULL and including a density of 1.29 kg/m³, an initial internal energy of 0.25 MPa, and a specific volume of 1. The card used to describe the equation of state for the air was the *EOS_LINEAR_POLYNOMIAL, where C4 = C5 = 0.4 and the rest of constants is equal to zero [13].

2.5 Boundary Conditions

The boundary conditions for fluid domain are shown in Fig. 6(a). All the bottom walls are non-slip condition, while other regions have opening boundary. The bottom of the container has the fixed boundary condition as shown in Fig. 6(b).



(a) Fluid domain



(b) FEM and SPH domains

Fig. 6. Boundary conditions for domains.

3. Simulation Results

3.1 The Preliminary Calculation Results

Fig. 7 shows the over pressure due to blast load by 50 kg of TNT mass. The peak pressure is about 80 MPa.

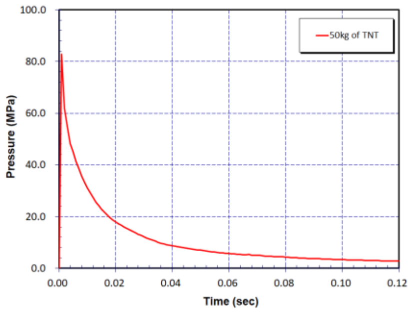
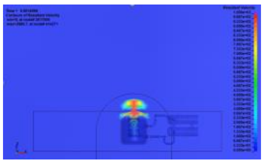


Fig. 7. A conceptual design of the micro MSR inside a truck.

For the sample results of the upper penetration case in Fig. 8, the velocity contour clearly shows the scattering of the molten salt through upward opening.



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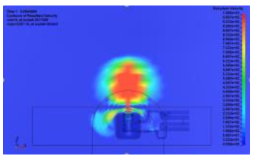

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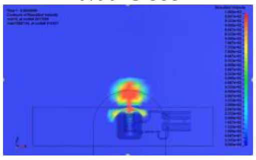

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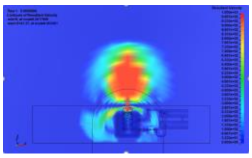

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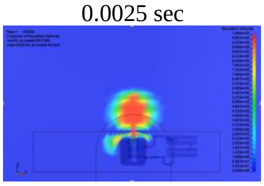

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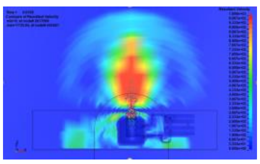

0.0105 sec

Fig. 8. Velocity contour by scattering of the molten salt.

The integrity of the structure boundary of reactor vessel is shown to be maintained from Fig. 9 with effective stress contours. Therefore, the direction of the penetration opening is very important to estimate the scattering distance of molten salt.

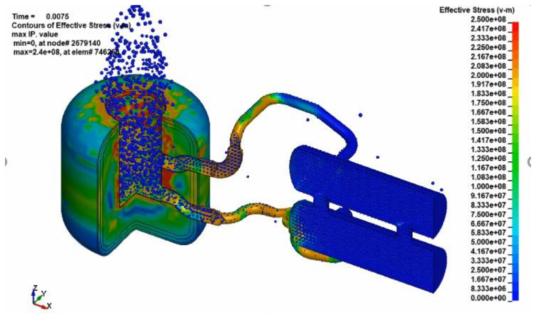

Fig. 9. Contours of effective stress (v-m) at time =0.0075 sec.

3.2 Identified Problems from the Present Calculations

The present calculations are based on coupling of fluid, structure, and SPH particle. Therefore, the computation time is too slow with a limited computing resources.

However, it is expected to shorten the computing time by assuming the boundary structure to be a rigid bod, since the damage to the boundary structure containing the molten salt is insignificant except around the penetration part.

4. Conclusions

Blast load on a truck-transportable micro MSR is simulated by LS-DYNA. The present simulation results show that the penetration path assumed by external attack of missile is a key parameter to estimate the scattering distance of molten salt. The SPH model in the LS-DYNA is also shown to be effective for simulation of the fragments of molten salt and scattering out.

For the future works, following case studies are required:

1) Change the penetration direction:
   - In the existing scenario, the penetration direction is set vertically or horizontally, so the molten salt does not spread far, which may not be conservative in terms of scattering distance.
   - Set the penetration direction to 45° for conservative scattering distance assessment.
2) Change the penetration size: By reducing the penetration diameter and so concentrating the explosion pressure, it is judged that the scattering distance can be more increased.
3) Change the TNT mass: The blast load is proportional to the explosive mass, which is effective to prediction of the scattering distance of molten salt.

ACKNOWLEDGMENTS

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