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Parameter Studies to Determine Sensitivity of Slug Impact Loads to Properties of Core Surrounding Structures

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Abstract

A sensitivity study of the HCDA slug impact response of fast reactor primary containment to properties of core surrounding structures was performed. Parameters such as the strength of the radial shield material, mass, void and compressibility properties of the gas plenum material, mass of core material, and mass and compressibility properties of the coolant were used as variables to determine the magnitude of the slug impact loads. The response of the reactor primary containment and the partition of energy were also given. A study was also performed using water as coolant to study the difference in slug impact loads.

1. Introduction

The major objective of the reactor safety analysis is to assure the public that the primary reactor containment of a liquid metal fast breeder reactor (LMFBR) can be designed to sustain the consequences of hypothetical core disruptive accidents (HCDAs) and the margin of safety provided by design with respect to structural strength and functional dependability is adequate.

In general, the destructive energy in a disassembly core can be released to the surrounding media through propagation of pressure waves and expansion of core gas. Under the action of pressure wave propagation and core expansion, the bulk of the coolant above the core will accelerate upward with a large velocity and produce a large impact force on the reactor cover. This impact force could damage the reactor upper internals, reactor cover and upper vessel wall, if it contains a sufficient amount of kinetic energy. Therefore, it is necessary to perform safety analysis to assure that the reactor cover and vessel wall will not produce excessive deformation as a result of coolant slug impact. Unfortunately, LMFBR reactors are very complex structures. To perform a manageable safety analysis, the mathematical model of the reactor internals has to be simplified. How the slug impact loads will be affected by the use of a simplified mathematical model is a concern in safety analysis. This paper deals with parameter studies to determine sensitivity of slug impact loads to properties of reactor surrounding structures. Particular attention is focused on those structures which are situated directly above the reactor core.

2. Results of Parametric Study of the Slug Impact Problem

2.1. The Reference Problem

The design of the Clinch River Breeder Reactor (CRBR) is used as the reference case to study the response of LMFBR reactors to slug impact loads. The HCDA energy used in the study has a magnitude of 661 MJ when the core gas expands from the excursion pressure (273 bars) to one atmosphere. The mathematical model used in the analysis is given in Fig. 1. The analysis was performed with the REXCO code [1]. The slug impact occurs at t = 81.60 ms after the start of excursion. The dynamic equilibrium is achieved at t = 116 ms. The maximum strain on the reactor vessel is 5.26% and the maximum strain of the core barrel is 3.58%.

The energy partitions at two instants: t = 81.60 ms and t = 116 ms are given in Table I. As can be seen, at the start of slug impact, core has released 107 MJ of energy: 78.81 MJ is the kinetic energy, 9.78 MJ is the strain energy, and 17.84 MJ is the internal energy. The sodium coolant has 29.55 MJ of kinetic energy and the core heavy materials have 25.53 MJ of kinetic energy. At the time of system equilibrium, the core has released about 130 MJ of energy, of which only 27.98 MJ is the kinetic energy, 71.04 MJ is the strain energy, 25.02 MJ is the internal energy, and 2.63 MJ is the energy loss due to impact. The sodium coolant has only 1.01 MJ kinetic energy, and the above core heavy materials have only 2.09 MJ of kinetic energy.

2.2. Hydrodynamic Modeling of Radial Shield Materials

In the computer analysis, radial shield materials are often treated as hydrodynamic materials to reduce the mesh distortions. The purpose of this study is to examine how the partition of energy will be affected by the modeling of the radial shield material as a hydrodynamic material. The configuration of the reactor and material properties used in the analysis are exactly the same as in the reference case except the removable and fixed radial shield materials are modeled as hydrodynamic material.

Since the hydrodynamic radial shields allow the core gas to expand easier in the radial direction, more core energy should be transformed into the slug in the form of kinetic energy. This is especially true at the early stage of core expansion. Figure 2 is a plot of the core energy release of the hydrodynamic radial shield model as a function of time. For the purpose of comparison, the core energy release of the elastic-plastic model is also shown. As can be seen from Fig. 2, the core energy release in the hydrodynamic model is faster than that of the elastic plastic model. The total upward axial KE at the time of slug impact for the hydrodynamic model is 69.59 MJ. It does not differ too much with that of the elastic plastic model (69.05 MJ). However, the slug impact time for the two cases is quite different. In the hydrodynamic model, it occurs at 67.68 ms whereas in the elastic plastic model, it occurs at 81.60 ms. Table II compares the partition of various energies at the time of slug impact. The upward axial KE of the sodium slug in the hydrodynamic model is only 20.93 MJ which is about two-thirds of the kinetic energy of the sodium slug in the elastic plastic model. As can be seen, a large amount of kinetic energy is in the above core heavy material and radial shield material. For the hydrodynamic model, this amounts to 43.87 MJ of energy, whereas in the elastic plastic model it has 25.53 MJ of energy. Since the radial shield material in the elastic plastic model has very little of axial kinetic energy, all the 25.53 MJ of kinetic energy can be assumed is in the heavy material above the core. Since the hydrodynamic material does not have membrane strength, the core barrel in the hydrodynamic model is deformed more than that of the elastic plastic model. It has a strain energy of 19.77 MJ at the time of slug impact.

It becomes apparent that the modeling of radial shield material as hydrodynamic material in the mathematical model will underestimate the damages produced by the slug impact and the sodium slug kinetic energy will be underestimated.

2.3. Mass of the Above Core Materials

In the current design of LMFBRs, there is a gas plenum situated on the top of the reactor core for storing fission released gases. If the subassemblies are partially melted during the excursion, the plenum will become unconnected with the subassemblies and can be moved upward under the expanding gas. The only resisting force is the inertia of the plenum. However, if the subassemblies are not melted, the motion of the plenum will be resisted by the strength of the subassemby wall. The only part that can be moved freely is the sodium coolant. For this reason, we have performed another analysis in which the plenum is replaced by sodium coolant to simulate the moving sodium. To further study the inertia effects of above core material, another analysis was performed in which the density of the plenum was reduced from the design value of 2.4841 gm/cc to 0.825 gm/cc. In other words, the plenum material is assumed to have the same density as the sodium coolant, but still has the same equation of state as before. The results of these analyses can be used to study the effects of voids on the distribution of excursion energy.

Results show that the rate of energy release in the reduced plenum mass case is faster than that of the sodium above core case even though they both have the same mass above the core gas. This is because the voids in the reduced plenum mass case provide additional volumes for core gas to expand at the early stage of excursion. However, the kinetic energy of the coolant slug in the reduced plenum mass case is less than that of the sodium above core case. The reason for this is that a part of the core release energy is expended in the compression of the voids. The slug kinetic energy curve in the reduced plenum mass case does not show any increase until 5 ms after the excursion, whereas in the sodium above case it starts at 2 ms after the excursion. The slug positive kinetic energy of the reduced plenum mass case at the time of impact is slightly less than that of the sodium above core case. The average slug velocities for both cases are about the same. The slug impact time in the reduced plenum mass case occurs at 59.28 ms, whereas in the sodium above core case it occurs at 56.44 ms. The core release energy at the time of slug impact for the reduced plenum mass case is slightly larger than that of the sodium above core case.

Table III compares the core released energy, total upward axial kinetic energy, slug kinetic energy, and slug velocity of the reduced mass case at the time of slug impact with those of the reference case. It shows that a reduction of gas plenum mass by a ratio of 2.4841/.825 = 3.01, the slug kinetic energy increases by a ratio of 1.74, the slug average and surface velocities by a ratio of 1.33 and 1.37, and the peak slug impact force by a ratio of 1.77. Since both cases have voids in the gas plenum material, the differences between the two results can be attributed due to the inertial effects of the gas plenum material.

2.4. Water Versus Sodium as Coolant

Experiments are often used to study the response of reactor primary tank under slug impact loads. However, liquid sodium at the LMFBR reactor operating temperature has a density of 0.825 and a bulk modulus of 42.992 kbars, whereas water at room temperature has a density of 1.0 and a bulk modulus of 21.786 kbars. The difference in coolant mass and compressibility will affect the speed of pressure wave propagation and the magnitude of the slug impact pressure. Thus, the response of a primary tank performed in the laboratory using water as coolant could be quite different from that of a reactor under accident condition with sodium as coolant. This has long been a concern among safety analysts. Several attempts have been made before using computer codes to study the differences in response for reactors having sodium or water as coolant. However, due to numerical difficulties, calculations were often terminated before the system has reached the dynamic equilibrium state. Since then the computer codes have been improved extensively and the techniques used in HCDA analysis are so advanced that calculation can be carried to the system equilibrium with no major difficulties. For this reason, a study was performed using water as coolant to study the difference in slug impact loads. The other material properties used in the analysis are the same as those of the reference case.

Since water is heavier than sodium, the rate of core energy release in the water case is slightly slower. But the difference is very small. The peak axial positive kinetic energy and slug axial kinetic energy in the water case has a large magnitude, but it occurs at a later time. This shows that the heavy inertia will have more constraint effect on the release of core energy. It will cause the coolant to move slower. Since the mass of water is about 20% heavier than sodium, the kinetic energy of the water slug is larger than that of sodium slug. However, this is not the case for the total axial positive kinetic energy. Since the mass of the core surrounding structures in both cases are identical, the total axial positive kinetic energy in the water case is smaller than that of the sodium case if they are compared at the same instant of time. The total axial positive kinetic energy of the water case at the time of slug impact is larger than that of the sodium case. The peak of the impact force of the two cases are about the same, but the pressure pulse of the water case has a longer duration. The residual pressures for the two cases are about the same with the sodium case having a slightly larger magnitude. However, the pulse width of each peak in the sodium case is slightly narrower.

3. Conclusions and Recommendations

The most important component of the reactor model in the slug impact analysis is the radial shield material. It must be properly modeled in the computer analysis. To model the radial shield material as hydrodynamic material will underestimate the damages of the slug impact loads. Mass of the above core materials also plays an important part in the determination of slug impact loads. If lighter masses are used in the analysis for the above core material, the sodium slug will move with a larger velocity and impact at an earlier time. To obtain the maximum impact loads as an upper bound estimate, one should replace all the above core materials with sodium coolant. Water can be used as a substitute material for sodium coolant in the laboratory tests. The slug kinetic energy and its impact forces on the reactor cover is about the same.

References

[1] CHANG, Y. W., GVILDYS, J., "Structural Dynamics in LMFBR Containment Analysis - A Brief Survey of Computational Methods and Codes," Paper E 1/1, Trans. of the 4th International Conference on Structural Mechanics in Reactor Technology, San Francisco, CA (August 15-19, 1977).

FIGURE CAPTIONS

1. Mathematical Model of the Reactor Used in the Slug Impact Analysis
2. Comparison of Core Energy Release of the Hydrodynamic and Elastic Plastic Radial Shield Models

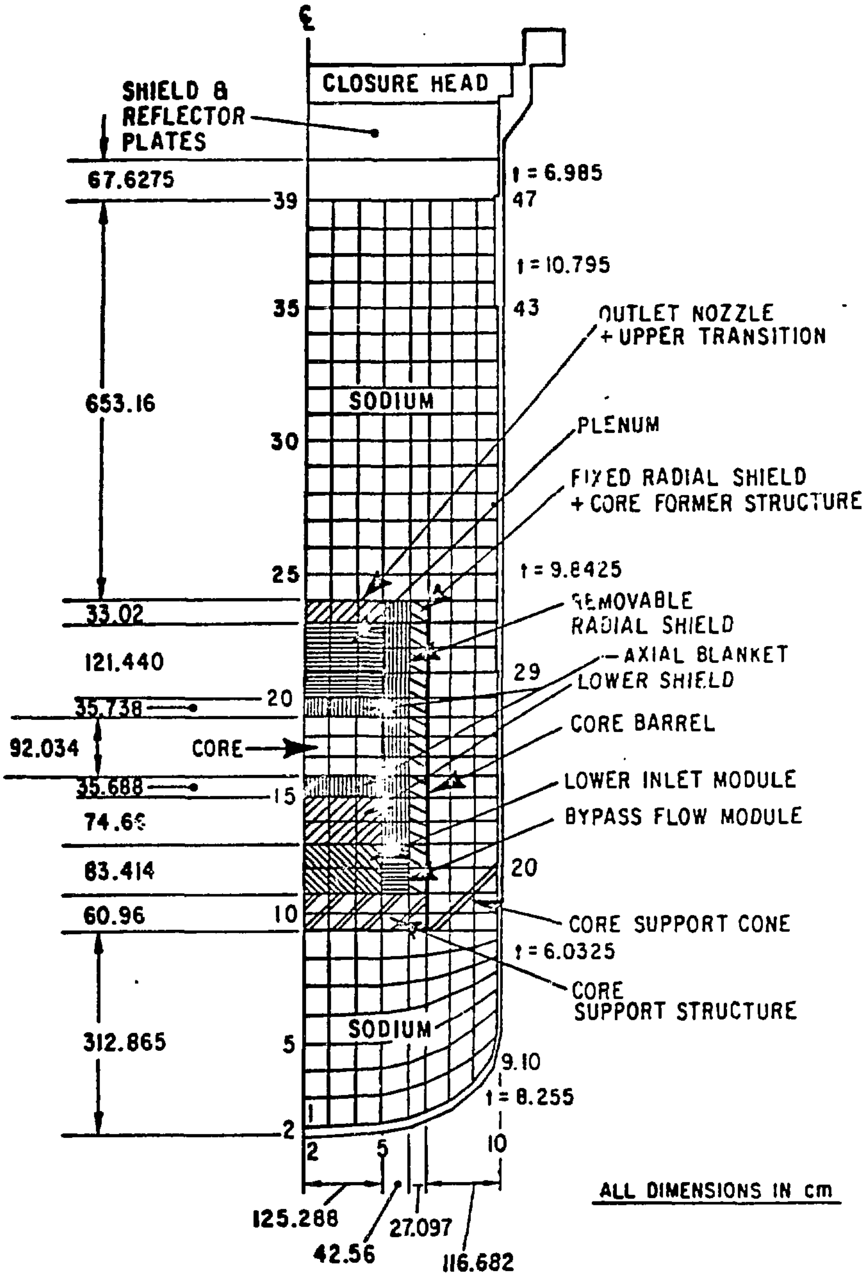

Fig. 1 Mathematical Model of the Reactor Used in the Slug Impact Analysis

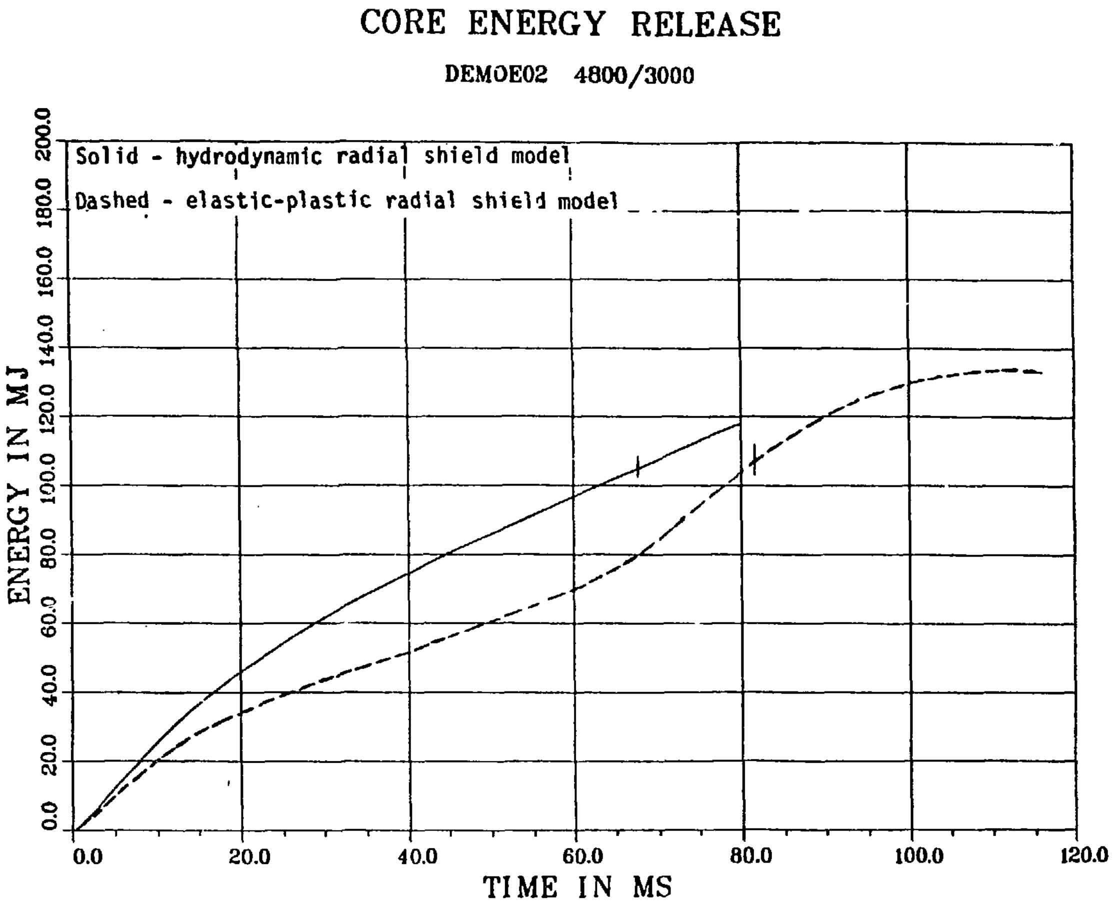

Fig. 2 Comparison of Core Energy Release of the Hydrodynamic and Elastic Plastic Radial Shield Models

Table I. Partition of Energy

Items	At Beginning of Slug Impact	At System Equilibrium
Time, ms	81.60	116
Upward Sodium Slug KE, MJ	29.55	1.01
Heavy Material KE, MJ	25.53	2.09
Core KE, MJ	13.98	19.59
Downward KE, MJ	0.14	2.15
Radial KE, MJ	9.61	3.14
Core Barrel Strain Energy, MJ	7.12	7.14
Vessel Strain Energy, MJ	2.64	63.19
Plug Energy, MJ	.02	.71
Internal Energy, MJ	17.84	25.02
Core Internal Energy, MJ	554.09	528.08
Energy Loss due to Impact, MJ	0	2.63
Total System Energy, MJ	660.52	654.75

Table II. Comparison of Partition of Energy at the Time of Slug Impact

	Hydrodynamic Modeling of Radial Shield Material	Elastic Plastic Modeling of Radial Shield Material
Slug Impact Time, ms	67.68	81.60
Upward Sodium Slug KE, MJ	20.93	29.55
Heavy Material KE, MJ	43.87	25.53
Core KE, MJ	4.79	13.98
Downward KE, MJ	0.12	0.14
Radial KE, MJ	1.85	9.61
Core Barrel Strain Energy, MJ	19.77	7.12
Vessel Strain Energy, MJ	3.93	2.64
Plug Energy, MJ	0.01	0.02
Internal Energy, MJ	9.61	17.84
Core Internal Energy, MJ	555.90	554.09
Total System Energy, MJ	660.78	660.52

Table III. Comparison of Core Energy Release, Slug Axial Kinetic Energies and Slug Velocities at Time of Slug Impact

Items	Reduced Mass Case	Reference Case
Slug Impact Time, ms	59.28	81.60
Core Energy Release at Time of Slug Impact, MJ	105.37	106.91
Total Axial Positive at Time of Slug Impact, MJ	76.45	69.20
Slug KE at Time of Slug Impact, MJ	51.58	29.60
Slug Velocity (Average), m/s	22.25	16.67
Slug Surface Velocity (Average), m/s	27.40	20.0
Peak Slug Impact Force, MN	1556.6	880.0