PREPRINT UCRL- 80562

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conf 780508--8

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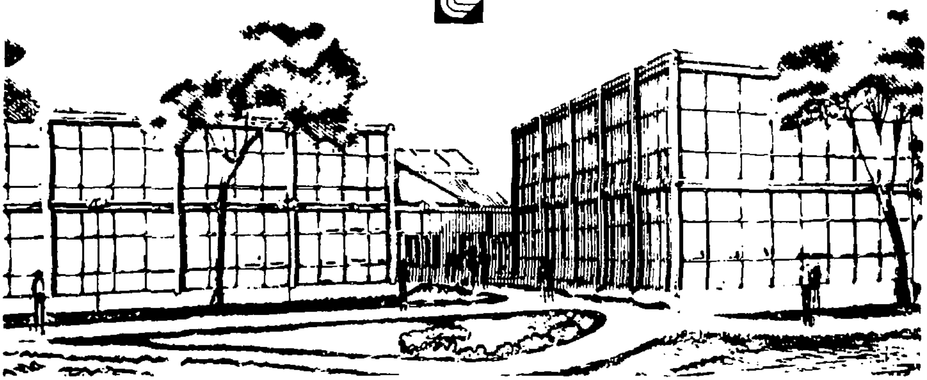
May 31, 1978

This paper was prepared for submission to the Proceedings of the Third ANS Topical Meeting on Fusion, held May 9-11, 1978, in Santa Fe, New Mexico.



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RESPONSE OF A LITHIUM FALL TO AN INERTIALLY CONFINED FUSION MICROEXPLOSION*

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One of the most difficult technology problems in an inertially confined fusion reactor is the survival of the structure from the repeated stresses caused by the microexplosion products. To mitigate the damage from the microexplosion products, a thick lithium fall can be circulated in front of the structure. This fall will absorb the short-ranged products and moderate and attenuate the neutrons. This paper discusses the response of the fall to the microexplosion products, and estimates the resulting loading and stresses in the first structural wall.

INTRODUCTION

One of the most difficult technology problems in an inertially-confined fusion reactor is the survival of the first wall from the repeated stresses caused by the microexplosion products. The short ranged products such as soft x-rays and charged particle debris are deposited in short times such that pressure pulses are produced in the first wall causing it to have a much shorter lifetime than the remainder of the power plant.[1,2] In addition, damage from the high energy neutrons can result in a shortened structure lifetime.[3] To mitigate the damage from the microexplosion products, a

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore Laboratory under contract No. 7405-Eng-48.

thick lithium fall can be circulated in front of the structure.[4] This fall will absorb the short ranged products and moderate and attenuate the neutrons. Thus, in principle, the structure can have a lifetime approaching that of the power plant.

A conceptual lithium fall protected reactor is being designed by a team including LLL, LMEC and AI.[5-10] This paper describes the output from a 2700 MJ microexplosion, the interaction of the microexplosion products with the fall, the response of the fall, and the resulting loading and stresses in the reactor structure. The calculations are based on a one meter thick fall in a four-meter radius chamber in spherical geometry for initial fall inner radii between 0.5 m and 2.5 m.

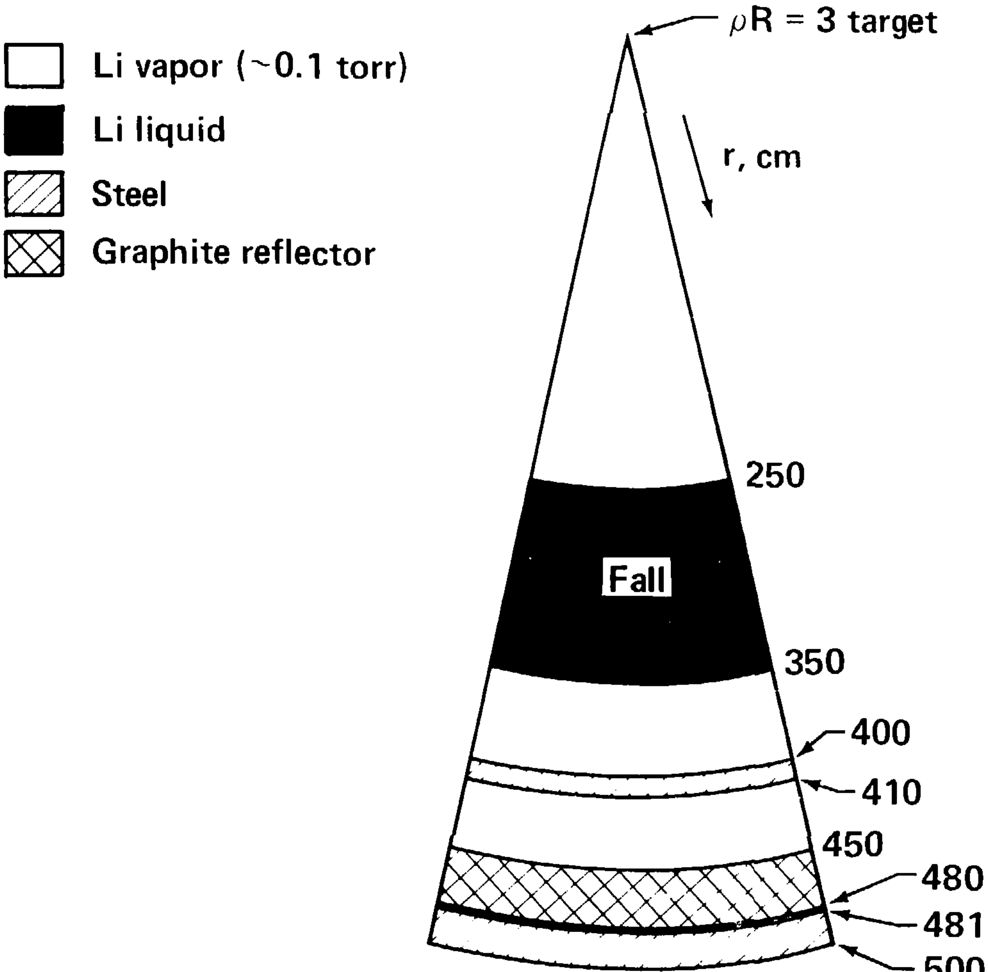
THE MICROEXPLOSION PRODUCTS

The D-T fusion reactions in the compressed target (ρR_{fuel} ~ 3) release about 80% of their energy as 14.1 MeV neutrons and 20% as 3.5 MeV alpha particles. However, the alpha particles and some of the neutrons are attenuated and absorbed in the compressed target. Of the 2700 MJ produced by D-T reactions, 35 MJ is lost due to endoergic neutron reactions in the target, 1800 MJ escapes the target as neutrons, and the remaining 865 MJ escapes as x-rays plus energetic target debris. The x-rays include a hard component generated from the hot burning pellet and cold components radiated from the cooling debris as it expands.

INTERACTION OF MICROEXPLOSION PRODUCTS WITH THE FALL

The geometry used in our 1-D Monte Carlo neutronics calculations using the TARTNP code[11] is shown in Figure 1. The x-ray deposition profile was calculated using the BUCKLE code,[12] and the debris deposition was determined analytically using previously described methods.[13]

The energy flow in the reactor is shown in Figure 2. The soft x-rays and debris are absorbed in a thin region at the inner surface of the fall. The neutron plus gamma ray energy is increased by 27% in the reactor primarily due to the exoergic ^{6}Li-neutron capture reaction. The fall absorbs 92% of the neutron plus gamma energy. Of the total 3156 MJ_t, 94% is absorbed by the fall, 6% is absorbed in the walls and reflector, and only about 0.01% leaks from the reactor vessel.



Li vapor (~0.1 torr)
Li liquid
Steel
Graphite reflector
ρR = 3 target
r, cm
250
Fall
350
400
410
450
480
481
500

Fig. 1

ENERGY FLOW THROUGH THE REACTOR CHAMBER

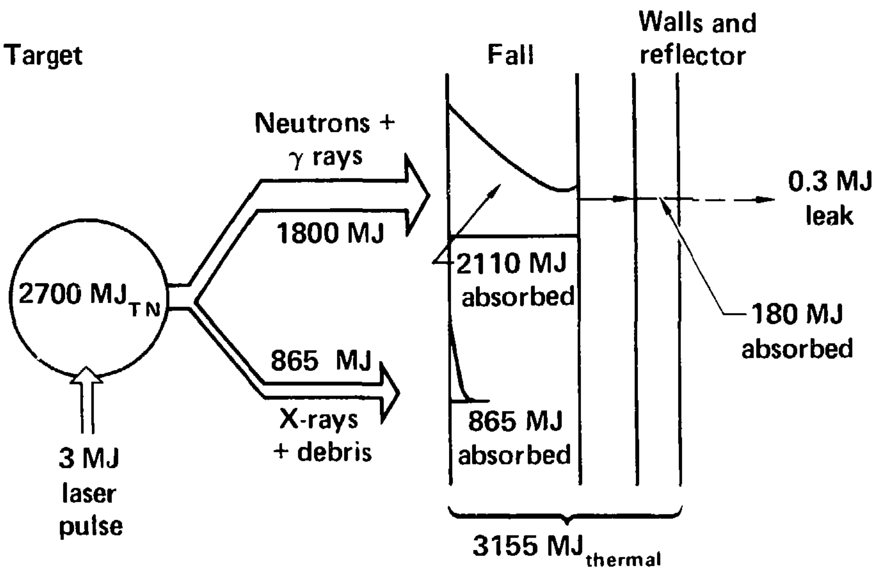


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Fig. 2

QUALITATIVE RESPONSE OF THE FALL

The x-ray and neutron energy deposition times are much shorter than the time for an acoustic wave to traverse their deposition regions.[1] Consequently, a pressure rise occurs which violently disassembles the fall since the liquid lithium is assumed to have no tensile strength. The debris energy arrives over a much longer period of time; therefore, the pressure rise in the fall due to debris energy deposition is small relative to that of the x-rays and neutrons.

The liquid strikes the structural wall causing both erosive and inertial loading. Our initial calculations used spherical geometry with a point source and cylindrical geometry with a line source. These geometries produce the worst loading on the structural wall. Several alternate geometries that could mitigate the loads are described in a later section and in another paper.[5]

Figure 3 shows a snapshot of the reactor at 50 ns. The x-ray pulse arrived at 3 ns and the soft portion was absorbed near the inner edge of the fall. The resulting high energy density in the thin region vaporized a portion of the liquid. This very hot gas is moving inward toward the chamber center, while a pressure wave is moving outward through the liquid with a velocity of about 0.5 cm/μs.

Figure 4 shows a snapshot of the reactor at 50 μs. The hot gas has filled the chamber center and is beginning to exert outward pressure on the fall. The soft x-ray induced pressure wave is now about 25 cm into the fall. The target debris was absorbed by the hot gas. The neutron energy was deposited throughout the fall (primarily in the 55 ns - 1 μs time frame) resulting in a sudden temperature rise in the fall. The thermal expansion waves are already moving both surfaces of the fall.

Figure 5 shows the velocity distribution of the fall at 200 μs when both the x-ray induced and neutron induced pressure waves have traversed the fall thickness. The narrow x-ray pulse spalled the outer few cm of the fall, and the thermal expansion due to neutron deposition produced a velocity profile in the fall. Although the thermal stress has been relieved, the fall will continue to expand because of its inertia. Finally, the hot vapor in the reactor center is pushing outwards on the fall.

LITHIUM FALL RESPONSE TO THE FUSION MICROEXPLOSION – I

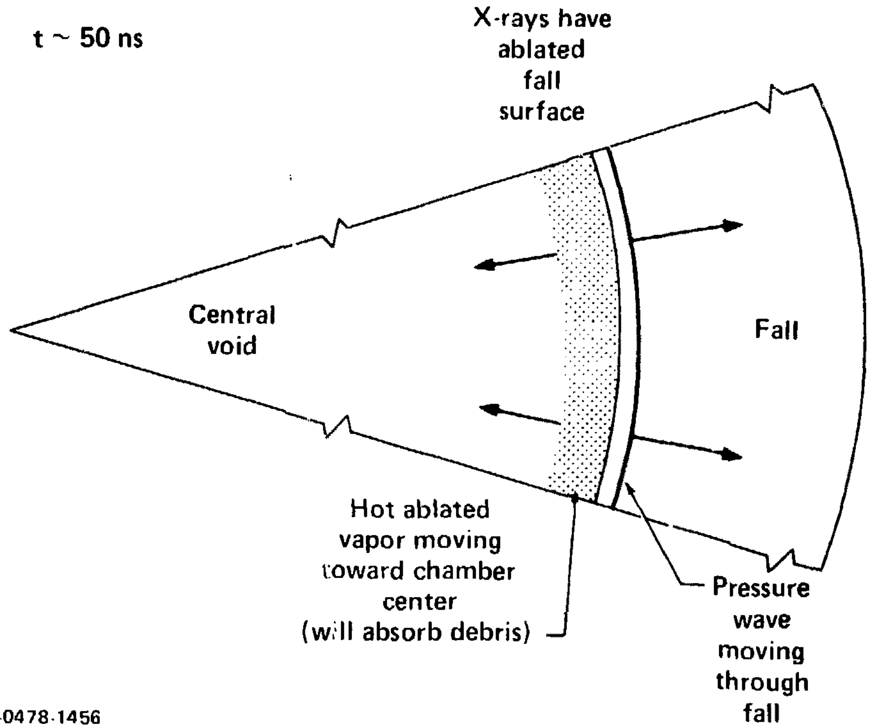

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Fig. 3

LITHIUM FALL RESPONSE TO THE FUSION MICROEXPLOSION – II

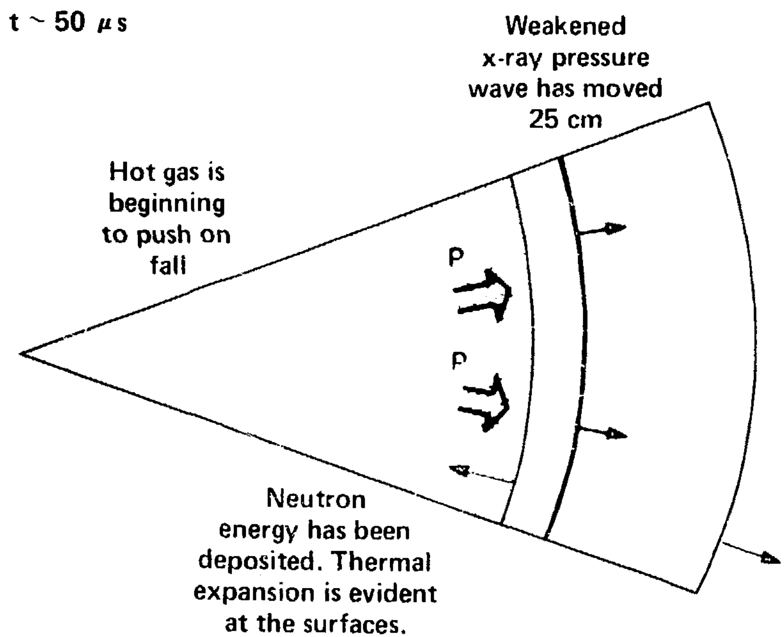

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Fig. 4

LITHIUM FALL RESPONSE TO THE FUSION MICROEXPLOSION – III

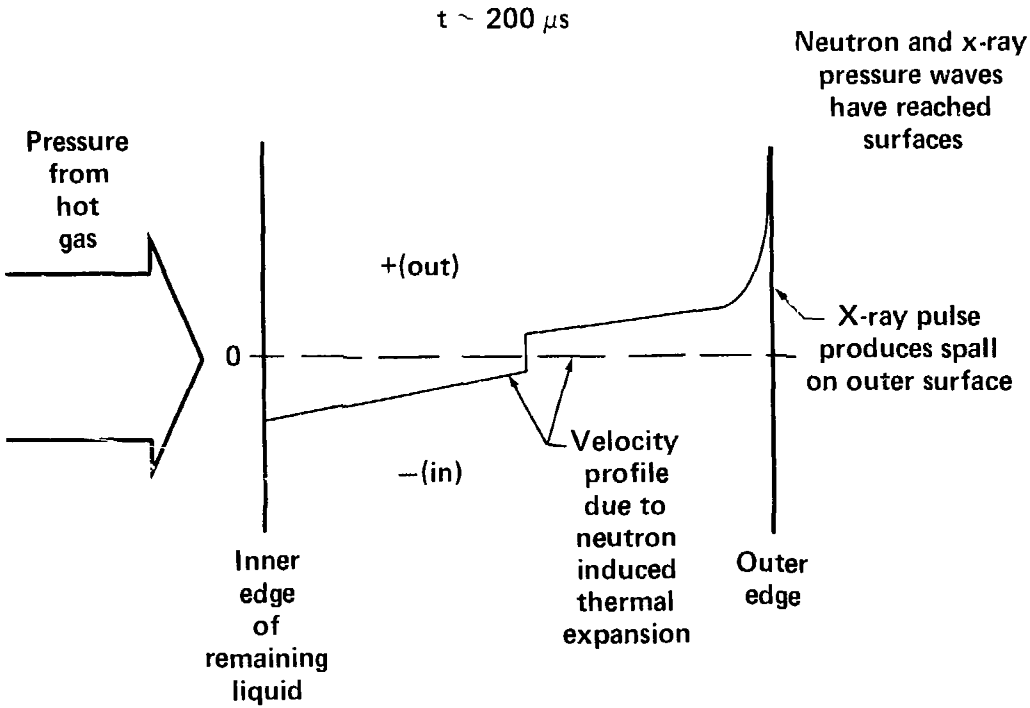

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Fig. 5

As time progresses, the leading edge of the fall (x-ray spall region) breaks into drops because of its velocity profile and the diverging geometry. Meanwhile, the majority of the fall is being compacted into an accelerating liquid slug. Figure 6 shows the two possible fall profiles at the time when the leading edge of the fall strikes the wall. If the spall velocity is high and if the fall is initially much closer to the wall than the microexplosion, the fall will impact as shown on the left. If the spall velocity is low and if the fall is initially far from the wall, the slug will overtake the drops before impact on the wall as shown on the right.

RESPONSE OF FALL TO ENERGY DEPOSITION

For energy deposited in a period of time so short that the pressure cannot relieve itself during the deposition time,[14] the pressure rise at any position x is

$$\Delta P(x) = \rho\Gamma[q'''(x)/\rho] \qquad (1)$$

where ρ and Γ are the density and the Gruneisen constant of the material, and $[q'''(x)/\rho]$ is the energy deposition per unit mass at position x. A relief wave moves into the material, and spalls the surface if the tensile strength is exceeded.

For a liquid with essentially no tensile strength, the velocity of the spalled material at any position x is given by

$$v(x) = \lim_{\delta \to 0} \left(\frac{1}{2\rho c \delta} \int_{2x}^{2(x+\delta)} \Delta P(y) dy \right) \qquad (2)$$

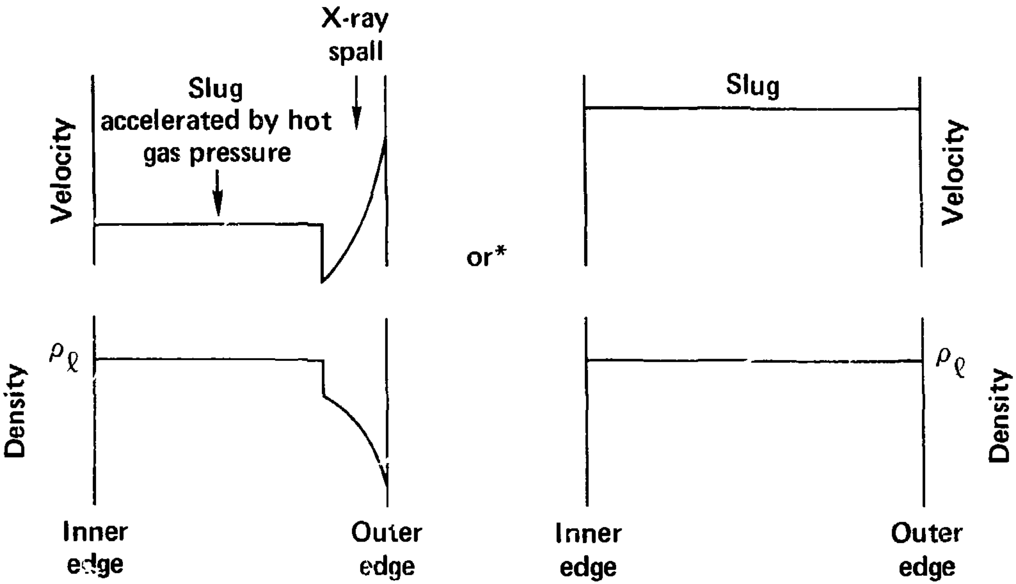
where c is the acoustic velocity of the material, and $\Delta P(x)$ is given above.

Consider the following cases for the energy deposition profile in a material: For

$$[q'''(x)/\rho] = [q_0'''/\rho] \left(1 - \frac{x}{\lambda}\right) \qquad (3)$$

LITHIUM FALL RESPONSE TO THE FUSION MICROEXPLOSION – IV

Fall at impact on wall (5–50 ms)



*Depends on geometry and pellet yield

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Fig. 3

where $[q_0'''/\rho]$ is the energy deposition at the surface

$$\Delta P(x) = \rho\Gamma[q_0'''/\rho]\ (1 - \frac{x}{\lambda}) \qquad (4)$$

$$v(x) = \frac{\Gamma}{c}\left[\frac{q_0'''}{\rho}\right]\left(1 - \frac{2x}{\lambda}\right) \qquad (5)$$

For

$$q'''(x)/\rho = \left[\frac{q_0'''}{\rho}\right] e^{-\sigma x} \qquad (6)$$

$$\Delta P(x) = \rho\Gamma[q_0'''/\rho]\ e^{-\sigma x} \qquad (7)$$

$$v(x) = \frac{\Gamma}{c}\left[\frac{q_0'''}{\rho}\right] e^{-2\sigma x} \qquad (8)$$

The use of these models is described below.

RESPONSE OF THE FALL TO NEUTRONS

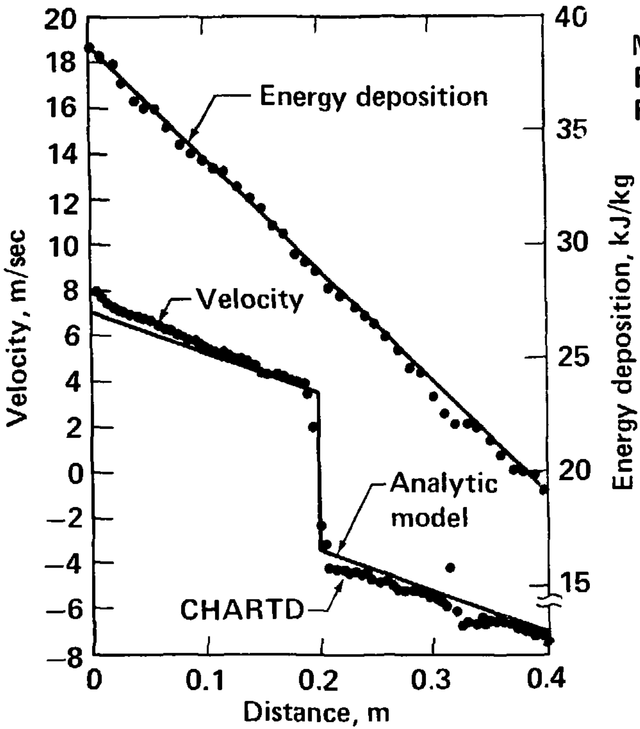
The neutron energy is deposited throughout the thickness of the fall since the 14 MeV neutron mean free path in lithium is long. Therefore the pressure rise in the lithium is small because the specific energy is small. The fall disassembles into the cavity from the front surface with a relief wave moving into the fall at about the acoustic velocity of the material.[15] The velocity of the spalled material into the chamber is essentially as given above for the appropriate energy deposition profile. The momentum from the spalled lithium causes the back surface of the fall to move toward the structure with a velocity profile that is the mirror image of the lithium moving into the cavity (Figure 7). The lithium striking the structure will be a mixture of vapor and droplets because of the velocity profile and the geometrical divergence.

A coupled radiation-hydrodynamic code, CHART D[16] was used to evaluate the analytic results (Figure 7). The analytic model describes the response of the fall to the neutrons very well.

RESPONSE OF THE FALL TO γ-RAYS

The hard x-rays have little effect on the motion of the fall due to their low specific energy. The range of the soft x-rays in the lithium fall is short relative to the neutrons, resulting in high specific energies and associated high pressures at the inner surface of the fall. The analytic model

RESPONSE OF LITHIUM FALL TO NEUTRON ENERGY DEPOSITION



Microexplosion energy = 750 MJ
Fall inner radius = 2 m
Fall thickness = 0.4 m

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Fig. 7

used for neutron deposition produced spall does not apply here because the material properties vary over the large pressure gradient in the thin deposition region. The large pressure gradients cause the pressure wave to form a shock wave moving through the fall. However, the relief wave from the front surface travels faster than the shock wave so that the pressure wave moving through the fall is highly attenuated by the time it reaches the back surface of the fall.

Because of the large pressure gradients, the response of the fall to x-rays is calculated using codes such as CHART-D[16] or AFTON.[17,18] The fine zoning required to adequately represent the x-ray energy deposition in the fall requires excessively long computational times using CHART-D. The zoning problem has been solved using the variable zoning option of AFTON. In this option, the problem initially has fine zones in the deposition region and coarse zones elsewhere. As time progresses, the zones are resized such that fine zoning is always present in the region of the moving pressure pulse.

Since the ultimate target design is still unknown, a wide range of x-ray yield fractions and spectra must be considered. We are unable to consider actual target parameters here. However, for a $\rho R3$ target, about 32% of the output is in x-rays and debris. From a worst case view, if all of this energy is in soft x-rays, the spall velocity may be several hundred times the neutron spall velocity. On the other hand, if all the energy is in hard x-rays, the spall velocity may be of the same order as the neutron spall velocity. Of course, both of those views are unrealistic, but they do bound the parameter space. Because the equation of state used for these calculations needs improvement, the results have large error bars.

At first glance, the above results are discouraging; however, due to the diverging geometry and the velocity profile in the spall, the leading edge of the fall strikes the wall as a series of drops. Although the pressure under each of these drops is very large, the pressure duration is small, resulting in low hoop stress (cf. equation (11) in a later section). Further, the relatively long time between pressure pulses permits relief of the hoop stress between impacts. Therefore, the inertial loading of the wall by the x-ray spall is not significant. Because of the insensitivity of the hoop stress to the x-ray spall velocity, we have used a value of ten times the neutron spall velocity in the remainder of this paper. However, the erosive loading of the wall is very dependent on the x-ray spall velocity. The erosive loading of the wall will be addressed later in the reactor study.

EFFECTS OF VAPORIZATION

Lithium ablated from the fall by the x-ray deposition converges toward the reactor center and absorbs the target debris energy. Within tens of microseconds, this hot lithium vapor fills the central chamber and exerts pressure on its container, the fall. Detailed calculations of the pressure require an accurate equation of state; however, we have made crude estimates using the two simple models described below.

1) The x-ray energy is input as a surface heat flux. An energy balance between heating, thermal conduction into the fall, and evaporation is performed. Recondensation of vapor is not included in the model.

2) The x-ray energy is deposited instantaneously. Any lithium receiving more than the latent heat of vaporization (21 kJ/g) is vaporized. Recondensation or heat conduction before vaporization is not included in the model. The two models give remarkably agreeable results.

FALL RESPONSE TO CAVITY PRESSURE

The fall response to the cavity pressure is determined by solving the equation of motion of a spherical shell with internal pressure and no stress.[19] The cavity gas is treated as an isentropic expansion of a monatomic gas. The velocity of the fall at radius r is

$$v(r) = \sqrt{\frac{PAr_0}{m}\left[1 - \left(\frac{r}{r_0}\right)^{-2}\right]} \qquad (9)$$

where P, A, r_0 and m are the initial cavity pressure, inner surface area, radius, and mass of the fall respectively. The time of arrival of the fall at a radius r is

$$t(r) = \sqrt{\frac{mr_0}{PA}\left[\left(\frac{r}{r_0}\right)^2 - 1\right]} \qquad (10)$$

WALL RESPONSE TO LIQUID IMPACT

The pressure of liquid colliding with the wall is $P = \ cv$, where v, c, and are the velocity, the acoustic velocity, and the density of the condensed lithium. The pressure pulse width is $= w/c$ where w is the thickness of the condensed lithium region impacting on the wall. The stress in the wall due to the condensed phase lithium impact is approximately

$$\left(\frac{P}{\ }\right)\left[1-\cos\left(\sqrt{2(1+\ )}\left(\frac{w}{R}\right)\left(\frac{c_w}{c}\right)\right)\right] \qquad (11)$$

where c_w, R, , and are the acoustic velocity, radius, thickness, and Poisson's ratio of the wall, respectively.

The hoop stress from the impact of the condensed phase is minimized if

$\left(\frac{w}{\ }\right)$ is small.

Thus

$$c_w v\left(\frac{c_w}{c}\right)\left(\frac{W}{\ }\right)\left(\frac{w}{p}\right)\ \sqrt{(1+\ )} \qquad (12)$$

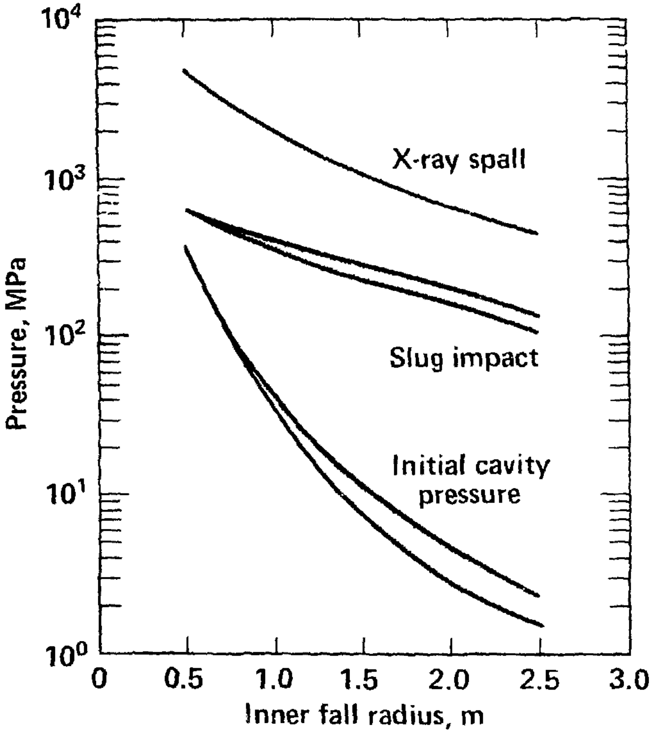
For a given velocity of a thick slug of condensed phase lithium, the stress is minimized by using a large, thick structure.

For droplets of a reasonable velocity, the hoop stress in even a relatively thin wall is small. However, the localized pressures under the drops are still proportional to (ρcv). These pressures, while not producing a high hoop stress in the structure, will cause localized spall on the surface of the structure, gradually eroding it.

QUANTITATIVE RESULTS

The methodology described above was used to analyze the response of the fall and estimate the stress in the wall from the fall impact. The 2700 MJ microexplosion was contained in a 4 m radius wall protected by a one meter thick fall placed in various initial positions. The cavity pressure from the two thermodynamic models used for estimating the vaporization from the inner fall surface is shown in Figure 8. The velocities of the slug, neutron spall and x-ray spall are shown in Figure 9. The x-ray spall velocity was assumed

LITHIUM IMPACT PRESSURE ON STRUCTURE AND CAVITY PRESSURE



Microexplosion energy = 2700 MJ
Lithium thickness = 1 m
Structure radius = 4 m

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Fig. 8

IMPACT VELOCITIES OF LITHIUM ON THE STRUCTURE

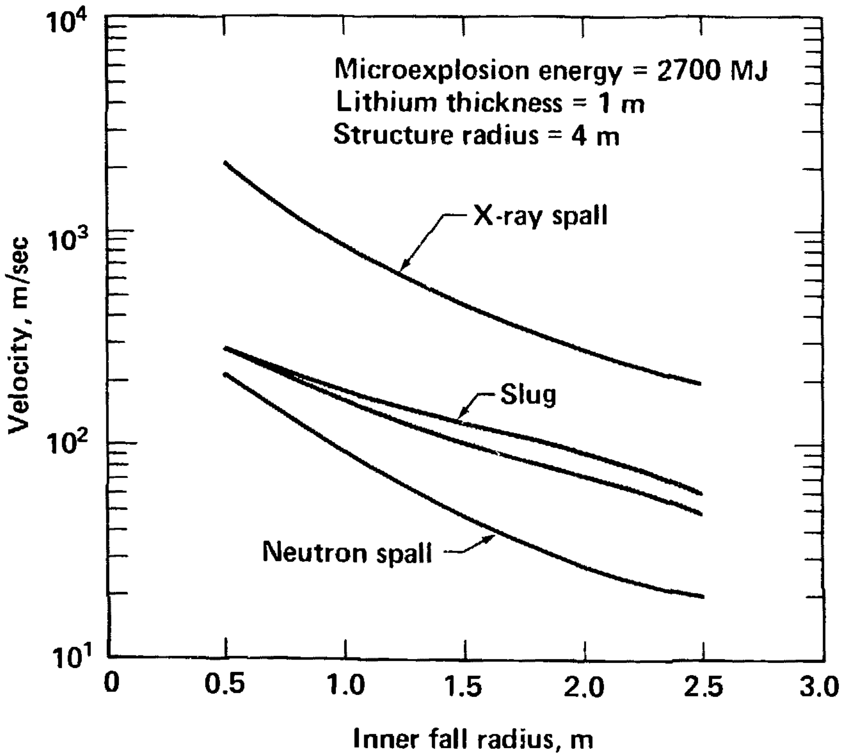

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Fig. 9

to be ten times the neutron spall velocity. Arrival times at the structure for the x-ray spall, the neutron spall, and the liquid slug are shown in Figure 10. Note that although the slug has a higher terminal velocity than the neutron spall, it arrives at the structural wall at the same time as the neutron spall and at a later time than the x-ray spall. The pressure on the wall due to the slug impact and x-ray spall impact are shown in Figure 8.

The product of the wall thickness and the hoop stress in the wall due to the slug impact is shown in Figure 11. This stress increases with the initial inner fall radius in spite of the decreasing slug velocity and pressure. The reason for this apparent anomaly is that for a given fall thickness, the slug thickness at the wall is much smaller for a small initial inner fall radius. Therefore, the pressure duration is less, resulting in a lower stress. The erosive pressures from the x-ray spall are also shown in Figure 11.

DISCUSSION OF RESULTS

The results for the 2700 MJ microexplosion are promising for a one meter thick fall with an inner radius less than 1.5 m and a wall radius of four meters. The structural wall thickness can be less than 0.1 m (R_w/Δ_w ~ 40) with hoop stresses of 100 MPa (1 kbar). For reasonable temperatures of about 700K the wall should have a lifetime of about 30 years if the erosion rate is small and if the effects of lithium corrosion and neutron damage on the strength of the wall material are not excessive. The small inner fall radius is also desirable from liquid lithium pumping power and tritium inventory considerations.

The effect of the x-ray spall erosive pressures on the wall lifetime have not been analyzed. The hoop stress from this pressure is very low, but the rate of removal of structural material is currently unknown. In addition, this erosive pressure from x-ray spall is only an estimate based on ten times the pressure of the neutron spall. To get better quantitative results, additional work needs to be done to determine the equation of state of expanded lithium and the opacities of lithium for low energy photons.

Other fall arrangements could reduce the loads on the wall. If liquid-liquid collisions are not perfectly elastic, multiple cylindrical falls or a series of small circular jets will reduce the wall loading (due to thermal dissipation and motion in the z and θ directions, (i.e., increased entropy) as

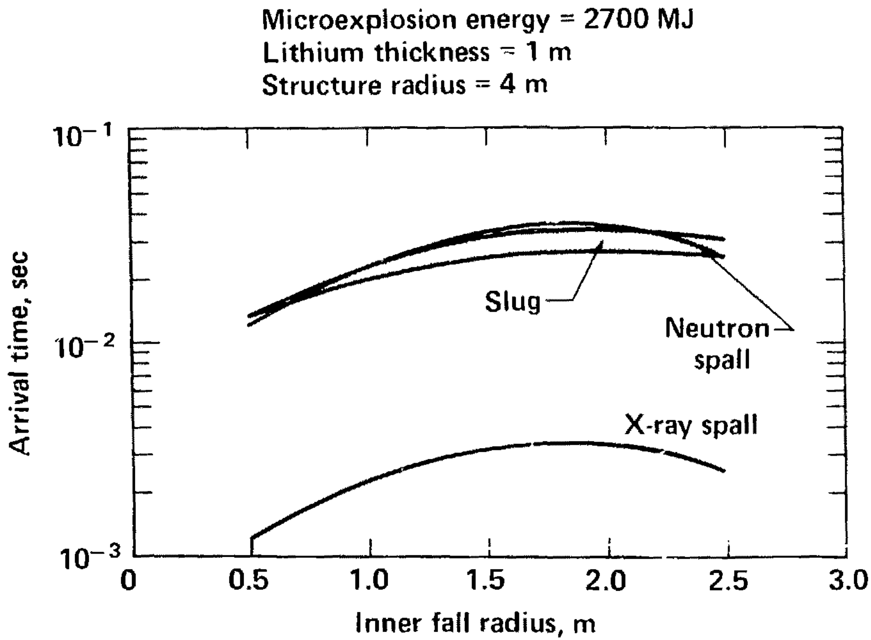

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Fig. 10

STRUCTURAL HOOP STRESS FROM SLUG IMPACT AND EROSIVE PRESSURE FROM X-RAY SPALL

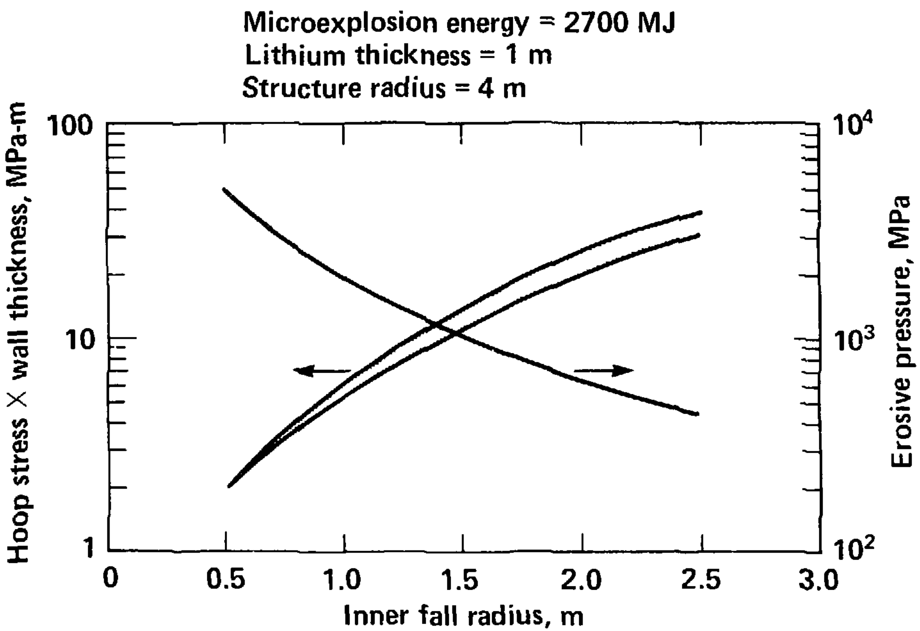

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Fig. 11

well as distributing it in time. The series of small circular jets also vent much of the pressure in the reactor center which greatly reduces "slug-type" loading on the wall. Alternatively, a thin inner fall near the microexplosion could absorb the x-rays and debris while a thick outer fall near the wall absorbs the neutrons. The inner fall could be initially configured to optimize its venting via the Rayleigh-Taylor instability.

To reduce the effect of droplet erosion on the structure, the microexplosion side of the structure could be covered with a thin layer of liquid lithium. Unfortunately, there may be a sufficient amount of hard x-ray energy that passes through the lithium fall and is deposited in the structure to produce a small pressure rise in the structure. The particle velocity of the structural material could couple to the thin lithium layer causing the lithium to spall off the surface of the structure before the droplets arrive. However, a screen could be placed over the inner surface of the wall such that surface tension could insure the wall and screen are always covered with liquid lithium.

CONCLUSIONS

A structural wall with a radius of 4 m and a thickness of 0.1 m can withstand the repeated impacts of a 1 m thick lithium fall located less than 1.5 m from 1.1 Hz-2700 MJ microexplosions for a lifetime of 30 years. The largest uncertainty in the calculations are the erosive pressure on the wall from droplets produced by x-ray spall of the fall back surface. To reduce this uncertainty, better equation of state properties of expanded lithium including opacity data for low energy photons are required. The erosion rate from the high velocity droplets must be experimentally determined.

ACKNOWLEDGEMENTS

We would like to acknowledge valuable discussions with I. O. Bohachevsky of LASL and S. L. Thomson of Bechtel, neutronic calculations by W. R. Meier of LLL, and equation of state data from M. Ross and D. Young of LLL. We would also like to acknowledge the support of J. A. Maniscalco and J. L. Emmett of LLL.

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