

DYNAMIC LOADING OF THE STRUCTURAL WALL IN A LITHIUM FALL FUSION REACTOR

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In one version of an inertial confinement fusion (ICF) power reactor, the laser-imploded pellet is surrounded by a thick, annular "waterfall" of liquid lithium. The fall has three functions: to breed tritium for pellet resupply, to act as an energy sink and heat exchange medium with an external power loop, and to protect the first wall of the reactor from excessive neutronic and hydrodynamic loading. Our primary concern here is with this last function.

We formulated a simple model of a lithium-fall ICF reactor and calculated the fall disassembly and the subsequent fluid-wall interaction resulting from the energy deposition by the imploded pellet. Two potential mechanisms for wall damage were identified: surface erosion and hoop failure. For single fall designs, the erosion problem appears to be serious. Concentric annuli (multiple fall) or packed jet configurations may be feasible but experiments are needed to clarify the physical model, especially with regard to the characteristics of the cavitated liquid lithium and of the two-phase liquid-vapor region.

1. Introduction

Depending on the specific design, an ICF reactor will generate from 200-4000 MJ of thermonuclear energy per pulse, at repetition rates of from 1-20 Hz [1,2,3]. The impulse from such an explosion is, to first approximation, proportional to the square root of the pellet debris mass and is therefore much smaller than that from a TNT explosion of the same energy; an early estimate gave the fusion explosive mass as $< 10^{-6}$ that of the TNT [4]. Nevertheless, a 4000 MJ TNT explosion involves almost a metric ton of that substance, so that our ICF reactor must still withstand the equivalent of 1 kg of high explosive detonated each second for, say, 30 years--the estimated lifetime of the reaction chamber.

A more detailed analysis of the energy release from the microexplosion shows that up to about seventy-five percent of the fusion energy is in the form of high energy x-rays and neutrons [2] which penetrate the entire fall thickness. Since this energy is distributed over a large mass of lithium, the specific energy is relatively low. The remainder of the x-ray output and the total collection of pellet debris are unable to penetrate beyond a very thin layer at the inner radius of the annular fall. As a result, the specific energy of the lithium in this layer increases by several orders of magnitude and the instantaneous pressure may exceed 100 GPa.

It is our main purpose in what follows to describe the subsequent disassembly of the annular fall and show how it interacts with the first wall.

2. The Fall Disassembly Model

The thickness of the lithium fall is controlled by the requirement that the fusion neutron spectrum be sufficiently degraded to assure a 30 year lifetime for the structure; calculations have shown [2] that the required thickness is 0.6-1 m.

The most likely design calls for a pulse repetition rate of ~ 1 Hz. On each pulse, the fall is disassembled. Between each pulse it is re-established. Most of the important aspects of the disassembly are completed in the time for an acoustic wave to traverse the fall thickness. For a 1 m thick fall, this amounts to little over 200 μ s. In this period, the vertical motion may safely be neglected so that, to first approximation, the fall-wall interaction problem reduces to one-dimensional motion with cylindrical symmetry. The most severe interaction will be at the horizontal plane intersecting the equator of the pellet. Figure 1 schematically depicts the initial value problem. Both the inner and outer surfaces of the annular fall are assumed to be free. After energy deposition, the inner surface will implode on the cylinder axis and the outer surface will contact the first wall which, insofar as the fluid is concerned, remains rigid.

The lithium was treated as an inviscid compressible fluid. Due account was taken of the liquid-vapor phase change and of ionization of the gas. A detailed account of the material equation of state is given in [5]. The equations of motion in one-dimensional cylindrical symmetry were formulated in a generalized coordinate frame, i.e., the velocity associated with the convective term in the material derivative was taken as arbitrary and not assumed to be zero as in Lagrangian coordinates or equal to the particle velocity as in Eulerian. This formulation is the basis of the AFTON code [6,7] which allows the conservation equations to be numerically integrated on any convenient mesh rather than one that is embedded in the material or fixed in space. For our problem, accurate resolution of the short-range deposition required extremely fine zoning initially at the inner radius; the first zone thickness was $\sim 0.3 \mu$ m. Yet, it was necessary to extend the mesh over the

entire annulus to simultaneously account for the long-range deposition. The strategy adopted was to satisfy the initial conditions on a mesh each successive radially increasing element of which was 2% wider than its predecessor. With this geometric progression, and using 500 zones, the initial thickness of the last zone at the outer radius was ~ 13 mm. Both the inner and outer fall radii were taken to be Lagrangian surfaces so that no lithium was convected across these. The mesh lines in between were gradually allowed to move towards an equal spacing as the motion progressed. In this way, the shock zone which developed from the short-range deposition was always contained in an "optimally" fine mesh structure as it traversed the fall annulus, and the cost of the calculation was low; a typical disassembly calculation used ~ 5 min. of machine time on our CDC 7600. The minimum resolution of the shock pulse, as it arrived at the outer radius of the annulus, was about 1 mm.

3. Results of the Fall Disassembly

The spatial distribution of energy in the lithium annulus can conveniently be characterized as short- or long-range according to whether the specific energy does or does not exceed the specific energy of cohesion for lithium ($e_c = 23$ MJ/kg). The long-range deposition carries most of the energy from the pellet and penetrates the entire annular thickness. This results in isochoric heating and a concomitant pressure rise with the peak pressure typically < 100 MPa. The short-range deposition is confined to a very thin layer at the inner fall radius and as a result the fluid in this layer is raised well above e_c and the instantaneous pressure may exceed 100 GPa. A strong shock pulse is then propagated into the fall, but is quickly attenuated by a rarefaction centered about the inner radius. The peak pressure at the shock front is typically reduced by two orders of magnitude in the first microsecond. In traversing the fall thickness the pulse is further weakened, however a peak spall velocity in excess of 60 m/s can be expected at the outer radius, deriving mainly from the short range deposition. Further details of the disassembly process are given in [5].

The results of the fall disassembly are illustrated in Figure 2 which shows the pressure applied to the first wall for a 700 MJ pulse deposited in a lithium annulus whose inner and outer radii are respectively 2.0 and 2.6 m. This result was obtained by applying a rigid wall boundary condition to the outer fall radius at the instant of spall (when the pressure in the outward moving fall had everywhere vanished).

That a rigid wall boundary condition is appropriate here may be deduced from the ratio of the mechanical impedance of the actual wall to that of lithium. For the most likely construction material, a corrosion-resistant steel [2], this ratio is in excess of 17, so that the error in the impact Hugoniot is at most $\sim 5\%$.

The wall loading in Figure 2 is seen to decrease sharply from the impact pressure of 150 MPa to zero in 7 μ s. 15 μ s later a much smaller pressure is evidenced which however persists for a much longer period. The initial spike results mainly from the short range deposition. The 15 μ s zero pressure period is due to the "cavitation tail" behind the spall layer. The fluid contained in this region must be recompressed by the impact before significant momentum transport to the wall can be effected. The overall loading time of 150 μ s reflects the 15 μ s delay. When subtracted from the total, the difference accounts for an acoustic wave originating at the wall, to traverse half the original fluid annulus, reflect at the fall split, and return.

In reality, it is unlikely that the wall will initially be exactly coincident with the outer fall radius at the plane of the pellet; it is probably even desirable that there be some gap. If the gap is small compared with the lithium thickness, the result will not differ much from the no-gap case. In [5] we demonstrate that, under certain circumstances, when the residual pressure in the reactor cavity is not reduced quickly enough, a large gap can have a very detrimental effect on the wall stress.

4.0 Dynamic Loading

4.1 The Hoop Stress

For an internally pressurized cylinder, and neglecting end effects, the equation of motion is:

$$PR - \sigma_{\theta} \delta = \rho R \delta \ddot{u} \quad (1)$$

where $P = P(t)$ is the applied pressure, R is the cylinder radius, σ_{θ} is the hoop stress, δ is the wall thickness, ρ is the wall density and u is the displacement. Equation (1) is strictly applicable to the case where $\delta/R \ll 1$ which, for any realistic ICF reactor, will always be satisfied. If we now require linear elastic constitutive behavior,

$$\sigma_{\theta} = Eu/R \quad (2)$$

where E is Young's modulus. Equation (1) reduces to

$$\ddot{u} + \omega^2 u = P/\rho\delta \quad (3)$$

where $\omega = \sqrt{E/\rho R^2}$; the natural period of the wall structure is $T \equiv 2\pi/\omega = 2\pi R/\sqrt{E/\rho}$.

Equation (3) is subject to the initial conditions:

$$u(0) = \dot{u}(0) = 0 \quad (4)$$

Given $P(t)$, this system is easily integrated by conventional methods. Figure 3 shows the variation of hoop stress with time for the loading history of Figure 2 and an assumed wall thickness of 100 mm. The peak stress of 57 MPa occurs at just over 800 μ s (t_{**} in Figure 3), long after the applied pressure has ceased. The reason for the delay is that the duration of load application, t_* , is very much less than the wall period T (≈ 3 ms).

When the loading time is small compared with the natural period of the wall, the maximum hoop stress is proportional not to the applied pressure, but to the impulse and furthermore, is formally independent of the wall radius (although the impulse itself may be a function of the wall radius) [5]. If the pressure is applied as a Heaviside function so that $P = \text{constant}$ for $t < t_*$ and vanishes thereafter, it is easy to show that

$$\sigma_{\theta}(t_{**}, t_*/T \ll 1) = (Pt_*/\delta) \sqrt{E/\rho} \quad (5)$$

If the "average" pressure required by (5) is taken as the overall energy density (at the plane of the pellet, and including both the long- and short-range deposition) in the cavity bounded by the outer fall radius, and the loading time is assumed to be the acoustic travel time across the annulus, the predicted peak hoop stress is just over 55 MPa, within 3% of the Figure 3 value of 57 MPa.

The 57 MPa peak stress value appears acceptable if a stainless steel is used for the wall. Kramer [8] has listed the allowable stress for 316 SS at 10^5 hours and 800 K as 106 MPa. Austenitic steels, however, may be too susceptible to damage by neutron irradiation and lithium corrosion at elevated temperature. Low chromium content ferritic steels (such as 2 1/4 Cr - 1 Mo) are superior in these respects and have been suggested as a possible substitute, but the allowable working stress may be too low.

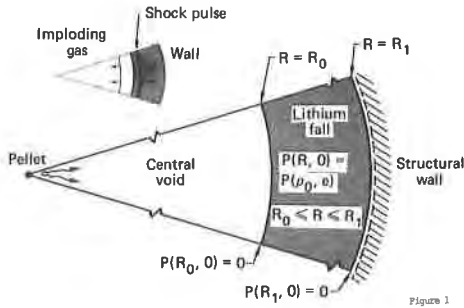
4.2 Erosion

Another question, potentially even more significant, is the extent to which erosion will damage or weaken the structure. In writing equation (1) we have tacitly ignored the stress distribution within the wall. Since the wave speed in steel exceeds 5 km/s, one acoustic transit across a 100 mm thick wall takes less than 20 μ s, so that 50 or so transits occur in t_{**} , the time to reach the peak stress. This is more than adequate time for the stress within the wall to equalize. Nevertheless, Figure 2 shows that in the first few microseconds, the inner surface of the wall is subjected to an impact pressure of at least 150 MPa (numerical dispersion inherent in this calculation assures us that this is indeed a lower bound). Moreover, if the outer radius of the lithium fall is separated from the wall by any significant distance, the spall layer will not reach the wall as a continuous slug, but rather as liquid fragments or drops. In this case, the local impact pressure may exceed the one-dimensional Hugoniot value by as much as a factor of 3 due to the impact geometry [9]. These localized impacts will be of microsecond or submicrosecond duration so that any individual drop will be of little interest. Over the 30 year anticipated lifetime, however, there will be of the order of 10^9 microexplosions, implying at least an equivalent number of droplet impacts. Hancox and Brunton [10] have demonstrated considerable erosion damage to stainless steel by water drop impacts at 90 m/s and after only 10^5 - 10^6 impacts. At high temperature, in the lithium environment, and with 10^3 - 10^4 times as many impacts, we can speculate that the situation will not be improved.

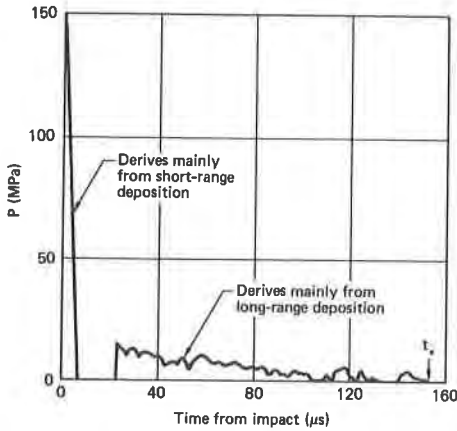
One way of mitigating the erosion damage would be to provide a gap between the main fall and the wall and to place a quiescent layer of lithium in this gap. The Hugoniot impact pressure of the spall fragments on the buffer layer would only be half that on the steel wall and if the buffer layer were several times as thick as the fragments, the rate of momentum transfer to the steel wall could be very much reduced. An extension of this idea would be to employ multiple lithium annuli separated by gaps to more effectively smear out the impulse, although it might be difficult to maintain stable flow and prevent break-up of the annular sheets prior to the microexplosion. A further extension is to replace the continuous annuli with a series of circular cross section jets arranged in a close-packed annular array. This is Monsler's HYLIFE concept [11]; in addition to minimizing possible erosion damage, this scheme appears to be effective in eliminating any adverse effects of the blowoff gas in the core of the inner annulus [5].

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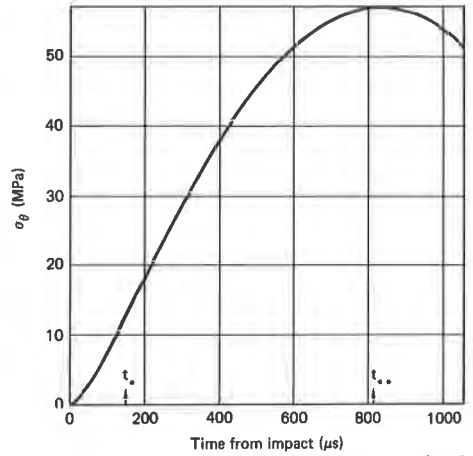
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1. Schematic representation of the fall disassembly as a one-dimensional initial value problem with cylindrical symmetry. Inset illustrates subsequent motion.



2. Pressure applied to the first wall for a 700 MJ pulse deposition in a lithium annulus whose inner and outer radii are respectively 2.0 and 2.6 m.



3. First wall hoop stress as a function of time from impact given the loading history of Figure 2.