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FUSION TECHNOLOGY INSTITUTE
UNIVERSITY OF WISCONSIN
MADISON WISCONSIN

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G.L. Kulcinski

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

<http://fti.neep.wisc.edu>

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G. L. Kulcinski

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Nuclear Engineering Department
University of Wisconsin

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FIRST WALL PROTECTION SCHEMES FOR INERTIAL CONFINEMENT FUSION REACTORS

G. L. KULCINSKI

University of Wisconsin, Madison, Wisconsin 53706, U.S.A.

The successful containment of thermonuclear yields ranging from 100-4000 MJ has presented a great challenge to the fusion reactor designer. It is shown that the thermal pulses associated with such pellet design can exceed the melting temperature in first walls unless either the chamber size is made unreasonably large (>10 to 20 meters in diameter) or something is done to modify the energy spectra of the pellet debris. The various approaches to absorbing the photons and slowing down the charged particles and neutrons are reviewed. Fluidized walls and low pressure gases show great promise for protection of the cavity surfaces, but there are a number of critical experiments that need to be performed on both of these concepts before a final decision on their use in reactors can be made.

1. INTRODUCTION

One of the most unique requirements for current first wall designs in Inertial Confinement Fusion Reactors (ICFRs) is the need to repeatedly absorb large amounts of energy in short (10^{-9} to 10^{-5} second) pulses. Single pellet yields that are presently being investigated range from as low as 50 to 100 MJ for electron or proton beam ICFRs [1] to as high as 4000 MJ for laser driven ICFRs.[2] Roughly 25% of this energy is released in the form of charged particles or photons which have a very short range in the metallic first walls under consideration. If allowed to strike the first wall unaltered, this energy will be deposited over the period of a few microseconds. Most metals cannot stand more than ~ 0.02 MJ per m^2 in this time frame without melting so that the area of the first wall must be increased to at least a thousand square meters to prevent such damage to the structure. Assuming spherical geometry, one finds that the radius of the chamber walls must be at least 7-8 meters for a 100 MJ total pellet yield and ~ 20 to 25 meters for a 1000 MJ yield to prevent melting. Such large chambers represent a challenge to the economics of a fusion power plant. It is then obvious why scientists have sought ways to modify the spectra, or even totally absorb the particle debris, before it strikes a solid surface.

It is the purpose of this paper to first outline the consequences of no first wall protection and then to review the methods which have been proposed to protect the first wall in ICFRs. The limitations of each technique will then be examined as they apply to current reactor designs. The reader is cautioned that this is a rapidly changing field and many of the current conclusions may have to be modified in the future as pellet designs become unclassified and more details about the final driver design are released.

2. WHAT HAPPENS IF WE DO NOT PROTECT THE FIRST WALL?

The consequences of depositing all the pellet debris and X-ray radiation in an unprotected first wall can be illustrated by some very simple calculations. Putting aside differences between pellet designs for laser and particle beam fusion reactors for the time being, a typical spectra could be represented by the components listed in Table 1 for a 100 MJ yield.[3]

Table 1: Reference Spectra (100 MJ)

	Energy (MJ)	Spectra
Laser	0.2	10.6 μ
X-ray	2	1.0 keV - BB
D	4.6	160 keV - M
T	6.9	240 keV - M
He (Slow)	1.2	320 keV - M
He (Fast)	5.4	$2 \pm .5$ MeV - G
Silicon	2.7	800 keV - M
Neutrons	77.	14 ± 1 MeV - G

BB = Blackbody M = Maxwellian G = Gaussian

When considering laser fusion reactors, one might add ~ 0.2 MJ of reflected laser light. Other pellet designs indicate that there may be more energy in softer X-rays [1] and some of the kinetic energy of the neutrons [4] is transferred to the ions, but within the present uncertainties of pellet design, the above spectra are not unreasonable.

The impact of pellet debris, such as that described above, on an unprotected first wall has three major consequences. First, it can generate extremely high temperatures for a short period of time. Second, the photons can produce shock waves in the first wall. Third, the implantation of the various gaseous particles can cause blistering and erosion.

Because of the differences in energy, hence velocity, the various components strike the wall at different times, and for different pulse durations. The X-rays strike the wall for essentially the compression and disassembly time (10^{-8} to 10^{-7} seconds) and it takes R_w/c seconds for the first X-rays to reach the wall, where R_w is the radius of the first wall and c is the speed of light. The time over which the neutrons strike the wall is determined by the down-scattering of the 14.1 MeV neutrons in the dense pellet. An example of the chronology of particle arrival for the above spectra is shown in Figure 1. [3] It is shown here that the first

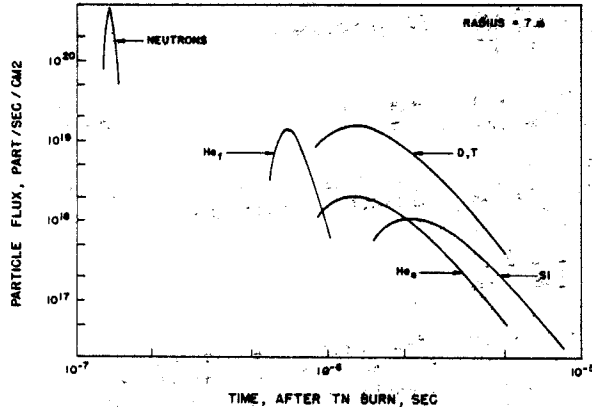


Figure 1 - Particle Flux to First Wall Placed 7 Meters from Pellet Debris in Table 1

neutrons arrive at a cavity wall 7 meters from the pellet implosion roughly 150 ns after the X-rays. The much slower pellet debris does not arrive until 400 ns after the neutrons and they continue to arrive over the next 8 μ s.

Because of the fact that the particles arrive at different times and with different energies (i.e., different ranges in the wall) simple solutions to describe the temperature increase are no longer valid. In the past, these temperatures have been calculated by assuming all the energy is deposited at the front surface in a time which is short compared to the thermal diffusion time. Other calculations have assumed that the energy deposition is uniform over the range of the particle. However, due to the nature of the energy loss mechanisms by particles, a complex temporal and spatial description is required. A recent analysis of this situation reveals that the temperature at any position within the first wall can be described as follows. [5]

$$T(x,t) = \int_{t'=0}^t \int_{x'=0}^x \frac{f(t')}{\rho c_0} g(x') G(x,t,x',t') dx' dt' \quad (1)$$

where $f(t')$ is the function which describes the arrival of the various photon and ionic species,

$g(x')$ is the energy deposition function for the various forms of radiation,
 ρ is the density,
 c_0 is the heat capacity,

$G(x,t,x',t')$ is the Green's function for a semi-infinite slab. [6]

The solution of this equation is contained in the computer program, T-DAMEN. [7]

The temperature increase due to each of the component from a multi-specie pellet design is given in Figure 2. The data is for stainless steel at 7 meters from our hypothetical

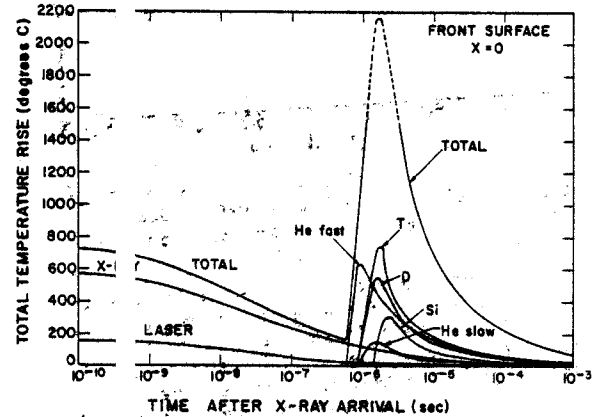


Figure 2 - Temperature Increases in Stainless Steel Due to the Pellet Spectra of Table 1 ($R_w = 7$)

pellet (we have included 0.2 MJ of reflected 10.6 μ laser light as well). [8] The very high temperatures generated at 7 m from a 100 MJ explosion are indicative of the magnitude of the problem faced by reactor designers if they wish to avoid temporary melting, radiation damage or the associated property changes that might occur. [9]

One can get a rough idea about the minimum size chamber required to prevent melting in a steel first wall if the operating temperature of the steel is ~30% of the melting point. This is shown in Figure 3 and the minimum size is determined from only the temperature increase due to the pellet debris. [10] We can neglect the temperature increase due to the neutrons ($<5^\circ\text{C}$) and will assume that the temperature increase due to the photons is equal to or less than that due to the ions. The minimum cavity radius to avoid melting is less than that predicted by a geometric argument alone, i.e.,

$$R_w^{\min} < R_w = \left(\frac{1}{4\pi} \frac{fY}{\Delta H} \right)^{1/2} \quad (2)$$

where Y is the pellet yield,
 f is the fraction of yield in ions,
 ΔH is the energy required to raise the first wall temperature from its operating value to the melting point.

The above inequality is true because in addition to lowering the total energy deposited per unit area by making the cavity bigger, the increased distance allows the time spread between

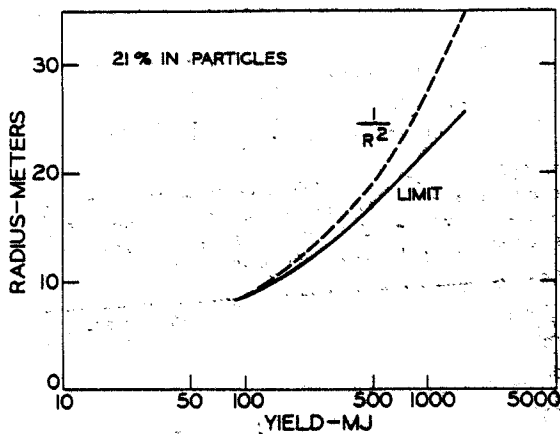


Figure 3 - Minimum Cavity Radius to Avoid Melting Steel Wall Impacted with Pellet Debris from Table 1. Note the Departure from R^{-2} Behavior

the fastest and slowest particles to increase. The longer duration of the energy pulse then allows more heat to diffuse away during the pulse, thus lowering the ultimate temperature increase. Nevertheless, one can see that in order to contain pellet yields of more than 100 MJ without melting the first wall would require unreasonably large chambers (greater than 8 meters in radius).

There is also another problem associated with the unrestrained flux of pellet debris and X-rays on the first wall: the formation of shock waves. These pressure pulses come from three main effects.

- Momentum of pellet debris, P_m
- Shock waves generated by chamber gases, P_g
- Shock waves generated by material ablated off the first wall, P_A

The magnitude of these effects can be estimated as follows: [11]

$$P_m = \frac{\sqrt{fYM}}{2\pi\sqrt{2} R_w^2 \tau} \quad (3)$$

where M is the mass of the pellet,
 τ is the duration of the pulse to the wall.

For typical high gain pellet designs, $f = 0.20$; $Y = 500$ MJ, $M = 1$ g and $\tau \approx 10$ μ sec, one finds that

$$P_m \approx \frac{3.5 \text{ MPa}}{R_w^2(m)} \quad (\sim 35 \text{ atmospheres})$$

Thus, a 7 meter radius chamber wall would experience on the order of a 0.7 atmosphere pressure from the momentum of the pellet debris.

When the chamber gas density exceeds 10^{-7} g cm^{-3} (e.g., 0.3 torr (40 Pa) of Xe) one can calculate the blast wave pressure by the theory of Taylor and Sedov, [12] extended by Freiwald and Axford, [13] from the following expression [11]

$$P_g = \frac{K(\gamma) fY}{R_w^3} \quad (4)$$

where $K(\gamma)$ is a function of γ , the ratio of specific heats of the gas and where $\gamma = 1.4$, $K = 2.39$.

For $f = 0.2$, $Y = 500$ MJ the above equation predicts

$$P_g \approx \frac{230 \text{ MPa}}{R_w^3(m)} \quad (2300 \text{ atmospheres})$$

Hence, for a 7 meter radius chamber the shock overpressure is ~ 7 atmospheres.

Finally, the wall pressure due to evaporation recoil has been estimated by Bohachevsky to be, [11]

$$P_A = \frac{\eta xY}{4\pi R_w^2 \tau^2 2H} \quad (5)$$

where η is the effectiveness coefficient to account for the fact that not all the ablated material moves with the maximum velocity into the chamber,
 H is the heat of vaporization,
 x is the fraction of energy in X-rays.

For typical values of X-ray deposition in steel one finds that using $\eta = 0.15$, $x = 0.02$, $Y = 500$ MJ, $H \approx 6.3$ KJ/g, and $\tau \approx 100$ ns, gives

$$P_A \approx \frac{333 \text{ MPa}}{R_w^2(m)} \quad (3330 \text{ atmospheres})$$

For a wall radius of 7 meters and Bohachevsky's assumptions on the mass of metal ablated, the recoil shock wave would be equal to 7 MPa (~ 70 atmospheres).

Hence, one can see from the above analysis that total pressures of 5-10 MPa (50-100 atm.) could be experienced by chamber walls with radii of 7 meters or less. The ability of various cavity designs to withstand such pressures will be design dependent, but the imposition of such loads on the first wall 10's of millions of times per year represents a real challenge to the design engineer.

The overall conclusion from this simple example is that the area of unprotected metal walls will probably have to be extremely large to withstand the thermal and pressure loading from economically attractive pellets. The inclusion of sputtering and chemical interactions will only make the situation worse. Hence, it is easy to understand the motivation behind the various cavity protection schemes.

3. PROPOSED MECHANISMS OF FIRST WALL PROTECTION

Before proceeding with this very brief review it must be noted that practically all of the work thus far has been aimed at laser fusion systems and only recently has there been consideration of particle driven (e.g., electron, proton or heavy ion beam) designs. The first known effort in the laser field is a paper by Lubin and Fraas in 1971. [14]. In that paper the "Blascon" concept was proposed in which a pellet was dropped into the vortex of a swirling lithium fluid in a spherical vessel (Figure 4) and

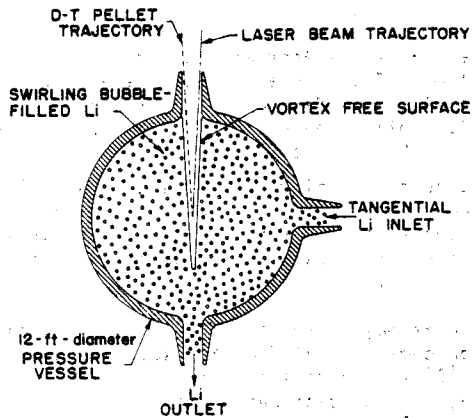


Figure 4 - Blascon Concept of Lubin and Fraas [14]

ignited by a laser beam from one side. Baird and Anderson [15] later showed how this concept could be extended by using the vortex to focus the beam on the pellet. The thickness of the lithium in the chamber should be sufficient to absorb the X-rays and pellet debris as well as extracting a large fraction of the kinetic energy of the neutrons (i.e., on the order of 1 meter). The shock wave generated by the explosion was to be partially reduced by filling the chamber with bubbles to allow the kinetic energy of the explosion to be dissipated by blowing liquid off one side of a bubble and depositing it on the other side. Calculations [16] and some preliminary measurements with water filled chambers [17] indicated that one might be able to contain yields of 50-100 MJ without exceeding the elastic limit on thick (~30 cm) steel walls.

The next group to propose a protection scheme was at Los Alamos Scientific Laboratory. In 1972, [18] the first comprehensive study of an electrical power station based on laser driven fusion proposed that the first wall be covered by a thin film (~1 mm) of Li between shots to absorb the X-rays and pellet debris (see Figure 5). It was proposed that this lithium would then be vaporized and removed from the chamber before the next shot (some 100 ms later) and the Li coating in the first walls would be re-established. Approximately 3 to 4 kg of Li would be vaporized per 100 MJ pellet yield if the spherical chamber radius was 1 meter.

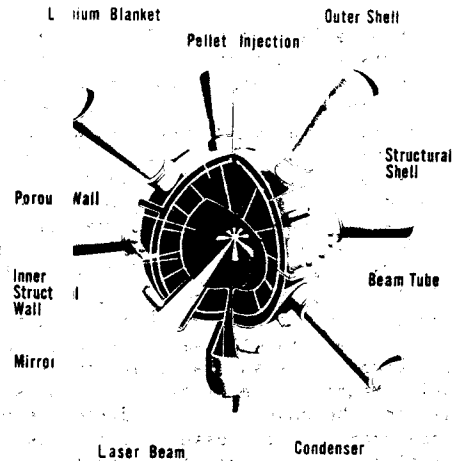


Figure 5 - Wetted Wall Concept of First Wall Protection [18]

Finally, the ablating Li could produce a significant shock wave (10 MPa (100 atm.)) that would be transmitted through the first wall and into the blanket region. Analysis of this shock wave and the reliability of attaining 100% film coverage before every shot led scientists to propose a other scheme in 1973, the so-called dry wall approach. [19]

The dry wall concept relied on a thin ablative line of carbon. A small amount of that liner would be ablated each shot and it was hoped that the liner would cool enough between shots to permit recondensation of the ablated material. The analysis of this concept was incomplete when the workers at LASL proposed yet another scheme, first fully discussed in 1974; the magnetic protection design. [20]

A schematic diagram of the protection of reactor cavity walls from energetic charged particles by means of magnetic fields is shown in Figure 6. The cavity is now cylindrical in

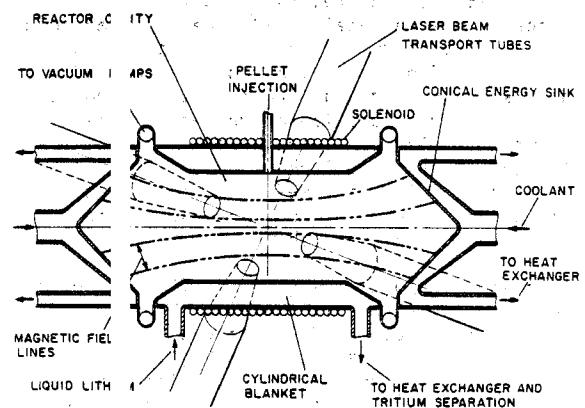


Figure 6 - Magnetic Protection Scheme for Protecting Laser Fusion Reactor First Walls [20]

shape with an axial magnetic field. The reaction products (alpha particles) and ionized pellet debris are diverted along magnetic field lines to energy sinks at the ends of the cavity. Originally it was assumed that the particles deposited their energies in liquid lithium reservoirs but this later was expanded to include solid target dumps. Since the magnetic fields have no effect on X-rays, the cavity walls were lined with dry wall ablaters such as C or Be. The cavity pressure was assumed to be 13 Pa (0.1 torr), low enough so that the particles could escape to the heat sinks in times considerably less than those required to develop plasma instabilities such as flute modes ($<10^{-6}$ seconds). Magnetic fields of 4 kilo-gauss were proposed and the possibility of direct recovery of energy from the compressed field lines was also examined. The overpressure at the chamber walls from a 100 MJ shot, 15 MJ of which is released in energetic charged particles, is a few atmospheres for radii of a few meters.

In 1974, workers at Lawrence Livermore Laboratory suggested the "suppressed-ablation" concept [4] similar to the wetted-wall design described earlier. The major differences are, 1) a lower yield pellet design, 2) larger surface area because of increased chamber size, and 3) larger surface area because of pyramidal first wall design. The net result of the above approach is to reduce the amount of Li evaporated and hence the magnitude of the shock wave generated and the time necessary to prepare for the next shot.

The possibility of using chamber gases to modify the pellet debris spectra was mentioned by Booth et al., in 1975. [21] However, at that time they did not think that chamber pressures of >400 Pa (3 torr) were possible due to laser induced breakdown of gas around the pellet and they did not pursue the features of gas protection any further.

In 1976, Hovingh reconsidered the dry wall concept in more detail. [22] He proposed to use a 2 cm thick carbon liner to protect a steel first wall from a 10 MJ microexplosion. The analysis revealed that due to evaporation resulting from absorption of reflected laser light, one might only expect a 1 year lifetime for the liners. Hovingh also suggested that 1 torr of gas might be useful in reducing the effect of the pellet debris but he did not report any details of the calculations.

Another proposal emerged in 1976 related to the dry, ablative wall concept. Varnado and Carlson [23] suggested that a graphite cloth shield, such as that shown in Figure 7 could be used to protect the wall from pellet debris and soft X-rays. The advantage of the cloth design is that it is flexible and should not be greatly affected by the shock wave. It is also possible to replace damaged portions by simply advancing the roll of carbon cloth. This would also tend

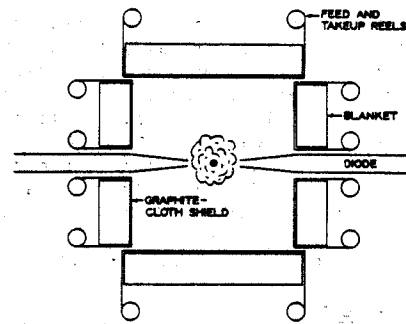


Figure 7 - Sandia Approach to First Wall Protection. The Blanket Surfaces are Protected by Flexible Carbon Cloth Which can be Periodically Changed Without Disrupting the Chamber Configuration [23]

to reduce the problems by implanted particle buildup (i.e., implanted heavy metal ions just below the surface which would alter the X-ray absorption profiles) and reduce the implanted T₂ inventory.

The next major proposal for first wall protection came in 1977 from Maniscalco and Meier [2] in the form of fluidized walls. Actually, this concept was first proposed in 1974 by Burke [24] as a possible configuration for an electron beam ignited fusion reactor (Figure 8)

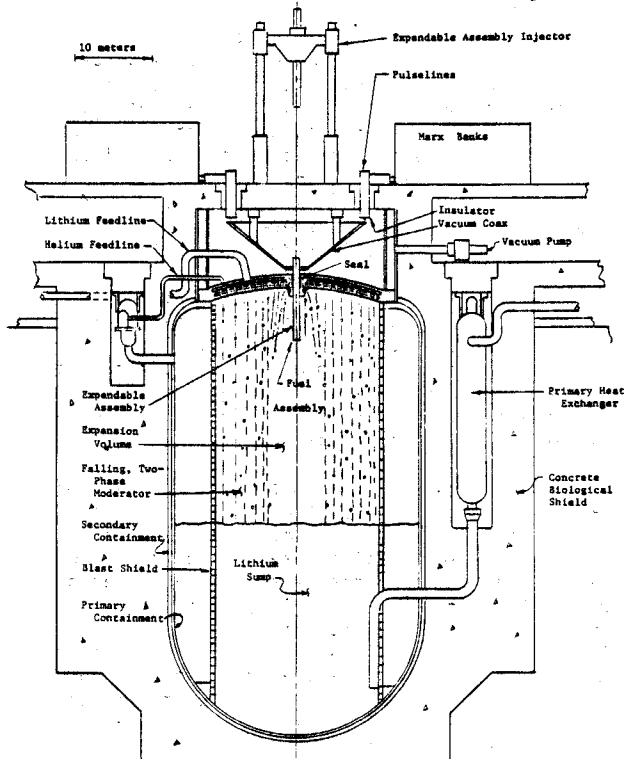


Figure 8 - Schematic of E-Beam Cavity Chamber Protected by Falling Two-Phase Lithium Moderator. [24]

but very little detailed analysis was performed. Maniscalco et al., [25] proposed both solid (Figure 9) and liquid (Figure 10) fluidized

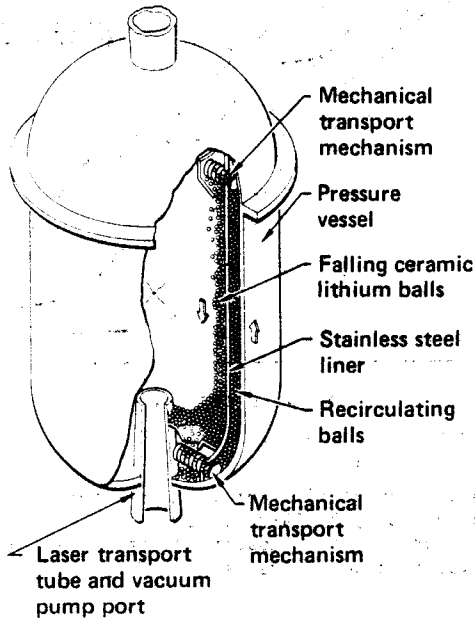


Figure 9 - Schematic of the Use of Ceramic Balls to Protect the First Wall Surfaces from Pellet Debris [25]

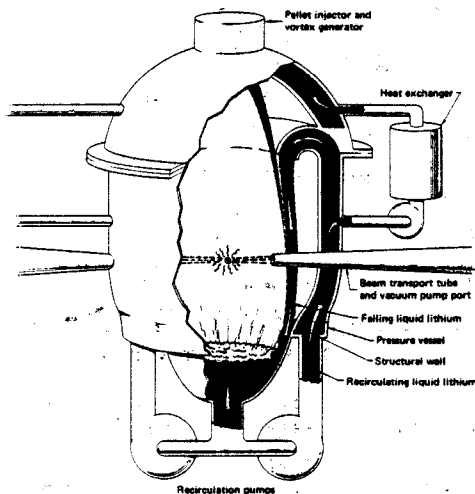


Figure 10 - Fluidized Wall Approach to First Wall Protection [25,27]

walls to collect the pellet debris and photons. Powell also suggested a similar liquid system for ion beam systems. [26] The solid fluidized wall was proposed because it was feared that the vapor pressure of the liquid would prevent the introduction of focusable lasers to the pellet, but this later proved to be unnecessary. It was felt that beam defocusing and attenuation of 1 micron light by cascade breakdown and/or thermal blooming could be reduced to acceptable levels

with a chamber pressure of 13 Pa (0.1 torr) or less. [27] Most of the work from that time has concentrated on the liquid concept.

The liquid lithium 'waterfall' design has emerged as a promising concept for a laser fusion power plant. It features a thick continuous fall of liquid Li that protects the first structural wall, absorbing photons, pellet debris, and in some cases moderating the neutrons. If the thickness of the liquid fall (either Li or Pb-Li) exceeds ~50 cm, the lifetime of the first walls can be extended to roughly the lifetime of the plant. [28,29] The effect of the liquid layers on the reduction of displacement damage (Figure 11) and helium gas

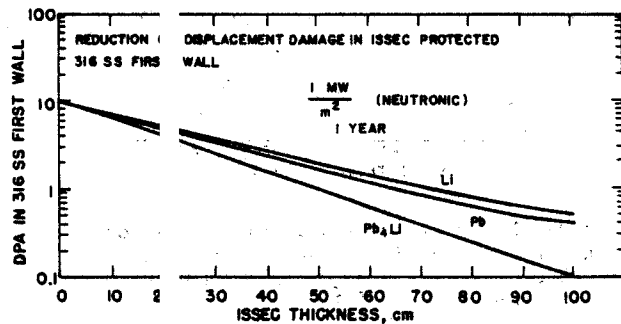


Figure 11 - Reduction in Displacement Damage by the Use of Liquid Metal Fluidized Walls [28]

production [28] demonstrates that neutron damage to the reactor first walls can be held to levels similar to those already encountered in fission reactors. In fact the softening of the neutron spectra by Pb-Li alloys can even 'adjust' the helium gas atom to displacement ratio in the first wall to that produced in present day fast test facilities (Figure 12). Finally, by keeping the liquid off the first wall, the shock waves generated in the fall are not directly transmitted to the structural wall. However, the liquid collected in the bottom of the chamber can present some problems in this regard.

The original lithium 'waterfall' concept was proposed to allow extremely large yield pellets to be used (~4000 MJ) in reasonably sized chambers. In that regard, the pulse rate can be relaxed to on the order of one per second and still produce roughly 1000 MW_e of power. Preliminary analyses of the concept showed that the chamber pressure can be restored to <0.1 torr in less than one second and the fall conditions re-established without expending more than a few % of the plant output to circulate the lithium.

Shortly after the fluidized wall concept was proposed, the use of a cavity gas to protect the first wall was investigated by the SOLASE Reactor Design group at the University of Wisconsin in 1977. [30] Figure 13 is a schematic of the SOLASE cavity design. The effectiveness of low pressure (13 to 1400 Pa (0.1 to 10 torr)) inert gases (He, Ne, and Xe) was reported in detail in several subsequent publications. [3,7,8,31] The

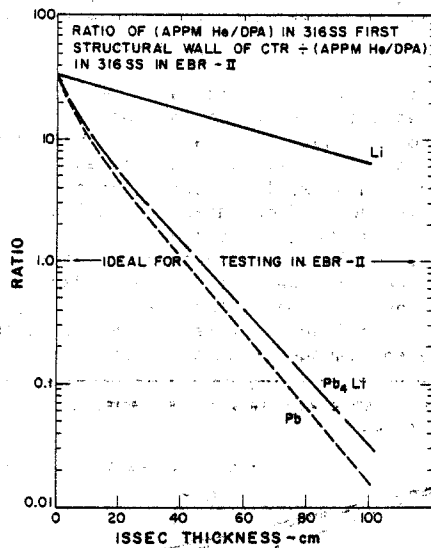


Figure 12 - Demonstration of How the Use of Liquid Metal Fluidized Walls can be Used to Reduce the High He/dpa Ratios Characteristic of Fusion Reactors [29]

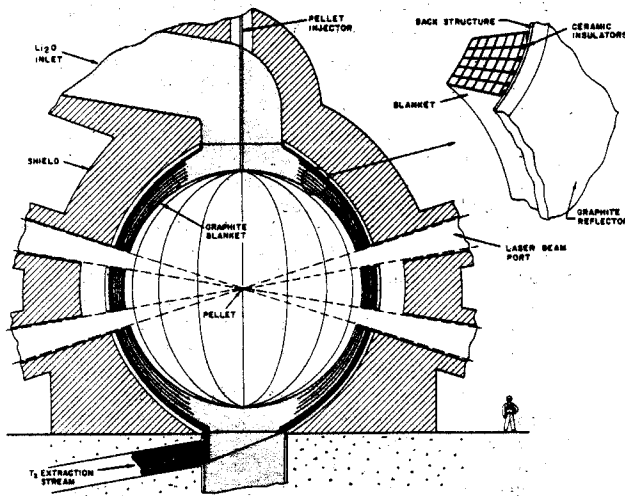


Figure 13 - Schematic of SOLASE Reactor Cavity Which Relies on a Few Torr of Inert Gas in the Chamber to Slow Down the Pellet Debris and Absorb the X-rays [30]

basic concept is as follows. The reaction chamber was filled with a low pressure (a few torr) gas prior to irradiation of the pellet. The gas pressure was kept low so that it would not interfere with the propagation of the laser beam to the target and also so that the pellet trajectory would not be significantly altered. The chamber gas, even at these low pressures, can absorb most, if not all of the soft X-rays and significantly degrade the energy of the charged particle debris. (See Figure 14 for

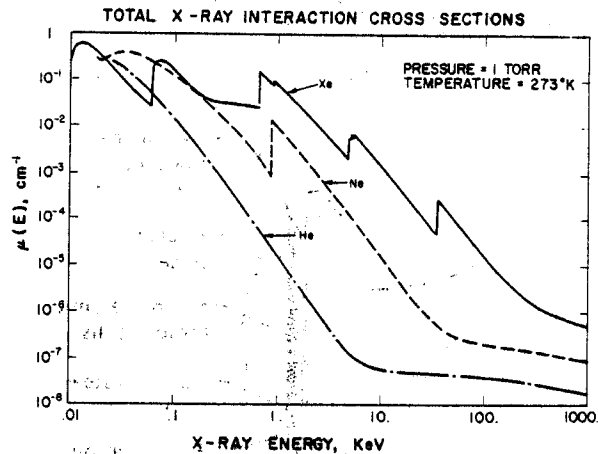


Figure 14 - X-ray Absorption Coefficients for Inert Gases

absorption coefficients.) For example, it was found that 3720 Pa-m (28 torr-meters) of Ne gas was sufficient to absorb 90% of the energy of a 1 keV blackbody X-ray source [8,31] (Figure 15).

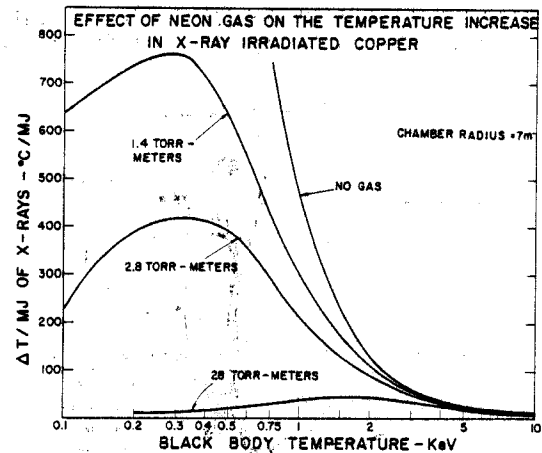


Figure 15 - Effect of Ne Gas on X-ray Induced Temperature Increases in Copper [31]

This same amount of gas is also sufficient to absorb practically all of the energy from 200-400 keV light ions, several MeV heavy ions, and 2 MeV helium ions. To illustrate the effect that even a very dilute gas background can have on the temperature increase, we have calculated the temperature response of steel placed 7 meters from the reference pellet. Figure 16 shows that 67 Pa (0.5 torr) of Ne can cut the magnitude of the temperature increase by a factor of ~2. [8] The effect would be even greater at higher pressures but only 133 Pa (1 torr) of Ne was used in SOLASE because of the concern for gas breakdown effects around the pellet when the intensity exceeds 10^{14} to 10^{15} watts/cm². The

EFFECT OF CHAMBER GAS ON TEMPERATURE

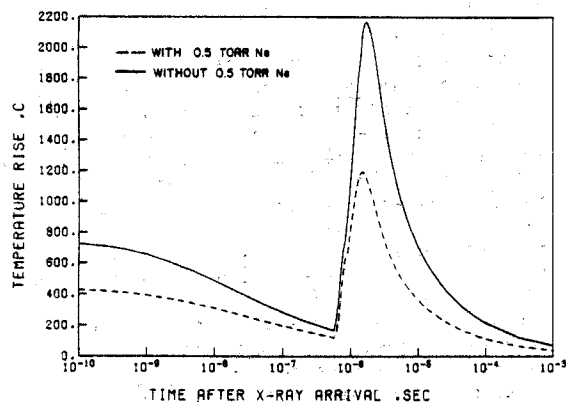


Figure 16 - Effect of Chamber Gas on the Temperature Increase in 316 SS Placed 7 Meters from the Pellet Spectra of Table 1 [3]

shock pressure at this density is less than 0.2 atmosphere.

One of the disadvantages of the gas protection scheme is the high temperature that the gases achieve when high repetition rates are required. It was determined in SOLASE-H, a hybrid laser fusion reactor design, [23] that the equilibrium gas temperature for a pulse rate of 10 pps is $\sim 4000^\circ\text{K}$. The exhaust mechanisms, associated materials problems, and pellet interactions are currently under investigation.

Shortly after the LLL liquid Li "waterfall" concept was proposed, Bohachevsky et al. showed early in 1973, that the thick lithium fall would break up into two or more sections due to neutron, X-ray, and charged particle heating. [33] It was also pointed out that the restoration of the cavity to acceptable conditions for another shot would take some time. The design group at the Lawrence Livermore Laboratory then proposed in 1978, a slightly modified liquid Li fluid wall design called Hylife [34] (Figure 17). The main two new features are the use of many smaller circular liquid Li streams and the use of a porous catcher to isolate the shock wave in the lower Li pool from the chamber walls. The multiple Li streams are useful in diffusing the momentum of the disassembling Li stream. A recent analysis showed that the shock waves to the first wall could be reduced to less than 10^4 Pa (0.1 atm.) by this scheme. [35]

The catcher concept removed one of the previous faults of the single fall concept because now there is no longer a stagnant pool of liquid metal at the bottom of the chamber (compare Figures 10 and 17).

The most recent attempt to find protection for heavy ion beam reaction chambers comes from Argonne National Laboratory. [36] Their concept is shown schematically in Figure 18 and it could

HYLIFE CHAMBER

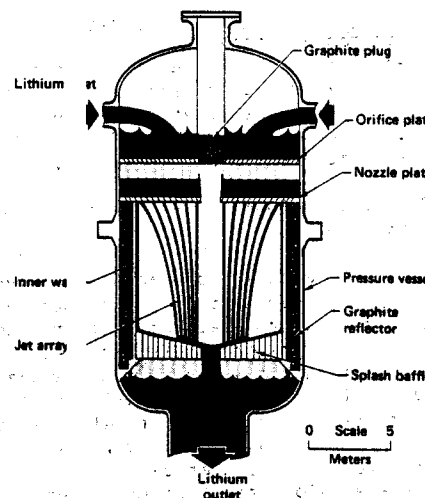


Figure 17. HYLIFE First Wall Protection Scheme Which Uses Multiple Liquid Lithium Streams to Absorb Pellet Debris and Shock Waves [34]

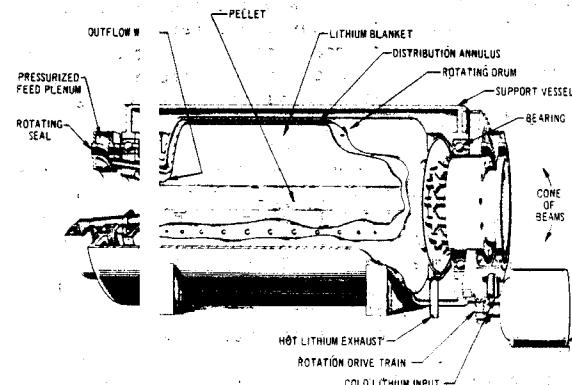


Figure 18. Reactor Design Using a Rotating Liquid Blanket to Protect the First Wall [36]

be described as the "rotating drum" design. The basic idea is to have a thick layer of liquid lithium held up against the rotating chamber wall by centrifugal force. The beams of heavy ions, as well as the pellet, would be introduced along the horizontal axis through fixed beam ports. The magnitude of rotational speed required to establish such a thick (>50 cm) lithium layer, the time required for re-establishment of the fall after a shot, and the level of the shock wave transmitted to the first wall all remain to be specified.

In summary, there has been a surprising variety of schemes proposed to protect the first walls of ICFRs in the last eight years. It is possible that the final design will be a combination of

several of these schemes, e.g., liquid lithium fluidized walls in a dilute inert gas background, a magnetically protected wetted wall concept, etc. It is safe to say that while there is no clear cut solution now, the possibilities for one are much greater now than at any time in the past.

4. SPECIAL CONSTRAINTS IMPOSED BY CURRENT ICFR DRIVERS

Not all of the cavity protection schemes proposed above are compatible with the three major ICFR drivers: laser, electron or light ions, or heavy ions. The major problem arises in the particle beam fusion area. Since the energetic charged particles are either ballistically focussed or steered into their final trajectories by magnets, the imposition of any other strong magnetic fields for pellet debris diversion would have a major effect on the power which could be delivered to the pellet.

Heavy ions also require relatively low chamber pressures to effectively transmit the beam to the target. [36] This would place limits on the allowable background gas pressure. It could also have a major impact on the repetition rate in liquid containing cavities because of the finite time required to exhaust the vaporized liquids.

There is a different sort of limitation set by the e-beam and light ion beam fusion designs. The present approach to the transmission of the beams from the diode to the target requires a "dense" chamber gas (6650 to 13,300 Pa (50-100 torr)). [37] This gas is broken down by a laser and a pre-pulse of energy to create a "low" density channel to the target. Obviously, these systems make full use of the gas protection mechanisms but inclusion of liquids in the chamber would now present a problem. Aerosols, convection currents, and reverberating shock waves would make something like the Hylife concept very difficult to implement in such a "high" pressure environment.

5. CRITICAL NEAR TERM EXPERIMENTAL DATA REQUIRED TO TEST VARIOUS PROTECTION SCHEMES

One of the important features of cavity protection research is that a great deal of it can be investigated without having the final driver and pellet design in hand. Each of the concepts described in this paper has one or more serious questions that must be answered before the community will finally accept it. A few of the most important of these experiments are listed in Table 2. Most of these have already been mentioned in this article and no attempt will be made here to discuss the merits of the many possible experiments that could be conducted. However, it is appropriate to make a few general remarks at this time.

First of all, for all the concepts that utilize liquid inside the reaction chamber it is

important to insure that one can get both the imploding beam and the pellet to the desired location. Experiments can be conducted today on determining laser breakdown in the 10^{16} watts/cm² range or the maximum allowable pressure for heavy ion transmission. It is equally important to begin experiments on the ability to transmit pellets (quite likely cryogenic) through hot, dilute liquid metal vapors. It is also important for all of these concepts to obtain opacity data on the liquid metals to determine the re-radiation times of the chamber vapor and the associated effects on the blast wave generated by the pellet explosion. Finally, the rate of redeposition of vaporized liquid metal on the colder fluid could be determined as well as the minimum time required to reestablish the required fluidized wall configuration. This data is necessary so that the feasibility of the proposed rapid firing requirements can be reasonably assessed.

More specific tests could be conducted on shock transmission through liquid metals containing inert gas bubbles, through multiple streams of liquid lithium or through a layer of liquid metal held up against a wall by centrifugal force. Such experiments could use conventional explosives or intense X-ray sources.

The utility of dry wall concepts could also be assessed with high intensity X-ray sources. Measurements of redeposition rates of the ablated wall material and the amount of vaporized first wall that ends up in the vacuum systems could also be determined. This is especially important for environment hazard potential assessments and to determine the tritium inventory in the first walls.

The validity of the magnetic protection concept could be tested with pulsed beams of intense charged particles injected into the desired magnetic field configuration. These studies could measure the growth of flute instabilities as well as determining how accurate one can predict the deposition profile on the particle dumps.

Finally, there are some very critical experiments that need to be performed with respect to the gas protection schemes. It is imperative to understand the breakdown limits of various wavelength lasers in a wide variety of gases. Currently, the estimates of the upper limits range from 13.3 to 133 Pa (0.1 to 1 torr). But is not entirely clear what will happen even if the gas breaks down, i.e., if breakdown occurs within 10-20 cm of the pellet how much will the effective absorption of the pellet be reduced. If the limit of 0.1 torr is all that can be tolerated, then there is very little utility for this concept. Similarly, the transmission limits for heavy ion beams in low density gases need to be clearly established before the investigators of heavy ion fusion power reactors can even begin to design the reactor cavity.

Table 2

Some of the more critical near term experiments that could be conducted to test the validity of proposed first wall protection schemes

Concept	Applicable*	P I N [†]	Critical	Near Term Experiment
Blascon	L, H	✓ ✓ ✓	. Reduction of Shock . Time to Re-establish	Shock Transmission Shock Suitable Vortex
Wetted Wall	L, H	✓ ✓	. Reliability of Liquid . Exhaust . Ablative Shock Loading	Liquid Metal Coverage Loading Design
Fluidized Wall	L, H	✓ ✓ ✓	. Hydrodynamic Stability . Exhaust Mechanism . Reduction of Shock	Stability Transmission
Rotating Drum	L, H	✓ ✓ ✓	. Establishment of (rotational speed) . Re-establishment . Shock Transmission	Equilibrium Liquid Metal Thickness Time of Liquid Layer
All of the Above	---		. Interaction of the . Laser Breakdown . Effect of Vaporized . Opacity Data of Liquid	Hot Vaporized Liquid with Pellet Pressure of Vaporized Liquid Liquid on Heavy Ion Transmission Liquid Metal Vapor
Dry Sacrificial Wall	L, E-L, H	✓ ✓	. Recondensation Rate . Reduction of Shock . Lifetime Under Re	Recondensation Coupling to Blanket Heated Pulses
Magnetic Protection	L	✓	. Growth of Instabilities . Design of Particle	Instabilities in Expanding Plasma Dumps
Gas Protection	L, E-L, H	✓ ✓	. Breakdown Pressure Laser Wavelength . Exhaust of Hot Gases . Opacity Data . Maximum Pressure Instabilities	Pressure of Various Gases as a Function of Exhaust Allowed to Prevent Heavy Ion Beam

*L=Laser Reactor, E-L=Electron-Light Ion Reactor, H=Heavy Ion Reactor

[†]Major effect on P=Photons, I=Ions, N=Neutrons

Finally, opacity data for the inert gases can be measured and included in the "fireball" calculations to measure the rate at which the energy absorbed in the gas gets reradiated to the first wall. Preliminary calculations show that this reradiation can significantly diminish the severity of the pressure pulse. [38]

This analysis would also not be complete if it failed to mention the need for more precise pellet spectra. Currently, the most pertinent data is classified and workers are forced to perform parametric studies which diffuse the issues and make any definitive conclusions very difficult to achieve.

6. CONCLUSIONS

This brief review has shown that a large variety of cavity protection schemes have been proposed over the last 8 years since ICFR designs were first started. At the present time, the fluidized wall concept appears to have the greatest potential for reducing the effects of the thermonuclear explosion on the reactor components. However, serious questions still remain about liquid metal fall stability, driver

beam transmission and pellet injection. The fluidized wall concept also does not lend itself easily to electron or light ion fusion reactor designs. The next most promising protection scheme is the gas concept but it does nothing for the reduction of neutron damage. The most serious questions remaining with this scheme are the maximum allowable pressure from the driver standpoints, the exhaust of the hot chamber gases, and the interaction of those gases with the pellet. Finally, it is felt that many of the answers required to choose the most favorable protection scheme can be obtained in the next 5-10 years, about the time that breakeven experiments are performed. In general, the outlook for success in controlling the energy release from thermonuclear pellets is optimistic.

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