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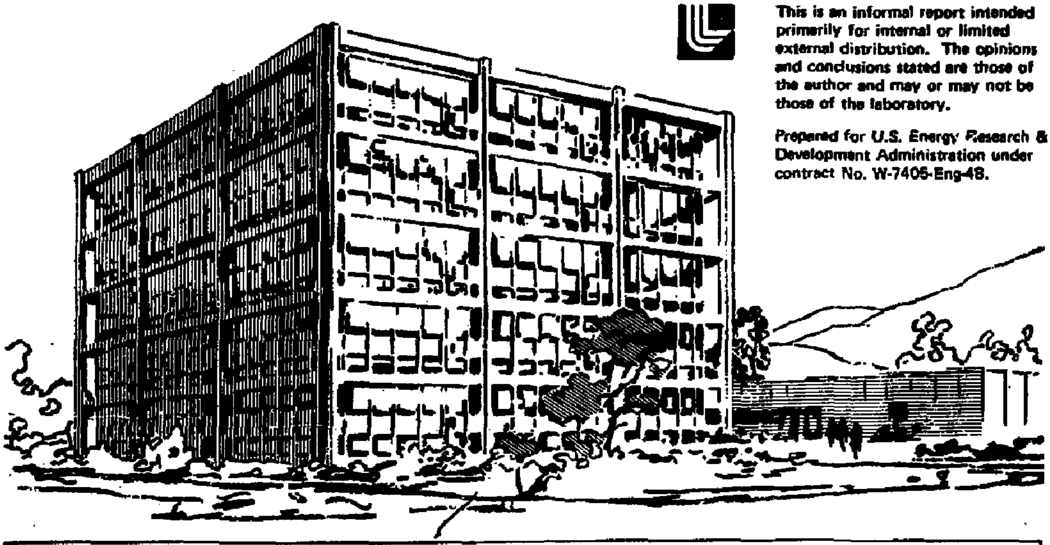
August, 1977



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FIRST WALL COSTS OF AN ION-BEAM FUSION REACTOR*

Jack Hovingh

Lawrence Livermore Laboratory
University of California
Livermore, California 94550

ABSTRACT

This paper parametrically investigates the effects of microexplosion energy on the first wall costs of a 4000 MW_t ion-beam initiated, inertially confined fusion reactor for several first wall materials. The thermodynamic models and the results for microexplosion energies between 400 and 4000 MJ are presented. A solid stainless steel or a composite isotropic graphite over stainless steel first wall can operate for a year at a cost of 0.6 mills per kWh gross electric power output.

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INTRODUCTION

A viable reactor design for inertially confined fusion must deal with two major problems which result from the fusion microexplosion. These problems are:

1. The response of the first wall to the short ranged energy (x-rays and debris) deposition from the microexplosion in the first wall.
2. The effects of high energy neutrons and cyclical stresses on the reactor blanket.

This paper will be concerned only with the first wall designs that attempt to cope with the first problem.

A first wall design study for a 4 x 10^9 J per microexplosion, 4000 MW_t fusion reactor was performed for the ERDA Summer Study of Heavy Ions for Inertial Fusion.[1] This paper broadens the parameter space considered in the earlier work.

FUSION REACTOR PERFORMANCE CHARACTERISTICS

To investigate possible reactor first wall designs we assumed a reactor power of 4000 MW_t, with a gross electrical output of 1320 MW_e. The thermonuclear yield was varied between 400 and 4000 MJ per microexplosion while the total yield in x-ray and debris energy was fixed at 32% of the thermonuclear yield, divided between 2% in x-ray energy and 30% in debris energy.

THERMODYNAMIC ANALYSIS

A thermodynamic analysis was performed on various first wall materials as a function of first wall radius for the microexplosion. This analysis assumed that all the x-ray and debris energy was deposited at the surface of a semi-infinite solid. The initial temperature of the solid was assumed to be 800 K, and the thermal properties of the solid were assumed to be invariant with temperature. During the times when no energy flux was acting on the surface, the surface is assumed to be adiabatic. Finally, the solid was assumed to undergo no phase change, and the surface position did not move even when the surface temperature exceeded the melting point or the boiling point of the material.

FIRST WALL MASS TRANSFER ANALYSIS

Another consideration in the design of a fusion reactor first wall is the mass loss of first wall material during a shot cycle. This mass transfer will, in part, determine the vacuum pumping requirements for the reactor system. This mass transfer analysis assumed only surface vaporization due to the difference in the vapor pressure of the first wall material and cavity pressure as a function of the surface and cavity gas temperatures and time. The initial cavity partial pressure of the first wall material is assumed to be the vapor pressure of the material at 800 K. When the partial pressure in the chamber due to the vaporization of the first wall material is the same as the vapor pressure, mass transfer from the wall is assumed to cease. Mass transfer from the cavity to the first wall during the portion of the shot cycle that the surface temperature is decreasing is not considered. An upper limit of the mass transfer was established based on the latent heat of vaporization at the boiling point of the first wall material.

Two first wall lifetime criterion were assumed. The first criterion is a surface recession rate criterion, based on the loss of 10 mm of first wall material per year. The second criterion is a neutron damage criterion based on a neutron fluence of about 10^{26} n/m^2, which is a one year exposure to a first wall neutron flux of 5 MW/m^2.

FIRST WALL MATERIALS

The materials considered for the first wall included lithium (wet wall), niobium, stainless steel, and two types of graphite. The first type of graphite was assumed isotropic, while the second type was assumed to be highly anisotropic, with the direction of maximum thermal conductivity in the radial direction of the reactor.

RESULTS FOR A 4000 MJ MICROEXPLOSION

The peak temperature at the surface of the first wall as a function of the reactor radius for the various material is shown in Fig. 1 for the 4000 MJ pellet. The stainless steel first wall will have a peak temperature above its melting point, and the lithium will always have a peak surface temperature above its boiling point (760 torr) to radii greater than 25 m. Niobium does not exceed its melting point for reactor radii greater than 16 meters. The isotropic graphite does not exceed its sublimation point (760 torr) for reactor radii greater than 13 meters. The pyrolytic graphite can operate without exceeding its sublimation temperature at first wall radii greater than 9 meters.

The mass lost from the surface of the reactor first wall is shown in Fig. 2. The inflections in the curves occur where the energy is conducted away from the surface at a rate such that the mass lost is less than that possible considering only the latent heat of vaporization.

The surface recession of first wall material per shot is shown in Fig. 3. Using the 10 mm/year (10^{-3} μm/shot) criterion, a niobium or isotropic graphite first wall radius must be greater than 14 m, while the pyrolytic graphite first wall radius must be greater than 10 m. A stainless steel first wall radius must be greater than 21 m, while a lithium first wall at 20 m requires the replacement of an 8 μm thick layer each shot.

The surface recession of the first wall material determines the minimum reactor radius. The results from Figs. 1 through 3 are summarized in Table I for a surface recession rate of 10^{-3} μm per microexplosion. Lithium is not listed in Table I, since the surface recession rate of lithium is not relevant because the surface is replenished after each microexplosion.

FIGURE 1: PEAK LINER SURFACE TEMPERATURE AS A FUNCTION OF REACTOR RADIUS WITH A 4000 MJ MICROEXPLOSION

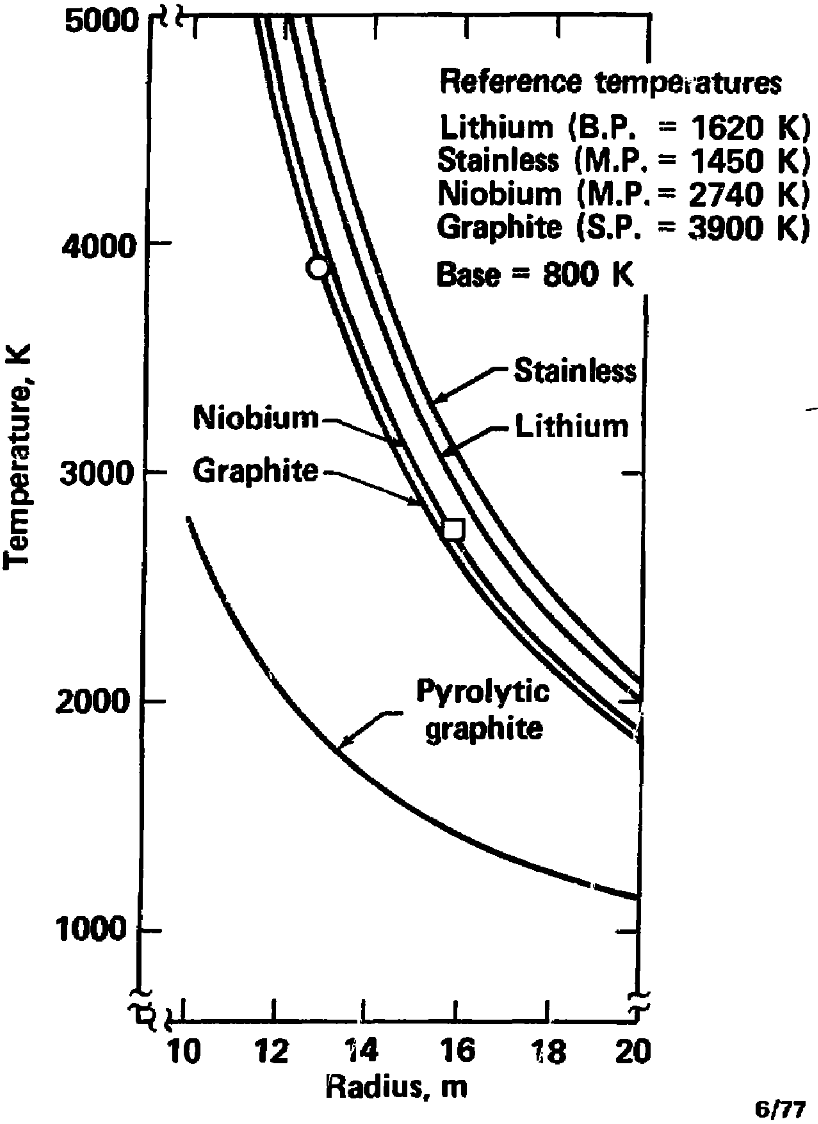

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FIGURE 2: FIRST WALL MASS LOSS PER 4000 MJ MICROEXPLOSION AS A FUNCTION OF REACTOR RADIUS FOR SEVERAL CANDIDATE FIRST WALL MATERIALS

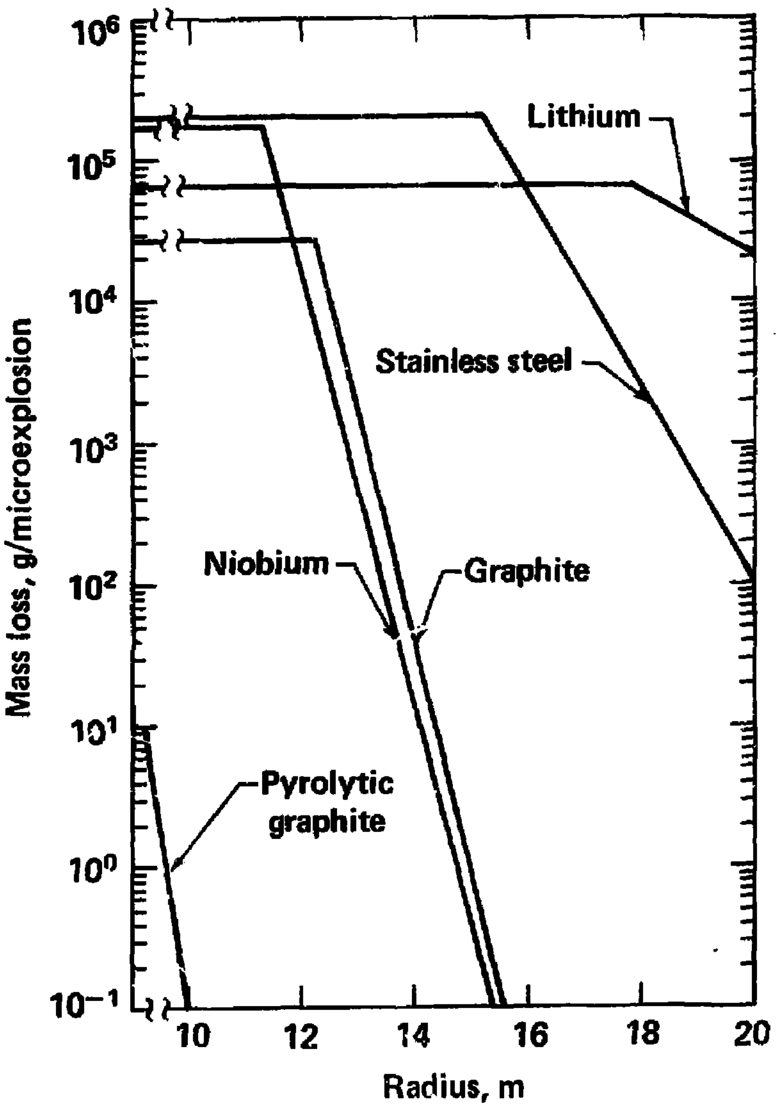

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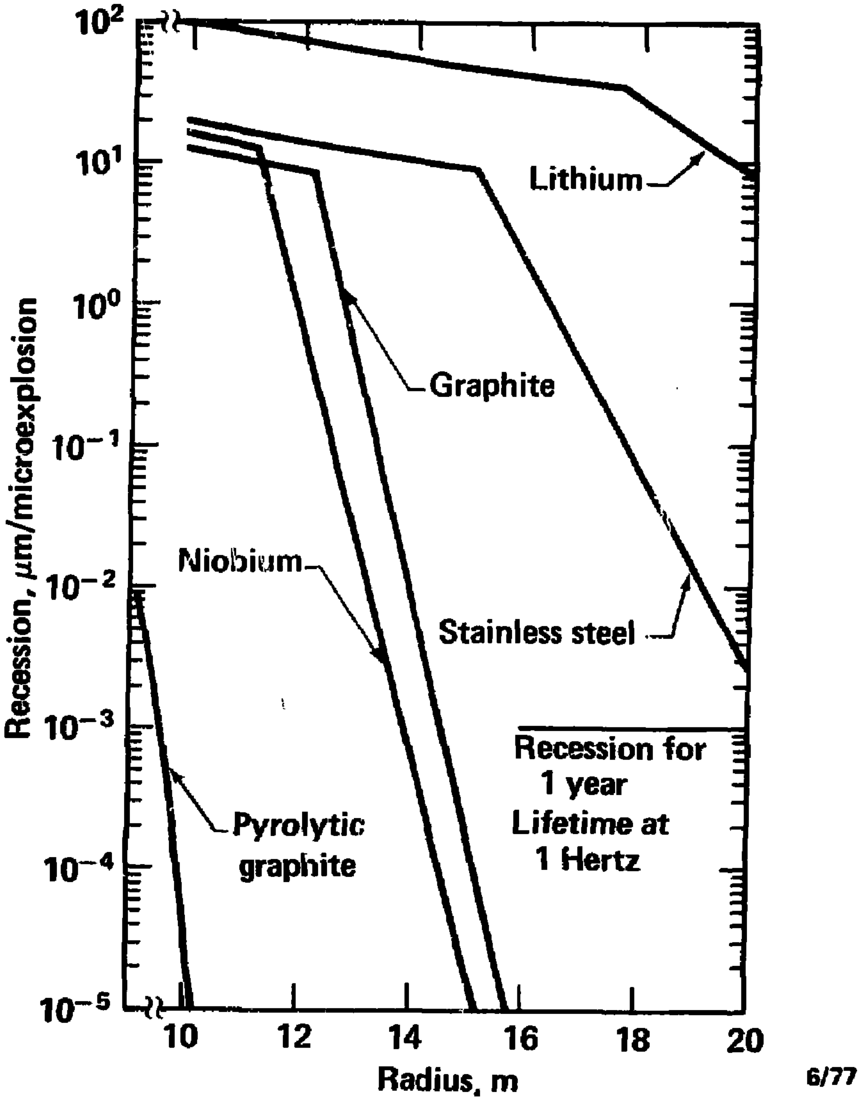
FIGURE 3: FIRST WALL RECESSION PER 4000 MJ MICROEXPLOSION AS A FUNCTION OF REACTOR RADIUS FOR SEVERAL CANDIDATE FIRST WALL MATERIALS



If the cavity pressure is limited to maximum of the order of 10^{-2} torr prior to each microexplosion from ignition beam injection considerations, then lithium is not a viable candidate for a first wall material. If the maximum cavity pressure is not a limitation on the efficiency of the ion beam injection, then the lithium wet wall concept is a viable alternative to the dry wall concept since the recirculation of 70 kg of lithium between shots is not anticipated to be troublesome. Since the maximum allowable chamber pressure between shots is currently an open question, the use of lithium as a first wall material will not be discussed further in this paper.

TABLE I: Characteristic Performance of Several First Wall Materials in a 4000 MW_t Reactor With a 4000 MJ Yield Per Pulse and a Surface Recession of 10^{-3} μm per second.

Material	Radius m	Neutron Flux MW/m^2	Peak Temp. K	Mass Lost g/sec
Niobium	13.9	1.1	3200	21.
Stainless Steel	20.6	.51	2000	42.
Graphite	14.5	1.0	3100	4.4
Pyrolytic Graphite	9.41	2.4	3100	1.8

DESIGN OPTIONS

For a given blanket design (including structure) several first wall designs are apparent. Basically, they consist of using a liner which is mounted independently of the blanket such that the liner can be replaced without removing all the blanket. The geometry which is the easiest to accomplish the removal of the liner without removing much of the blanket is a hollow cyclindrical blanket with covers on the top and bottom. Thus, to change all the liners, only the top cover of the blanket need be removed. Since the impulse load from the pellet can be handled for millions of shots (without consideration of neutron damage) by a 20-30 mm thick cyclindrical shell of either niobium or stainless steel at 800 K, the following designs are possible:

1. A stainless steel or niobium liner 40 mm thick.
2. A niobium inner liner 20 mm thick in a 30 mm thick stainless steel shell.
3. A graphite inner liner 20 mm thick in a 30 mm thick stainless shell.

The backside of these liners can be cooled by a gas or a liquid metal as shown in Fig. 4. Note that the inner liner is not a load carrying member, but only used to reduce the vacuum pumping loads, increase lifetime, and to decrease the cost of the liner by using a cheaper material (stainless steel) as a structural material to support the more expensive material (niobium), or to support a weak (in tension) material (graphite).

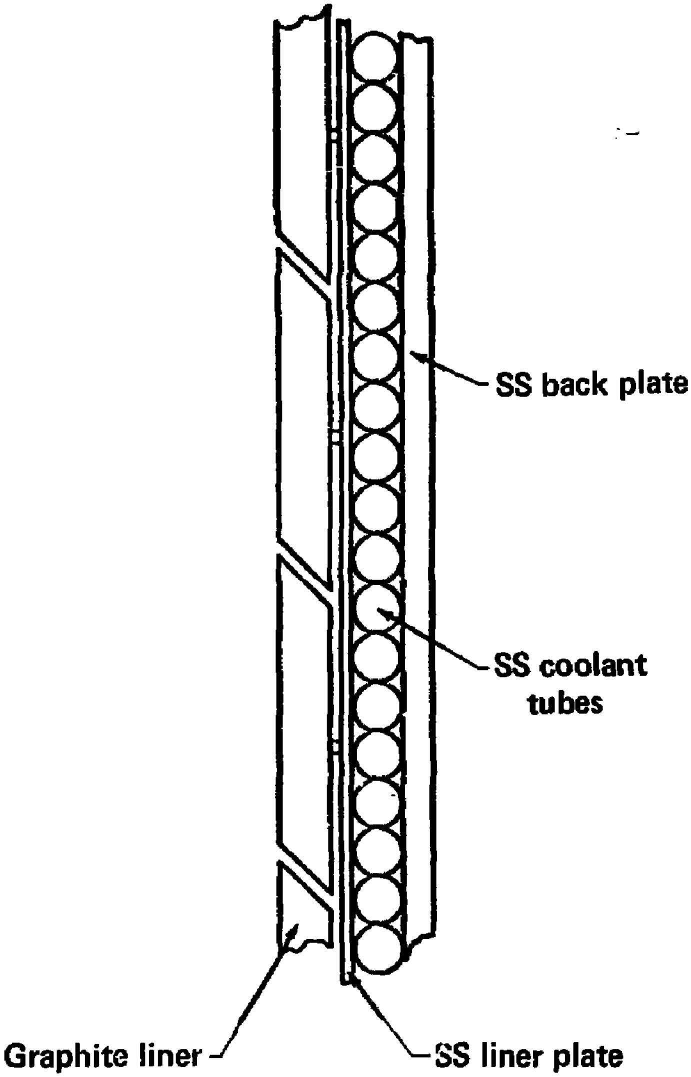
FIRST WALL MATERIAL COSTS

The fabricated costs of the first wall materials is given in Table II below. These costs of fabricated materials are only best guesses, and should not be regarded as written in stone. For comparison, Fleischer et al[2] give a fabricated cost of 316 stainless steel as 13.2$/kg and Nb-1 Zr as 176$/kg.

TABLE II: Fabricated Costs of Various First Wall Materials[1]

Stainless Steel	30$/kg
Niobium	120$/kg
Graphite (Isotropic)	22$/kg
Pyrolytic Graphite	3000$/kg

FIGURE 4: DRY SACRIFICIAL FIRST WALL FOR INERTIALLY-CONFINED FUSION REACTORS



COST OF THE FIRST WALL FOR A 4000 MJ YIELD REACTOR

The volume of the first wall is based on a "square" cylinder with top and bottom covers. The cost of the first wall liner for various material combinations and pellets in a 4000 MW_t reactor using 4000 MJ microexplosions is given in Table III below, using data from Tables I and II. The cost of the first wall liner per unit of gross electrical power for various materials combinations is also given in Table III. Note this cost assumes a liner lifetime of 4000 MW_t-years (1320 MW_e-years).

TABLE III: Cost of First Wall Liner for 4000 MJ microexplosions and 4000 MW_t

Cost Units	M$		mills/kWh_e	
Material Combination	*	**	*	**
Stainless	75.	33.	6.5	2.9
Niobium	150.	220.	13.	19.
Niobium/Stainless	100.	120.	8.7	10.
Graphite/Stainless	31.	15.	2.7	1.3
Pyrolytic Graphite/ Stainless	180.	170.	15.	15.

* Cost from Table II.

** Stainless and niobium cost from Fleischer et al.

For a 4000 MW_t reactor with 4000 MJ microexplosions, the isotropic graphite over stainless steel liner is the cheapest first wall liner, with solid stainless steel the next cheapest liner. The solid niobium liner cost is about 50% greater than the niobium over stainless steel combination. The maximum fabricated price for pyrolytic graphite such that the pyrolytic graphite over stainless steel liner costs less than the isotropic graphite over stainless steel liner is given in Table IV. The maximum permissible cost of pyrolytic graphite is sensitive to the cost of the stainless steel for a 4000 MJ microexplosion. The lower the cost of the stainless steel, the lower the maximum permissible cost of pyrolytic graphite for the pyrolytic graphite liner cost to be equal to the isotropic graphite cost.

TABLE IV: Maximum Permissible Cost of Pyrolytic Graphite for a 4000 MW_e Reaction With 4000 MJ Microexplosions

Cost of SS	Cost of Pyrolytic Graphite
13.2 $/kg	180 $/kg
30 $/kg	350 $/kg

EFFECT OF FIRST WALL RADIUS ON MICROEXPLOSION ENERGY

The effect of the first wall radius and neutron flux on the size of the microexplosion for several different pellets and materials is shown in Figs. 5 and 6 for a one year lifetime due to surface recession in a 4000 MW_t reactor. For a given radius, pyrolytic graphite can accommodate the largest yield microexplosion while stainless steel is limited to the smallest microexplosion.

The microexplosion energy as a function of the first wall radius in meters is roughly

$$E \approx CR^{5/2} \quad \text{MJ} \qquad (1)$$

where C is dependent on the first wall material. The microexplosion energy in terms of the first wall neutron flux in MW/m^2 is roughly

$$E \approx D\phi^{-5/4} \quad \text{MJ} \qquad (2)$$

FIGURE 5: MICROEXPLOSION ENERGY AS A FUNCTION OF FIRST WALL RADIUS FOR A 1 YEAR LIFETIME IN A 4000 MW_T FUSION REACTOR

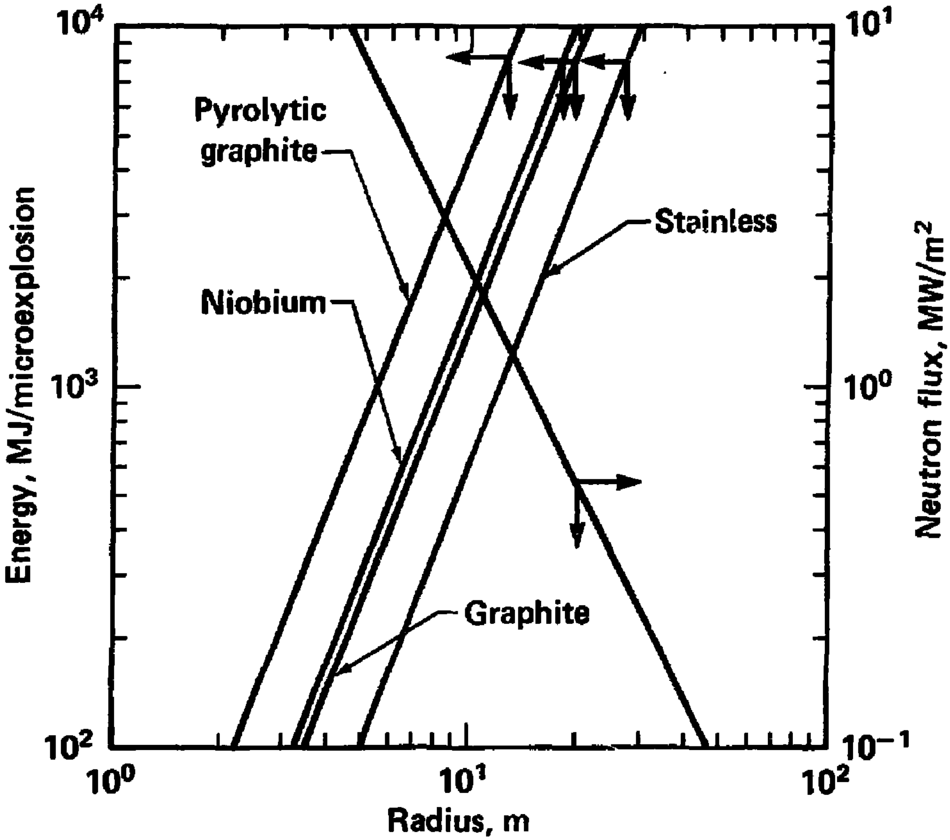
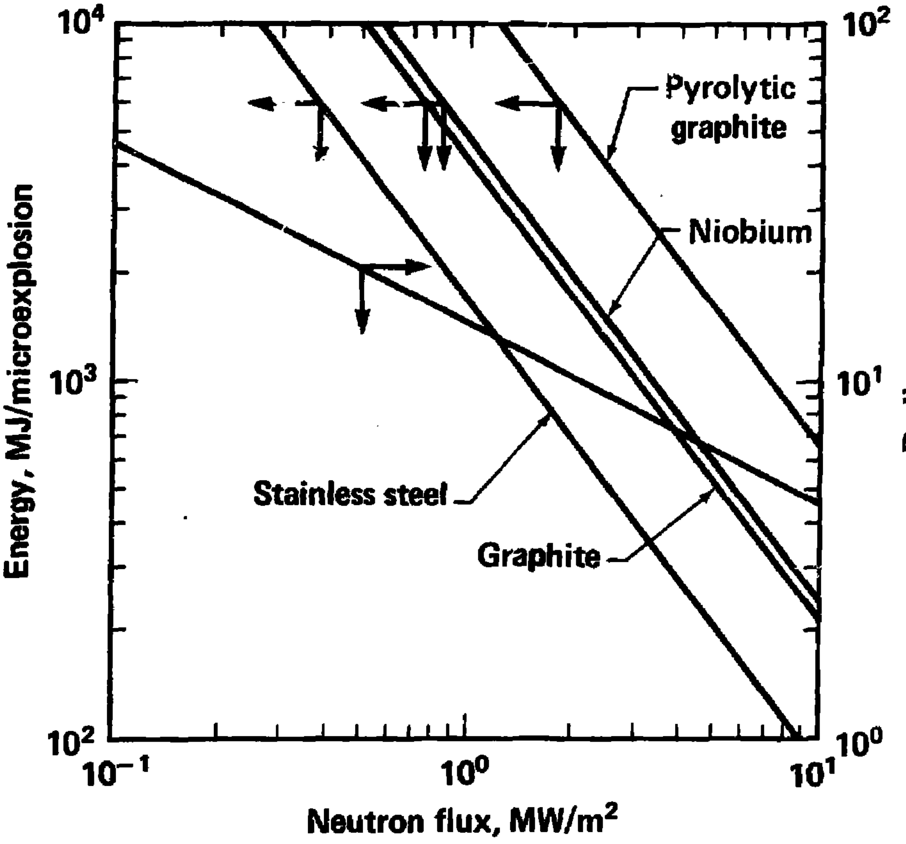


FIGURE 6: MICROEXPLOSION ENERGY AS A FUNCTION OF FIRST WALL NEUTRON FLUX FOR A 1 YEAR LIFETIME IN A 4000 MW_T FUSION REACTOR



where D is dependent on the first wall material. The values of C and D for various first wall materials for a one year lifetime in a 4000 MW_t reactor are given in Table V. Also shown are values of C and D from an earlier, less refined calculation.[3]

TABLE V: Constants for Determining Microexplosion Energy as a Function of Radius and First Wall Neutron Flux for Several First Wall Materials in a 4000 MW_t Reactor.

Material	C(Radius, m)		D(Neutron flux, MW/m^2)	
		***		***
Stainless Steel	1.9	1.6	1600	1300
Niobium	5.4	4.5	4500	3800
Graphite	4.8	4.1	4000	3400
Pyrolytic Graphite	14.	12.	12000	9700

*** Early Work by Hovingh

EFFECT OF MICROEXPLOSION ENERGY ON FIRST WALL COSTS

The first wall cost per unit of time integrated gross electric power produced as a function of first wall neutron flux is:

$$C = \frac{\beta}{\phi} \text{ mills/kWh}_e \tag{3}$$

where β is a function of the first wall material. The constant β is given in Table VI for the various first wall designs.

TABLE VI: Constant β for First Wall Cost Expression (Eq. 3) for First Wall Lifetime of One Year for 4000 MW_t (1320 MW_e) Ion Beam Reactor

Material Combination	*	**
Stainless	3.3	1.5
Niobium	15.	21.
Niobium/Stainless	9.8	12.
Graphite/Stainless	2.7	1.3
Pyrolytic Graphite/Stainless	37.	36.

* Cost from Table II

** Stainless and niobium cost from Fleischer et al

The effect of the microexplosion energy for a first wall lifetime of one year with various first wall materials on the first wall costs are shown in Figs. 7 and 8. Also shown are the neutron flux at the first wall. Figure 7 shows the first wall cost based on the cost factors given in Table II. Figure 8 shows the first wall cost per unit of time integrated gross electric power output of a 4000 MW_t reactor operating with a thermal conversion efficiency of 0.33.

The graphite and the stainless steel first walls are the least expensive, while the pyrolytic graphite and solid niobium first walls are the most expensive. For a given first wall neutron flux, the solid niobium first wall costs about five times more than the composite niobium over stainless steel first wall. As to be expected, the first wall cost for a one year lifetime decreases with an increase in first wall neutron flux and with a decrease in the microexplosion energy.

FIGURE 7: FIRST WALL COST AS A FUNCTION OF MICROEXPLOSION ENERGY FOR A 4000 MW_T REACTOR WITH A FIRST WALL LIFETIME OF 1 YEAR.

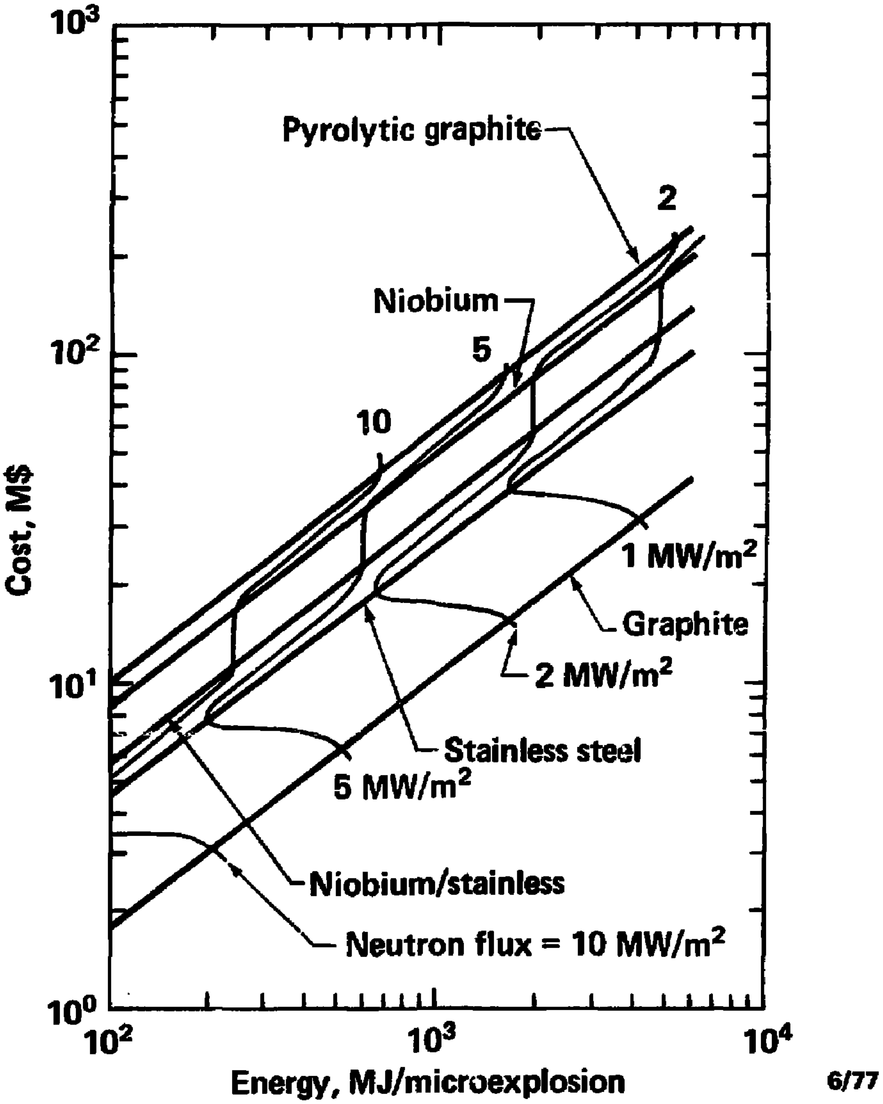
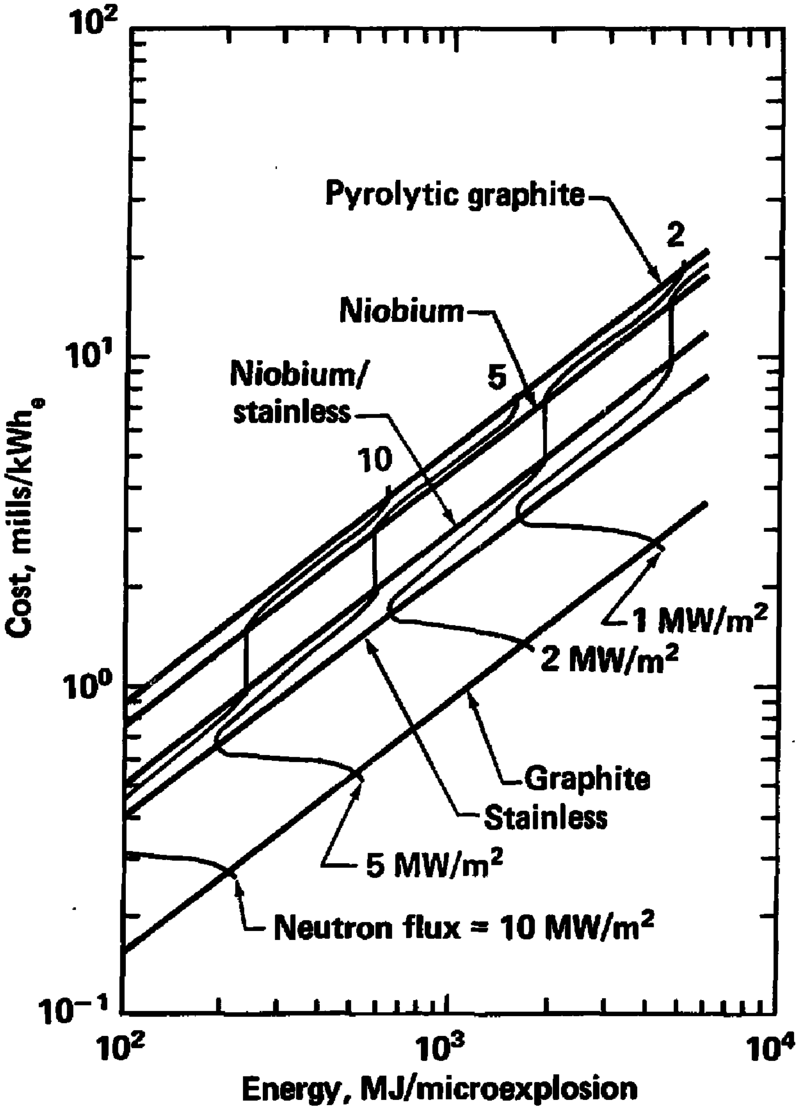


FIGURE 8: FIRST WALL COST IN MILLS/kWHE AS A FUNCTION OF MICROEXPLOSION ENERGY FOR A 4000 MW_T REACTOR WITH A FIRST WALL LIFETIME OF 1 YEAR.



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The first wall cost and the cost per unit of time integrated gross electrical power for several first wall materials as a function of microexplosion energy for a one year lifetime are shown in Figs. 9 and 10. Since the damage threshold of stainless steel from high energy neutrons is a fluence of about 10^{26} n/m^2, the maximum first wall neutron flux for a one year lifetime due to neutron damage is 5 MW/m^2. The minimum first wall cost occurs when the lifetime due to neutron damage is the same as that for surface recession. Note that operating at a fixed neutron flux, but smaller microexplosions does not affect the first wall cost. Operating at higher microexplosion energies results in increased first wall costs for a given wall lifetime. The cost of various first wall material combinations for a one year lifetime and first wall flux of 5 MW/m^2 is given in Table VII for a 4000 MW$_t$ reactor.

TABLE VII: Cost of First Walls in a 4000 MW$_t$ Reactor Based on a First Wall Neutron Flux of 5 MW/m^2 and a Lifetime of One Year. (First Wall Radius is 6.6 m).

Cost Units	M$		mills/kWh$_e$	
Material Combination	*	**	*	**
Stainless	7.6	3.4	.66	.29
Niobium	34.	49.	2.9	4.3
Niobium/Stainless	23.	27.	2.0	2.4
Graphite/Stainless	6.3	3.1	.55	.27
Pyrolytic Graphite/ Stainless	87.	83.	7.5	7.2

* Cost from Table II.

** Stainless and niobium cost from Fleischer et al.

FIGURE 9: FIRST WALL COST AS A FUNCTION OF MICROEXPLOSION ENERGY FOR A 4000 MW_T REACTOR WITH A FIRST WALL MAXIMUM NEUTRON FLUX OF 5 MW/m^2 AND A LIFETIME OF 1 YEAR.

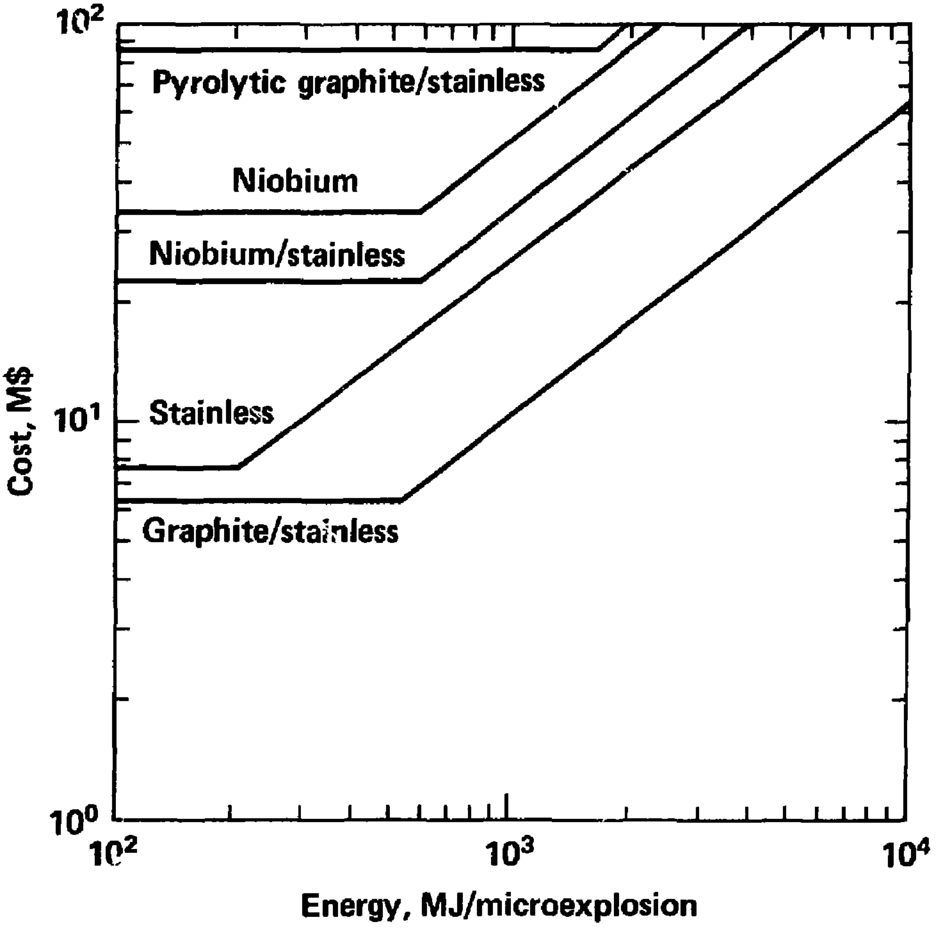

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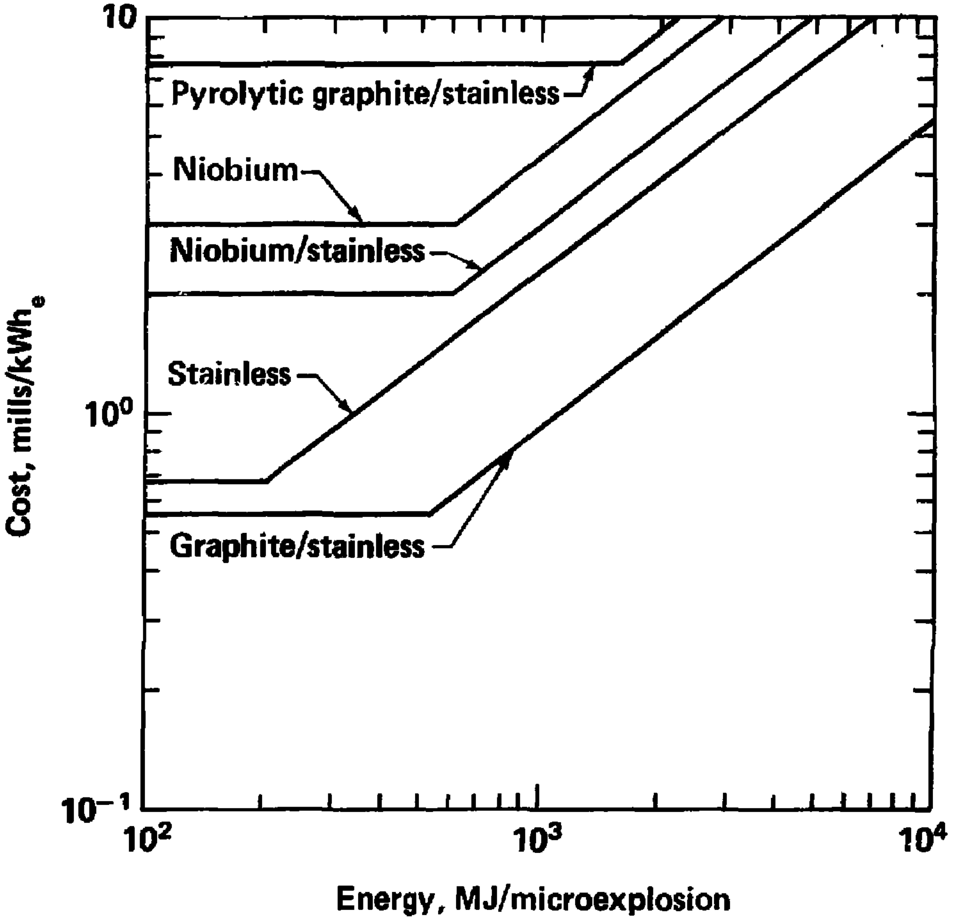
FIGURE 10: FIRST WALL COST IN MILLS/kWhe AS A FUNCTION OF MICROEXPLOSION ENERGY FOR A 4000 MW_T REACTOR WITH A FIRST WALL MAXIMUM NEUTRON FLUX OF 5 MW/m^2 AND A LIFETIME OF 1 YEAR.



DISCUSSION

The maximum pellet performance, defined as the pellet yield for which the lifetime of the first wall due to surface recession is the same as that due to neutron damage, for various first wall materials in a 4000 MW_t reactor based on a first wall neutron flux of 5 MW/m^2 and a lifetime of one year is given in Table VIII. Also given in Table VIII are earlier estimates of maximum pellet performance,[3] with a comparison of the recession rates at a first wall neutron flux of 5 MW/m^2 for the current and earlier work. If the recession rate is greater than that estimated using vapor pressure considerations due to, say, sputtering, the maximum pellet performance can be reduced. For example, if the surface recession rate due to, say, sputtering, is 45 times that due to vaporization using a graphite first wall, a reduction of the maximum pellet yield from 530 MJ to 450 MJ will still allow a first wall lifetime of one year in a 4000 MW_t reactor with a neutron flux of 5 MW/m^2 at the first wall.

TABLE VIII: Maximum Pellet Performance for First Wall Materials in a 4000 MW_t Reactor Based on a First Wall Neutron Flux of 5 MW/m^2 and a Lifetime of One Year. (First Wall Radius is 6.0 m).

Material	Energy, MJ		Recession Rate Ratio ****
	Maximum	***	
Stainless	210	170	16
Niobium	600	510	29
Graphite	530	450	46
Pyrolytic Graphite	1600	1300	130

*** Early work by Hovingh

**** Current work to early work at flux of 5 MW/m^2

If the first wall is neutron flux limited for a given lifetime, pyrolytic graphite can cost no more than isotropic graphite. For a given first wall neutron flux, the allowable microexplosion energy for pyrolytic graphite is about three times that of isotropic graphite.

From a cost viewpoint, a solid niobium first wall does not make sense. The cost of a solid niobium first wall is about 50% higher than that of a composite niobium over stainless steel first wall. This composite first wall features the desirable qualities of niobium as a first wall material, with a reduction in first wall cost from that of solid niobium.

Note that for a reactor with a given power and with a given maximum pellet yield, the use of smaller microexplosions than the maximum will result in a constant first wall flux since the given lifetime of the first wall is determined by neutron damage. The penalty for the use of smaller than maximum microexplosions will be a reduction in the allowable cost of each pellet due to the higher pulse repetition frequency for a given fuel cycle cost. This reduction in cost per pellet may not be possible. Using larger microexplosions than the maximum will result in a decrease in first wall flux since the lifetime of the first wall is now surface recession rate limited. This will result in higher first wall and blanket costs for a given lifetime of the first wall, and for a given system cost in mills/kWh$_e$, require lower fuel cycle costs in mills/kWh$_e$. Thus the design condition for minimum first wall costs may not result in the minimum power plant costs.

FIRST WALL AREAS NOT INVESTIGATED

Problem areas on the first wall design discussed in this paper which need investigation include:

1. Attachment of graphite to structural wall
2. Ion sputtering
3. The effect of cyclic stresses in the first wall. These

problem areas should be investigated because dry walls may be the only viable approach for inertially confined fusion systems that require vacuum chamber pressures less than 10^{-3} torr.

CONCLUSIONS

The least expensive first wall for a 4000 MW_t ion beam initiated, inertially confined fusion reactor requiring a low pre-shot cavity pressure will be either an isotropic graphite over stainless steel, or solid stainless steel design. These walls can be built for less than 10 M\$, or about 0.6 mills/kWh_e gross electric with a neutron flux of 5 MW/m^2. Microexplosions energies as large as 200 MJ can be used in the solid stainless steel design, and 500 MJ in the isotropic graphite over stainless steel design. Lower fluxes will increase the allowable microexplosion energy, with a concurrent increase in the first wall cost.

This report does not cover all the issues of a dry wall concept for inertially confined fusion reactors. Other considerations and problems are discussed in the literature.[1,4-7] For the high pre-shot cavity pressure case (> 0.1 torr), the wet-wall or fluid wall concepts[8-12] may be viable competitors to the isotropic graphite liner.

ACKNOWLEDGMENTS

I would like to gratefully acknowledge the discussions with, and the support of, James Maniscalco of LLL.

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