First Wall and Divertor Plate Material Selection in Fusion Reactors

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Abstract

The criteria for selecting first wall materials in magnetic and inertial confinement fusion reactors are discussed. These criteria include radiation damage, compatibility, thermomechanical properties, fabricability, joining, industrial capability, the existing data base, cost, induced radioactivity, and resource availability. At present, stainless steel remains the primary choice for a structural material because of the large existing data base and industrial capability. Titanium and vanadium alloys are the primary backup materials. The influence of surface heating on the allowable neutron wall loading is described in detail for magnetic and ICF reactors. The use of divertors may permit reactors to operate with higher neutron wall loadings but heat transfer and excessive wall erosion by sputtering of the collector plates are fundamental problems requiring resolution before divertors are employed in reactors.

I. Introduction

The performance of materials in fusion reactors has long been recognized as a fundamental issue affecting the ultimate technological and economic feasibility of fusion power. In the early days, the structural materials discussed were those capable of high operating temperature since these would permit high thermal efficiency and presumably good plant economics. The niobium alloy, Nb-1Zr, was a common choice. In 1973, the first extensive analysis of materials performance in a fusion reactor was reported by the Wisconsin group in the context of the conceptual tokamak reactor design, UWMAK-I.[1,2] The alloy 316 stainless steel was selected as the structural material, consistent with the group's design philosophy of using present-day technology wherever possible. It was argued (arguments that are still appropriate) that the steel industry has a long and well established record of providing large quantities of high quality, fabricated components. In addition, a large body of data exists on thermal, mechanical, chemical, physical, and neutronic properties of stainless steels in both liquid metal and radiation environments. The blanket coolant in UWMAK-I is liquid lithium and the maximum operating temperature, limited by compatibility, is 500°C.

Such considerations effectively established a set of criteria upon which the choice of a structural material can be made. A major conclusion of the UWMAK-I study is that the lifetime of 316 stainless steel may be as little as 2 $MW\text{-}y/m^2$. This limit is based upon embrittlement caused by displacement damage although at higher temperatures, the loss of ductility would be due to excessive helium gas production. Swelling at 500°C appears to limit the lifetime to approximately 6 $MW\text{-}y/m^2$.

Extensive efforts have been made in recent years to improve the data base for materials selection[3-5] and to improve the analysis of materials performance.[6-8] In the latter area, it it now recognized that an approach which integrates a structural analysis with materials performance at specified irradiation and operating conditions is required. In this paper, the criteria for selecting first wall materials in conceptual magnetic and inertial confinement (ICF) reactors will be described. We will also present both data and analysis to support a priority ordering of these criteria. The influence of surface heating on first wall material selection is especially emphasized, as is the problem of limiter design in tokamaks and magnetic divertor plate design in both magnetic fusion and magnetically-protected ICF reactors.

II. Criteria for Selecting First Wall Materials

A priority list of criteria for selecting first wall materials is given on Table 1. As expected, no one material is clearly favored and a final choice will depend upon the objectives of a reactor design. Radiation damage is the most important criteria because it has the greatest influence on material performance and lifetime. It therefore impacts the design in terms of reliability and maintainability. On the other hand, materials in near term reactors will have low irradiation exposures and the criteria for material selection will be reordered. A priority list of criteria for near term experimental reactors is given on Table 2.

Materials actually selected in near term experimental tokamak reactor designs[9-15] are summarized on Table 3 together with the primary reason the material is selected. One can see that, overall, the near term reactor

Table 1

Criteria for Selecting First Wall Materials[†] in Fusion Reactors in General Priority Order

Criteria	Favored Materials	Less Favored
1. Radiation Damage and Lifetime		
a. Swelling (Dim. Stability)	Ti, V, Mo, SS	Nb, Al, C
b. Embrittlement	C, Nb, V, Ti, SS	Mo, Al
c. Surface Properties	V, Ti, Al, C	SS, Nb, Mo
2. Compatibility with Coolants and Tritium		
a. Lithium	Ti, V, Nb, Mo, SS	(Al, C)*
b. Helium	SS, Ti, Mo, Al, C	(Nb, V)*
c. Water	SS, Al, Ti	(C)*
d. Tritium	Mo, Al, SS	Ti, V, Nb, C
3. Mechanical and Thermal Properties (Irradiated)		
a. Yield Strength	Mo, Nb, V, Ti, SS	Al, C
b. Fracture Toughness	SS, Ti, Al	V, Nb, Mo, C
c. Creep Strength	Mo, V, Ti, SS	C, Al, Nb
d. Thermal Stress Parameter $\left(M \equiv \frac{2\sigma_y k(1-\nu)}{\alpha E}\right)$	Mo, Al, Nb, V	Ti, SS, C
4. Fabricability and Joining	SS, Al, Ti	Nb, V, Mo, C
5. Industrial Capability and Data Base	SS, Al, Ti, C	Mo, Nb, V
6. Cost	C, Al, SS, Ti	Mo, Nb, V
7. Long Lived Induced Radioactivity	V, C, Ti, Al	SS, Nb, Mo
8. Resource Availability (U.S.A.)	C, Ti, Mo, Al, SS	Nb, V

[†] Alloys. Ti-6Al-4V, V-20Ti, TZM, Nb-1Zr, 316 SS, Al-6061. This is an illustrative list.

* Materials in parenthesis are unacceptable with stated coolant.

Table 2

Criteria for Selecting Wall Materials in Near Term Experimental Fusion Reactors

1. Industrial Capability and Existing Data Base
2. Compatibility with Coolants and Tritium
3. Fabricability and Joining
4. Mechanical and Thermal Properties
5. Induced Radioactivity
6. Cost
7. Radiation Damage

Table 3

First Wall Material Selections in Near Term Fusion Reactor Designs

Study	Machine Objective	Material Selected	Primary Reason for Selection
TNS/ORNL-W(9)	Tokamak to Follow TFTR	316 SS	Industrial Capability Plus Data Base
ITR/GA-ANL(10)	Tokamak Ignition Test Reactor	Inconel 625 + Be Coating	Efficiency with He Cooling
MTF/JAERI(11)	Tokamak to Follow JT-60	Inconel 625	Not Given
TETR/UW(12)	Tokamak Engineering Test Reactor	316 SS	Industrial Capability, Data Base, Adequate Life
EPR/USA(13)	Experimental Power Reactor	316 SS	Industrial Capability Plus Data Base
EPR/JAERI(14)	Experimental Power Reactor	TZM + Low Z Coating	High Temperature High Efficiency Operation
DEMO/ORNL(15)	Tokamak Demonstration Power Reactor	316 SS	Industrial Capability, Data Base, Adequate Life

requirement to select a material for which there is an industrial capability and an extensive data base dominates all other factors. By contrast, the materials selected in conceptual reactor designs[16-26] cover a wider range and reflect a balance between different design objectives. An extensive list is given on Table 4.

Without developing a complete discussion of every item on Table 1, it is appropriate to make some specific comments. On radiation damage, the only truly well characterized material is stainless steel. Data exists for other materials, such as Al, C, Mo, and V, but this is typically low fluence data without helium gas production. Titanium and vanadium alloys do not show signs of swelling in low fluence neutron irradiation tests or in heavy ion simulations but high fluence data is not available.

Extensive new data from Oak Ridge[4,5] on stainless steel summarized in Fig. 1 shows that there is a rapid ductility loss when the temperature exceeds 500°C and that void swelling is enhanced by helium gas production. These findings are consistent with the conclusions drawn in the UWMAK-I study.[1,2] On the other hand, swelling is found to be only about 2% for temperatures less than 500°C and values of uniform elongation exceed 2%. The Oak Ridge group[15] has therefore suggested that an optimum operating temperature is about 400°C for stainless steel. The predicted lifetime is about 15 MW-y/m^2.

Conn[27] has suggested lowering the temperature still further to about 300°C where swelling is expected to be quite small. Wolfer,[7] in a preliminary analysis of fracture toughness and crack propagation, showed that the lifetime could be in excess of 30 MW-y/m^2. However the influence of fatigue has not yet been included. To achieve adequate thermal efficiency with a structure at 300°C, it is suggested[27,28] that water

Table 4

First Wall Material Selections in Conceptual Fusion Reactor Designs

Study	Material Selected	Primary Reason for Material Selection
UWMAK-I, II[1,2,16]	316 SS	Existing Technology
ORNL[17]	Nb-1Zr	High Temperature, High η_{th}
PRD[18]	PE-16	Low Swelling
UWMAK-III[19]	TZM	High Temperature, High η_{th}
LLL-Mirrors[20]	316 SS and Inconel 718	Existing Technology, High Temperature
BNL-Tokamaks[21]	Al Alloys	Industrial Capability, Low Radioactivity
GA-Doublets[22]	Graphite, SiC	Industrial Capability, Low Radioactivity
SOLASE-ICF[23]	Graphite	Industrial Capability, Low Activity, Low Stress Design
Jülich-Tokamak[24]	316 SS + Mo	High Temperature, High η_{th}
NUWMAK[25]	Ti-6Al-4V	Industrial Capability, Fatigue Properties, Long Life, Low Activity
ANL-Parametrics[26]	V-20Ti	Long Life, Low Activity, High Temperature

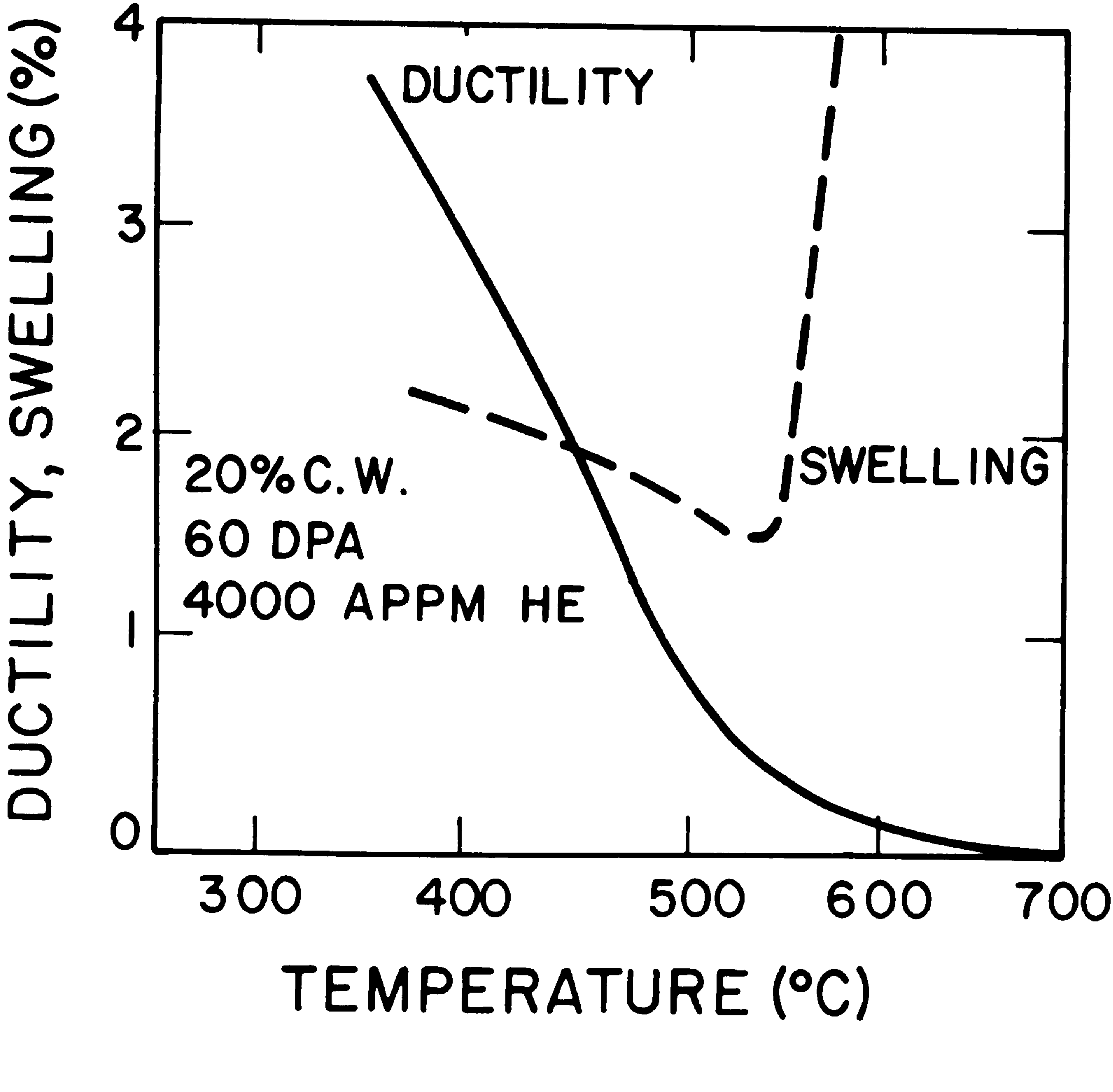

FIGURE 1 Swelling and ductility in 316 stainless steel as a function of temperature.(5)

cooling be used for the first wall and that the blanket design be based on flowing lithium oxide (Li_2O).[29] Analysis shows that the Li_2O temperature can be effectively decoupled from the structure temperature, thereby permitting an Li_2O exit temperature of 600°C. The point is that new data on materials often suggests new operating modes which can potentially allow long first wall life and adequate thermal efficiency.

The thermal properties of materials can be effectively compared in terms of the thermal stress parameter, M, defined as

$$M = \frac{2\,\sigma_y\,k(1-\nu)}{\alpha E} \qquad (1)$$

where σ_y is the yield strength, k is the thermal conductivity, ν is Poisson's ratio, α is the coefficient of thermal expansion and E is Young's modulus. Large values of M are most effective in reducing thermal stress. A graph of M versus temperature for several materials is shown in Fig. 2 and explains the priority ordering on Table 1.

Compatibility is a key issue in selecting first wall materials. Oxygen pickup and embrittlement in V and Nb alloys effectively rules out helium as a coolant. It is not practically feasible to maintain the oxygen content in the helium at the part per billion level. Excessive corrosion eliminates the use of aluminum alloys with liquid metal coolants and limits the maximum operating temperature of steels (and nickel based alloys) to about 500°C. The solubility and diffusivity of tritium is low in Mo, Al and steel but high in V and Nb at their anticipated operating temperatures. The need to double-line high temperature piping to prevent excessive tritium leakage has been found to present a severe economic penalty[19]

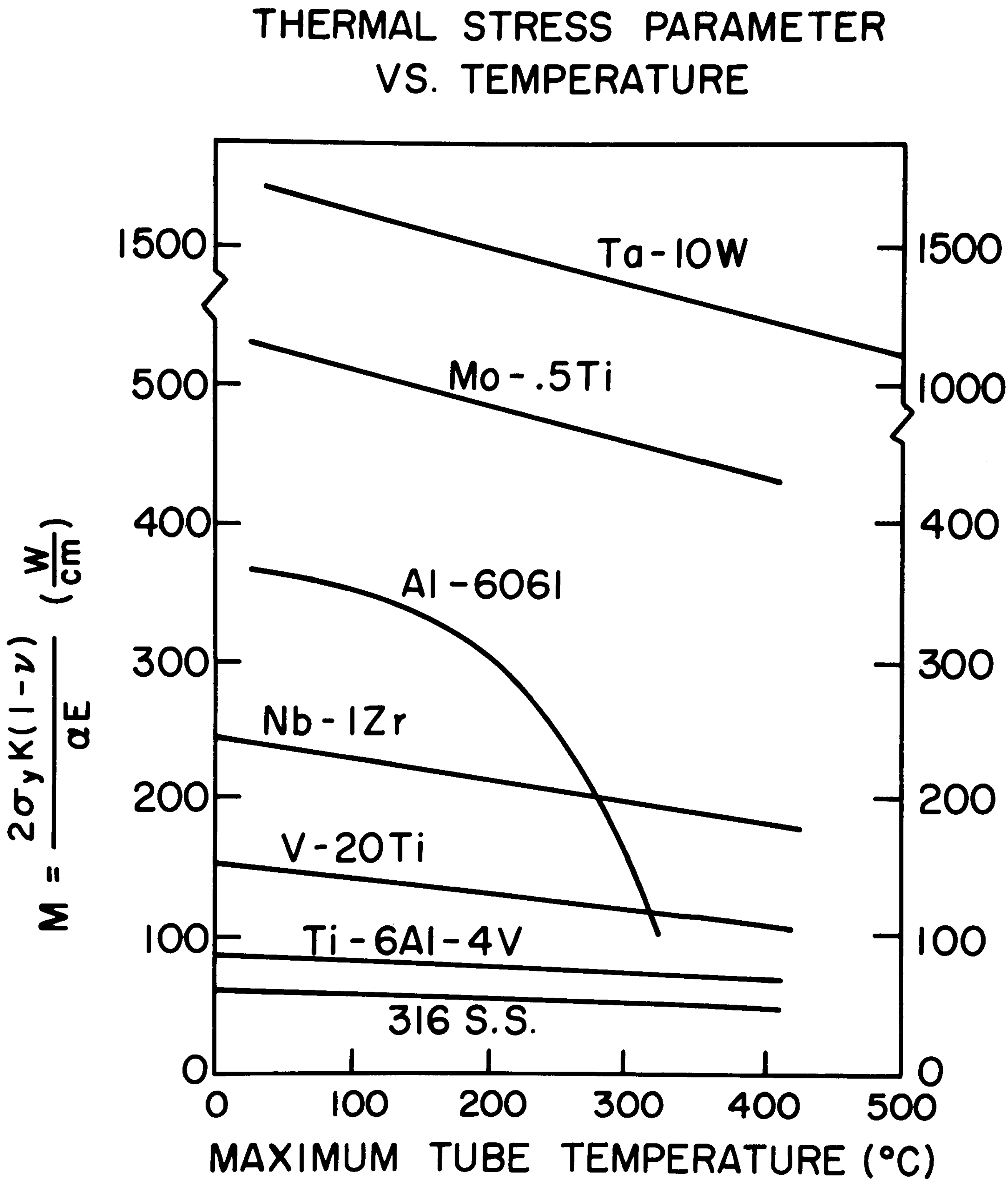

FIGURE 2 Thermal stress parameter versus temperature. The value of M for copper at 20 °C is 727 W/cm.

which could rule out these alloys even if they were acceptable on other grounds.

A comparison of induced radioactivity as a function of time after reactor shutdown is given in Fig. 3. V-20Ti is most favored on this basis but other choices, such as aluminum(21) and titanium alloys(30) and graphite, are also quite good. This points to an important general feature of fusion, namely, that long lived radioactivity is not inherent to the process and can be controlled by appropriate selection of structural materials.

III. Influence of Surface Heating on Maximum Neutron Wall Loading

Eighty percent of the D-T fusion energy is released as 14.1 MeV neutrons which, in turn, produce volumetric heating in the first wall and other materials. Twenty percent of the fusion energy is released as a 3.5 MeV alpha particle which is confined and heats the burning plasma. This energy is subsequently released by the plasma primarily in the form of X-rays and charged particle debris. (Some can also be in the form of charge exchange neutral atoms.) As a fraction of the neutral wall loading, P_n, the maximum surface heat loading is 25%. (This neglects neutron stopping in ICF targets.)

In magnetic mirrors, most of the alpha energy is deposited in ions that are subsequently lost from the ends of the device and collected in a direct convertor. The surface heat load on the first wall can thus be as little as 1% of the neutron wall loading.(31) In other devices employing magnetic diversion of the charged particle debris, the surface heat load could be reduced to about 10% of the neutron wall loading.

a. General Analysis

We consider three different structural materials (V-20Ti, Ti-6Al-4V, and 316 stainless steel) and three different coolants (helium at 5.2 MPa (750 psi),

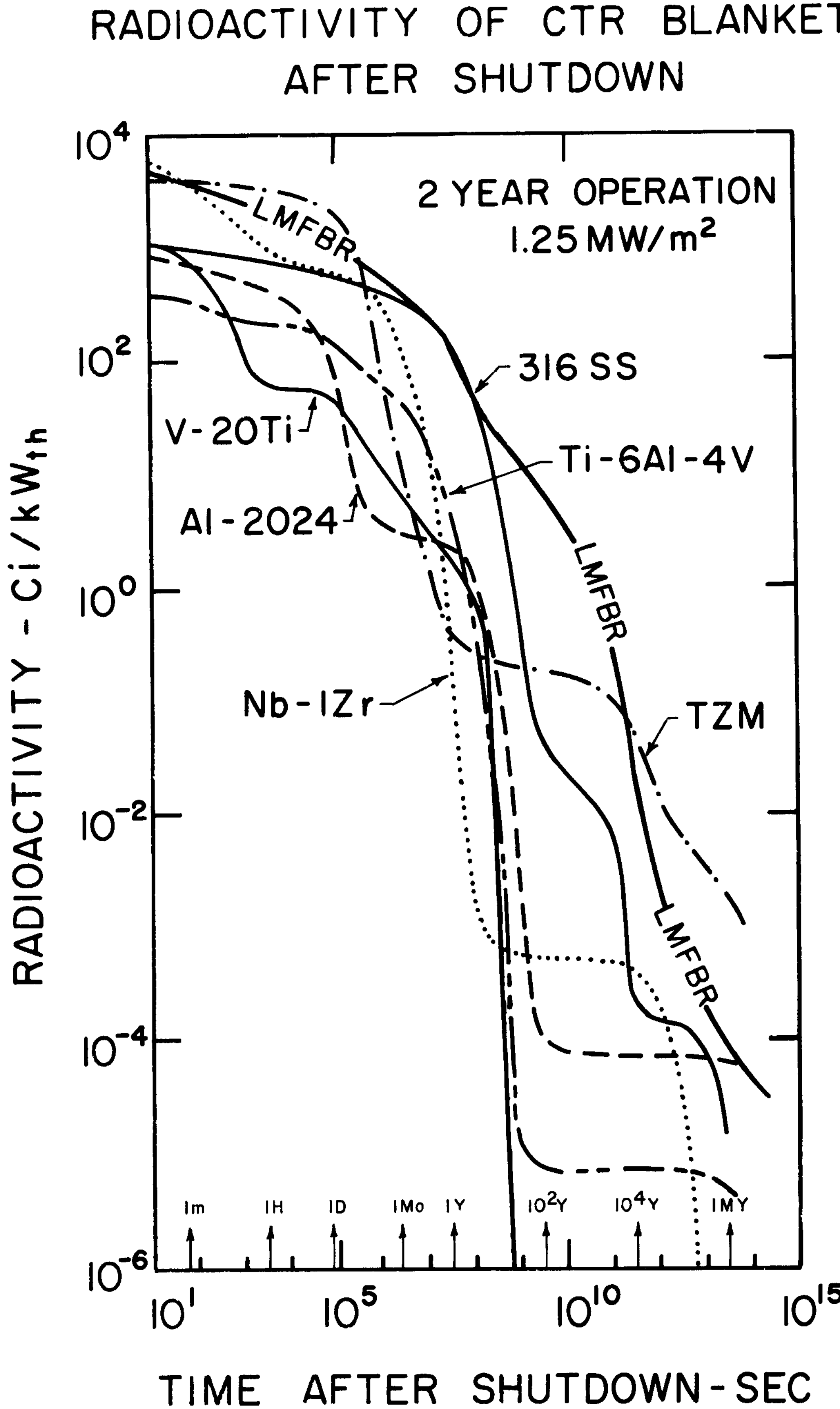

FIGURE 3 Comparison of the decay of radioactivity in several materials following shutdown after two years of operation in a fusion reactor.

boiling water at 6.9 MPa (1000 psi), and liquid lithium at 0.1 MPa (15 psi). This last case is typical of a liquid metal coolant in an ICF reactor or a magnetic fusion reactor without accounting for MHD effects.) The first wall is assumed to be constructed of 1 cm I.D. tubes that have a 1 mm wall thickness. The maximum allowable stress is set at 103 MPa (15 ksi) and the maximum allowable temperature difference between the coolant and structure is 200°C. The volumetric neutron heating is 10 W/cm^3 per MW/m^2 of neutron wall loading, a well-established result from many neutronics studies.

The results for boiling water cooling are shown on Fig. 4. Thermal stress buildup limits the performance of each material and the ordering on the figure is consistent with their respective values of the thermal stress parameter. Note that without surface heating, heat removal is possible even for a neutron wall loading as high as 100 MW/m^2. This can be important in a mirror or laser fusion reactor with magnetic protection(33,28) where the surface heat load can be as low as 1-10% of the neutron wall loading. Tokamak reactors with divertors(1,2,16,18,19) can have a surface heat load, P_s, that is 1 to 20% of the neutron wall loading, depending on the fraction of energy released as radiation and the impurity content. From Fig. 4, we see that when the surface heat load, P_s, is equal to 25% of P_n, the neutron wall loading is limited to 3 MW/m^2 for SS, 5 MW/m^2 for Ti-6Al-4V, and 11 MW/m^2 for V-20Ti.

When helium is the coolant, one finds the wall loading limit is essentially independent of the structural material because the performance is limited by heat transfer. That is, the poor heat transfer coefficient of helium forces the temperature difference between the coolant and the

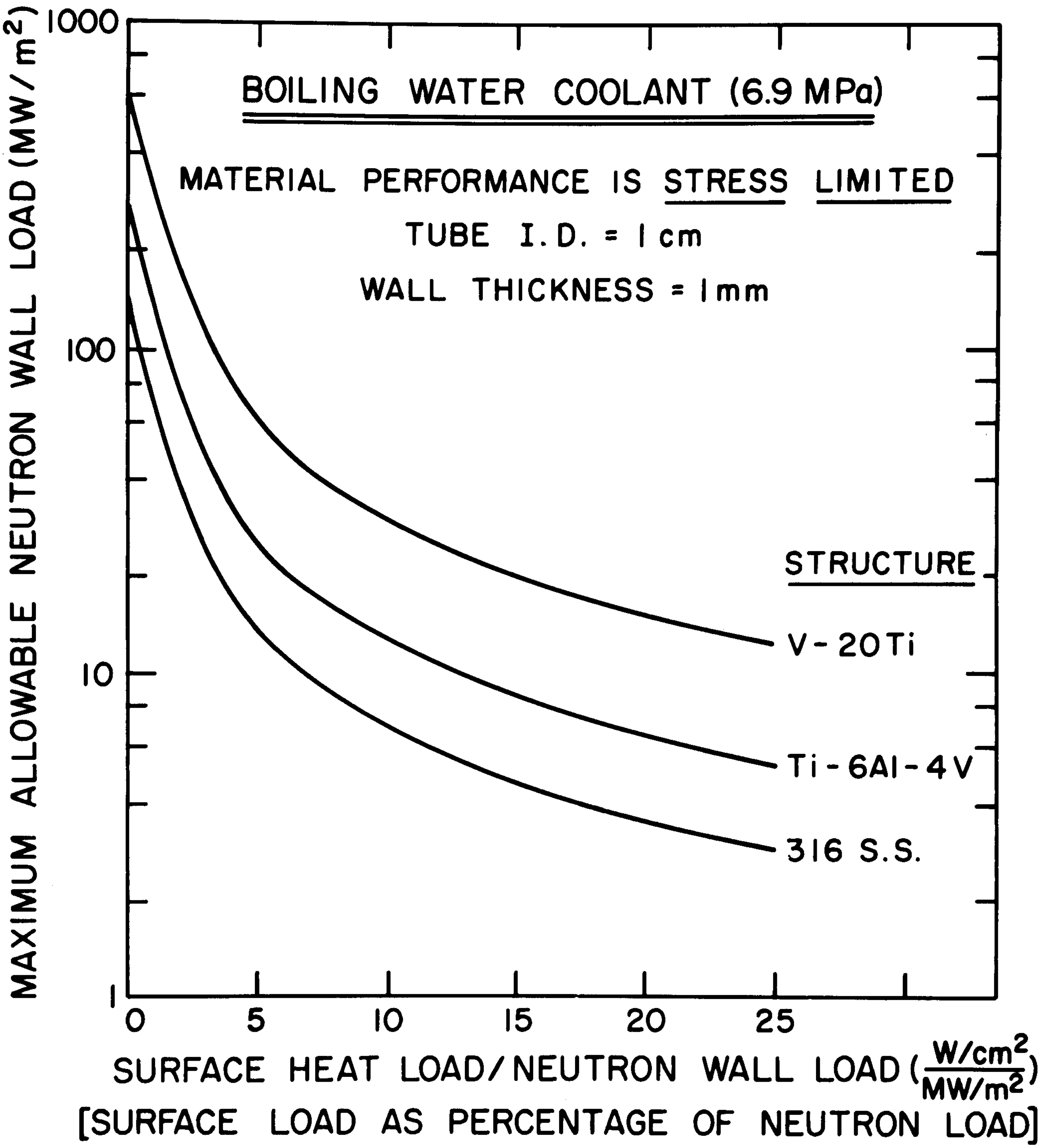

FIGURE 4 Maximum allowable neutron wall loading as a function of surface heat load when boiling water is the coolant.

structure to exceed 200°C. The results are given on Fig. 5. When P_s/P_n is 25%, the neutron wall loading limit is 2 MW/m^2.

For liquid lithium cooling at 1 atm pressure, it is found that the performance of 316 stainless steel is stress limited while that of Ti-6Al-4V and V-20Ti is heat transfer limited. The results are given on Fig. 6. Lithium cooling in a small tube does permit the highest neutron wall loading at any ratio of P_s to P_n but such a cooling scheme will not be possible in a magnetic fusion reactor because of MHD effects. A lithium cooled tokamak blanket(1,19) typically employs a large cell in which the lithium velocity is small and the first wall is thick. The allowable wall loading is much lower. This is shown on Fig. 6 for the case where the first wall thickness is 3 mm. P_n is limited to 1.2 MW/m^2 for 316 stainless steel, 2.5 MW/m^2 for Ti-6Al-4V, and 7 MW/m^2 for V-20Ti when P_s/P_n is 25%.

In summary, minimizing the surface heat load can permit a higher first wall neutron loading based upon thermal considerations. A divertor in a tokamak, for example, can thus be used to minimize P_s and allow higher values of P_n. The same argument holds for magnetic protection in ICF reactors. Of course, heat diverted from the first wall surface must be collected somewhere and this constitutes the other "first wall" problem discussed in section III.

b. Surface Heat Load in ICF Reactor Chambers

The very short times associated with energy release in inertial confinement fusion reactors leads to some special and very interesting problems. Here, we make a rather straightforward point; a bare, unprotected reactor chamber will not survive reasonable microexplosions at economical values of the neutron wall loading. The details of the method to calculate surface heating in this case are reported by Hunter and Kulcinski.(32)

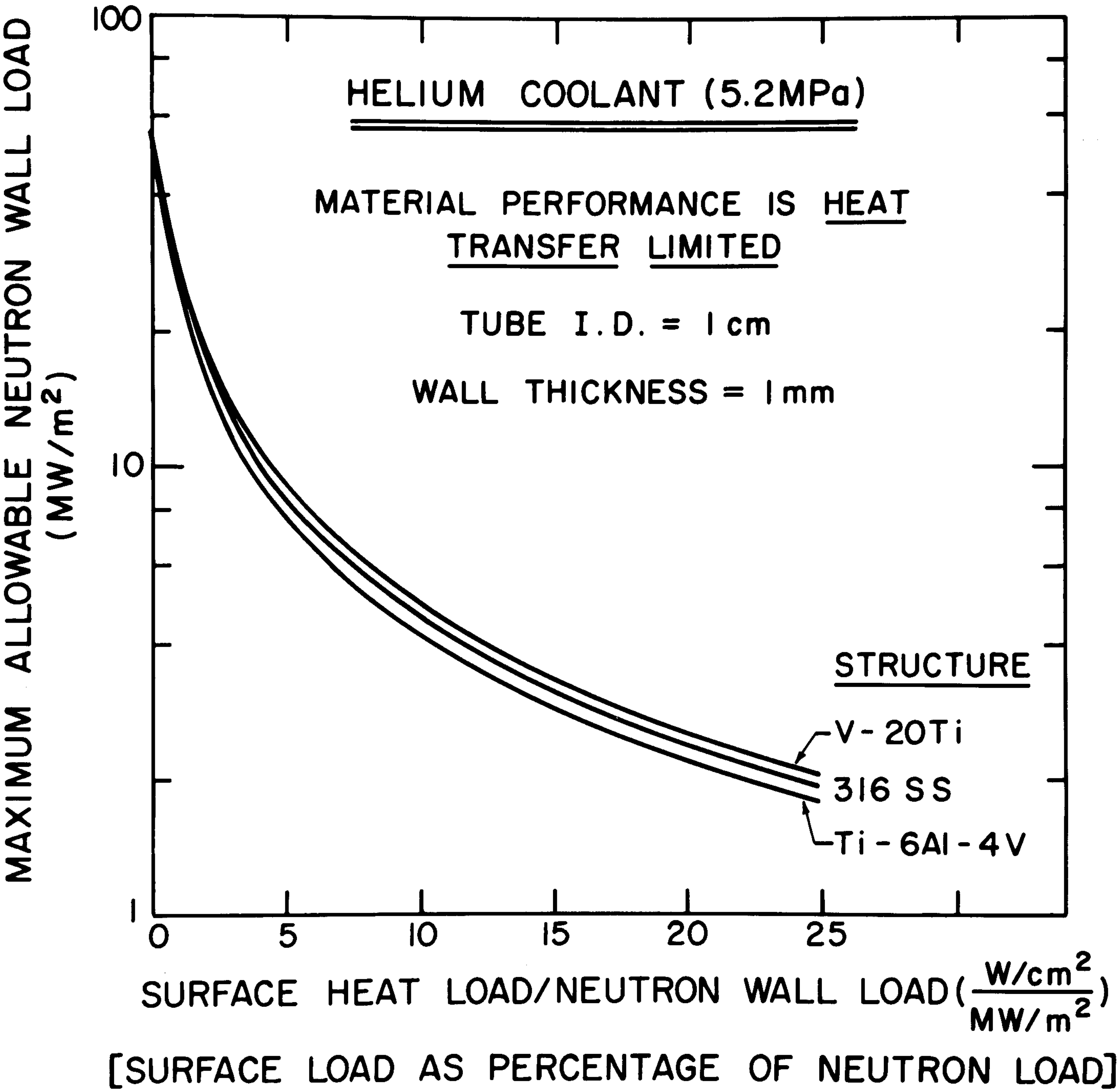

FIGURE 5 Maximum allowable neutron wall loading as a function of surface heat load when helium is the coolant.

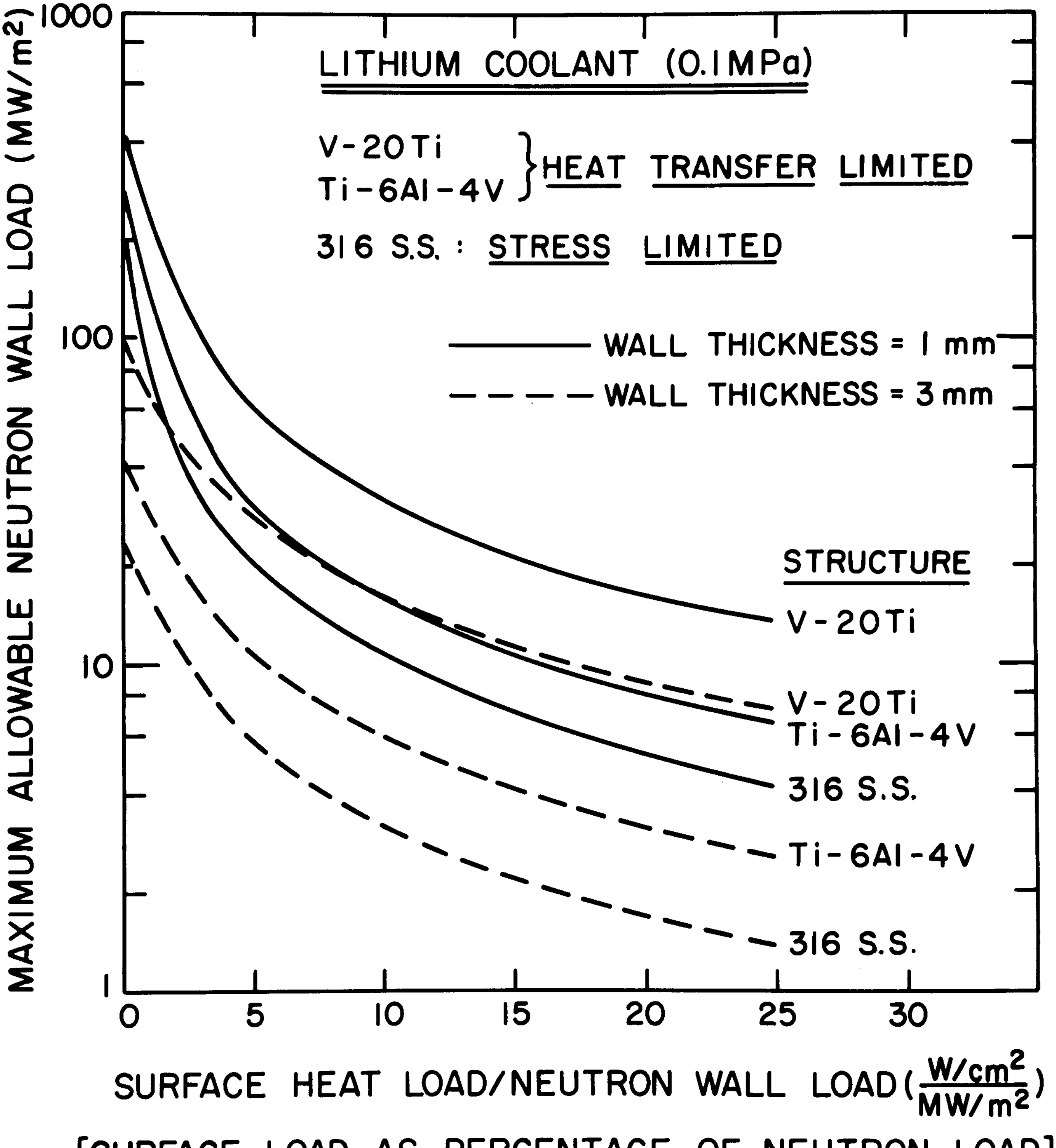

FIGURE 6 Maximum allowable neutron wall loading as a function of surface heat load when liquid lithium is the coolant.

We consider the most straightforward design in which the reactor chamber is made of 316 stainless steel and operated at 600°K. The peak surface temperature rise as a function of chamber radius for two typical values of pellet energy yield, 100 MJ and 1000 MJ, is given on Fig. 7. The minimum chamber diameter needed to avoid melting for short times is 16 m when the yield is 100 MJ and 40 m when the yield is 1000 MJ. A neutron wall loading can be associated with each case if the power output (or repetition rate) is fixed. A 1000 MW_e reactor will have a repetition rate of approximately 30 Hz for a 100 MJ yield/pellet and 3 Hz at 1000 MJ yield/pellet. The neutron wall loading is then about 2.5 MW/m^2 for the 16 m diameter case and just 0.06 MW/m^2 when the yield is 1000 MJ. 30 Hz is a very high repetition rate.

The conclusion is that the most straightforward approach to cavity design, namely an unprotected stainless steel chamber, is very difficult or unacceptable for ICF reactors. All studies to date have therefore employed some form of first wall protection. The SOLASE design of the Wisconsin group[(23)] uses a buffer gas of xenon to stop the X-ray and charged particle debris. The gas is heated and re-radiates its energy on a longer time scale, thereby lowering the instantaneous power on the first wall. A thick lithium fall is used by the Lawrence Livermore Laboratory group[(34)] to stop neutrons as well as X-rays and charged particles. Magnetic protection has been discussed by both the LASL[(33)] and Wisconsin[(28)] groups. All these methods add a degree of complexity to the reactor design. Questions of plasma stability aside, the last approach is similar to the use of divertors in magnetic fusion devices, the final topic of discussion.

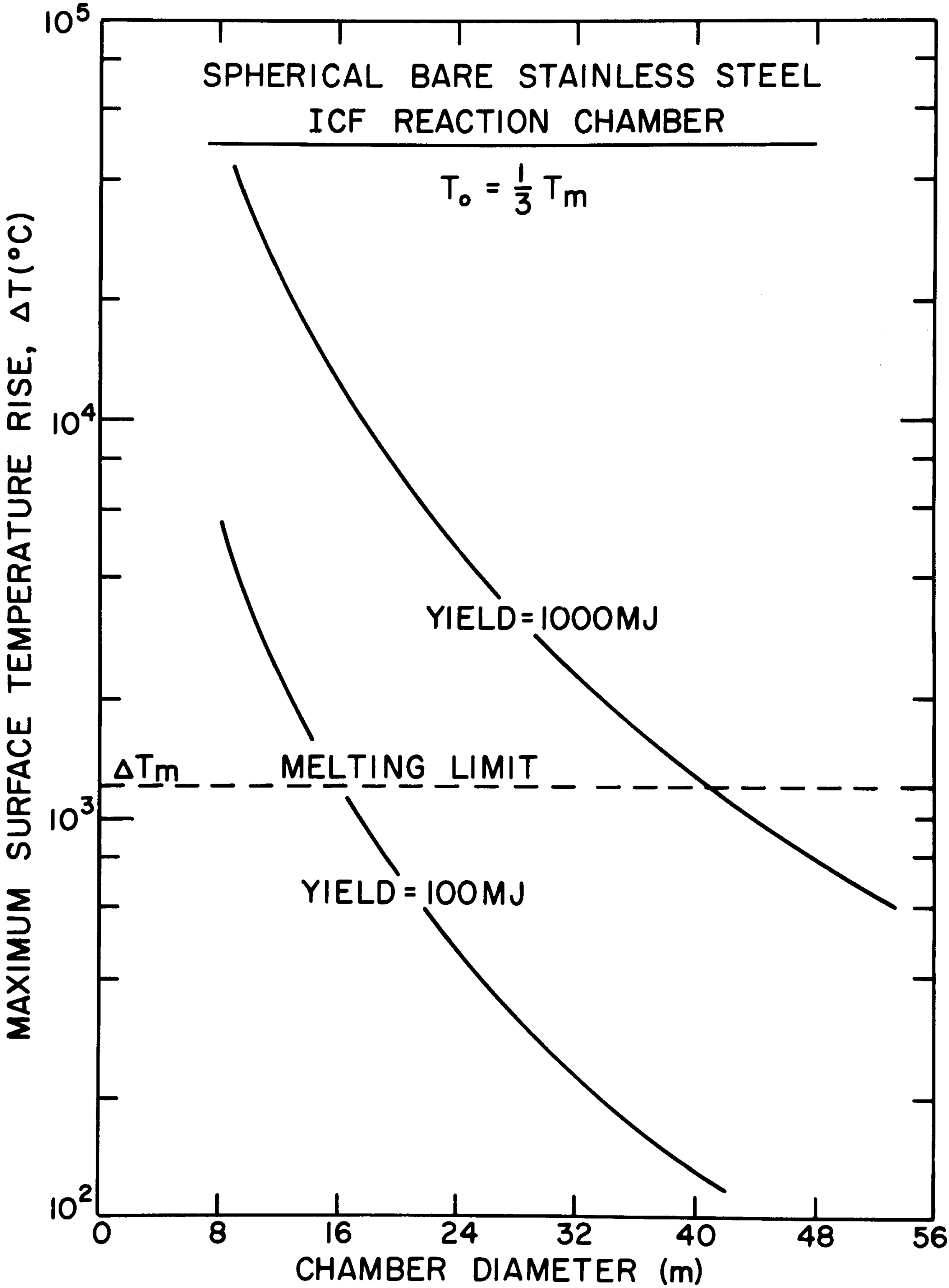

FIGURE 7 Maximum surface temperature rise in a bare stainless steel ICF reactor chamber following a given microexplosion. The melting limit is indicated. The chamber size must be large enough to avoid melting.

IV. Criteria for Selecting Divertor Plate and Limiter Materials

The divertor collector plate is the surface where charged particle debris that is magnetically diverted from the reactor chamber first wall finally deposits its energy. Such a surface will exist in magnetic fusion devices with a divertor[1,2,16,18,19] and in ICF devices with magnetic protection.[28,33] Essentially the same considerations hold at the limiter in tokamaks so that the discussion to follow is also applicable to that problem. For specificity, a tokamak with a divertor will be used as the example.

The process of diverting the charged particles from the first wall generally transports this debris to an area of the reactor where neutron radiation damage is less significant. On the other hand, the heat flux is typically more concentrated. In a tokamak, particles escaping across a separatrix boundary travel to the collector plate on a timescale short compared with the timescale for cross field diffusion. As such, the heat flux on the plate is peaked on field lines near the separatrix. This makes thermal stress and energy removal two of the key criteria that must be used in selecting the divertor collector plate structure. The other criteria are sputtering and material loss from the plate, particle collection, and tritium recovery.

Liquid lithium films and falls[1,2,16] have been proposed for both heat removal and particle collection but the maximum heat load is limited to about 100 W/cm^2. Recent studies suggest that the actual heat load may be much higher. In the Tokamak Engineering Test Reactor (TETR),[12] a neutral beam driven two component tokamak that is designed for engineering and materials testing, the maximum surface heat load on a plate oriented normal to the magnetic field is 6670 W/cm^2. Curving the plate such that field lines intercept it at an angle lowers the peak load to 670 W/cm^2, still too high to permit the use of a liquid lithium sheet. Therefore the key criteria are thermal stress and heat removal.

From Fig. 2, we see that Ta-10W is the most favored material and this is selected in the TETR study along with high velocity water cooling. Details of the plate design are summarized on Table 5. A summary of the particle fluxes striking the plate and the mean energy per particle, including the effect of the sheath at the plate, are given on Table 6. Thinning of the plate by sputtering limits the lifetime to just 4 weeks, an especially short time. It thus appears that while a divertor can allow reactors to operate at a higher value of neutron wall loading, the very short lifetime of the collector plates, the severe heat removal conditions, and the added design complexities present fundamental difficulties that must be resolved before divertors can be used in reactors.

V. Summary

Many factors influence the choice of a structural material in a fusion reactor. Integrating over the factors discussed in section II, one must conclude that stainless steel remains the primary choice for a structural material because of the large existing data base and the extensive industrial capability. Titanium and vanadium alloys are the primary backup materials. There is a large titanium industry associated with aircraft applications and titanium alloys have good fatigue properties, are compatible with all potential coolants, and can have low levels of long term radioactivity. Vanadium alloys have the best thermomechanical properties and low induced

Table 5

Divertor Collector Plate Design in a Tokamak Reactor TETR[12]

Structural Material	Ta-10W
Coolant Tube I.D.	1 cm
Tube Wall Thickness	1 mm
Coolant	water
Coolant Pressure	1.4 MPa
Inlet Temperature	65°C
Outlet Temperature	71°C
Coolant Velocity	30 m/s
Maximum Structure Temperature	295°C
Maximum Stress	140 MPa
Stress Safety Factor ($\frac{\sigma_y}{\sigma_{th}}$)	6
Plate Life Due to Erosion by Sputtering	4 weeks

Table 6

Particle Fluxes to the Divertor Plate in a Tokamak Reactor
TETR[12]

Particle	Maximum Flux (cm^{-2}-s^{-1})	Average Energy (keV)	Power (MW)	Average Sputtering Yield*
D^+	2.37×10^{16}	9.8	10	5×10^{-3}
T^+	3.27×10^{17}	9.8	136	1×10^{-2}
He^{++}	3.27×10^{14}	13.3	0.15	3×10^{-2}
e^-	3.51×10^{17}	2.0	44	-
			190	

* τ_p = 30 ms; $\bar{n}\tau_E = 4 \times 10^{12} cm^{-3}$-s ; typical of a two component tokamak with a divertor.

radioactivity levels at long times. They may also prove quite resistant to radiation damage. The major drawback is the absence at present of an industrial capability. No vanadium alloy for testing or structural applications was produced in the United States in 1977.

The severe pulsed surface heat load in ICF reactors appears to rule out the most straightforward cavity design approach, an unprotected stainless steel structure. All ICF reactor designs to date therefore employ some form of first wall protection at a cost of increased complexity.

Magnetic divertors in magnetic fusion and ICF reactors can lower the surface heat load on the first wall and permit the use of a higher neutron wall loading. However, divertors also add complexity. The heat transfer problem at the collector plate is severe and estimates of plate erosion by sputtering limits the useful lifetime to just one to two months. These fundamental problems must be resolved before divertors can be used in reactors.

Acknowledgements

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