Critical Materials Problems in INTOR

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CRITICAL MATERIALS PROBLEMS IN INTOR

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Abstract

Even though the INTOR reactor is conceived to be a near term device, there are still a few materials problems that require considerably more research. One of the more critical problems is the first wall which must handle heat loads of more than 20 W/cm^2, charge exchange neutral fluxes of ~3 x 10^{16}s^{-1}, as many as 2000 disruptions, and neutron fluences of over 6 MW-y/m^2. This article discusses the ability of steel and aluminum first walls to withstand those conditions for the lifetime of the device.

Introduction

When the INTOR project (or UNITOR as it was originally known) was first proposed by Acamedician Vehlikov in early 1978, it was envisioned to be "the maximum reasonable step" beyond the TFTR/JET/T-15/JT-60 class of tokamak physics experiments. It was not until late 1978 that a small group of fusion scientists from the USSR, USA, Japan, and the European Community met in Vienna to set both the physics and technology requirements for the device. After a year and a half of study, over 400 scientists (who put in over 100 man years of effort) agreed that most of the data base was available to build, by the early 1990's, a near term DT burning tokamak that could test most of the reactor relevant technologies required for future demonstration plants.(1) As the design effort continued in 1980, it became apparent to all the countries involved that, while most of the materials related problems appeared to be within reach of the major research programs throughout the world, there were a few problems for which additional research was required.

The object of this paper is to illuminate one of those materials problems which appear to be the most difficult to solve, namely that involved with the first wall. For a description of the entire INTOR materials requirements, the reader is referred to references 1-5.

General Features of INTOR

The technical objectives of the INTOR project are summarized in Table 1. A key feature of INTOR, which sets it apart from the TFTR class of devices, is that there must be a reactor relevant mode of operation. This means using D-T fuel, burn times of 100 seconds or more, and a reactor relevant neutron wall loading of > 1 MW/m^2. In addition, heat loads typical of charge exchange neutral fluxes, transient conditions on limiters, heat fluxes to divertor plates, and the pulsed nature of disruptions need to be handled in a manner which would indicate that reactor availabilities of 25 to 50% could be achieved. The duty cycle should also be greater than 70%.

Reactor relevant technologies must be used in INTOR. These include superconducting TF and PF coils, plasma purity control mechanisms (e.g. divertors), relevant plasma heating and fueling technologies, and tritium handling equipment. The device should be built to test tritium breeding blankets, advanced first wall and structural materials, and advanced plasma engineering technologies (e.g. rf launchers). Finally, the INTOR reactor should generate some electricity (~ 10 MWe), produce significant amounts of tritium, demonstrate safe and reliable operation, and show that reactor availability can approach the 50% value in the later stages of operation.

A list of the major parameters for INTOR is given in Table 2 and Figure 1 is an artist's rendition of the Japanese design and Figure 2 is a schematic of the U.S. version. The DT power level is 620 MW at an average beta of 5%. The reactor produces an average neutron wall loading of 1.3 MW/m^2. The plasma current is 6.4 MA and it is heated to ignition by 6 seconds of 75 MW - 175 keV neutral beams. Impurity control is by a poloidal divertor, single null in some designs and double null in others. The toroidal field on axis is 5.5 T and the maximum tritium inventory, including that required for a reserve of one day's throughput, is 3 kg.

Table 1
INTOR Technical Objectives

I. Reactor-Relevant Mode of Operation

a) Ignition of a D-T plasma.
b) Controlled $\geq$ 100 s burn pulse.
c) Reactor-level particle and heat fluxes ($P_n \gtrsim 1$ MW/m^2).
d) Duty cycle $\gtrsim$ 70%.

II. Reactor-Relevant Technologies

a) Superconducting toroidal and poloidal coil technology.
b) Plasma composition control (e.g. divertor) technology.
c) Plasma power balance control technology.
d) Plasma heating and fueling technology.
e) Tritium fuel cycle technology (excluding breeding and extraction).
f) Remote maintenance technology.
g) Vacuum technology.
h) Fusion power cycle technology.

III. Engineering Test Facility

a) Tritium breeding blanket and extraction technology testing.
b) Advanced structural and breeding materials, coolants, etc.
c) Blanket technology for simultaneous electricity production and tritium breeding.
d) Materials testing.
e) Advanced plasma engineering technology testing.

IV. Demonstration

a) Electricity production by fusion.
b) Tritium production by fusion.
c) Safe and reliable operation of a fusion reactor.
d) Availability ~ 25-50%.

The proposed operating schedule for INTOR is given in Table 3. It is anticipated that there would be three major stages of operation; the first one for plasma and engineering checkout alone (with demonstrations of electricity production), the second one for short term (a few months in duration) tests of blanket modules, tritium production and limited materials testing, and the third one for long term, integrative tests of materials and blanket designs. It is anticipated that the reactor availability will continue to improve throughout its lifetime starting at 10% in the first year followed by 2 years at 15%, 4 years at 25% and up to 10 years at availabilities averaging 42%. The later stage is aimed at accumulating an integrative neutron fluence of 5 MW-y/m^2.

Table 2
INTOR Suggested Major Parameters

Major Radius, R (m)	5.2
Plasma Radius, a (m)	1.3
Chamber Radius, r_W (m)	1.4
Elongation, k	1.6
Burn time(s)	> 100
Duty cycle (%)	> 70
Burn average $\langle\beta\rangle$ (%)	5
Ave. D-T Density $\langle n_i\rangle$ (m^{-3})	1.3×10^{20}
Ave. Ion Temperature $\langle T_i\rangle$ (keV)	10
Plasma Current, I (MA)	6.4
D-T Thermal Power, P_{th} (MW)	620
Neutron Wall Load, P_n (MW/m^2)	1.3 (1.7 peak)
Lifetime (No. of Burn Pulses)	1.2×10^6
NB Heating Power, P_B (MW)	75
NB Energy, E_B (keV)	175
Fueling	pellet, gas puffing
Impurity Control	divertor
Toroidal Field Coils	NbTi and/or Nb_3Sn
Toroidal Field at Centerline, B (T)	5.5
Poloidal Field Coils	NbTi
Tritium Inventory (kg)	3
Maximum Availability (%)	25-50
Tritium Consumption During Stage II (kg/yr)	6

Most Demanding Materials Environment in INTOR

There are two main locations in the INTOR design where severe demands are placed on materials performance.

A) First Wall
B) Divertor Collector Plates

It should be quickly pointed out that there are many other regions which face harsh environments in INTOR (e.g. limiters) and neglect of these areas here does not mean that they can be ignored in the design of the reactor. For the sake of brevity here, we have chosen only to discuss the unique conditions on the first wall to illustrate areas where research still needs to be done. Discussion of the divertor plate problems can be found in references 2 and 5.

First Wall

There are basically 4 main energetic components to consider here:

1) neutrons;
2) charge exchange neutral flux to the first wall;
3) heat flux from photons;
4) plasma disruptions.

It is not possible to consider these radiation and energy fluxes independently because they do have synergistic effects that may require unique approaches to first wall design. This will

Table 3
INTOR Operation Schedule

Stage	Years	Phase	Availability	# of D-T Shots	Annual T_2 Consumption, kg
I	1	Hydrogen plasma, engineering checkout	10%	---	---
	2	D-T Plasma ($1.3\ MW/m^2$) 1) ignited plasma 2) controlled burn > 100 s 3) $\geq$ 70% duty cycle 4) reactor level particle and heat fluxes 5) preliminary engineering studies Electricity production (10 MWe)	15%	6.6×10^4	4.8
II	4	Engineering testing ($1.3\ MW/m^2$) 1) blanket modules 2) T-production 3) combined T and electricity production 4) materials properties 5) advanced plasma engineering	25%	2.2×10^5	6.0
III	< 10	Accumulate $5\ MW\text{-}y/m^2$ of neutron fluence 1) Demo Materials Test 2) Full Segment Tests	42% (Ave.)	9.4×10^5	10 (Ave.)

become more apparent when we consider the disruptions.

As indicated in Table 2, the average neutron flux is $1.3\ MW/m^2$ and the peak flux is $1.7\ MW/m^2$ on the outboard side. Table 4 lists both the maximum and cumulative wall loading as a function of operation time. Also listed in Table 4 is the displacement damage and helium production in the two metallic materials considered for INTOR first walls, stainless steel and Al alloys. The maximum cumulative neutron wall loading amounts to $\sim 6.6\ MW\text{-}y/m^2$ over the anticipated lifetime and this translates into 72 and 92 dpa for steel and Al respectively. This displacement damage level for steel is slightly less than that experienced by a $2 \times 10^{23}\ n\ cm^{-2}$ ($E > 0.1$ MeV) fluence in a fast breeder reactor. The helium production in the steel approaches 1000 appm while that in Al would be over 2000 appm.

The charge exchange neutral flux to the first wall is a difficult number to calculate. Several values were considered during the initial

Table 4
Neutron Damage Parameters for INTOR

End of Year	Peak Wall Load MW-y/m² per year[a,b]	Cumulative Peak Wall Load MW-y/m² [a,b]	Cumulative dpa (max) SS	Cumulative dpa (max) Al	Cumulative Appm He (max) SS	Cumulative Appm He (max) Al
1	---	---	---	---	---	---
2	0.18	0.18	2.0	2.5	26	57
3	0.18	0.36	4.0	5.0	53	114
4	0.30	0.66	7.3	9.2	97	209
5	0.30	0.96	10.6	13.4	141	303
6	0.30	1.26	13.9	17.6	185	398
7	0.30	1.56	17.2	21.8	229	493
8-17	0.42 (Ave.)	6.56	72.2	91.8	964	2073

[a] maximum wall loading is 1.3 times 1.3 MW/m^2 = 1.7 MW/m^2

[b] includes a 70% duty cycle

course of the INTOR project[2] and the most recent set of numbers is given in Table 5. Note that while the radiation load is uniformly spread around the chamber, the charge exchange flux can be very high in regions where the neutral gas density is high, e.g., around divertor slots. The choice of the particle energy depends on the plasma edge temperature and it is generally believed that values around a few hundred eV are reasonable. The total heat flux values are important when determining the allowable thickness of the coolant tubes and the particle flux is important in determining the total wall erosion. Finally, note the charge exchange neutral flux around the divertor throat depends on whether there is a single or double null divertor.

The most severe, and undoubtedly the least understood, radiation environment is associated with plasma disruptions. This phenomenon, which is unique to tokamaks, is known to occur in present day devices and it is anticipated that it will occur in future power reactors. The key parameters to consider for disruptions in INTOR are shown in Table 6. Approximately 70% of the 240 MJ in the plasma is assumed to be deposited on the inboard side while 30% of the 240 MJ is deposited uniformly around the chamber by radiation. The energy deposition on the inboard side is expected to have a spatial peaking factor of 2 over the average value. With the assumptions in Table 6, the maximum energy flux is assumed to be on the inboard wall and amounts to 314 J/cm^2, or ~ 15.7 kW/cm^2 for 20 ms.

Finally, the number of disruptions is expected to be higher in the early stages and a value of 1% was felt to be reasonable. The fraction of shots that end in disruptions is postulated to drop to the 10^{-3} level after 3 years of operation. The total number of disruptions over the lifetime of INTOR is slightly more than 2000.

Approach to INTOR First Wall Design

Because of the severe first wall environment it was recognized that there might be a need for protective armor at selected positions on the wall. The Japanese[3] have proposed a molybdenum armor while the U.S. favors a passively (radiation) cooled, graphite liner. A schematic of a U.S. module with a carbon liner is shown in Figure 3. Because it is anticipated that the disruptions are most likely to go to the inboard side (or even to the top or bottom of the reactor), the carbon is placed only in those regions. The heat reradiated from the carbon liner to the outer walls results in a heat load of 39.4 watts cm^{-2} to the outer wall. Another option is to place carbon all around the chamber walls but this has the disadvantage of causing very high carbon temperatures because they cannot radiate heat to the "colder" parts of the reactor. At typical INTOR conditions, the maximum surface temperature is given in Figure 4 as a function of armor thickness.[6] It can be seen that the surface temperature can range from 1300°C for thin liners to 1500°C for 5 cm thick plates.

It has been recently proposed[7] that one might consider an actively cooled carbon liner which is brazed to the first wall. In this design the maximum carbon surface temperature only reaches 400°C for a 1.5 cm thick tile arrangement. It was hoped that the maintenance of a low surface temperature would reduce the chemical sputtering of carbon which occurs in the 400 to 1000°C range.

Various combinations of bare metallic walls and walls protected by carbon liners have been investigated by the U.S. The main combinations are listed below.

Table 5
Summary of a Possible Heat Flux Environment to the First Walls of INTOR and to the Region Around the Divertor Throat

	First Wall	Region Around Divertor Throat
Radiation		
Total Power From Plasma - MW	80	80
Average Heat Flux, W/cm^2	21	21
Charge Exchange Neutrals		
Total Power From Plasma	3	2
Average Heat Flux, W/cm^2	0.78	11.1 (single null)
		5.5 (double null)
Time Peaking Factor	2	2
Max. Heat Flux, W/cm^2	1.56	22.2 (single)
		11.1 (double)
Total Heat Flux - W/cm^2	22.5	43.2 (single)
		33.1 (double)
Average CX Energy, eV	150	150
Average Particle Flux, $cm^{-2}\ s^{-1}$	3.25×10^{16}	4.8×10^{17} (single)
		2.4×10^{17} (double)

1. Bare steel first wall.
2. Bare Al alloy first wall.
3. Passively cooled carbon liner over inboard, top and bottom portions of a stainless steel first wall.

We will now proceed to calculate the implications of the previous irradiation and thermal environments on the first wall designs listed above.

Response of First Wall Designs to INTOR Conditions

From the previous discussion it can be seen that there are two competing requirements for the first wall facing the plasma.

A. Because of the high heat flux, the wall thickness should be as thin as possible to reduce the thermal stresses to acceptable levels.

B. Because of the charge exchange induced erosion, evaporation by disruptions, and the need to provide resistance against fatigue cracks, it is desirable to make the wall as thick as possible.

In the absence of erosion mechanisms, it is possible to calculate the required tube thickness necessary to withstand the desired number of cycles per year. Cramer[8] and Wolfer[9] have performed such calculations for INTOR considering the first wall to be made of water cooled, thin walled tubes. Figure 5 shows how the useful life varies with wall thickness for the 22.6 W/cm^2

Table 6

Key Assumptions for Plasma Disruptions in INTOR

	Value
Plasma Thermal Energy - MJ	240
Heat Deposition Time - ms	20
Current Decay Time - ms	20
Frequency - Stage I	10^{-2}
Stages II & III	10^{-3}
Deposition Profile	
Uniform to FW, %	30
To Inboard Area (30% of Total Area), %	70
Peaking Factor to Inboard Side	2
Ave. Energy Flux - Outboard - J/cm^2	19
Ave. Energy Flux - Inboard - J/cm^2	166
Peak Energy Flux - Inboard - J/cm^2	314
Peak Power - Inboard - kW/cm^2	15.7
Number of Disruptions - Stage I	833
Stage II	220
Stage III	930
Total	2033

case. Because of the higher thermal conductivity, the allowable thickness for the Al alloys is much larger than for steel, by as much as a factor of three in some cases.

The erosion rate of the first wall by the charge exchange neutrals is simply

$$\Delta \ell = \frac{\phi S}{N}$$

where ϕ = the CX flux,
S = sputtering coefficient, and
N = number atom density.

A summary of the sputtering coefficients applicable to INTOR conditions have been reported in References 10 & 11.

	S (atom/ion) at 150 eV			
	D	T	He	Ave.[a]
316 SS	0.013	0.025	0.07	0.022
Al	0.022	0.044	0.15	0.039
C[b]	0.02	0.03	0.07	0.027

(a) 47.5% D, 47.5% T, 5% He, Maxwellian distribution of energy around 150 eV.
(b) Without chemical sputtering.

Combining the sputtering coefficients above with the CX particle flux and availability curves yields the erosion rates given in Figure 6. The lower erosion rate in the first few years is due to the lower availabilities. It can be seen that after 17 years of operation the CX erosion of the steel is 1.03 cm, for C it is 0.97 cm whereas the erosion of the Al is 2.61 cm.

The evaporation due to disruptions is more difficult to calculate because there have been no previous models that apply to the conditions to be experienced in INTOR. A model by Behrisch[12] is useful when the material does not melt or a negligible amount of energy, compared to that incident on the sample, is used in vaporizing the metal. This model will tend to underestimate the amount of material evaporated. Loebel and Wolfer (LW)[13] have recently published a moving boundary model which is applicable when a large fraction of the incident energy is used in vaporization.

Typical results from the LW model for Al and Fe are shown in Figure 7 where the erosion rate per shot is given if the pressure of the vaporized material in the vicinity of the first wall is $\sim 10^{-3}$ torr.

A summary of the material evaporated per 1000 disruptions is given below.

	Behrisch Model[12]	Loebel-Wolfer Model[13]
Steel	0.6	1.0
Al	<0.001	~0
C(1500°C)	1.4	1.3
(400°C)	Not Calc.	0.4

The evaporization erosion values for steel and carbon are much larger than the CX neutral erosion values and are plotted in Figure 8. The high erosion rate for the steel and carbon during the early years is due to the high disruption rate assumed for stage I (~0.01). Depending on whether the LW or Behrisch model is used, 1 cm of steel can be lost in 4 or 10 years, respectively. Aluminum shows a negligible evaporation rate.

Finally, the total erosion rates are plotted on the fatigue life curves for the steel and Al alloys (Figures 9 and 10). It can be seen that the erosion rates due to charge exchange neutrals alone are sufficient to limit the bare steel wall life to less than 10 years. However, when the vaporization due to disruptions is added, the lifetime comes down to less than the first 4 years of operation. We have not calculated the corresponding values for the outside steel wall facing a radiatively cooled inboard carbon liner, but the reduced thickness required to withstand the 39.4 watts/cm^2 heat load will result in lifetimes considerably less than 17 years. In fact it is estimated that such a wall may have to be replaced 3 or 4 times due to charge exchange erosion alone.

The case for Al is quite different. First, the CX neutrals do not limit the life to less than the required 17 years. Second, because of the high thermal conductivity, the disruption does not cause any significant additional material to be evaporated. However, there is one qualifying statement that needs to be made. Approximately 1 mm of the Al is melted during the disruption and if that melt layer is thrown off by the resultant magnetic fields, this would obviously be unacceptable and the useful life may be only 20-30 disruptions. Further tests are needed in this area to understand the behavior of the melted layer.

The erosion due to the CX neutrals alone does not limit the useful life of either the actively cooled (1.5 cm thick) or the passively cooled (~5 cm thick) carbon liners. However, the evaporation due to the disruptions would limit the useful life of the actively cooled carbon liners to the first 4 years of operation. Fortunately the passively cooled liners can be made thick enough to withstand the total erosion of approximately 3.8 cm over 17 years. In fact, even if the total sputtering coefficient (kinetic + chemical) was 0.06 (~75% of the maximum chemical sputtering rate measured at 600°C), a 5 cm thick, passively cooled carbon plate could stand for the entire INTOR life.

Finally, we have not covered, in this paper, the mechanical response of the Al, steel or C due to neutrons. This has been done in references 1, 2, 8, 9, and 14. The general conclusions drawn from those studies are that if the maximum temperature of the steel could be held to less than 300°C, and that of the Al alloys to less than 150°C, the swelling and ductility loss of the alloys would be sufficiently low for INTOR operation. Al alloys are particularly sensitive to the operating temperature because of their low melting points.

Conclusions

It is obvious from the INTOR activities that the disruptions are a major factor in determining whether a steel first wall is viable. Under the current set of assumed disruption conditions it is apparent that bare steel first walls will not be able to withstand the heat loads without excessive erosion. Covering the steel walls with a passively cooled carbon liner ~5 cm thick will protect the inboard regions of the first wall from these disruptions and should allow the possibility of full reactor lifetimes to be seriously considered.

The Al alloy first walls appear to be able to withstand erosion from charge exchange neutrals and disruptions. However, the stability of the melt layer and the ability to keep the operating temperature below 150°C are critical questions that need to be addressed before final decisions can be made.

Acknowledgement

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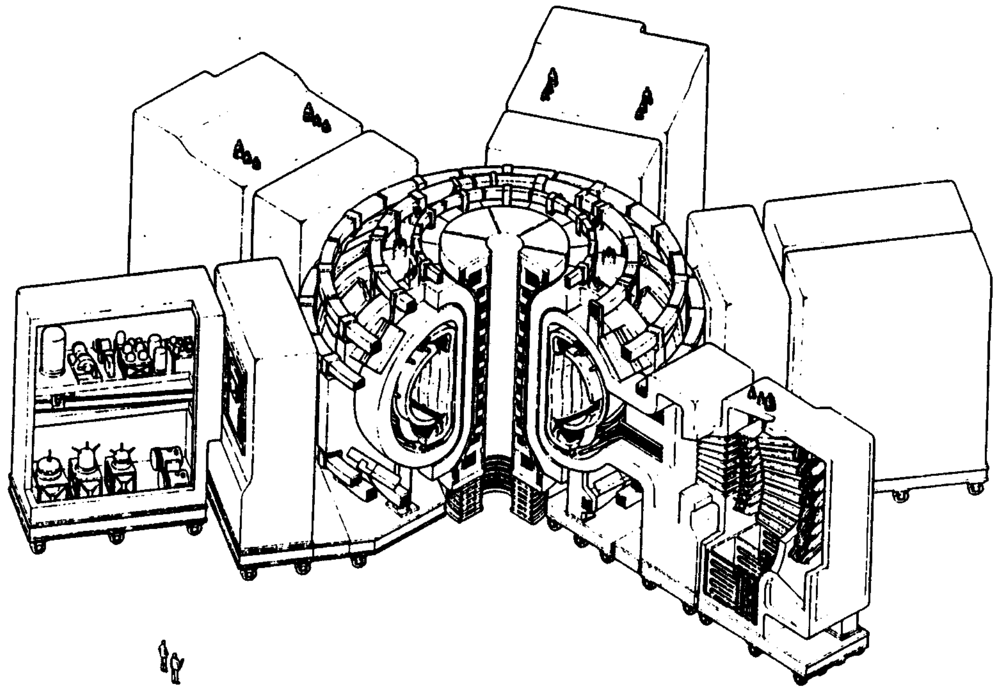

Figure 1. Schematic of Japanese Version of INTOR(3).

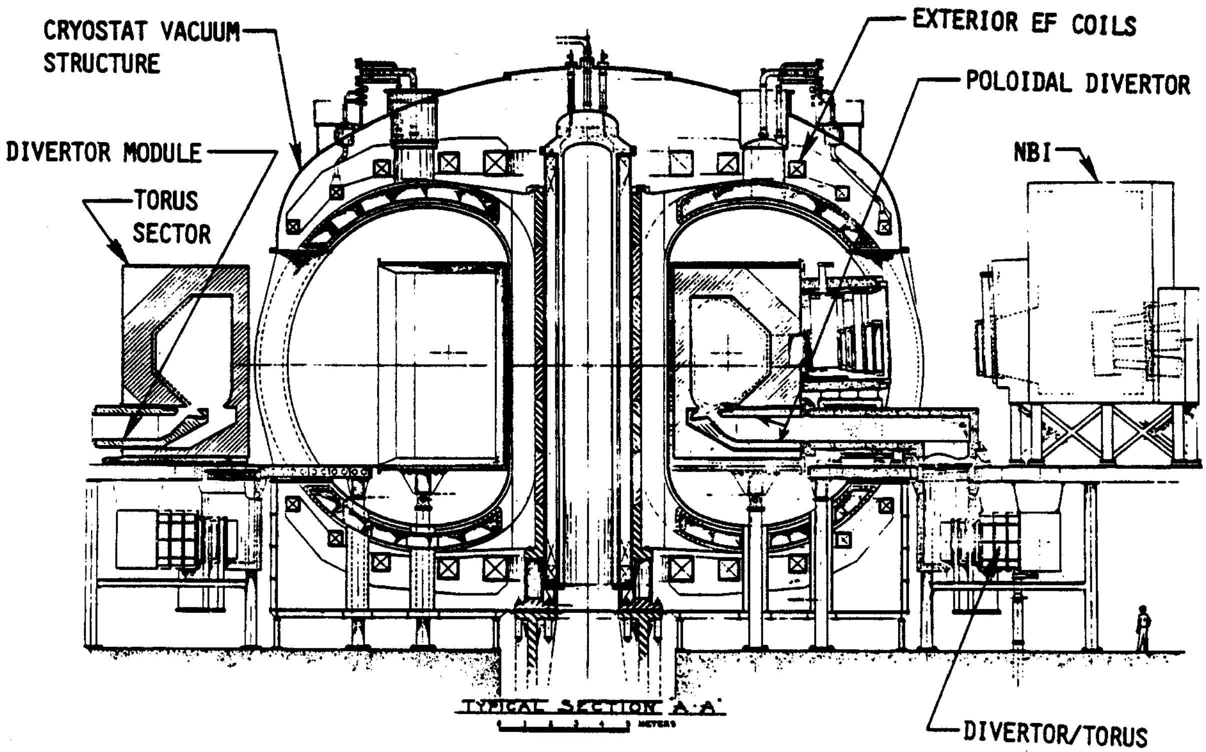

Figure 2. Schematic of USA Version of INTOR(5).

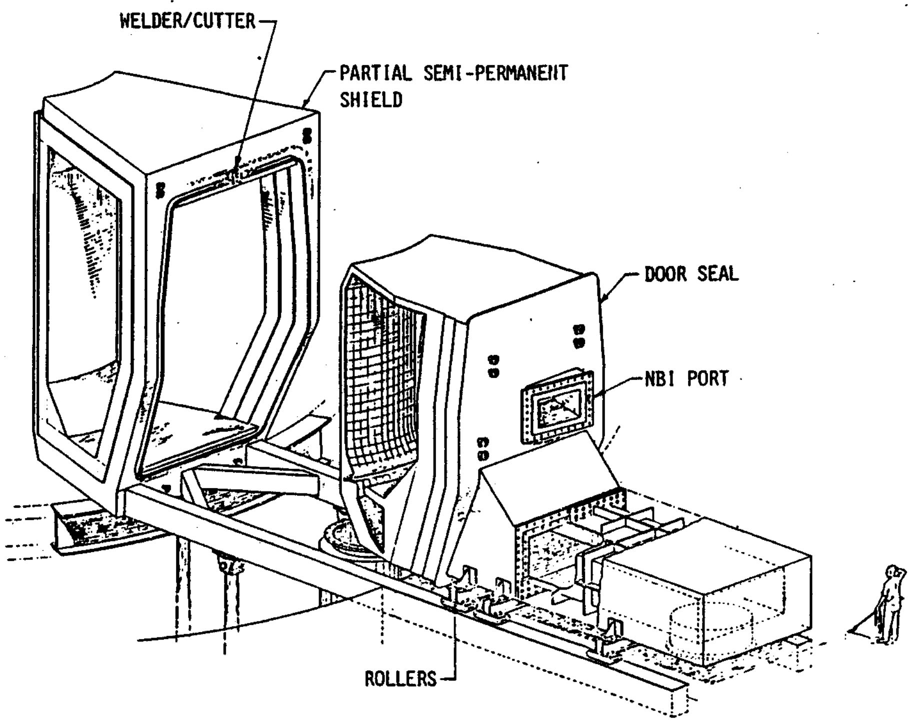

Figure 3. Schematic of USA INTOR Blanket and Shield Assemblies (5).

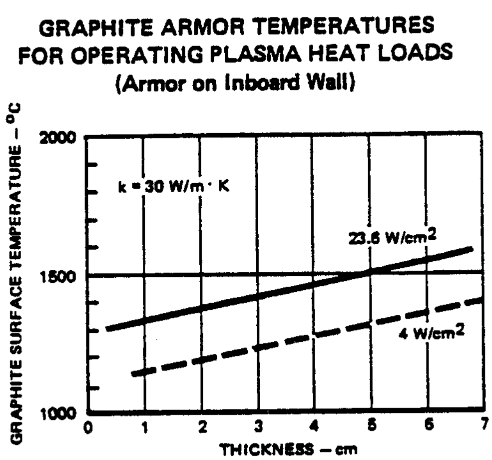

Figure 4

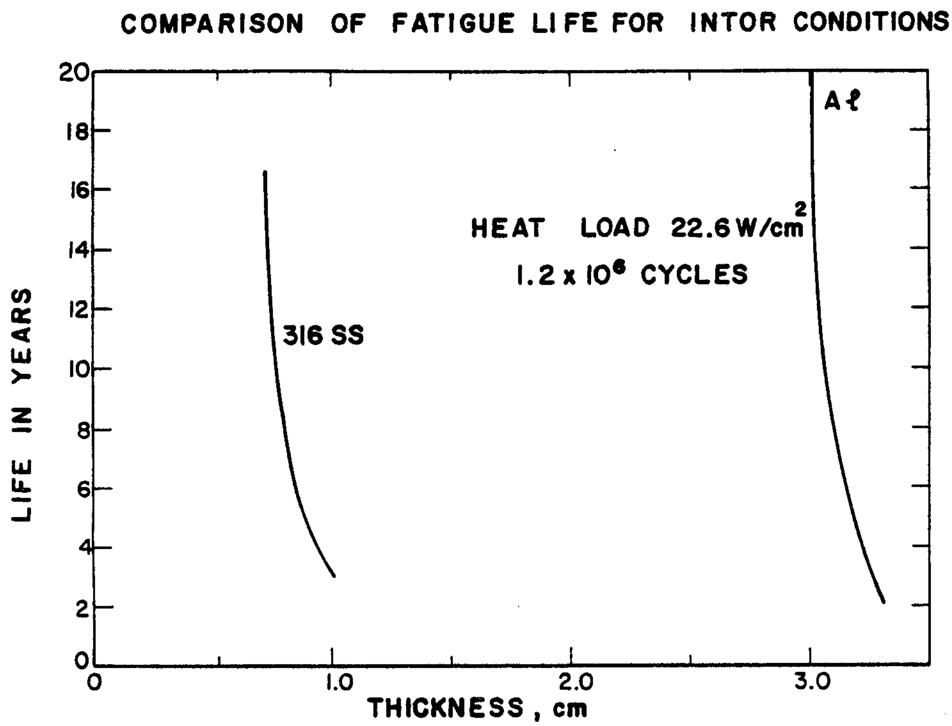

Figure 5

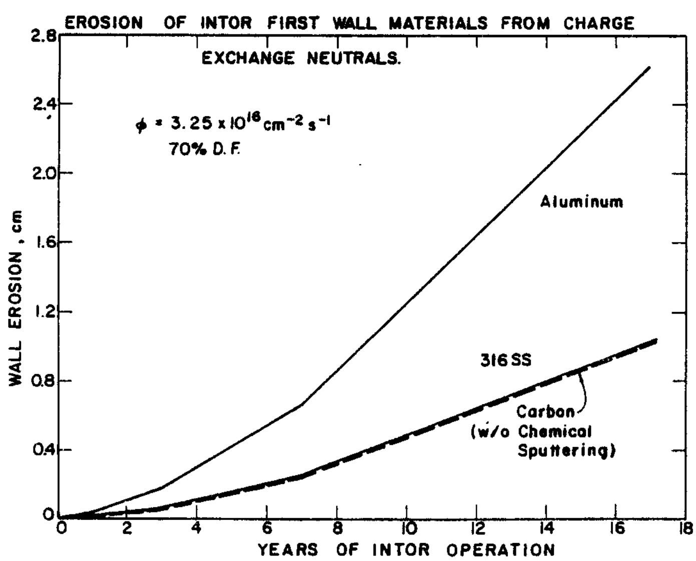

Figure 6

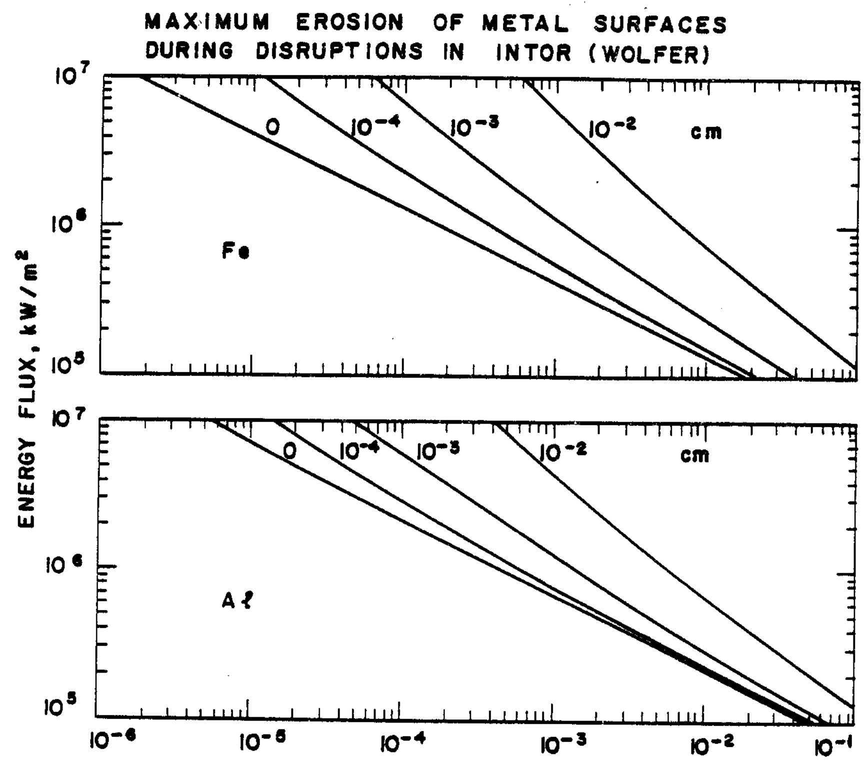

Figure 7

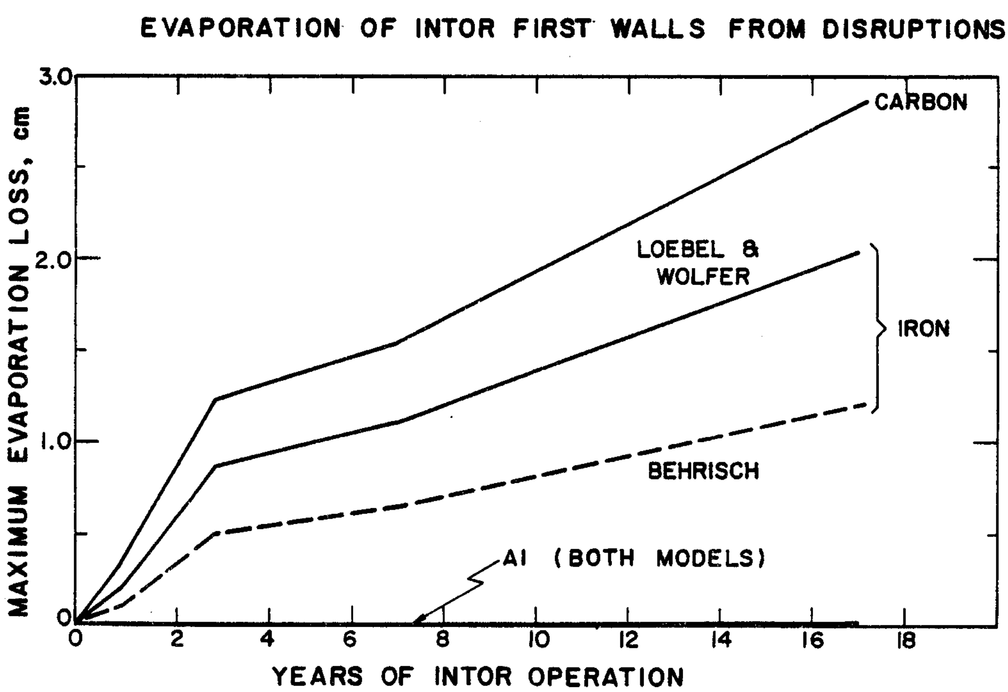

Figure 8

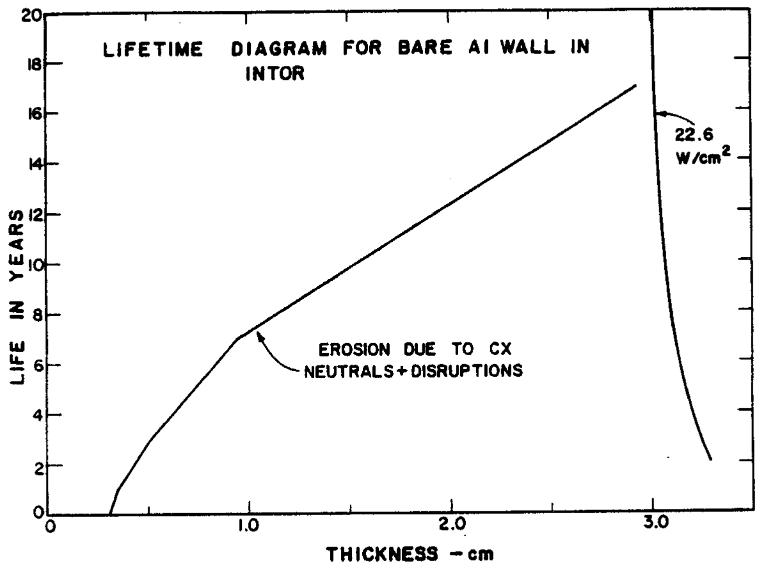

Figure 9

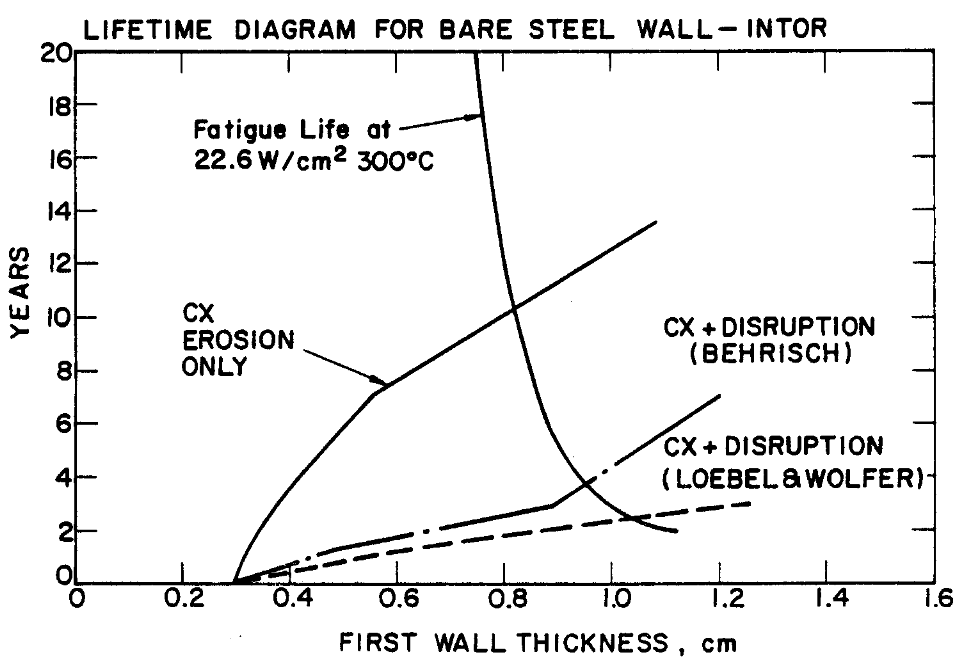

Figure 10