Major Technological Problems for Fusion Reactor Power Stations

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I. INTRODUCTION

The time has come to seriously consider not only the general concepts, but also the details of how we might extract the energy from controlled thermonuclear fusion and convert it into electricity for the benefit of man. Even though plasma scientists are fairly optimistic about achieving the Lawson criteria by the end of this decade, or early in the next, their efforts will be in vain if we are not able to design and construct economically sound reactor systems. It is important that we put the present lead time of 10 years or so to good use such that there will be a minimum of time delay from the achievement of the first sustained fusion reaction to the lighting of the first city with fusion power.

In principle, the problem of building a fusion reactor should not be too difficult after confinement has been achieved. We must first scale up the fuel injection, confinement and heating schemes to produce more energy than it takes to initiate the fusion reactions. The kinetic energy of the fusion products must then be converted to heat, and the heat to electricity. In some systems, like those which use fuels not found in nature, we must also breed more fuel (i.e. tritium). The confinement and sustainment of the fusion reactor can be accomplished by either magnetic fields or by high powered lasers as pointed out by Hirsch[1] and Ribe[2] in this conference. The conversion of kinetic energy of photons, charged particles and neutrons is a problem with which we have considerable experience from fission reactors. We have also been producing tritium for some time via the $Li(n,T)He$ reaction and have considerable experience in that area. However, while all of these processes sound simple it is not possible to completely design and build a fusion reactor with todays materials and technology.

In early 1972, the USAEC commissioned a group of scientists to summarize the state of the art with respect to building a commercially economic fusion reactor.[3] This committee, with the help of many of their colleagues, labored for several months to assess the state of technology at that time (with the assumption of course, that the plasma physics problems could be solved). What follows is a condensed version of the committee findings and some observations by the author. The reader should recognize that such studies quickly become dated as some of the current problems are solved and new ones appear.

It is convenient at this point to subdivide the discussion into the problem areas associated with the four major objectives of fusion reactors as listed below. We will confine our remarks to the D-T cycle.

Objects of Fusion Reactor	Major Problem Areas
-Confine and Sustain Fusion Reactions	Magnet Design Magnetic Energy Storage Lasers Fuel Injection Heating
-Convert Kinetic Energy of Fusion Products into Electricity	Radiation Damage High Temperature Materials Compatibility MHD Pumping Problems Power Conversion Systems Neutronics
-Breed New Fuel	Neutronics Tritium Removal and Containment
-Be Competitive with other Energy Sources	Economics Environmental Considerations

The topic of lasers was treated by both Hirsch[1] and Ribe[2] in this conference and will not be
covered here except to point out a few problems where laser systems may be considerably different
than magnetic systems. Furthermore, Frans[3] has covered the areas of economics and environmental
considerations leaving some 11 areas of technology to be covered here. These topics will be briefly
discussed with respect to three fundamental questions:

Definition of Problems
Status of Technology
Required Information

A few of the more pertinent literature references will be cited but no attempt will be made to
provide an exhaustive literature survey in this relatively short paper.

II. MAGNET DESIGN

DEFINITION OF PROBLEMS

The major requirements of the magnets in a controlled thermonuclear reactor (CTR) are to provide
large volume, high magnetic fields to confine, guide, and stabilize the plasma. In some systems,
superconducting magnets will have to provide inductive energy storage for plasma compression and
ohmic heating (see III). The magnets will have to be larger than anything yet constructed (Figure 1),
and for technical, and most certainly for economic reasons, superconductors or perhaps cryoconductors
are essential. Even with superconductors, the cost of the magnet, its supporting structure,
refrigeration, and insulating system, will form a major part of the capital cost of the CTR. A
number of diverse factors lead to this high cost. They include; large highly stressed structures,
expensive superconductor materials, requirement of high reliability factors, very low temperatures
and evacuated dewars, very efficient insulation and good heat transfer.

STATE OF TECHNOLOGY

Recent reviews of superconducting magnet technology[5] and stability techniques[6] were given at the
International Working Session on Fusion Reactor Technology. A summary of the current materials of
interest to CTR Technology is given in Table I. For a typical ductile superconductor like NbTi which
can be co-extruded and co-reduced, the upper useful field is ~85kG. Above this field the compounds
Nb_3Sn and V_3Ga could be used. These are commercially available only in the form of thin ribbons at
the present time. Although the Nb_3Sn and V_3Ga tapes have been used in small high field magnets,
they have some disadvantages which may render them unsuitable for the large fusion reactor magnets.
They are brittle, fragile, not easily joined in lossless joints, exhibit unstable performance in
perpendicular fields, and are not readily stabilized electrically or thermally.

Multifilament Nb_3Sn and V_3Ga metallurgically bonded in a copper matrix have been developed.[5]
In the case of V_3Ga, complete reaction of the vanadium core was achieved but in the Nb_3Sn wires the
niobium core remains with a coating of Nb_3Sn. In both materials an outer jacket of copper of low
resistivity was obtained. The potentially very important binary compound, Nb_3Al (with an upper
critical field of 295kG and a critical temperature of 18.7°K) as well as the more complicated pseudo-
binary $Nb_3(Al_xGe_{1-x})$ (with an upper critical field of 410kG and a critical temperature of 20.7°K) are
other materials which have been investigated. To date, these materials have not been commercially
developed even in ribbon form. For the most part, all the experiments have been on small-sized
samples, but a long length (2000 ft) of V_3Ga has been successfully prepared and is in the process of
being wound into a small solenoid.[5]

There are four NbTi superconducting magnets with bores of 1 m or larger in operation: 1.0 m,
41kG, 10.5MJ BIM magnet at Saclay;[7] 2.44 m, 28kG, 64MJ bubble chamber magnet at Brookhaven;[8] 4.8 m,
18.5kG, 80MJ bubble chamber magnet at Argonne;[9] and very recently, 4.8 m, 30kG, 400MJ bubble chamber
magnet at the National Accelerator Laboratory.[10] In addition to these solenoids, the baseball
(minimum B design) magnet at Livermore[11] has approximately a 1.2 m bore and has operated with a maxi-
mum field at the windings of 55kG and stored energy of 10MJ. All of these magnets used the cryogenic
stability design concept (i.e., superconductor embedded in a large amount of copper and liquid
helium in intimate contact with all the windings). No large adiabatically stabilized NbTi magnet
or large high field Nb_3Sn or V_3Ga magnets have been built. There are three large bubble chamber
magnets (NAL, and two at CERN) which have been built but two have not been tested yet. Finally,
the IMP quadrupole magnet (minimum B design) (30 cm bore) at ORNL is perhaps the most complex
Nb_3Sn magnet, and it has been operated with a maximum field at the winding of about 60kG.[12]

Less work has been done on pulsed systems. Small magnets, mostly for synchrotron programs
(E_s < 100kJ), have been developed which can be pulsed at 100kG/sec up to 50kG without undergoing a
quench.[13] The largest energy storage magnet is the 600kJ, 76 cm bore coil built at the Laboratory
de Marcoussis of Compagnie Generale d'Electricite.[14]

REQUIRED INFORMATION

It is possible, using existing materials, to build the magnets envisioned for CTRs although it will be a difficult and expensive task. Thus, efforts should continue in the search for better superconducting materials and the development of known materials to commercial availability. The desired new materials should exhibit intrinsic stability and would remain superconducting at higher fields, current densities, and (especially) temperatures, to ease the stability problems in the large magnet design. They should be economical, ductile, and easy to fabricate.

Of equal or greater importance is development of superconducting materials which are now available. Compounds such as Nb_3Sn, V_3Ga, V_3Si, or $Nb_3(Al_xGe_{1-x})$ are known to be capable of operation at high-magnetic fields, but they are also very difficult to fabricate and expensive. Development of these materials to exhibit better fabricability and better methods of fabrication such as plasma spraying, diffusion bonding, powder metallurgy, electron-beam welding, electroplating, sputtering, and other advanced fabrication techniques, may significantly reduce the cost of magnet fabrication with these advanced materials.

Closely coupled to the fabrication of the superconducting materials is the fabrication of the normal conductor and the reinforcing structure. The structure accounts for a major portion of the magnet cost, even with present-day costs of superconducting magnet materials. It has been postulated[15] that the cost of the superconducting material itself may be expected to reduce in cost by factors of about three to nine by the time large amounts of material are required for fabrication of CTRs. If this occurs, the cost of the supporting structure then becomes an overwhelming part of the magnet costs. Backing material currently used in large magnets has been stainless steel. Although the allowable yield or creep stress of this material has been improved, elasticity is a more crucial structural property since the superconducting compounds are generally strain-limited. Thus, if fabrication methods cannot be found to eliminate the strain limitation of the superconductors, it will be necessary to develop a backing structure to give very low strain even at high stresses. This is the most critical task to be accomplished for reduction of the costs of superconducting magnets.

Work should continue on the development of cryoresistive magnets i.e., magnets made with winding materials with very low resistance such as high-purity aluminum or sodium. This work should be considered as a backup to the superconducting magnet program. The structural problems are equally severe in these cases. If it is possible to operate these coils with only a small portion of the CTR power then they might become economic compared to either superconducting or normal room temperature magnets.

III. MAGNETIC ENERGY STORAGE

PROBLEM DEFINITION

This problem is particularly acute in pulsed thermonuclear reactors where the magnetic pulses (which compress and contain the plasma) have rise times and durations of the order of a few tens of msec and occur once every few seconds. In a conceptual Theta-pinch reactor,[2,16] superconducting material is used in a separate magnetic-energy storage coil, outside the coil which compresses and contains the plasma. However, there is the unique problem of changing the field in a superconducting storage coil as energy is transferred between it and the compression coil of the reactor, which can be at a temperature much higher than liquid helium. Owing to the transformer action of the changing magnetic flux, the magnetic field which compresses the plasma can be larger than that in the superconducting storage magnet.

It appears necessary to use variable inductors (rotating machinery with fields furnished by superconductors) to provide reversible energy transfer from storage magnet to compression coil in a pulsed reactor, where favorable energy balance and consequently low circulating power are important. A similar application, but at lower energy, occurs in the ohmic-heating supply for a Tokamak reactor. The impact of energy storage on reactor energy balance may be appreciable when there is cyclic operation.

STATUS OF TECHNOLOGY

There is an active program as LASL to develop pulsed magnetic energy storage switched by normal-going superconductors. It is presently at the 30-kJ, 1-kA level, and the goal is to produce 6-MJ, 40-kA units with 2-msec risetime. Stranded superconductor material in matrices optimized for stability under varying magnetic fields is being developed.

In the case of the variable inductor, Smith and Lewin[17] at Harwell have studied the concept of energy transfer for next-generation synchrotron magnets at the 1-GJ level. This particular concept uses rotating superconducting coils which act as transfer elements and require no net torque. Development of rotating electrical machinery using superconducting windings is also being carried out at various laboratories in the U.S.A.[15]

REQUIRED INFORMATION

Information relating to the stability of superconductors in varying magnetic fields and the composition and fabricability of various matrix materials is of basic importance. These materials must possess low eddy current and hysteresis losses during pulsed operations. The basic mechanical and electrical properties of rotating electrical machinery for the low-loss energy transfer must be developed.

IV. FUEL INJECTION

PROBLEM DEFINITION

Three methods of fueling a reactor are currently envisioned: neutral atom injection, pellet injection, and purging by simply flushing and refilling with gas. The first two injection methods are appropriate to reactors such as mirrors that remain ignited for times much longer than the particle confinement time. For reactors operating with a burning time short compared to the particle confinement time, such as the Theta-pinch,[16] refueling can be accomplished by purging the reaction chamber with new fuel. It is not clear at this time in which regime the Tokamak reactors will operate. However, since experimental Tokamak devices will operate only on a pulsed basis the purging method of refueling will be adequate for the purpose of demonstrating scientific feasibility. It is not known how far this technique can be pushed in reactor systems.

Injection of neutral atoms or pellets is complicated by the almost certain requirement for the fuel to reach the center of the reactor. The temperature and density of reactor grade plasmas imply that micron size pellets may "burn up" on the plasma surface. A large pellet may also seriously disrupt the plasma.

Neutral fuel atoms must be injected at several hundred keV if they are to penetrate to the center of a reactor.[19] The current levels required will be in the thousands of amperes equivalent.[20] Thus the technical problems imposed by energy and intensity are similar to those of heating plasmas by neutral particle injection. (see V).

The necessity of steady refueling will place more difficult performance requirements on the neutral beam injection system than if it were to be used only for ignition purposes. In particular, the overall efficiency of the injection system will be most important. To this end negative ions will probably have to be used in the first stages of the injection system as discussed in the Heating section. In addition, the energy of both the unneutralized and untrapped beam particles could be recovered directly. The development of "beam direct energy conversion" represents a relatively new technology.[21]

Injection of neutral atoms is a high energy, high power fueling scheme and is appropriate for mirror reactors, but is not attractive for Tokamaks which are expected to operate at plasma temperatures of only a few tens of kilovolts. The energy input from a 10^3 amp, ~1000 keV beam may upset the thermal balance of the plasma and the presence of such highly energetic particles in a cooler plasma may create instabilities.

A further aspect of the fueling problem for reactors is that the penetrations of the blanket associated with injection techniques may allow intense streams of neutrons to escape. The increased shielding problem is considered awkward, but not overwhelming.

STATE OF TECHNOLOGY

The technology of forming and accelerating micron size drops and pellets to speeds of 10^5 cm/sec is at hand.[22] Hydrogen pellets of about 1 mm diameter will require megavolt accelerators to achieve such speeds.[23] Development of technology using cryogenic liquids to make pellets suitable for subsequent acceleration has only recently started.

The status of ion source development for neutral atom injection is discussed in the Heating section. In regard to ion beam direct energy converters, some early design and testing of laboratory size devices has been done.

The purging method of refueling or, more accurately, replacing the working gas in fusion experimental devices has been the most commonly used method for nearly two decades. The present pertinent technology for this method seems adequate to meet the requirements of refueling reactor size machines.

REQUIRED INFORMATION

The technology must be developed for producing streams of millimeter size pellets of deuterium and tritium at speeds approaching 10^6 cm/sec. Detailed analysis of the interaction between a pellet and a thermonuclear plasma must be expanded. Much experimental work is needed with the hot plasmas that will become available in the 70's in order to determine the sizes and speeds required for pellet penetration of the plasma.

The overall power efficiency of the beam direct energy converters must be determined since it is most important for evaluating the power balance for mirror reactors.

V. HEATING

PROBLEM DEFINITION

A major problem in CTR devices is to heat the ions of the plasma to the operating temperature in a suitably short time. The operating temperature for almost all fusion devices using deuterium and tritium, will be about 15 keV. Mirror machines are the exception and in these systems the plasma particles are expected to be at about 300 keV.

There are five distinct methods of heating plasmas: ohmic, shock, compression, injection and RF heating. Heating is likely to be accomplished by a two stage process in the magnetic containment CTR concepts so that in Tokamaks, initial ohmic heating will probably be followed by either compression, energetic neutral particle injection, RF heating or a combination of these. For Theta-pinch machines shock heating is to be followed by adiabatic compression. In Mirror machines the plasma density is first built up and then maintained by energetic particle injection.

The ohmic heating method induces a current in the plasma which acts as the secondary circuit of a transformer. The resistive response of the plasma to this current results in the plasma being heated. In Tokamaks the induced plasma current has a dual role:[24] it provides the poloidal magnetic field that is an intrinsic part of the Tokamak magnetic field configuration as well as providing the ohmic heating of the plasma. The chief problem in inducing the plasma current lies in controlling the "skin effect"[25] that is anticipated in devices as large or larger than the proposed Princeton Large Torus (PLT). For the PLT experiment, planned for the mid 70's, control of the "skin effect" will be sought through both the use of an expanding limiter and control of the rise time of the induced current.

STATE OF TECHNOLOGY

Ohmic heating has been the principal method of heating toroidal devices such as Tokamaks. In applications to date, the energy to drive the ohmic heating circuits has been stored in capacitors at a few kilovolts. Inductive energy storage will be used for the larger Tokamaks envisioned in the mid 70's and certainly for fusion feasibility experiments, where the stored energy requirement will be in the tens of megajoules. The energy storage requirement for reactor-size Tokamaks approaches the gigajoule level. This energy will be stored in the energy storage system and switched into the poloidal flux of the plasma by the primary windings which will probably be superconducting for the prototype reactors of the late 70's. Aside from the problems attendant to superconductors, the chief technical problems appear to be associated with the switching and control of the primary circuit current. No major technological problems have been identified in this area.

Compression heating is accomplished in Tokamaks by reducing the major and/or minor radius of the plasma.[21] Reduction of the major radius requires relatively mild increases in moderate magnetic fields of a few kilogauss. Compression of the minor radius requires large changes in strong magnetic fields of several tens of kilogauss. Tokamak compression experiments through the mid 70's are to be modest in energy requirements. The technical problems seem conventional.

The plasma heating in the case of the Theta-pinch, will be accomplished by a two stage process: shock heating followed by adiabatic compression of the plasma minor radius.[16,27] This method has been shown to generate high density ($n \sim 10^{16}/cm^3$) plasmas at ~5keV temperatures, conditions which are close to the requirements of a pulsed reactor ($n \sim 10^{16}/cm^3$, $T \sim 15keV$). With one exception most of the technical problems associated with the heating of the Theta-pinch feasibility experiment appear to be under reasonable control. The exception is the necessity of obtaining a suitable insulating material on the inside of the shock-heating coil (first wall). This subject is discussed in high temperature materials section (VII).

Mirror machines have used beams of energetic neutral atoms for the production of energetic plasmas for more than a decade. The energetic neutrals are produced by passing energetic ions through a neutralizing medium. The development of ion sources for this injection is the major technical problem in this method of heating.

Ion sources are on hand that can produce several amperes of well collimated hydrogen ions at 20 to 50 keV.[28,29] These sources insure the adequacy of ion sources for neutral injection into experimental devices up to the mid 70's. Beyond 1975 there will be need for neutral beams of 100keV to 200keV. The way to accomplish this increase in energy for positive ions appears to be straightforward. Unfortunately the efficiency of neutralizing positive hydrogen ions above 100keV falls off rapidly with increasing energy [13] (for 200keV H^+ it is less than 10%). Neutralizing efficiency for H_2^+ and H_3^+ ions is approximately 20% at high energies. Consequently, while high energy positive ions sources will be adequate for fusion feasibility experiments and possibly for fusion reactor applications where the heating is used only for ignition, far more efficient ion sources are needed for continuous neutral injection at several hundred keV, such as expected in a Mirror reactor.

High energy negative ion sources appear to be the way to make an efficient neutral particle injector since negative hydrogen ions can be neutralized with better than 80% efficiency.[30] The favored path of development is to pass positive ions, at about 1keV, through an alkali metal vapor in order to produce negative ions. The Hall type accelerator appears to be the most promising source of large positive ion currents in the 1keV range of energy.[29,30] The efficiency of the conversion of positive to negative ions lies between 10% and 25% in this energy range.[31,32] However this low conversion efficiency occurs in the low electrical power part of the ion source and hence has only a small effect on the overall efficiency of the source. The negative ions are then accelerated to high energy and subsequently neutralized. This type of ion source represents a new departure in technique and would represent a major undertaking in ion source development.

RF heating includes all the heating schemes employing oscillating electromagnetic fields. The frequency spectrum runs from about 100kHz for magnetic pumping to about 100GHz for electron cyclotron resonance heating. The technology for the RF sources is at hand.

REQUIRED INFORMATION

The successful heating of a plasma has been, and still is, one of the principal objectives of plasma physics research. There is very little experience heating plasmas with either neutral beam injection or RF power at "lower hybrid" frequencies or compression in toroidal devices. The principal technical problems are the development of suitable ion sources for the neutral beam injectors and the development of suitable insulation material for the shock heating coil in the Theta-pinch machines.

VI. RADIATION EFFECTS

There are two main classes of radiation effects problems that must be considered; bulk and surface effects. The former result from high energy neutron bombardment and the latter from photon and charged particle irradiation. Although the magnitude of the problems encountered from each type of damage is not necessarily the same, it is easier to discuss the anticipated problems within the dual framework.

PROBLEM DEFINITION

A) Bulk Radiation Effects

The structural materials for fusion reactors will be expected to retain adequate strength, ductility, fatigue resistance, and dimensional stability while being stressed and irradiated at 500-1000°C with high fluxes of neutrons (thermal to 14MeV). However, we know from past experience that such an environment will most likely cause a serious degradation in the physical and mechanical properties of metals.[33,34] The main reason for this degradation is that all pure metals (Nb, Mo, V, Cu, Al) or alloys (Nb-Zr, Nb-Ti, Nb_3Sn, Mo-Ti-Zr, V-Ti-Cr, stainless steel) currently considered for CTR application have relatively large (n,α), (n,p) and displacement cross sections for high energy neutrons. The most serious problem is the production of helium gas atoms. For example, it has been shown that the presence of these atoms can cause severe embrittlement in metals at high temperatures.[35] Table II shows what effect 10-40 atomic ppm He has on the ductility of some metals considered for CTR's. The anticipated levels of He in metals vary from several hundred to several thousand appm over the useful lifetime of the components.[36] The agglomeration of helium gas atoms into bubbles, which in turn may migrate to grain boundaries, can induce premature fracture at strains of only a few percent.

The production of large numbers of vacant lattice sites can also have a deleterious effect if these vacancies agglomerate into voids. For example, figure 2 shows a large number of voids in Nb irradiated at an effective temperature of 620°C to 300 displacements per atom.[37] These voids cause the metal to expand and values of 5-10% swelling have already been observed in refractory metals such as Nb[37] and stainless steels irradiated at ~1/10 of their projected exposures in CTR service.[33,34,38] Similar swelling problems have already been reported in graphite which constitutes a significant fraction of the blanket of most reactors.[39] (see figure 3) The lattice expansion and degradation of both physical and mechanical properties of graphite results from the distortion of the crystallites by clustered vacancies. Nonuniform swelling due to neutron flux and temperature gradients in metals and graphite is undesirable in the warping of free standing structures and severe stressing of fixed members can occur. High stress levels are particularly troublesome in embrittled material because vacuum tightness is a major requirement of the CTR blanket and fracture of welds could occur at strains of only a few percent or less.

The effect of neutron irradiation on the electrical resistance of normal magnets and the stability of superconducting magnets is also of concern as any increases in resistance will ultimately result in increased heating load. One other problem that falls into bulk radiation effects results from the requirement of electrical insulators in CTR's. This problem is particularly acute for pulsed systems where voltage gradients of ~5kV/cm and resistance of $>10^5$ ohm-cm must be maintained at 600-800°C during high energy neutron irradiation up to 10^{22}-10^{23} n/cm^2. Very little, if any, meaningful information exists on the simultaneous effects of irradiation and temperature on such insulators.

B) Surface Radiation Effects

The bombardment of the first wall in a CTR blanket or the divertor surface with neutral and charged particles can cause blistering and sputtering. Both of these effects can have serious consequences in terms of wall erosion and plasma contamination if the flux of particles is greater than $\sim10^{15}$ cm^{-2}sec^{-1}.[34] Blistering can even be a problem if the helium ion flux is $>10^{13}$ cm^{-2}sec^{-1}.[40] (See figure 4 for example of blisters in Nb at 25 and 900°C.) Spallation of large chunks of material due to the agglomeration of the blisters could result in unacceptable wall erosion rates. Both sputtering and blistering can cause plasma contamination. The success of divertors (see figure 5 for an example) and cold gas flushing in some systems and coatings in others could significantly diminish this problem. In the case of cold gas flushing, the plasma energy is carried to the wall predominantly by low energy neutral atoms (<10eV) and low energy photons.

High fluxes of photons to the first wall could cause significant temperature gradients and desorption of absorbed gases. This effect may be particularly pronounced in the low thermoconductivity, electrically insulated first wall of pulsed reactors. The temperature gradients will cause a variation in the final configuration of defects within the metals and consequently, there could be a significant variation of mechanical properties through the first wall.

STATUS OF TECHNOLOGY

The reader is referred to recent and excellent summaries of neutron and charged particle bombardment of potential CTR structural materials.[33,34,36,39] The state-of-the-art for this field is quite adequately reported in these documents and will not be reviewed here. There is also a large body of information from the LMFBR program on irradiation effects to stainless steel, and from the HTGR and MSRE programs on graphite. These programs should be continually monitored for data of relevance to CTR studies. Little information currently exists concerning either neutron or charged particle irradiation of electrical insulators.[14] The design and operation of divertors has been studied for many years at PPPL[42] and more recently at the University of Wisconsin.[12] The ultimate success of such divertors is an open question.

REQUIRED INFORMATION

A) Bulk Radiation Effects

One of the most crucial pieces of information that must be obtained before any large scale fusion reactors can be built is the synergistic effect of interstitial impurities, displaced atoms and high energy neutron reaction products such as He and H, on the ductility of potential CTR materials. This data is required over the temperature range from 500-1000°C for Nb, Mo, V, and alloys of the refractory metals with Ti, Cr, and Zr and stainless steel. Information is also required on mechanical and physical properties of Cu and Al during lower temperature (RT to 300°C) high fluence irradiations for pulsed systems. The effect of the irradiation induced defects on the creep properties and fatigue life of the proposed metals and alloys is vital to the design of reliable structural components. An almost equally important area is the effect of irradiation on the swelling of candidate CTR materials. The effect of gases such as hydrogen and helium on the nucleation, growth and thermal stability of voids in metals is of particular importance. Measurements of the resistivity of Cu and Al after neutron fluences of $\sim10^{22}$ n/cm^2 and data on the stability of superconducting magnets is required. More information on the characteristics of graphite irradiated to more than 2-4×10^{21} n/cm^2 is needed with particular emphasis on dimensional stability. A considerable number of experiments in the near term must be performed utilizing current fission reactor and accelerator facilities. In order to properly interpret these experiments, it is necessary to correctly assess the damage produced by 14MeV and fission spectra neutrons as well as by high energy heavy ions. Such an analysis can be accomplished theoretically and by carefully designed experiments. In situ experiments of irradiated insulating materials must be conducted at high temperatures in order to assess any electrical degradation problems that might arise.

B) Surface Radiation Effects

There is an urgent need for more information about the type, energy and flux of particles which leave the plasma and strike the first wall of the divertor. It is difficult to assess the magnitude of the potential problems without more information from the plasma scientists. For the near term program special emphasis should be placed on the following three phenomena: (1) radiation blistering, (2) sputtering by MeV neutrons, and (3) particle emission and surface layer flaking by energetic photon impact. Survey experiments on the blistering, sputtering and desorption phenomena should sufficiently overlap the particle and photon flux, and energy estimates to account for the fluidity of current design. The effect of high fluxes of short wavelength radiation on potential CTR first wall materials must be understood before any final design decisions can be made.

VIII. HIGH TEMPERATURE MATERIALS

PROBLEM DEFINITION

There are two classes of materials to be discussed here; structural metals and electrical insulators.

A) Structural Materials

The major requirements of the structural metals will be to allow construction of blanket and shield components that will:

1) Provide a vacuum tight chamber for the plasma.
2) Contain the moderating, neutron reflecting and tritium breeding materials.
3) Provide coolant passages to remove the heat.
4) Contain the neutron and gamma absorbing materials that will protect the superconductors and operating personnel from excessive exposure.
5) Provide passages for fuel insertion, diagnostic equipment and possible ion removal.

The metals used to construct the blanket must satisfy these requirements with a minimum amount of material in order to perturb the neutronics of the system as little as possible. There is also a desire to reduce wall thickness to lower the thermal stresses. On the other hand, the reduction in wall thickness will raise nonthermal stress levels in vital components so that the metal used must have as high a tensile and creep strength as possible. The metal must also have a high thermal conductivity, low expansion coefficient and a low Young's Modulus in order to minimize the thermal stresses or to maximize the allowable heat loading on the wall. Figure 6 shows how the relative thermal stresses in four potential CTR materials varies with temperature for fixed wall thicknesses and nuclear heating rates. Note that the refractory metals have much lower induced stresses than for stainless steel.

The CTR blanket must also have extremely high fatigue resistance, especially in the case of laser and pulsed systems. The laser systems must contain 10^7 to 10^9 joule pulses from DT reactions anywhere from 1-100 times per second to deliver several hundred megawatts of electrical energy. Such energy pulses are equivalent to 50 to 500 lbs of high explosive and systems must be designed to withstand these shocks $\sim 10^7$-10^9 times per year. The cyclic pressure and thermal stresses associated with pulsed reactors such as the Theta-pinch may occur every 4-10 seconds so that some 5×10^7 to $\sim 2 \times 10^8$ cycles will be incurred over a 20-year lifetime.

The structural metals must also have reasonable intrinsic costs as well as acceptable fabrication and assembly costs in order to minimize the total cost of the system. It is also desirable to use materials with a satisfactory preservice ductility but, because of the many factors (i.e., voids, helium bubbles, interstitial impurities, and excessive metallic transmutation products) in fusion reactors which tend to degrade this property, there may be little relation between preservice ductility and long-term operating ductility. The design of the CTR structure will probably need to be made on the basis that a few percent, or less, of ductility will remain after a year of operation.

The above requirements appear to be best satisfied by stainless steels below 600°C, by the refractory metal V or its alloys below 800°C and by Nb, Mo, or their alloys (Nb-Zr, Mo-Ti-Zr) below 1000°C.

B) Electrical Insulator

The pulsed reactors, such as the Theta-pinch design,[16] have the most critical insulator requirements brought about by the necessity for an insulating inner liner for the first wall. Typical azimithal voltage gradients of ~6kV/cm will be required for shock heating voltages of 1.6MV around a first wall of radius 30 cm. The liner must be kept as thin as possible and be either thermally coupled to the first wall or separately cooled, to avoid overheating. The operating conditions of this liner are:[15]

- 600-800°C operating temperature
- Neutron fluence ($0<E<14.1$MeV) of 10^{22}-10^{23} cm^{-2}
- Bremsstrahlung radiation of ~1Å wavelength
- Cyclical operating stress
- Bombardment with hydrogen isotopes and helium from plasma.

The insulating liner must offer a dielectric strength as high as possible, and a resistance $\geq 10^5$ ohm-cm. However, the electric stress is absent when neutron and bremsstrahlung bombardment is intense. Any radiation-induced degradation of dielectric properties must decay in the few seconds between pulses. The insulator might be electrically or mechanically damaged by electrolysis, transmutation and atom displacement effects, thermal shock, stress effects, or hydrogen reduction.

There are other systems that need insulators in the irradiation environment of the CTR. The

ORNL Tokamak[44] for example, requires a low stress (~0.2kV/cm) insulator to operate at 500-800°C for its electromagnetic pumping components. Mirror systems require insulators with dielectric strength of 20kV/cm to be maintained under charged particle bombardment at energies in the range of 100-1000keV and fluxes of 10^{15}cm^2/sec. These insulators will operate at 400-500°C.

STATE OF TECHNOLOGY

A) Structural Metals

A Considerable body of information, too voluminous to list here, exists in the open literature with respect to the unirradiated physical and mechanical properties of the candidate CTR materials. Recent reviews have considered how the various materials might compare under typical CTR conditions[33,34] and extensive re-evaluation of NASA related work is in order. Despite the large body of information on some alloy systems, there are essentially no standards, codes or procedures for large-scale construction with refractory metals. This is especially true for systems that will be subjected to high stresses 10^7-10^9 times during their lifetime. Finally, there are very few large-scale industrial production facilities for refractory metals and these would be hard pressed to produce ~10^7 kg of finished products per year as might be required for a mature fusion industry.

B) Insulators

There is limited information on insulators subjected to high mechanical and thermal stresses as well as immersed in liquid metal environments.[41] However, most of the data comes from the effect of one environment at a time. Little has been published on the determination of physical properties during simultaneous exposure to more than one damaging environment. There is also a dearth of information on the compatibility of insulators and refractory metal substrates, especially under dynamic loading conditions.

REQUIRED INFORMATION

A) Structural Metals

An accurate assessment of the availability of various metallic elements is required before any long-term commitments are made with respect to the CTR structural material. This assessment should indicate what the cost of the material is likely to be in years 1990-2000, what effect a rather large yearly demand might have on that value, and the extent of U.S. reserves to avoid severe balance of payments problems.

There are three main areas of refractory metal technology which need further investigation. The first is the effect of interstitial impurities such as carbon, nitrogen and oxygen on the DBTT (ductile to brittle transition temperature) of the refractory metals and alloys. This is important in relation to maintenance and modification procedures which involve cooling down CTR structures to room temperatures. Some of this information already exists and requires only critical review by scientists in the light of CTR requirements. Such surveys will also point out inadequacies in the data which can be remedied by future work. The second problem is the fabricability of large components from Mo, V, or their alloys. A reasonable amount of information already exists on Nb and Nb-Zr alloys, and it appears that no insurmountable problems exist for this system. However, welding and joining of Mo systems does appear to be a major problem and a complete survey of the successes and failures in this area is required. Very little is known of the large scale fabrication of V alloys and some base line information is also needed in that area. Third, more information is required about the tritium inventories in CTR structural materials. The accumulation of tritium in various components is design dependent and very much a function of the breeding fluid. However, more definitive numbers are required in order to fully assess the problem of hydriding (and ensuing embrittlement) during frequency reactor shutdowns.[45] The situation for austenitic stainless steel appears to be adequate for embrittlement and fabricability while more information about the hydriding effect in steel is required.

There is also a requirement for detailed stress calculations of a toroidal vessel containing many perforations and subjected to thermal, magnetic, and swelling induced stresses. Such calculations are necessary to determine the optimum wall thickness for each candidate material and to make sure that these values do not conflict with the neutronic requirements of fatigue resistant alloys for pulsed systems is desirable.

B) Insulators

Aside from developing radiation damage resistant insulators, it is desirable to produce ceramics which can easily be bonded to metallic substrates and maintain that bond over repeated thermal and mechanical stress cycles. The effects on the dielectric constants of such insulators will be extremely important as will be their interaction with the fuel gases in a pulsed system. There is also a need to develop insulators that have corrosion resistance to lithium for other reactor concepts. Methods of metallic coating the ceramics should also be investigated.

VIII. COMPATIBILITY

DEFINITION OF PROBLEMS

The majority of the compatibility problems result from the action of a flowing coolant on metals, alloys or ceramics at high temperature. The currently envisioned operating temperatures of 500-1000°C for CTR blankets narrow the choice of coolants to liquid metals and inert gases. More over, if one wishes to use liquid metals it is wise to use pure lithium or a lithium containing salt because of the requirement to breed tritium for the early CTRs. The present candidate for coolants in the blanket are:

Lithium (plus K topping cycles in some systems[44])
Flibe (Li_2BeF_4)
Helium

Corrosion reactions of liquid metals and gases with metals may be strongly influenced by impurities such as hydrogen isotopes, carbon or oxygen.[46] The hydrogen isotopes could come from the tritium breeding fluid, from the plasma, from the steam power conversion system or be produced neutronically within the metal itself. Carbon or its compounds from the graphite or oxygen from the power conversion cycle could also have significant effects on corrosion resistance, especially for the refractory metals. Dissimilar metal systems must be carefully studied because of mass transport problems, i.e. carbon from steel could be absorbed by Nb or V. Therefore, compatibility with a pure coolant (i.e., Li or He) is not the whole criteria for compatibility considerations and allowances must be made for impurity effects.

There are also compatibility problems for ceramic insulators immersed in liquid lithium which must be considered. Most CTR blankets usually include a fair amount of graphite as a moderator-reflector material and suitable methods for chemically isolating graphite from lithium must be developed.

STATUS OF TECHNOLOGY

A) Lithium

It is well known that iron and nickel based alloys are limited to relatively low service temperatures in lithium.[47] This level is ≤500°C for austenitic stainless steels in dynamic Li and may be extended to ~700°C in static Li. Refractory metals appear to be highly resistant to lithium even above 800°C and Nb and Mo appear to be useful up to 1000-1100°C.[48]

Lithium is unlike Na in that oxygen impurities contained in Li apparently do not promote disolution of refractory metals. However, the oxygen level in the Nb and V is of importance in that when it exceeds ~200-500 ppm, severe lithium penetration occurs.[49] Alloying with Zr or Ti raises this threshold valve. Mo, which has a relatively low solubility for oxygen is not subject to attack by lithium. The compatibility of various insulating materials with lithium is shown in figure 7. Note that alumina is particularly vulnerable to Li corrosion at 375°C but that BeO, ThO_2 and Y_2O_3 are fairly inert.

B) Lithium-Fluoride Salts

The oxidation products formed by the exposure of metals to molten fluoride salts tend to be highly soluble in the salts and do not form protective films. Thus the corrosion resistance of a metal to fluoride salts correlates directly with the "nobility" of the metal.[46] Mo and Ni-Mo alloys are very resistant to LiF-BeF_2 salt mixtures.[51,52] Nb and Fe based alloys are less resistant to attack by fluoride salts[52] but both would be suitable for operation in the range of 600-700°C. There are no reported tests of V in fluoride salt mixtures, but on the basis of nobility, V would be expected to undergo considerable reactions even with fluoride mixtures of relatively low oxidizing potential.[46]

C) Helium

At first glance, helium appears to be completely compatible with any CTR structural material. However, this is only true for Nb and V above 600°C if the interstitial impurity contents, particularly oxygen, can be maintained to extremely low levels. Experience has shown that oxygen impurities must be maintained well below 1 ppm if these metals are to retain reasonable ductility.[53,54] Mo, because of its low solubility for oxygen is compatible with commercially pure helium up to ~1000°C.

REQUIRED INFORMATION

Methods of extending the useful temperature regime to 650°C for austenitic stainless steels in dynamic lithium need to be developed. The effect of hydrogen isotopes on the corrosion of metals by lithium or its salts should be defined. Metallic coatings for Nb or V need to be developed if these metals are to be used in oxygen contaminated helium environments. Methods of protecting ceramic insulators from flowing Li must also be established.

The effect of irradiation of Li salts, especially concerning free radical production of F^-, or H^+ (T^+), needs to be studied to see if the corrosion rates will be accelerated. Magneto-hydrodynamic effects on Li salts may also effect their chemical stability.

IX. MAGNETOHYDRODYNAMICS

DEFINITION OF PROBLEMS

The use of liquid metals in those reactors requiring a high magnetic field to confine the reacting plasma may incur severe magnetohydrodynamic problems. The high magnetic field may laminarize the flow and thus reduce or eliminate the eddy diffusivity which enhances the high heat transfer capacity of all liquid metals. Further, large pressure losses are caused by flow perpendicular to the high magnetic field. The magnitude of these pressure losses are highly design dependent, ranging from moderate to intolerable in designs reported.

In the pulsed Theta-pinch reactor, these problems are alleviated because the magnetic field is off for all but a few percent of the operating cycle. Thus, the first wall heat transfer coefficient will have nearly its normal field-free value and allow greater wall fluxes. However, during the magnetic pulse, the lithium flow in the inner blanket will be stopped or impeded for some 0.01 to 0.1 seconds, giving a pressure pulse with possible associated shock and fatigue effects.

STATUS OF TECHNOLOGY

A magnetic field limits the turbulence, (eddy diffusivity) of liquid metals. The field not only retards the transition to turbulent flow as Reynolds number increases, but also reduces the heat transfer coefficient after "transition". For the fields, duct sizes and liquid-metal velocities envisioned for CTR plants operating in the turbulent flow regime seems unlikely (particularly in view of the pressure forces required). Although nonmetallic lithium-containing salts may have conductivities only 1/10,000 of lithium, thus reducing their interaction with the magnetic fields, their reduced heat transfer coefficients may offset this advantage.

The elimination of turbulence will reduce the pressure losses parallel to the magnetic field, but pressure losses in flow perpendicular to the field will be greatly increased. Some typical values may be estimated using correlations from Hoffman and Carlson.[55] For a perpendicular field of 100kG, a velocity of 1 m/sec, and a duct width of 2 cm, both entrance and exit of lithium flow from the magnetic field require a pressure drop of about 50 psi. For flow through the uniform magnetic flux, the pressure loss is estimated to be 500 psi per meter of path length. This last number is directly proportional to the fluid velocity and to the duct-to-fluid conductivity ratio (taken above a 0.01), but is proportional to the magnetic field squared. Because of sensitivity to these factors, extreme design care is required to prevent excessive pressure losses. Some proposed designs have used novel configurations and low velocities to keep pressure losses small.[44,56]

Experiments in nonconducting ducts have shown good agreement with the theory developed in Ref. 55. Hoffman and Carlson have accounted for nonconducting walls in an approximate manner, but little applicable experimental work has been conducted to verify their theories.

An other possible MHD effect on heat transfer has received attention but only without superimposed magnetic fields. This effect is the superheat required to initiate boiling in a liquid. Many variables have been investigated, and investigators have found superheat values ranging over two orders of magnitude. A recent study[57] has shown that both the pressure-temperature history and the effect of inert gas on the boiling surface will control the superheat required to initiate boiling.

REQUIRED INFORMATION

There has been a considerable amount of theoretical work in the fields of heat transfer and pressure losses in a high magnetic field but experimental verification of the theory is sketchy, and has generally been done at conditions far removed from those which may exist in a CTR. Generally, no work has been done at fields above about 20kG, and work has been predominately confined to mercury or NaK alloy in nonconducting ducts. Thus confirmatory work in high magnetic fields using molten lithium in geometries and with duct conductance typical of CTR are required.

Work is required for the pulsed Theta-pinch reactor to investigate the water-hammer like effect of the pulsed magnetic field. There is expected to be little effect upon heat transfer or pressure losses, but some new fatigue problems may be induced.

X. POWER CONVERSION

The energy conversion-electric generation portion of a fusion power plant is a large fraction of the total cost of a CTR and significantly influences the design of the fusion reactor blanket.

Advanced thermal systems for CTR's depend on high temperature operation for achieving high thermal efficiencies. These include the direct cycle helium gas turbine[50,51] and topping cycles for steam systems such as MHD and the potassium vapor turbine.**

Environmental improvements required include the adaption of dry air cooling towers for dissipation of the reject heat directly to the atmosphere and thus requiring no cooling water. Other problems peculiar to fusion devices are:

- Tokamak type reactors may require cyclic operation with burn times of one second to several hundred seconds. This requires special attention since present day systems operate essentially at steady state.
- The Theta-pinch and laser systems are pulsed devices where the energy is generated in a small fraction of the duty cycle. This creates special problems in fatigue, energy storage and averaging the shock effects.
- The mirror system requires some form of direct conversion of charge particle plasma energy for efficient operation. This can be done with high efficiency (~90%) but requires development of a new technological area. A significant portion of the total energy still needs to be utilized in a thermodynamic cycle.
- The house loads in proposed plants for such things as the confinement magnets, lasers, fuel injection, heating, cryogenic cooling, and other auxiliaries are in many instances outside the range of present technology in terms of energy form and magnitude. These areas need considerable development.

System studies are needed in all reactor types and power conversion schemes to evaluate their applicability, to identify unacceptable areas, and to optimize the coupling of the power conversion system to the fusion energy source.

STATUS OF TECHNOLOGY

System studies and outlines of power plant concepts on each of the four major confinement schemes have been made.[2] A number of studies have also been made to evaluate the applicability of helium cycles, potassium turbine cycles, and MHD cycles to power plant concepts.[50-52] These demonstrate the range of applicability of each to fusion systems. Most of the identified problems arise in the blanket region of the reactor, and it is generally assumed that a large portion of the hardware for the power conversion will be developed by the fission and fossil fuel plants in the period 1970-1990.

REQUIRED INFORMATION

The preliminary work in the application of the several choices of power cycles to each of the four major confinement schemes needs to be continued. System studies are needed particularly for, 1) a better definition of the problems expected with each combination and the development programs required, 2) development costs, 3) evaluation of the range and degree of applicability to fusion systems and 4) engineering, environmental and economic optimization studies for the concepts. These are needed to provide adequate background information so that the best choice can be made for the first power plants.

XI. NEUTRONICS

DEFINITION OF PROBLEMS

The major requirements of neutronic-photonic calculations are to accurately predict:

1) Tritium breeding and lithium depletion,
2) Energy deposition distributions,
3) Displacement rates in materials,
4) Shielding of magnets and other components,
5) Induced radioactivity,
6) Transmutation rates in materials.

To this end adequate calculational techniques and nuclear data must be developed and verified by integral experiments. Both data processing and transport calculations must be reasonably inexpensive because of the many design calculations required.

STATE OF TECHNOLOGY

Extensive development of computer code systems and data libraries has been accomplished by the fission reactor and weapons program. The basic capabilities exist, but some gaps occur for certain materials and geometries of CTR designs. No major development programs are foreseen for neutronics because current technology is refined to the point where the program required to resolve uncertainties is clearly identified.

Cross section data for 14.1MeV neutrons is fairly well established with a few notable exceptions (i.e. Mo). However, the experimental cross section data in the 5-14MeV range is rather sparse especially for the (n,x) reactions. Neutronics calculations on relatively simple blankets have shown tritium breeding to be achievable, and have provided estimates of heating rates, displacement rates (see figure 8), and transmutation rates.[36,65] Calculations of the magnitude of afterheat have also been made showing that it is not a small problem, but certainly a manageable one (see figure 9).

REQUIRED INFORMATION

Accurate parametric studies must be completed on realistic conceptual designs with perforations and non-symmetrical shapes before CTR designs are allowed to mature. The techniques required to perform such analyses include multi-dimensional transport theory codes, shielding optimization codes, and time dependent burn up codes. Such codes are usually available or under development within programs outside of the CTR area; however, it appears that a modest effort will be required for both modification of existing codes and development of optimization procedures.

Ambiguities in current CTR neutronics calculations are to a large degree a result of cross section uncertainties. The types of cross section data needed are:

- Neutron and gamma-ray transport,
- Gamma-ray production,
- Tritium breeding,
- Helium and hydrogen production
- Transmutation and activation,
- Atomic displacement
- Energy deposition.

Those cross sections which present the greatest concern and which will require the most attention are neutron transport cross sections, alpha production cross sections for structural materials, gamma-ray production cross sections, and tritium breeding cross sections. In order to develop the needed data in an efficient manner one must 1) evaluate existing data and theoretical models for predicting cross sections in light of our priorities, and 2) conduct microscopic measurements of cross sections when such measurements are clearly required.

Integral experiments will be needed to 1) verify cross section and calculational techniques and 2) examine specific designs, i.e., blanket mock-ups. Those in category 1) are often called "clean" or "benchmark" experiments, and are relatively independent of a specific blanket design. They are intended to answer questions regarding basic cross section data, or to test computational methods in simple geometries. Experiments in the second category are relatively expensive and would probably be conducted as specific designs evolve. Even then they would be required only for CTR concepts with high probability of entering the prototype stage. The use of fusion-fission reactors[64,65] to

- "Burn" objectionable fission products (i.e., Sr^{90} and Cs^{137})
- Reduce the plasma confinement criterion for positive energy balance.
- Produce fissile fuel with a doubling time of ~5 years and

show be actively pursued. Such studies, even though confined to theoretical aspects the forseeable future may turn out to be extremely valuable in the future.

XII. TRITIUM REMOVAL AND CONFINEMENT

PROBLEM DEFINITION

Tritium must be efficiently recovered both from the plasma exhaust and from the blanket-coolant system for at least the early CTR systems. The exhaust recovery system will be required to:

1) operate with little overall net loss,
2) remove helium and other impurities,
3) remove hydrogen to prevent buildup in the plasma,
4) prepare D-T mixture for reinjection into plasma.

The blanket recovery system will be required to:

1) maintain tritium concentrations in the blanket-coolant system sufficiently low to prevent embrittlement of structural materials and to avoid excess inventory charges,
2) prevent a prohibitive tritium leakage rate to the environment via the steam system.

Considerable chemical and engineering development will be required to perfect both exhaust and blanket recovery systems, but recovery from the blanket system is likely to require a greater development effort because of the extremely low release rates required by environmental considerations.

At the high temperatures involved, tritium permeates all walls at a rate dependent upon the composition in the blanket and coolant streams and the permeability of the containing walls. The critical tritium loss is that permeating the water boiler and thus entering the steam system. Tritium passing through other walls can be recovered or at least retained by using double or triple containment (with at least one cool wall) and processing the atmosphere between these containing walls.

The tritium leakage rate to the steam system is determined by both the permeability of the water boiler tubing and the efficiency of tritium recovery process. Reduction in permeability of the boiler surface will allow higher tritium concentrations and thus smaller or less efficient removal equipment. Conversely, better removal methods will permit the use of more permeable materials for the boiler surfaces.

STATUS OF TECHNOLOGY

Techniques for performing all of the "processing" steps in the blanket recovery systems are available, but considerable effort may be required to achieve the high recovery required and to do this at reasonable costs. "Diversion" or removal of plasma to the process system and reinjection to the plasma are major problems. However, these problems are so closely coupled to the plasma system that they are not considered strictly tritium handling problems.

Several techniques have been suggested for recovering tritium from the blanket or coolant, but the severe release requirements eliminate some of these. Limited information suggest that some of the following techniques may prove to be satisfactory.

. The use of permeable metal (probably niobium) surfaces in contact with lithium appears promising. Distillation and gas stripping do not appear feasible.[66]

. A tritide forming sorbent which can be loaded at one temperature and desorbed at a higher temperature is suggested to recover the tritium from potassium coolants. Again distillation and gas stripping are not considered feasible for potassium.[66]

. Gas stripping does appear to be the preferred method for recovery from molten 2 $LiF-BeF_2$ blankets. The distribution of tritium between TF and T_2 is important to this process. From the standpoint of tritium removal, it is desirable to have a high pressure of TF and a low pressure of T_2. The T_2 pressure must be low to prevent high tritium leakage rates, but a much higher TF pressure is required if the gas sparge rate and the strip vessel size are to be practical. These required conditions run counter to the conditions desired from a corrosion standpoint, and a satisfactory compromise should be sought.

. To remove tritium from He coolants, hydride forming sorbents, again operating between a high and lower temperature are recommended. The use of oxygen in the He to form T_2O, which would be caught on a dessicant, will probably be impossible if the coolant tubes are made from Nb or V. (see compatibility section)

REQUIRED INFORMATION

Considerable information will be required to demonstrate that tritium can be effectively recovered from the blanket-coolant system. Chemical and engineering data are needed to establish the feasibility of proposed recovery systems and to evaluate methods for reducing the permeability of water boiler tubes. Chemical data are needed on vapor-liquid and solid-liquid equilibria and on permeability of promising materials. Engineering data will need to evaluate mass transfer rates, equipment size, and materials of construction. Eventually prototype demonstrations will be required for both the exhaust and blanket systems.

XIII. CONCLUSION

It is very easy to be discouraged by the rather long list of problems we have just discussed. However, it should be remembered that the sole object of this paper was to focus attention on areas of technology that must be developed in order to take full advantage of all the beneficial aspects of fusion power as described by others at this conference.[1,2,4] I am sure that other technologies have had equally as long, and perhaps as formidable a list in the early stages of their development. The space program, for example, could have certainly more than filled these pages with their perspective problems in the late 50's. Nevertheless, within a little more than a decade we had placed a man on the moon.

It is encouraging that some of the biggest CTR problems are economic in nature because they usually are the first to succumb to man's ingenuity. Developing cheaper superconductors and lowering the cost of stronger reinforcing materials will have a large effect on the attractiveness of fusion power. Development of a mature refractory metal industry with associated design codes and fabrication techniques is mainly an economic argument. No insurmountable corrosion problems appear to exist that could not be solved by paying the economic penalty of thicker walls or lower operating temperatures. The neutronics is fairly well developed and we should have no problem breeding tritium. The power conversion-electric generation systems are certainly within reach of todays technology. Perhaps the only non plasma physics problem that appears to be relatively free of economics is the radiation damage problem associated with high fluxes of 14MeV neutrons. However, even on this account, we have had some pleasant experiences i.e. irradiation induced swelling in

LMFBR cladding. The situation looked bleak in the late 1960's only to be displaced by optimism in the early 1970's by the development of virtually swelling resistant stainless steels.

No one can say when all of these problems will be solved, or even if they will, but it is the view of this author that most of the technology problems will be solved shortly after the first demonstration of controlled thermonuclear power. Once that hurdle has been overcome, there will be great pressure to commit more resources, both financial and intellectual, to the problems outlined here. Such an effort should hasten the day when a future reader of this article will marvel at our lack of perception.

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TABLE 1

Commercially Available Superconducting Materials

Material	Tc (°K)	Upper Critical Field at 4.2°K (kG)	Current Density at 4.2°K (A/cm^2)	Present Day Approx. Cost $/kAM (c)
Nb-48%Ti	9.5	122	80,000 at 75kG (a)	4
V_3Ga	14-16.8	208-210	60,000 at 200kG (b)	10-30
			170,000 at 100kG (b)	
			220,000 at 40kG (b)	
Nb_3Sn	18.2	245	280,000 at 100kG (b)	15

a.) A. C. Prior, Cryogenics, I, 131, 1967.
b.) K. Tachikawa, Applied Superconductivity Conference, Annapolis, Maryland, 1972.
c.) C. Henning, Intersociety Energy Conversion Engineering Conference, Energy 70, Las Vegas, Nevada, Sept., 1970, p. 1-90.

TABLE II

Effect of Helium on Ductility of Potential

CTR Materials at 800°C (35)

Alloy	appm Helium	%Total Elongation	appm He	% Total Elongation
316SS	0	47	40	6
V-20Ti	0	29	10	10
Nb-10W-3Zr	0	6	30	3
TZM	0	13	20	14

REFERENCES

1. R. L. HIRSCH, this conference.

2. F. L. RIBE, this conference.

3. The members of this committee were R. L. HIRSCH, USAEC; A. P. FRAAS (Chm) and M. S. LUBELL, ORNL; D. J. DUDZIACK, F. L. RIBE, and S. C. BURNETT, LASL; E. J. MILLS and F. TENNEY of PPPL; W. B. MYERS, LRL; M. PETRICK and T. COULTAS of ANL; and G. L. KULCINSKI, Univ. of Wisconsin. Many other scientist throughout the country were consulted on the various aspects of CTR technology but space limitations prohibits a full listing of their invaluable contributions.

4. A. P. FRAAS, this conference.

5. M. S. LUBELL, International Working Session on Fusion Reactor Technology, Oak Ridge, July 1, 1972.

6. R. HANCOX, ibid.

7. A. BERRUYER, R. BLONDEF, G. BRONCA, J. HOLTZ, J. KRIKORIAN, J. NEEL, and P. SOLENTE, Advances in Cryogenic Engineering 15, 158 (1970).

8. A. G. PRODELL, Proc. Intl. Conf. Bubble Chamber Tech., Argonne, June 1970.

9. J. R. PURCELL, ANL/HEP 6813 (June 1968).

10. J. PURCELL and H. DESPORTES, Private Communication.

11. C. D. HENNING, R. L. NELSON, M. O. CALDERON, A. K. CHARGIN, and A. R. HARVEY, Advances in Cryogenic Engineering 14, 98 (1969).

12. K. R. EFFERSON, D. L. COFFEY, R. L. BROWN, J. L. DUNLAP, W. E. GAUSTER, J. N. LUTON, and J. E. SIMPKINS, IEEE Trans. Nucl. Sci. NS-18, 265 (1971).

13. W. B. SAMPSON, R. B. BRITTON, P. F. DAHL, A. D. MCINTURFF, G. H. MORGAN, and K.E. ROBINS, Particle Accelerators 1, 173 (1970).

14. Company Data Sheet, July 1971.

15. J. R. POWELL, BNL-16580, Feb. 25, 1972.

16. S. C. BURNETT, W. R. ELLIS, T. A. OLIPHANT, JR., and F. L. RIBE, LA-DC-72-234, 1972.

17. P. F. SMITH AND J. D. LEWIN, Particle Accelerators, 155, 1970.

18. International Institute of Refrigeration, Law Temperatures and Electric Power, Pergamon Press (1970).

19. D. R. SWEETMAN, A. C. RIVIERE, H. C. COLE, E. THOMPSON, D. P. HAMMOND, J. HUGILL, G. M. MCCRACKEN, Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna, 1971) Vol. III, p. 393-403.

20. R. W. WEINTER, G. A. CARLSON, J. D. LEE, R. W. MOIR, R. F. POST, C. E. TAYLOR, Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna, 1971) Vol. III, pp. 329-349.

21. R. W. MOIR, W. L. BARR, R. P. FREIS, R. F. POST, Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna, 1971) Vol. III, p. 315-328.

22. H. SHELTON, C. D. HENDRICKS, JR., and R. F. WUERKER, J. Appl. Phys. 31, 1243 (1960).

23. C. D. HENDRICKS, JR., Charged Particle Research Laboratory Internal Report No. CPRL 71-4, Univ. of Illinois, Urbana, Illinois.

24. D. L. DIMOCK, D. ECKHARTT, H. P. EUBANK, F. HINNOV, L. C. JOHNSON, E. B. MESERVEY, D. J. GROVE, Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research, (IAEA, Vienna, 1971) Vol. I, pp. 451-463.

25. D. F. DUCHS, H. P. FURTH, P. H. RUTHERFORD, ibid.

26. H. P. FURTH and S. YOSHIKAWA, Phys. Fluids, 13, 2539 (1970).

27. Controlled Thermonuclear Research at LASL, Report No. LA-4656-MS (June 1971).

28. R. C. DAVIS, O. B. MORGAN, L. D. STEWART, W. L. STIRLING, Rev. Sci., Instr. 43, 278 (1972).

29. Proceedings of the Symposium on Ion Sources and Formation of Ion Beams, (Brookhaven National Laboratory, 1971) BNL 50310.

30. D. R. SWEETMAN, A. C. RIVIERE, H. C. COLE, E. THOMPSON, D. P. HAMMOND, J. HUGILL, G. M. MCCRACKEN, Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research (IAEA, Vienna, 1971) Vol. III, pp. 393-408.

31. A. S. SCHLACTER, P. J. BJORKHOLM, D. H. LOYD, L. W. ANDERSON, W. HAEBERLI, Phys. Rev. 177, 184 (1969).

32. W. GRUEBLER, P. A. SCHMELZBACH, V. KONIG, P. MARMIER, Helv. Phys. Acta 43, 254 (1970).

33. See Radiation Damage Section of the Proceedings of International Working Sessions on "Fusion Reactor Technology", Oak Ridge, Tennessee, July 1971 (Conf. 710624).

34. Summary of meeting on "Fusion Reactor First Wall Materials", Germantown, Maryland, January 1972, WASH-1206.

35. D. KRAMER, p. 50 in Ref. 34.

36. G. L. KULCINSKI, "Materials Problems for Fusion Reactors," Materials Engineering Congress, Cleveland, 1972, (to be published).

37. J. L. BRIMHALL and G. L. KULCINSKI; to be published Radiation Effects.

38. Proceedings of International Conference on "Voids in Metals," Albany, New York, June 1971 AEC Symposium Series, #26.

39. G. B. ENGLE and W. P. EATHERLY, "A Review of High Temperature Graphite Irradiation Behavior," Gulf-GA-A10933, March 1972.

40. M. KAMINSKY and S. K. DAS, Appl. Phys. Letters, Nov. 1, 1972.

41. Conference Record of 1969 Thermionic Conversion Specialist Conference, IEEE, New York, 1969.

42. For an excellent review of the topic see F. H. TENNEY, "Wall Limitations and the Divertor Problem," A Short Course in Fusion Power, Princeton, 1972

43. G. A. EMMERT, Private Communication.

44. A. P. FRAAS, *ORNL-TM-3096* (to be published).

45. T. E. SCOTT, *"Hydrogen Embrittlement and Other Effects in Thermonuclear Reactor Material"*, (to be published).

46. J. DE VAN, p. 25 in Ref. 30.

47. J. O. COWLES and A. D. PASTERNAK, *UCRL-50647*, April 18, 1969.

48. J. H. DE VAN, A. P. LITMAN, J. R. DISTEFANO, and C. E. SESSIONS, p. 675 in *Alkali Metal Coolants*, International Atomic Energy Agency, Vienna, 1967.

49. J. R. DISTEFANO, *ORNL-3551*, April, 1966.

50. H. L. KYLE and J. R. PAVLIK, *ANL-7888*, Dec. 1971, p. 59.

51. J. W. KOGER and A. P. LITMAN, *ORNL-TM-2724*, Dec. 1969.

52. J. H. DE VAN, *ORNL-TM-2021*, Vol. I, May 1969.

53. J. F. HOGAN, E. A. LIMONCELLI, and R. E. CLEARY, *TIM-901* in Pratt and Whitney Aircraft, CANL, Aug. 1965.

54. W. M. PHILLIPS, p. 197, in *Corrosion by Liquid Metals*, (ed. by Weeks and Draley) Plenum Press, New York, 1970.

55. M. A. HOFFMAN and G. A. CARLSON, *UCRL 51010*, Feb. 4, 1971.

56. W. STEWART and D. K. SZE, *"Lithium Cooling for a Low Beta Tokamak Reactor,"* to be published, University of Wisconsin.

57. R. E. HOLTZ, *ANL 7334*, November 1971.

58. G. HOPKINS and G. MELESE-D'HOSPITAL, *GA-9649*, Sept. 1969.

59. G. MELESE-D'HOSPITAL and G. HOPKINS, *GA-10004*, May 1970.

60. *Proceedings, British Nuclear Energy Society Conference on Nuclear Fusion Reactors*, Culham, England, September 1969.

61. *5th Intersociety Energy Conversion Engineering Conference*, *Energy 70*, Las Vegas, Nevada, September 1970.

62. S. FORSTER and T. BOHN, *IAEA-CN-28/K-13*, *Fourth Conference on Plasma Physics and Controlled Nuclear Fusion Research*, Madison, Wisconsin, June 1971.

63. P. STEINER, *Nucl. Appl. Tech.*, 9, 83, 1970.

64. W. C. WOLKENHAUER. *BNWL-SA-4232*, Battelle Northwest Laboratories, 1972.

65. W. C. WOLKENHAUER, B. R. LEONARD, JR., BNWL-1604, 1971.

66. A. P. FRAAS, Private Communication.

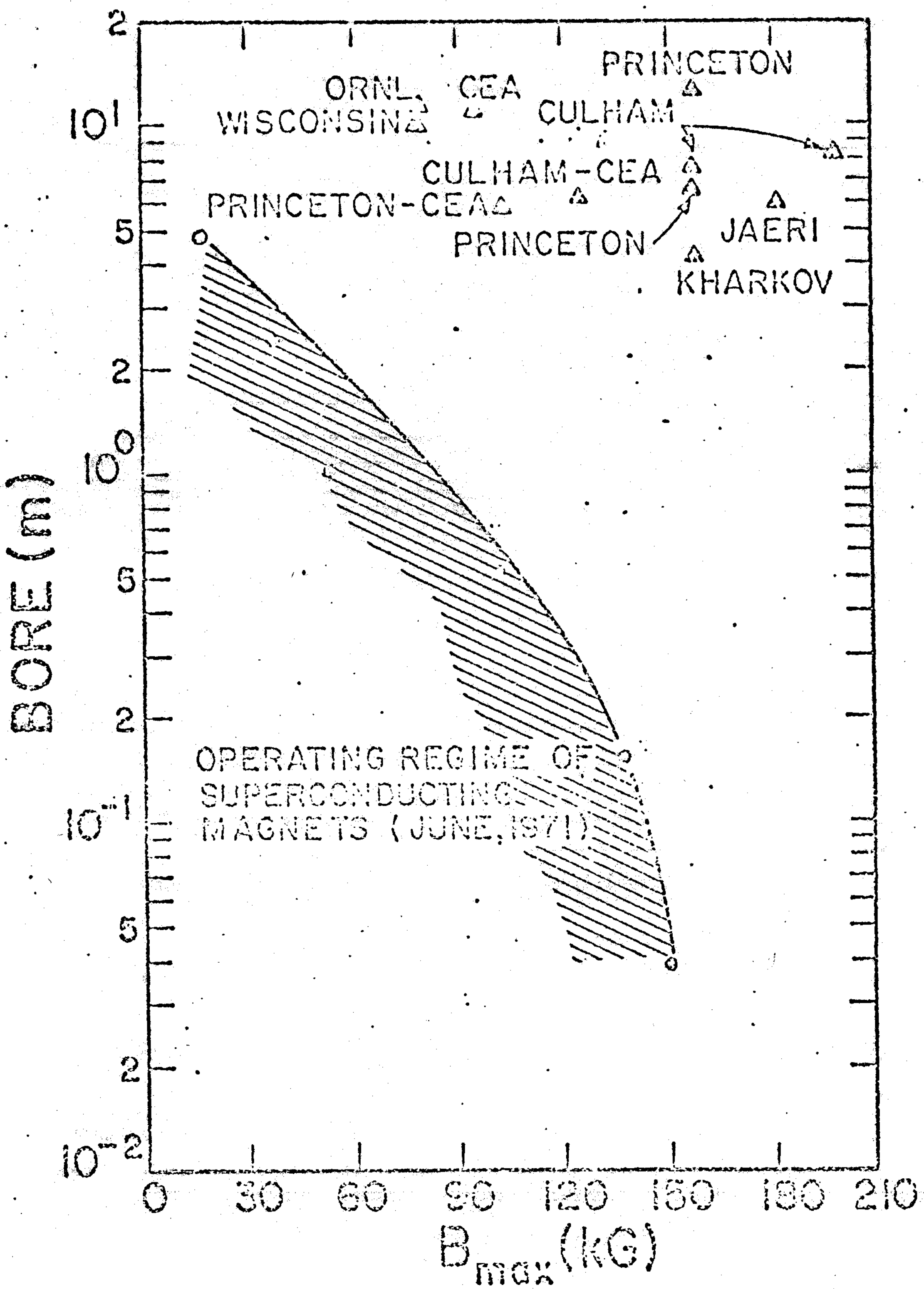

Figure 1 - State-of-the-art of superconducting magnets. Triangular data points represent recently proposed fusion reactor systems. Note that there are one to three orders of magnitude between what is proposed and what has been achieved. After Lubell.[5]

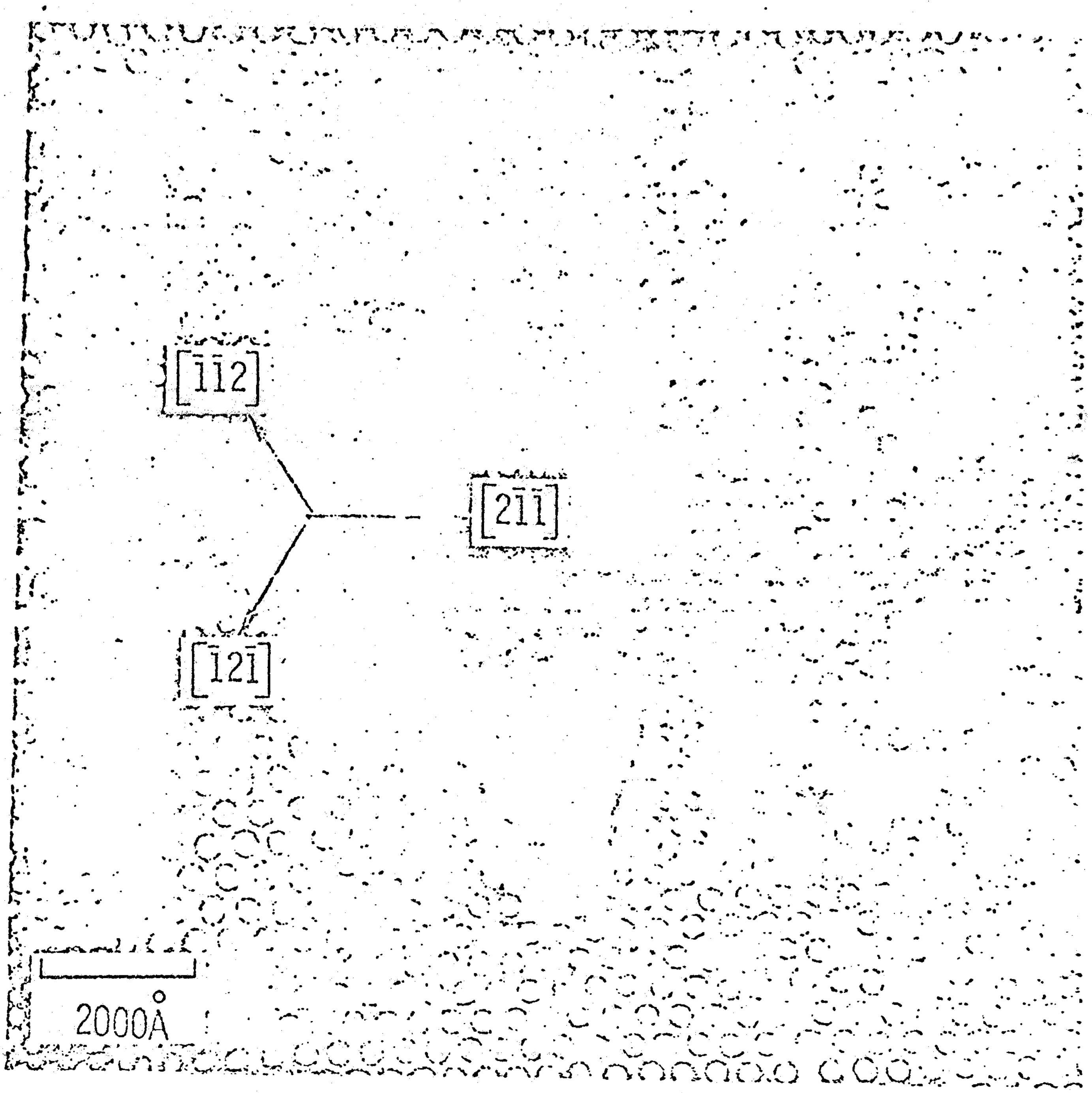

Figure 2 - Voids in niobium which has been irradiated at an effective temperature of 620°C to a point where every atom has been theoretically displaced 300 times during the irradiation.[37] The swelling in this sample is ~5%. This level of damage may be expected in 2 to 20 years of service depending on whether the neutron wall loading is 10 or 1 MW/m^2 respectively.

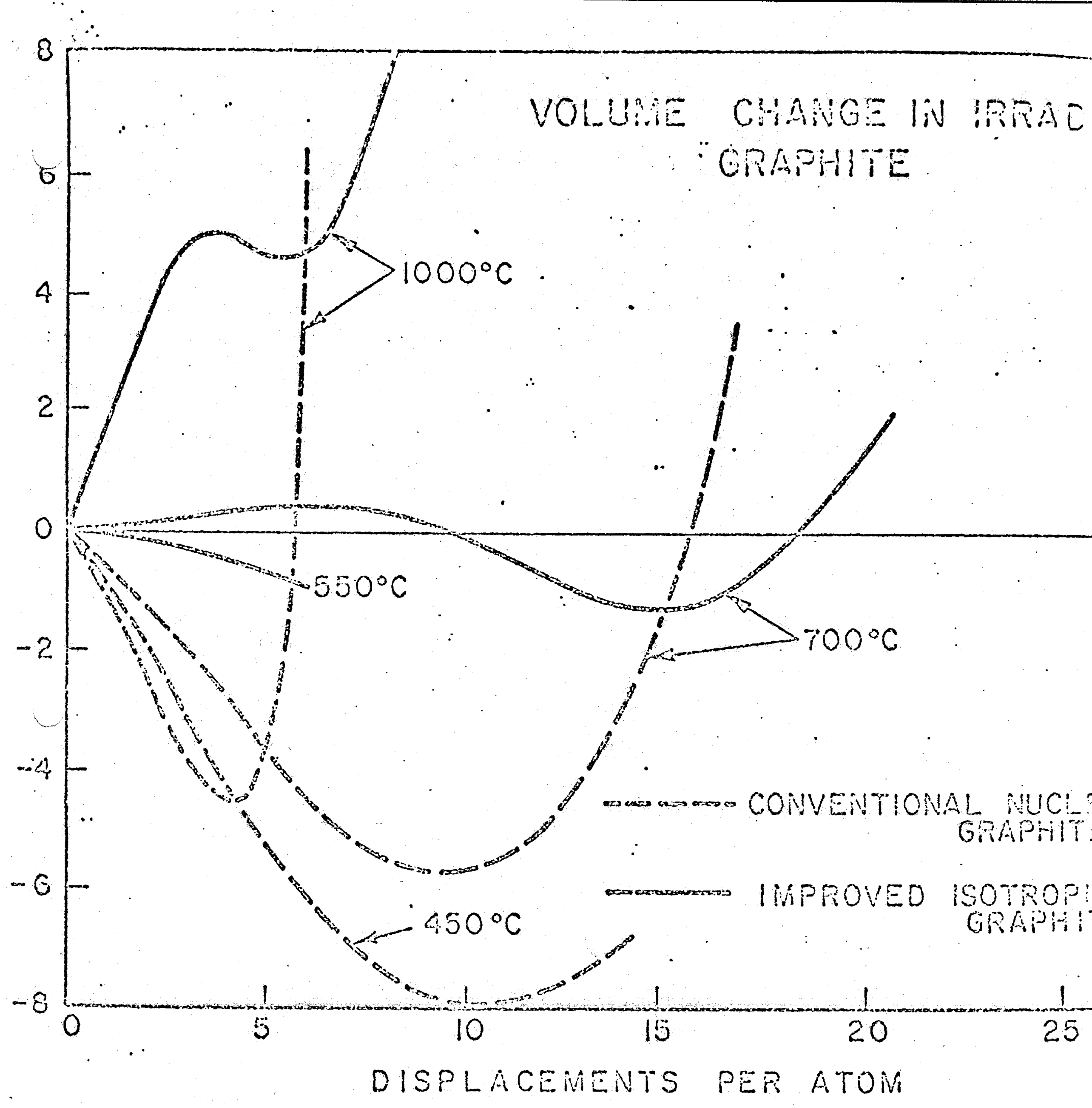

Figure 3 - Volume change of graphite as a function of the total number of times each atom is displaced during irradiation. Note that a typical 20 year exposure for a 1MW/m^2 wall loading is ~10 dpa if the graphite is 65 cm from the first wall. Courtesy of W. J. Gray and W. C. Morgan, Battelle Northwest Laboratories.

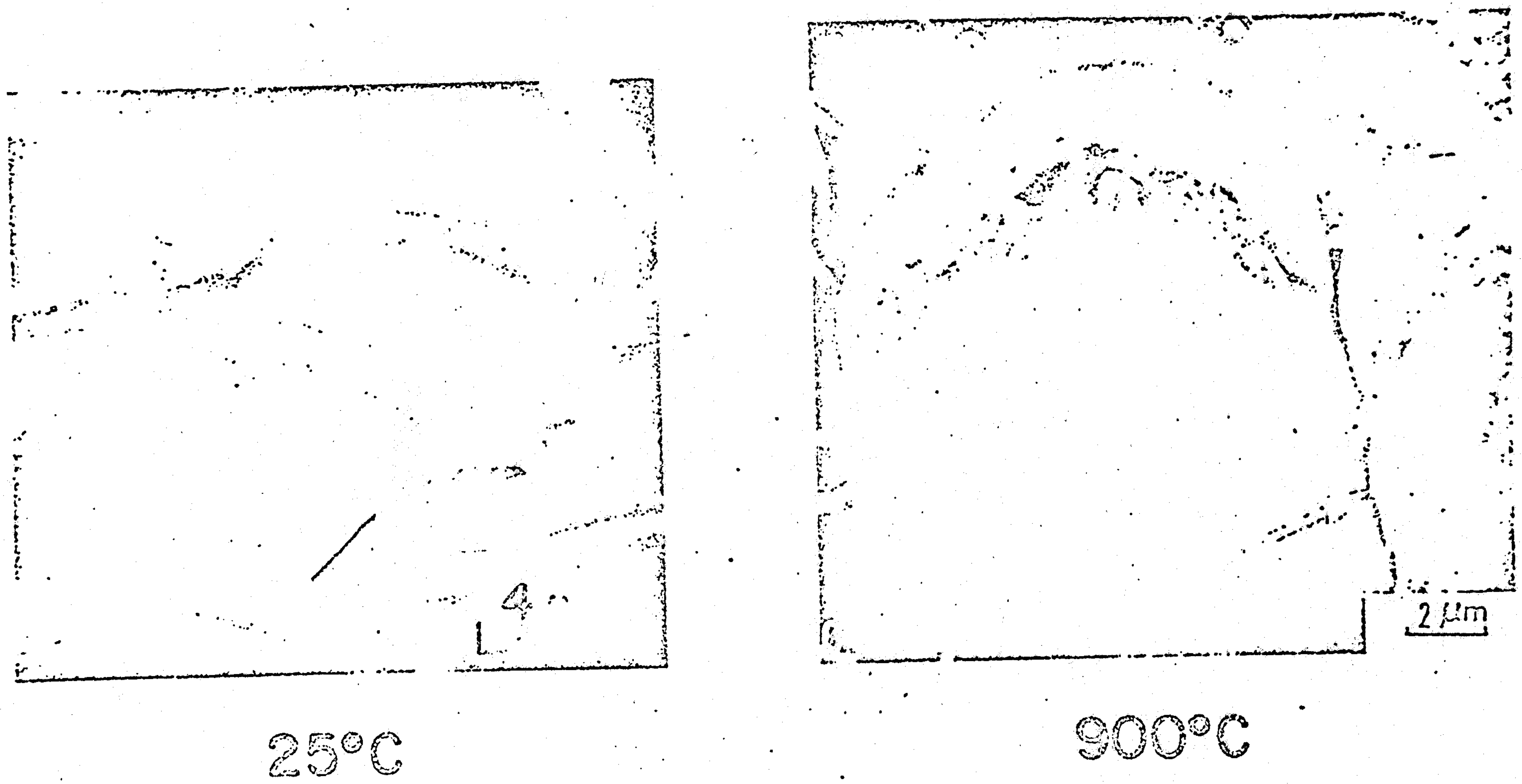

Figure 4 – Helium induced blisters in niobium after 25°C and 900°C bombardment with 6×10^{18} ions/cm^2. The energy of the helium ions was 500 keV. Note that some of the blisters have actually broken (see arrow on 900°C sample) and the metal is in the process of flaking off. Courtesy of M. Kaminsky.[40]

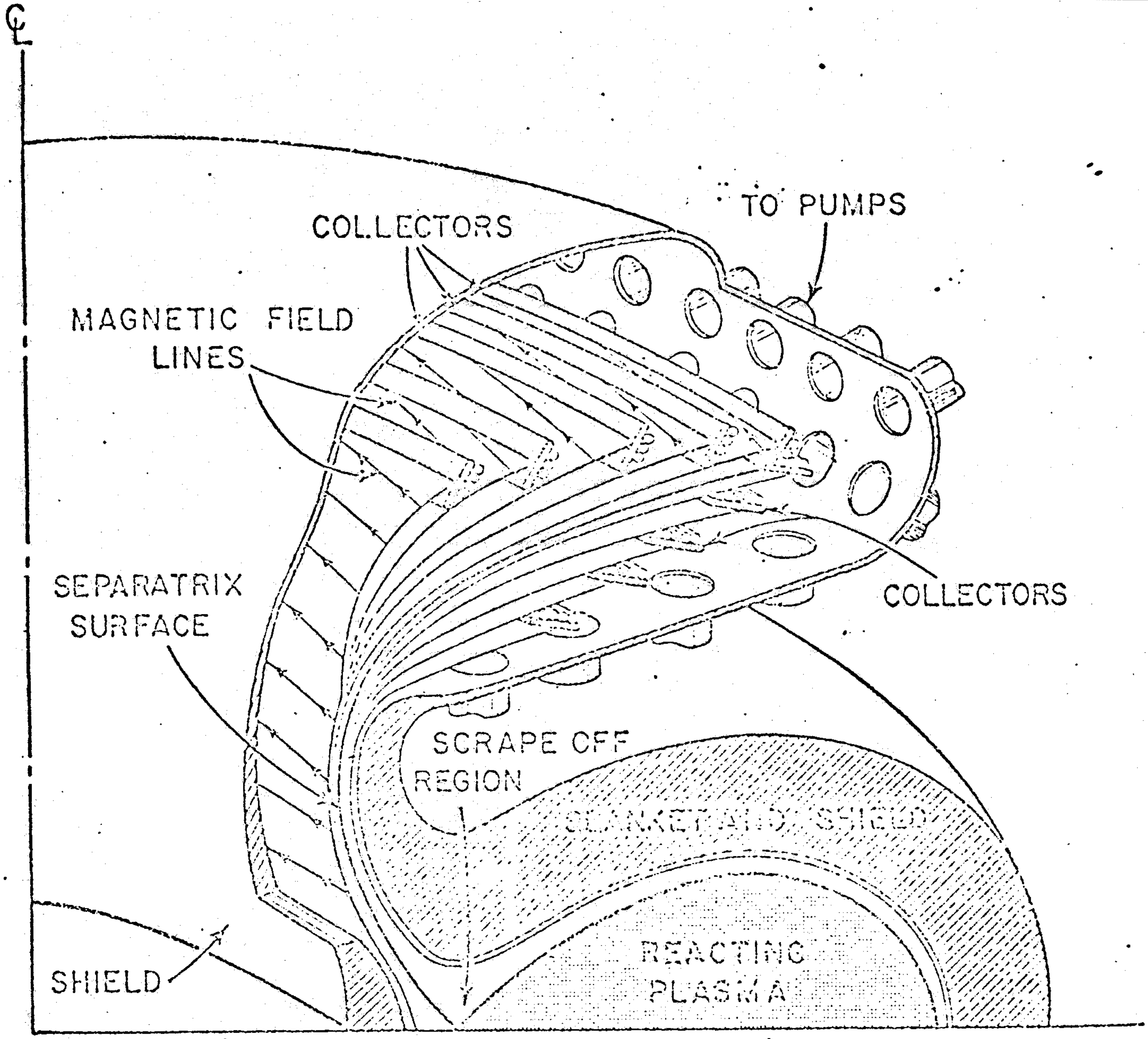

Figure 5 - Tokamak Divertor Concept-Courtesy of F. Tenny, PPPL. The ions which leave the plasma (D^+,T^+,He^{++}) are swept out of the inner vessel and on to collector plates above and below (not shown) the reacting plasma. After the ions have been slowed down in the collectors the hydrogen isotopes diffuse out and are removed by vacuum pumps. The fate of the helium atoms is unknown and depends on their energy when they hit the collectors. Blistering (figure 4) could result in the collectors.

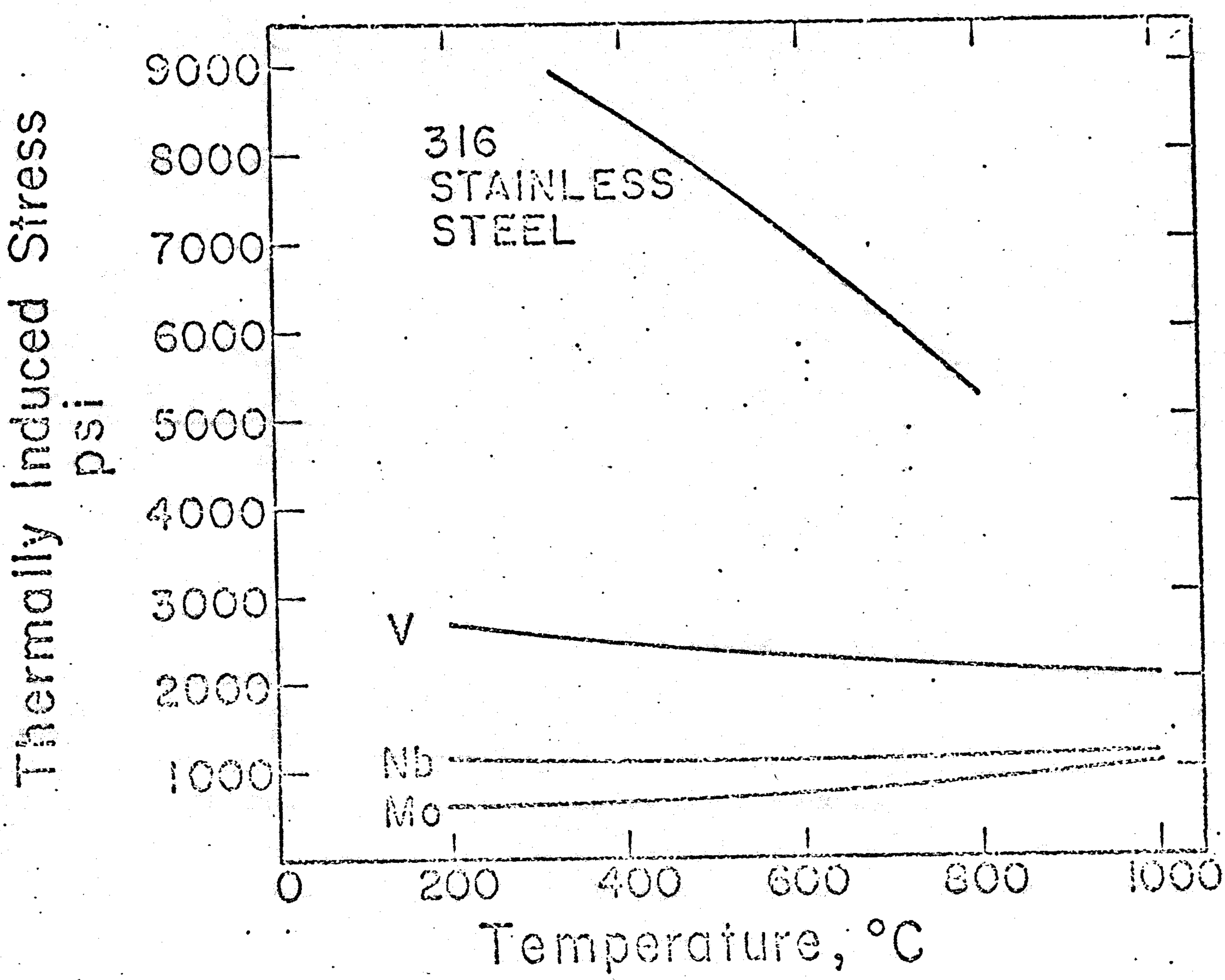

Figure 6 – Thermally induced stress in four potential CTR materials for a 5 mm wall thickness, a surface wall loading of 10 watts/cm^2 and an internal heating rate of 10 watts/cm^3. The low thermal conductivity and high thermal expansion coefficient of 316 stainless steel produces much higher stresses than in refractory metals.

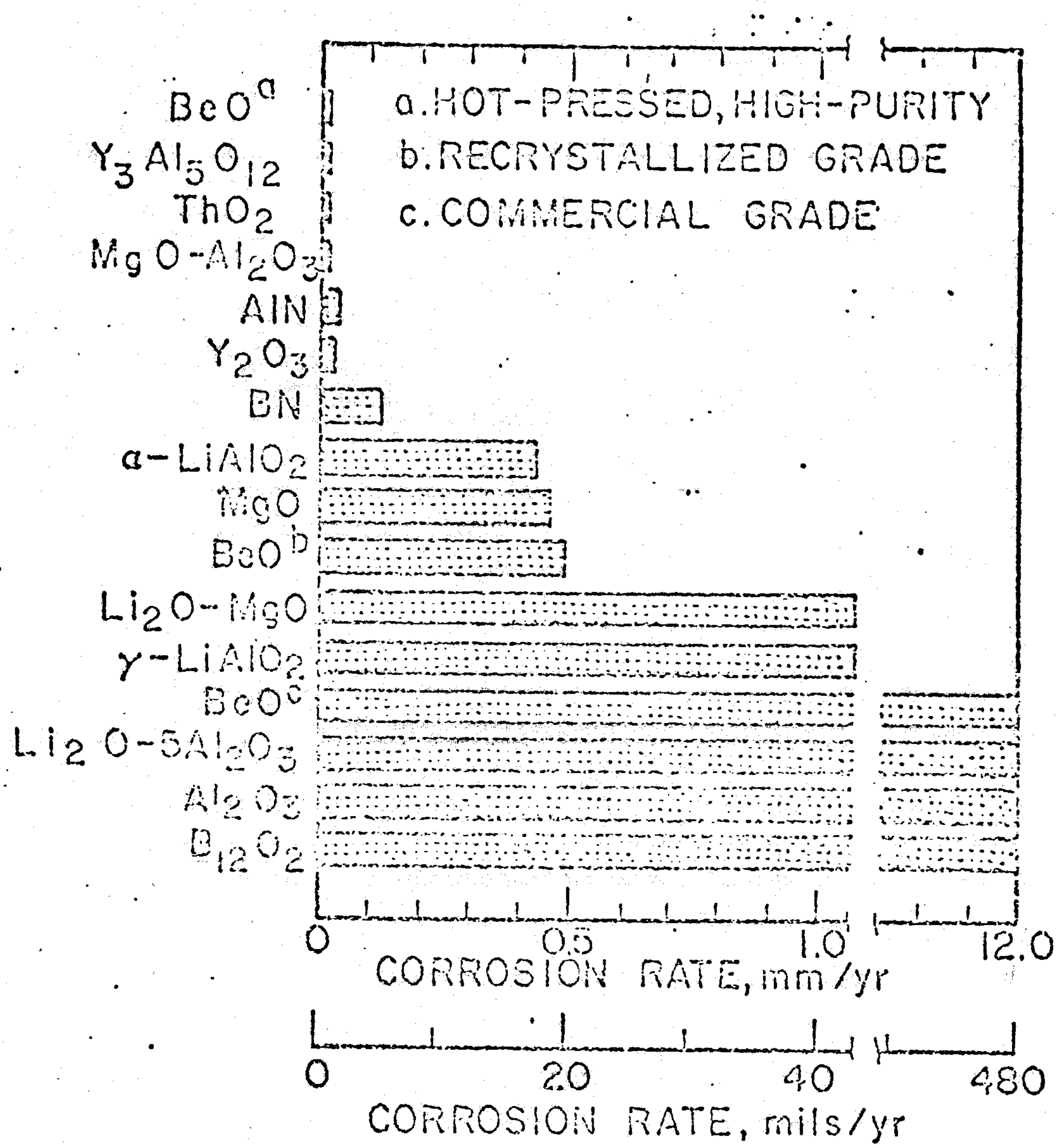

Figure 7 - Corrosion of Insulating Materials by Lithium at 375°C.[50] Note the large effect that processing has on BeO.

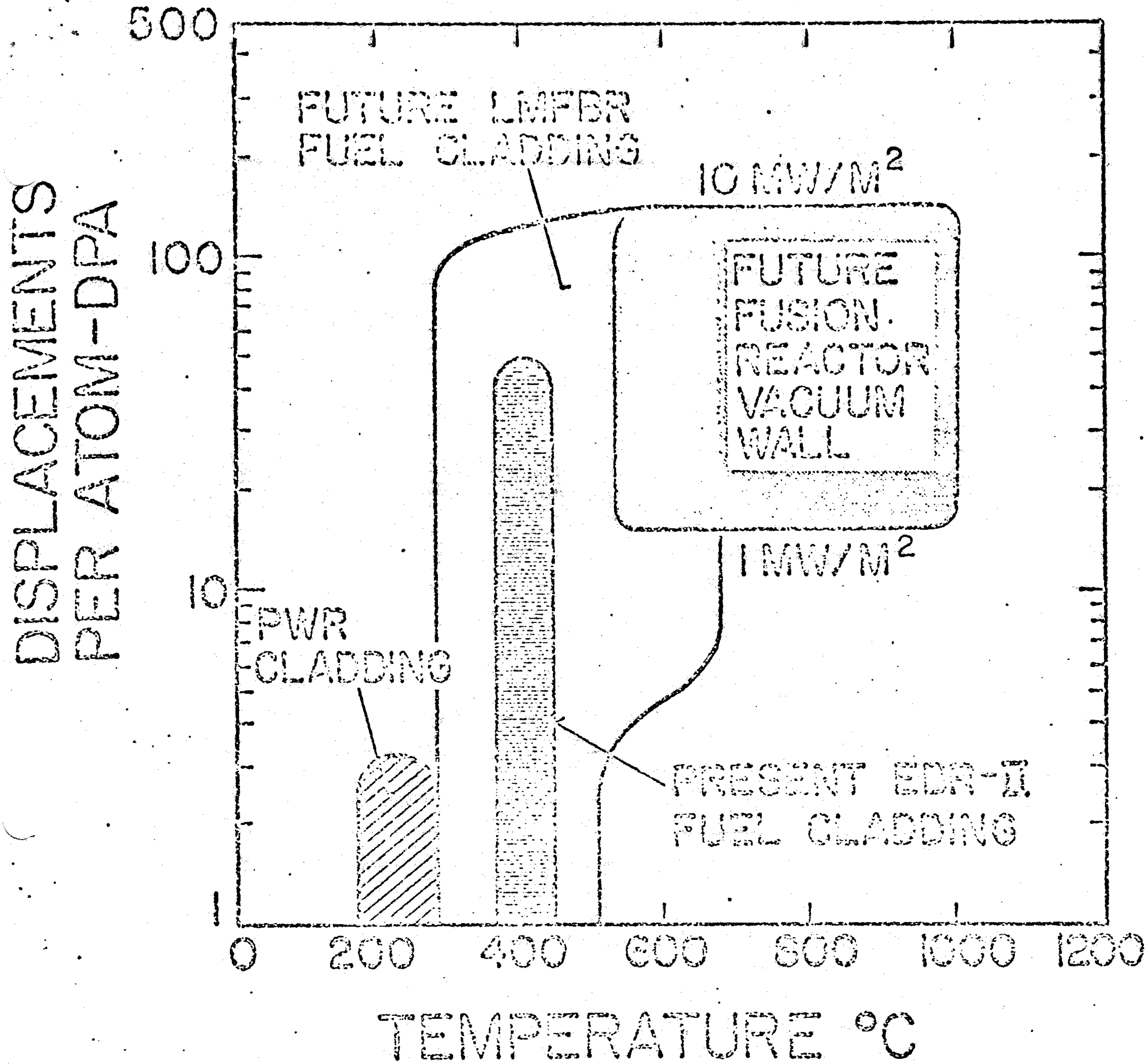

Figure 8 - Neutron Damage Incurred in One Year of Reactor Operation for Four Nuclear Systems. Note that the displacement rates for a Nb first wall of a fusion reactor is no worse than for the stainless steel cladding of a LMFBR fuel element. If the wall loading can be lowered to 1 MW/m^2, as is the current trend, then the displacement damage rate will be no more severe than we currently find in nuclear reactors.

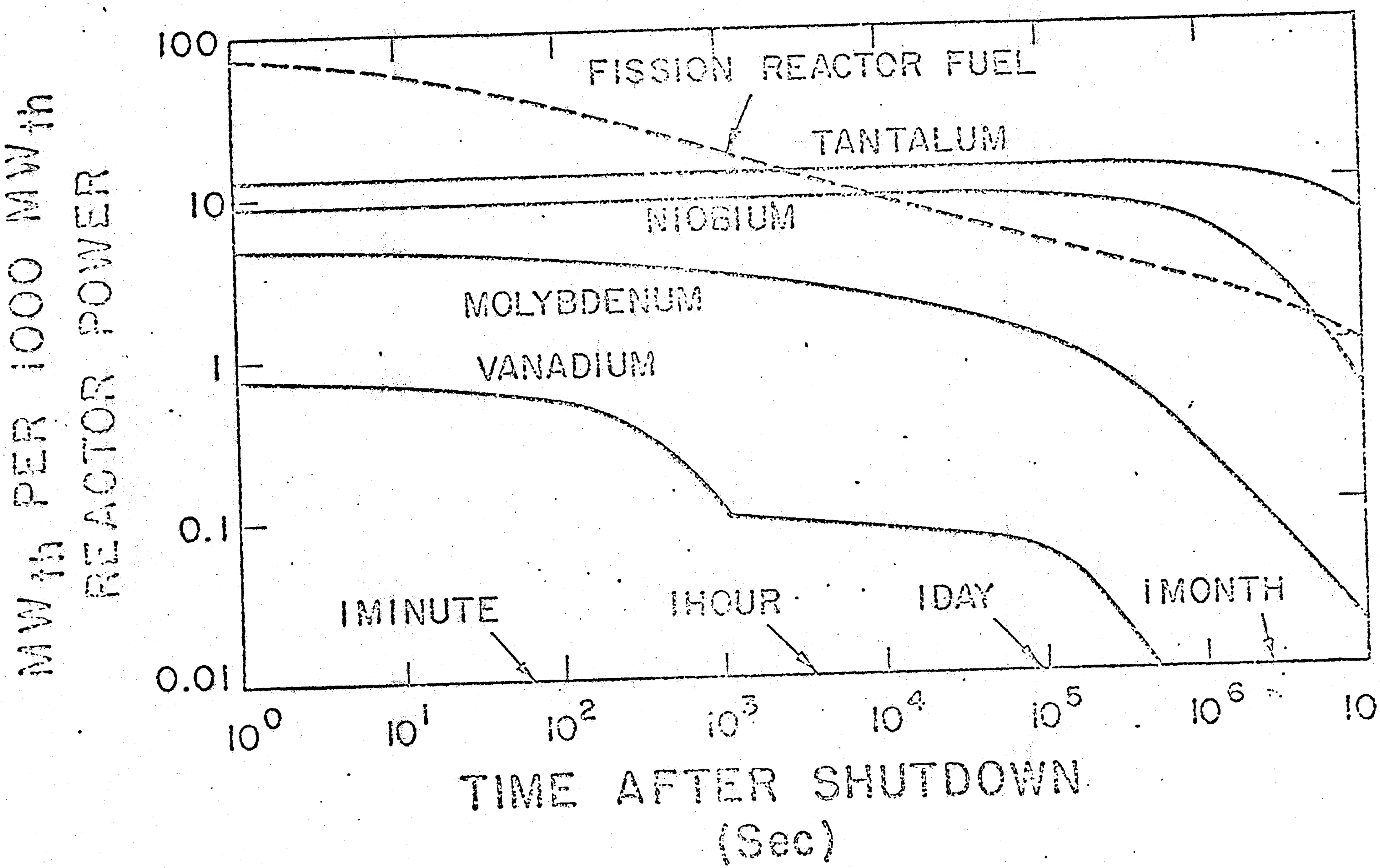

Figure 9 – Afterheat in fusion reactors. Note that immediately after shutdown, fusion reactor refractory metals generate considerably less heat than fission reactor fuel. $T_{irr} = \infty$ This is always true of V and Mo and true most of the time for Nb. Information from S. Blow[13] and D. Steiner.[63]