Engineering Feasibility of a Fusion Reactor

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FUSION TECHNOLOGY INSTITUTE

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Introduction

Preliminary design studies aimed at assessing the feasibility of producing power from fusion reactions have made considerable progress in the past few years. A number of groups have pursued the evaluation of various proposed devices. In particular the authors are members of a team organized at the University of Wisconsin at Madison which has been studying a system known as a Tokamak as a possible power reactor. While many of the problems are common to all approaches to achieving fusion power, we will restrict our comments to Tokamaks since these are the systems with which we are most familiar.

Rather than attempt a comprehensive discussion of all aspects of a power Tokamak which would be unduly long, this paper will present a brief overall description of the system followed by a more detailed discussion of four main problems which we regard as either particularly interesting or important for a Tokamak.

A Tokamak is a device which contains the fusion fuel in the form of a high temperature plasma in a toroidal region. In a Tokamak, the plasma acts as a single turn secondary of a transformer. It is a low beta device, which simply means that the kinetic pressure of the particles making up the hot plasma is small compared to the pressure associated with the confining magnetic field produced by suitable coils. As a laboratory device to study containment this is essentially all that is required, except for special start up equipment and necessary instrumentation.

The plasma in the power device is expected to be a mixture of deuterium and tritium. While deuterium occurs as a small fraction of the hydrogen in water, tritium does not appear in nature and must be produced by some nuclear reactions. The only practical reactions for this purpose are neutron reactions with the two isotopes of lithium. Since neutrons are produced in the fusion reaction between deuterium and tritium, the possibility exists of producing as much or more tritium that is consumed. This tritium production is usually referred to as the breeding of new fuel and calculations indicate that it should be possible to produce the replacement fuel required to operate the system. This requires that lithium in some form appear in the region surrounding the plasma in order to utilize the neutrons from the fusion process. The energy produced by the fusion reactions is partly absorbed in the plasma but most of it is carried away by the neutrons and by electromagnetic radiation to the first material wall of the system. This energy heats the walls and the lithium regions so that cooling is necessary, as with any other heat source. This cooling can be provided by the lithium itself either in the form of a liquid metal or as a constituent of a molten Li-Be-F salt. It is also possible to use helium as the coolant, in which case the lithium need be circulated only enough to remove the tritium that is being produced. The lithium bearing region in which most of the energy is deposited is referred to as the blanket. In order to keep the plant efficiency at a satisfactory level, it is necessary to use superconducting magnets to achieve the high magnetic fields required. This in turn demands a good radiation shield to prevent excessive energy deposition in the magnets which can cause either damage to the magnets or an excessive heat load to the cryogenic refrigeration system.

The power reactor will also need a number of auxiliary systems that are necessary to start up operation for fueling and in handling the exhaust, and for tritium recovery. Figure 1 shows schematically some of the regions and components described above. This is a cross sectional view and the plasma is located in the central region. The plasma is confined to a part of the total space within the first structural wall. A very low pressure sheath known as the divertor region occupies the volume between the plasma and the first wall. Collision processes in the plasma allow some ions and electrons to diffuse into the divertor region where they follow the magnetic field lines through the slots and into a wetted lithium wall from which both the energy and unburned fuel can be recovered. In the system shown here the coolant is liquid lithium which is also the fuel breeding medium. Behind this blanket is a shield which in a representative case, might consist primarily of steel with some boron carbide. The large "D" shaped region is one of the superconducting magnets and its dewar. Other features shown in the figure are the vacuum pumps at the ends of the divertor slots and the divertor coils which produce the fields that guide the particles through the divertor slots. These are the ends of the windings that are shown between the magnet "D" and the shield.

Operation of the system would begin with a gaseous fuel mixture in the confinement chamber. Windings in the central core of the torus are energized to induce a voltage in the fuel region which will ionize the gase and cause a current flow in the fuel. This heats the fuel and completes the ionization. The plasma may be further heated by injecting more fuel with particle energies that correspond to temperatures well above the ignition temperatures that is, well above the temperature at which heating of the plasma by fusion reactions exceeds the cooling by radiation losses and particle leakage. Since this injected fuel used for heating comes from outside the plasma the fuel atoms cannot be ionized if they are to cross magnetic field lines and reach the plasma zone. Therefore, outside the magnetic field, a fuel mixture is ionized and accelerated to high energy (>25 kev). This beam is then passed through a charge exchange cell which converts it to a neutral beam which can cross the magnetic fields and reach the plasma zone. The beam is, of course, ionized in the plasma by collisions which also distribute the energy of the beam. Beyond the ignition temperature of around 6 kev (a plasma temperature close to 50 x 10^6 degrees Kelvin), the alpha particles from the fusion reactions are sufficient to heat the plasma to a suitable operating point. The fuel and fusion product helium nuclei leak out into the divertor and are removed from the system, while the corresponding fresh fuel is continuously injected to replace the losses. Adjustments must be made in the system to create a steady state operating condition.

The four main problems to be discussed here are the following:

1) Those aspects of the plasma which are of particular interest and importance in a power reactor assuming that confinement of the plasma is assured from the results of the experiments currently being planned.

2) The materials problems anticipated are most severe in the first wall where the radiation and thermal environment is possibly the worst ever seriously envisioned for a real material. This problem poses the most serious challenge to the engineering feasibility of fusion power. 3) Induced radioactivity in the reactor components. As this is by no means negligible, it is important to have an early knowledge of the main features of the problem. 4) Finally, the largest contribution to the costs of a fusion plant is expected to be that of the very large superconducting magnets needed to produce the magnetic fields. The distinctive features of these units are discussed

Plasma Considerations

The important problems in plasma physics up the present have been concerned with confinement of the plasma, The work has been designed to eliminate unexpected instabilities and to establish basic loss mechanisms and rates. From our present point of view, plasma stability will be assumed and loss rates will be extrapolated on the basis of data presently available.

If a magnetic field level and confinement geometry and size are chosen which seem suitable and attainable, then one can work out the temperature and fuel density for a steady state operating point. This is obtained by finding the operating parameters for which energy insertion into the plasma fusion reactions from alpha particles products balances the losses by radiation, neutron transport, and charged particle leakage. With no impurities and confinement according to present scaling laws this occurs at a very low temperature,

(<10 kev ion temperature) or very high temperature (>50 kev) by fusion standards, and at relatively low fuel density. The result is to give a fusion power density which is so low as to be totally unacceptable, The reason is that a fraction of the fusion energy goes into the plasma and only as many fusion reactions can be allowed as the loss mechanisms of the plasma can balance. To obtain acceptable power levels, the loss mechanisms for removing energy from the plasma much be enhanced. This is most readily achieved by adding impurity atoms having a relatively high atomic number to the plasma. This increases the electromagnetic radiation from the plasma and allows the plasma temperature and density to increase. The result is an increase in the fusion rate needed to attain a new energy balance. The temperatures are now in a more acceptable range but this scheme gives rise to another problem. The fractional burn up of the fuel and the helium content of the plasma become too high (the large He content limits the amount of fuel which can remain in the plasma). To allow more fresh fuel to be added and to exhaust the system properly, confinement time must be reduced; that is, the mean confinement time of the particles must be reduced relative to that which is predicted by present plasma scaling laws. It may be possible to do this by introducing intentional flaws in the magnetic field. Thus by controlling the impurity concentration and the fields, the power level for steady state operation can be adjusted.

A knowledge of the necessary adjustments to obtain a desired operating point is only a beginning in controlling the system. One must have information about the thermal stability of the reactor. In the language of the reactor engineer, one must know the temperature coefficient of the power. A positive temperature coefficient results in an unstable operating point and will require a feedback control system for operation. A negative coefficient minimizes the control problem since any small perturbation of the power tends to be compensated for automatically. Our studies to date indicate that it is possible to obtain in many situations two operating points, one of which is stable and the other unstable, There are, however, some drawbacks to the stable operating point.

The unstable operating point typically occurs at an ion temperature of around 14 kev and this value is rather insensitive to the system geometry. The stable equilibrium point is usually at about 30-40 kev but this result is more sensitive to other reactor parameters. Generally, the cost per unit power produced will be greater for the stable than for the unstable point, often by a factor of two. In addition, it is not at this time evident that a negative power coefficient would make the control system appreciably simpler than would be required in the unstable case because the negative temperature coefficient is small. Thus, the choice of an operating condition is still open.

For an optimal system to be found in the sense that cost per unit power produced is to be a minimum for all acceptable plants, one must carry out an optimization study subject to a number of constraints imposed by the plasma and other parts of the system. For example, a Tokamak is a low-β device and requiring β to be lower than a specific value requires large (>40 kilograms) magnetic fields on axis. Other parts of the system also set limits on the maximum field attainable, such as the maximum radiation load to the magnets. The basic results indicate that the ratio of the major radius to the minor radius of the torus should be between 2 and 2.5, or as close to these values as possible subject to being able to put start up transformer coils and the main magnet windings in the central hole of the torus. The results show that, generally, one should use the largest magnetic field possible subject to the constraints that the power load on the first wall not exceed limits imposed by materials limitations. Fortunately, the cost per unit power is relatively insensitive to the trade off between maximum field and system size and this is the main degree of freedom available for optimizing. This allows the choice of magnetic field and major radius of the torus to be based on materials considerations with somewhat less economic penalties than might otherwise occur.

Requirements for Materials

Once the technical problems of confinement are solved, it will be necessary to design safe, efficient and economical reactor structures to convert kinetic energy of the plasma reaction products into heat. There have been many conceptual designs to accomplish these goals, but the materials requirements for all of these proposals can generally be categorized into the following five areas;

1. Satisfactory fabricability and high temperature mechanical properties.
2. Acceptable compatibility with the coolant.
3. Reasonable neutronic characteristics.
4. Satisfactory radiation damage resistance.
5. Acceptable costs and availability to U. S. markets.

Obviously, we cannot treat all of these areas in depth here and the reader is referred to reviews of these areas[1-3]. Let us touch on just a few points of each of the above areas.

The shear size of the neutron moderation and absorption region in fusion reactors requires that very careful attention be paid to minimizing the amount of structural material surrounding this zone. Also, the desire to lower the thermal discharge rates and to increase thermal efficiencies drives the operating temperature upward. The object will then be to find materials that have the best mechanical properties at the desired temperatures in order to reduce the wall thicknesses and hence, the total amount of material. Figure 2 shows some typical stress rupture values for materials that have been mentioned for controlled thermonuclear reactor (CTR) application. Typical stress levels of 10-20,000 psi will limit the useful operating temperatures to less than 650°C for 316 stainless steel, 800°C for vanadium and its alloys, 1000°C for niobium and its alloys and 1200°C for molybdenum and its alloys. Unfortunately, the best material from the standpoint of high temperature strength, molybdenum, has the worst fabrication characteristics. The best material from a fabrication standpoint is stainless steel. Both of these factors have to be weighed when contemplating the construction of a vacuum chamber which has an inner diameter on the order of the diameter of the fuselage of a 747 aircraft.

The chemical compatibility of the aforementioned materials with potential CTR coolants (i.e. lithium, helium or Li-Be-F Salts) is an important consideration. For example, Figure 3 shows the useful temperature ranges in which CTR materials can be used with respect to CTR coolants. The maximum temperature from a mechanical property standpoint is also given as a dashed line. Note that 316 stainless steel can be used up to its mechanical property temperature limit with lithium salts and helium, but that it must be limited to less than 500°C in dynamic (circulating) lithium. Both niobium and vanadium are extremely susceptible to interstitial impurity pick up at high temperatures. Thus, when using a helium coolant, if the oxygen level cannot be kept below one atomic part per million, then both vanadium and niobium cannot be used above 600°C. Molybdenum is not subject to this limit because oxygen is relatively insoluble in this metal. The situation improves when Li-Be-F salts are used raising the limit to 700°C in vanadium and 800°C in niobium, and 1000°C in molybdenum. Finally, all three of the refractory metals could be used close to their mechanical property temperature limits when lithium is used as a coolant.

The necessity for tritium breeding requires that the amount of parasitic neutron capture by the structural materials be minimized. It would also be advantageous if the structural material has a high (n,2n) reaction cross section to compensate for the nonproductive absorption of neutrons. These considerations tend to favor, in increasing order, stainless steel, vanadium, niobium and molybdenum. However, thus far the neutronic differences between the various materials have not been great enough to clearly favor any one material. The exceptions to this statement are radioactivity and after heat problems which will be considered later.

The most severe problems envisioned with CTR materials, namely radiation damage, is basically connected to the process of slowing down the 14 Mev neutrons. These neutrons lose energy to the atoms in the structure and coolant and these atoms in turn are propelled through the material displacing other atoms. In metals the vacant lattice sites remaining after the atoms are displaced have enough energy to migrate and collect into three dimensional aggregates called voids. These voids can cause the metal to expand and large volume changes may take place. The amount of swelling anticipated in one material, stainless steel,[4] is plotted in Figure 4 as a function of time for a reactor which has been recently proposed. Note that data is only available for five years of projected operation and various theories either predict a saturation of swelling at 15% or swelling that may approach 100% in 10 years. Not only will such expansions be difficult to control by themselves, the swelling gradients set up in the blanket between regions of different temperatures and neutron exposure will induce tremendous stresses. It is expected that all materials will show somewhat the same behavior, but there has been some recent evidence[4] that metallurgical treatments such as cold working could alter the final result. Vanadium-titanium alloys have also shown some swelling resistance.

There is perhaps an even more serious problem from a radiation damage standpoint and this is embrittlement. Figure 5 shows, again for 316 stainless steel in a particular reactor design, the variation of uniform ductility and yield strength expected during operation of a CTR. Unfortunately, experimental data[4] is again only available for the first 2-3 years of projected operation, but it does indicate that less than 1% uniform elongation can be tolerated after that time. The increase in yield strength is also quite dramatic in the first few years, but it will probably saturate thereafter at four time the unirradiated value. The main cause of the embrittlement is felt to be due to the helium generated by (n,α) reactions in the metals. The situation is particularly aggravated in a CTR as opposed to fission reactors because of the much larger gas production cross sections for 14MeV neutrons emitted from a D-T reaction. Niobium and vanadium have the lowest helium production cross sections of the materials considered for CTR application with stainless steel having the highest helium production cross section. Much more work is needed to clarify the role of helium in embrittlement before we can be sure that a CTR vessel will retain enough ductility over its lifetime to insure safe start up and shut down of the reactor.

The problem of material cost can be appreciated when it is realized that approximately 5000 metric tonnes of structural material alone will be required for the construction of 1000 MW plant (excluding the magnets). A large portion of this mass can be stainless steel because it will be at relatively low temperatures and in low irradiation fields. However, as much as 1000 metric tonnes per plant will be in the critical areas of the CTR where refractory metals might be used. Multiplying this by a thousand plants (to produce 33% of the projected electrical power in 2020) predicts requirements on the order of 10^6 metric tonnes.

Such numbers represent only 10% of the world's reserves of niobium, vanadium or molybdenum, but also represent 10 times the known U. S. reserves of niobium and vanadium. Fortunately, it is only 20% of the known U. S. supply of molybdenum. There are also concerns about the amount of chromium required for stainless steels; the U. S. has essentially no chromium reserves at its disposal.

It should be obvious from these figures that dependence on foreign suppliers for the structural material for energy sources is not much different than depending on them for fuel (i. e. oil). The associated national security and balance of payments problems should be closely examined. There are several problems which were not discussed here but which also present some possible limitations on the fusion reactor. These areas are charged particle and neutron sputtering of the wall facing the plasma, blistering due to helium injection from the plasma, degradation of electrical insulators in the blanket, swelling of non-metallic blanket and shield components such as graphite and B_4C, and radiation degradation of organic thermal and electrical insulation in the magnet, to name just a few. While the list is formidable, it is expected that it can be solved by properly conducted research programs.

In conclusion, there are many factors to consider in choosing materials for fusion reactors. Stainless steel, vanadium, niobium and molybdenum or their alloys are top candidates for structural materials and lithium, helium, or Li-Be-F salts are the most favored coolant materials. No particular metal or coolant combination has been shown to be far superior to any other in all of the required areas.

Afterheat and Radioactivity

In addition to the changes in physical properties of the reactor structure induced by the neutrons from the plasma, these neutrons may also induce radioactivity. In addition, the tritium produced from the lithium is radioactive. The magnitude of this radioactivity must be assessed since it bears upon the accessability of the plant for maintainance, presents a potential hazard should it be released, and if present in any quantity leads to an after heat which must be dissipated by the plant after the plasma is extinguished.

Regardless of the material chosen for the structure there are some quite general comments which may be made. The energy of the primary neutrons is quite high being approximately 14 MeV and nearly monoenergetic (the source neutrons from fission have a broad energy distribution with an average energy of approximately 2 Mev). Neutrons of this energy are above the threshold for many of the charged particle reactions, e. g. (n,α), (n,2n) (n,p), which must be considered in addition to the (n,α) reactions which are the most numerous reactions in a fission system. While the fuel is changed in a fission system about every three years, the structure in a fusion system may remain in use for up to twenty years. Thus the isotopes produced by successive capture of neutrons may also be important. These isotopes may not make a large contribution to the initial radioactivity, but if they are long lived they may be important in terms of long term storage and disposal of used structures. Also the volume of a fusion plant will be quite large so that while the power from radioactive afterheat may be significant the power density may be low. To obtain an appreciation of the complexity of the situation if a stainless steel system is considered with all minor alloying elements and impurities ignored and only captures in the isotopes originally present considered, the transmutation cross sections for a minimum of four reactions and the associated decay schemes must be known as a function of neutron energy for each of fourteen different isotopes leading to approximately three times as many daughter nuclei.

Steiner has considered the problem for the fusion system developed at Oak Ridge National Laboratories.[5] Since the calculations are dependent on the specific reactor design we have repeated them for the system proposed at Wisconsin and extended them to include stainless steel as a structural material. This reactor which was designed with a 316 stainless steel structure, operates at a power of 1000 MW thermal. As mentioned previously the volume of the system is quite large there being 1000 metric tonnes of structure in the blanket alone. The calculations reported here are for an operating time of 10 years and the radioactive decay is followed for 200 years after shutdown. Since cross section information is not available for most of the product nuclei, neutron reactions with the radioactive product nuclei were not considered. Thus these calculations represent a lower limit on the radioactivity but should still yield representative values.

The results are shown in Figure 6 in terms of the energy deposited by gamma and beta radiation as a percentage of the power prior to shutdown. The decay heat at shutdown is approximately 0.7% dropping rather slowly to a factor of ten lower in about two years. At long times after shutdown the residual activity is due to ^{63}Ni with a half life of 92 years. However, at these long times this activity has decayed sufficiently that long half lived isotopes from neutron capture in impurities could be important and must be considered in developing the complete picture. In further looking into the source of the decay heat it is found that approximately 50% comes from the wall between the plasma and blanket regions and that this fraction remains roughly constant with time.

To get some comparison, a fission reactor would have an initial decay heat about one order of magnitude larger. This would fall off somewhat more rapidly with time, but because of the long lived unstable fission products, the activity would be greater than for a comparable fusion reactor at long times. The results may also be expressed in terms of Curies of radioactivity per megawatt prior to shutdown and these results are shown in Figure 7 (1 Curie represents 3.7×10^{10} disintegrations /sec). The initial activity is about 1 M Curies/MW with the first wall contributing about 50%. After 200 years the activity is due to ^{63}Ni and has dropped to 0.217 Curies/MW. Because of the large mass involved this corresponds to a specific activity in the first wall of only 0.017 milli-Curies/cm^3 for this particular design.

Stainless steel is not the only material which has been suggested. In particular both niobium and vanadium are potential candidates offering the possibility of higher operating temperatures than stainless steel. The after heat and radioactivity were calculated for both these systems assuming a direct substitution of materials. The after heat and radioactivity for a niobium system are shown in Figures 6 and 7. It is seen that the initial after heat is about the same as for stainless steel but the initial drop off is somewhat more rapid coming down an order of magnitude in about 20 weeks. The long lived activity in niobium however is dominated by ^{94}Nb with a half life of 2×10^4 years and thus niobium will have greater after heat than stainless at very long times. The radioactivity curves show somewhat the same behavior.

The after heat and radioactivity curves for vanadium are also shown in Figures 6 and 7. Vanadium shows a somewhat higher after heat but drops off very rapidly coming down an order of magnitude in about two hours. The long lived activity in this case is ^{51}Cr with a half life of 28 days so that after only 10 weeks the decay heat is down four orders of magnitude. Certainly in this case the after heat at long times will be dominated by radioactive products of alloying elements and impurities. The radioactivity curve shows a similar behavior.

In summary it is found that because of the high energy neutrons produced in the fusion process the structure in the immediate vicinity of the plasma will become radioactive. The decay heat will not be excessive and should present no particular problems when considering loss of coolant. The radioactivity levels are quite significant and may be rather long lasting although the half lives for stainless and vanadium especially appear to be shorter than those of residual fission products. This will present problems in shielding and access to the reactor and maintenance will have to be remote. Provision will have to be made for the long term storage of used material and for preventing the dispersion of radioactivity released through corrosion.

Magnets

The confinement of plasmas by magnetic fields requires the use of superconducting magnets. Such use is far from routine since the magnets envisioned involve the new technology of superconductivity in which the conductor has zero resistance at temperatures near absolute zero. In this case we must consider extrapolations from a 100 ton magnet, the largest in present use, to 20,000 tons; or extrapolations to magnets larger by two orders of magnitude. Below are considered some of the engineering problems which cause these huge magnets to be the most expensive part of the reactor system.

An electromagnet is a pressure vessel with the force on each segment of current equal to I x B, where I is the current and B the magnetic field. Since B is caused by I the internal pressure is proportional to B^2 and can be scaled from 5800 psi at 100 kilogauss. The magnet for the reactor discussed earlier is of the constant tension design in which the local radius of curvature of the conductor and support structure is varied so that the tension in the structure remains the same.[6] The average tensile stress is

$$\sigma = p \frac{R}{t} \frac{1}{\lambda}$$

where p is the local magnetic pressure $\frac{B^2}{2\mu_o}$, R is the radius of curvature, t the structural thickness and λ is the structural space factor.

For example, in Figure 8 at r = 17.5 m, if the average stress for low temperature stainless steel is limited to σ = 24,00 psi, p = 794 psi (37 kilogauss), λ = 0.23 and R = 8.75m then t/R = 0.14. Thus the steel thickness is 1.25 m as shown in Figure 8 and the steel therefore weighs 7,600 metric tonnes. For magnets this size or larger the structural material completely dominates the weight and cost.

It can be shown[7] that the structural mass required to contain a magnetic field must satisfy

$$M \geq \rho \frac{E}{\sigma}$$

where E is the total energy stored in a magnetic field, ρ is the structure density and σ is the average working stress of the structure. For stainless steel at 48,000 psi this amounts to about

0.18 lbs/watt hr. magnetic energy

as the unavoidable minimum structure. We have mentioned stainless steel because it is a face-centered cubic metal which does not become brittle at low temperature. If the support structure could be at room temperature then ordinary carbon steel could be used at less cost.

The second most important design problem is the conductor choice. A composite superconductor-normal metal conductor supplies three functions for the operation of a magnet. First, the superconductor carries the transport current in a lossless fashion. The alloys of Ti-Nb are the best choice for use up to 86 kilogauss at 4.2°K and can be extended to 100 kilogauss by operation at lower temperatures. Second, the normal metal part of the conductor must be able to carry the current even when the superconductor has been driven normal. Copper, which is usually used, must be sized to carry this current without allowing the temperature to increase above the critical current for the Ti-Nb. In this way recovery to the superconducting state is possible. The third function of the conductor is to carry its unavoidable fraction of the mechanical load without deleterious effects on itself, the superconductors, or the insulator between the conductor and the steel support frame.

The composite conductor is mechanically in parallel with the steel structure and must experience the same strain. We would like to keep the copper strain below 0.001, the nominal yield point at 12,000 psi for OFHC copper. If copper is allowed to yield then its electrical resistance increases and mechanical hysteresis results, the latter accounting for additional helium colling losses. While neither effect is disastrous it is better to avoid yielding if possible. The superconductor is usually subdivided into many small filaments inside the copper matrix and is subject to breakage if excessive strains are allowed. While attempting to justify a design which limits the strain on the composite conductor we must admit that our allowed strain is subject to later adjustment. However, we propose a scheme[6] which uses the 304 stainless steel support to its yield point without yielding the copper so there is no need to consider yielding the copper. The steel forms would be solid forgings which can be stretched radially while the copper conductors are epoxied in grooves; after which removal from the winding fixture will relieve the tension in the steel and compress the copper to -12,000 psi. Under magnetic loading the prestressed copper can be carried from -yield to +yield by absorbing 24,000 psi load while at the same time steel will absorb 48,000 psi since its modulus is twice that of copper. Stainless steel yields at 60,000 psi at low temperature; therefore it is prudent to design to 48,000 psi since there is no recovery possible from structural yielding.

The 13,400 metric tonne magnet structure can be cooled in three stages, following Purcell's [8] example with the 12 ft. bubble chamber magnet at Argonne and the 15 ft. magnet at the National Accelerator Laboratory. The magnet will be divided into 12 sections or modules each with its own one kilowatt liquifier at 4°K. The following numbers are given for one section. The rate of heat extraction during cooldown must be limited to 60 KW due to differential stresses caused by contraction. The first stage cooling lasts 16 days, requires 300,000 liters of liquied nitrogen which exchanges heat with circulating helium gas and reduces the temperature to 115°K. The second stage cooling is accomplished by operating the liquifiers as refrigerators. The temperature can be brought down from 115°K to 20°K within 9 days. Fifteen thousand liters of liquid helium will be added to drop the temperature to 4°K and fill each module dewar with helium. The operating capacity of each liquifier is 1200 liters per hr. of which

900 liters per hr. is available for removal of the neutron and gamma ray heat load. Compromise designs will consider the trade-off between shield thickness, radiation heat load and cool down rate all of which affect the choice of refrigerator size.

Following the 30 day-cool-down the current is brought up to 10,000 amperes with a 100 volt power supply. Charging requires 4 days for the 2600 henry inductance at 100 volts. Low voltages are desireable so that cryogenic insulation between the conductors and the steel backing can be simple. An occasional short is tolerable for low voltage systems. Turning off the total magnet, warming up a magnet section, recooling and recharging add up to a 64 day turn around time for repair or replacement of parts.

Summary

In the context of examining the feasibility of using a large Tokamak device in a fusion power system we have briefly discussed four areas inportant to the system. It should be emphasized that we are a long way from being able to design a power reactor. In looking at these areas we find that while the problems are real and challenging there does not appear to be any reason why they cannot be solved. The materials problem may be an exception but even here a combination of ingenuity and additional data from a well thought out research program can be expected to resolve the issues.

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FIGURE CAPTIONS

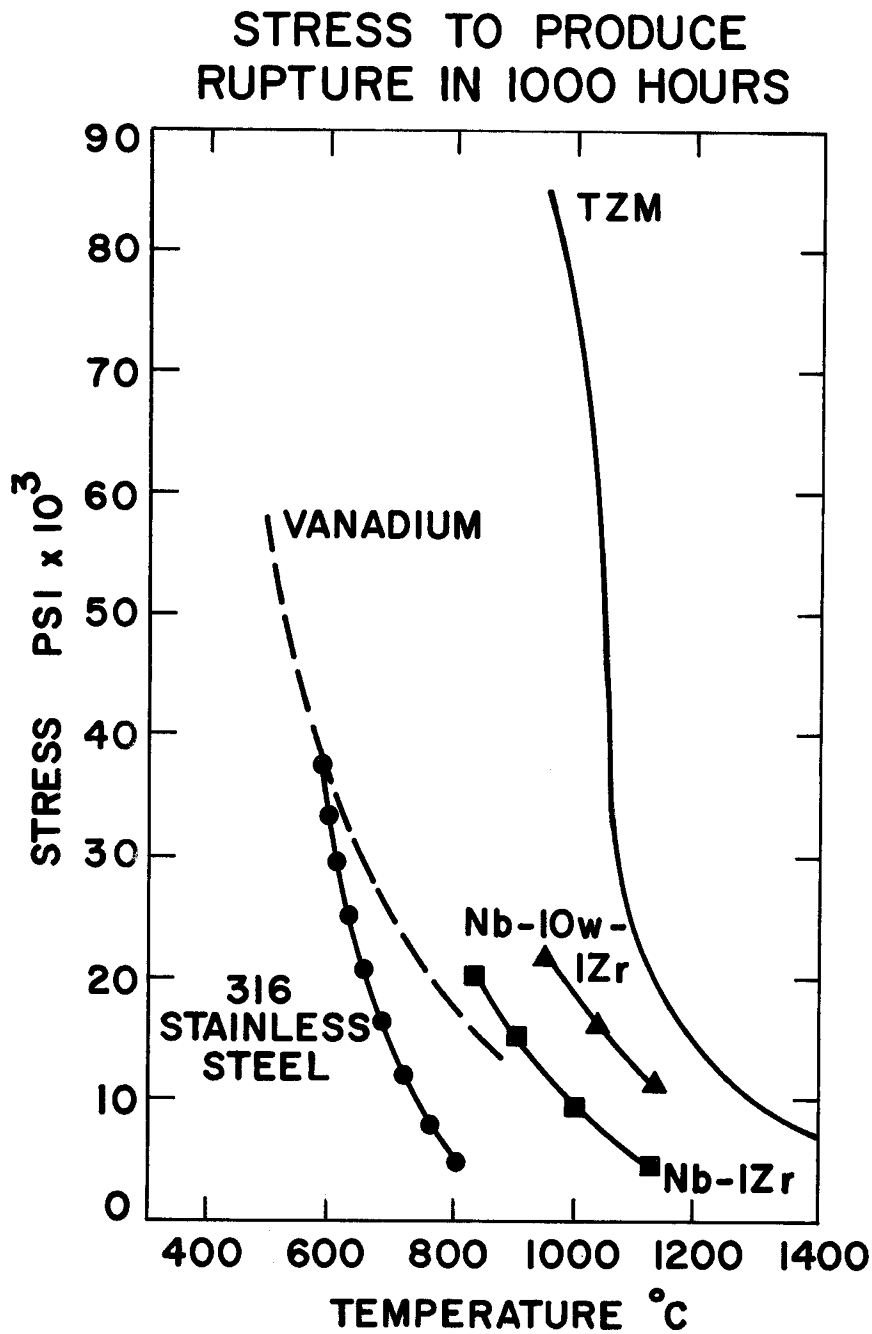

FIGURE 2 - Stress Rupture Values for Possible Fusion Reactor Materials

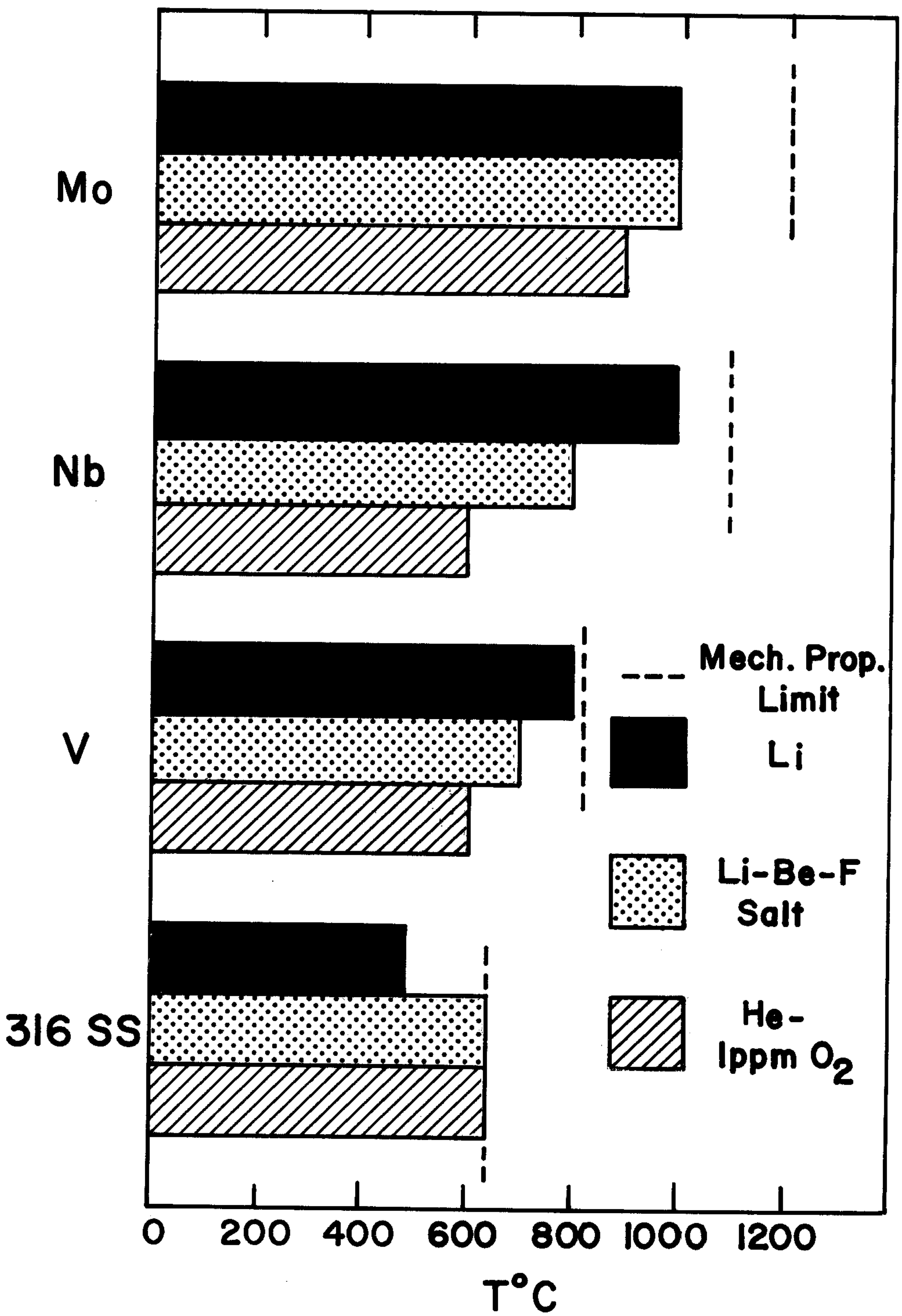

FIGURE 3 - Useful Temperature Ranges of Fusion Reactor Materials in the Presence of Possible Coolants

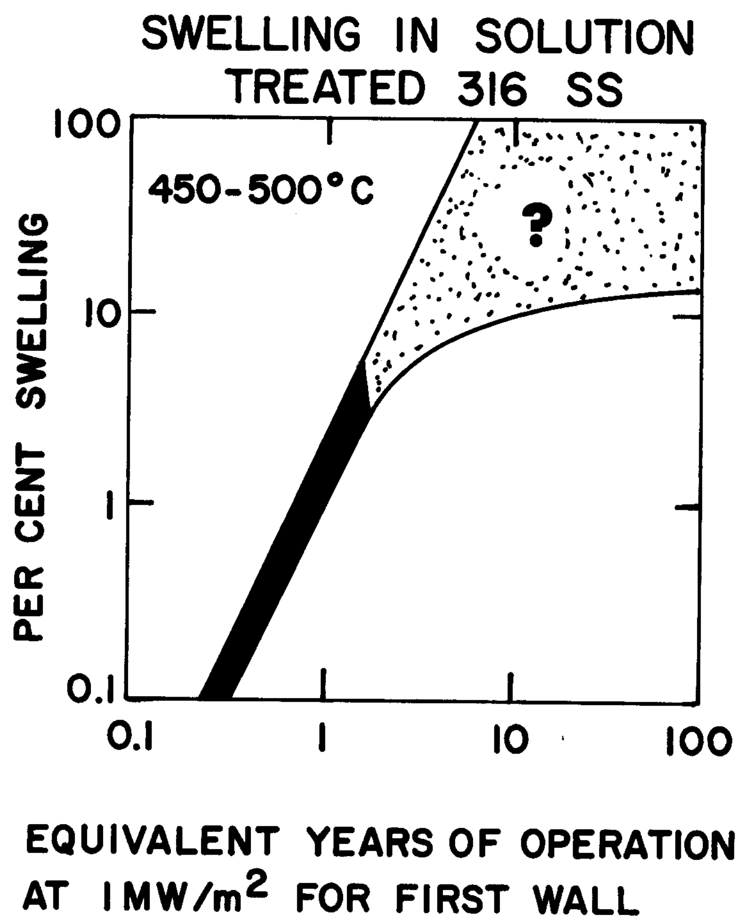

FIGURE 4 - Anticipated Swelling of 316 Stainless Steel with Time in a Fusion Reactor. Dark Area Represents Available Data.

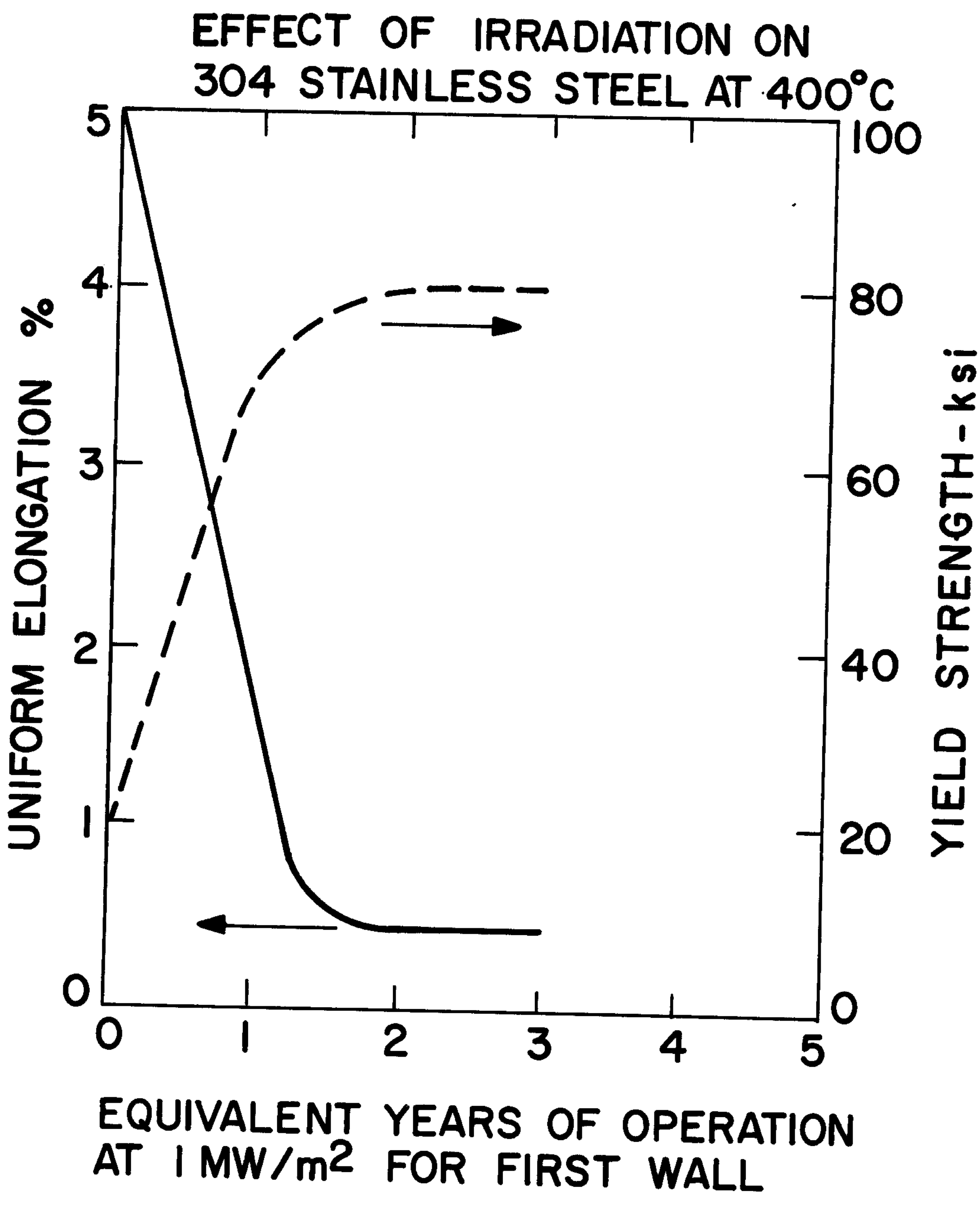

FIGURE 5 - Variation of Uniform Ductility and Yield Strength of 304 Stainless Steel with Time in a Fusion Reactor

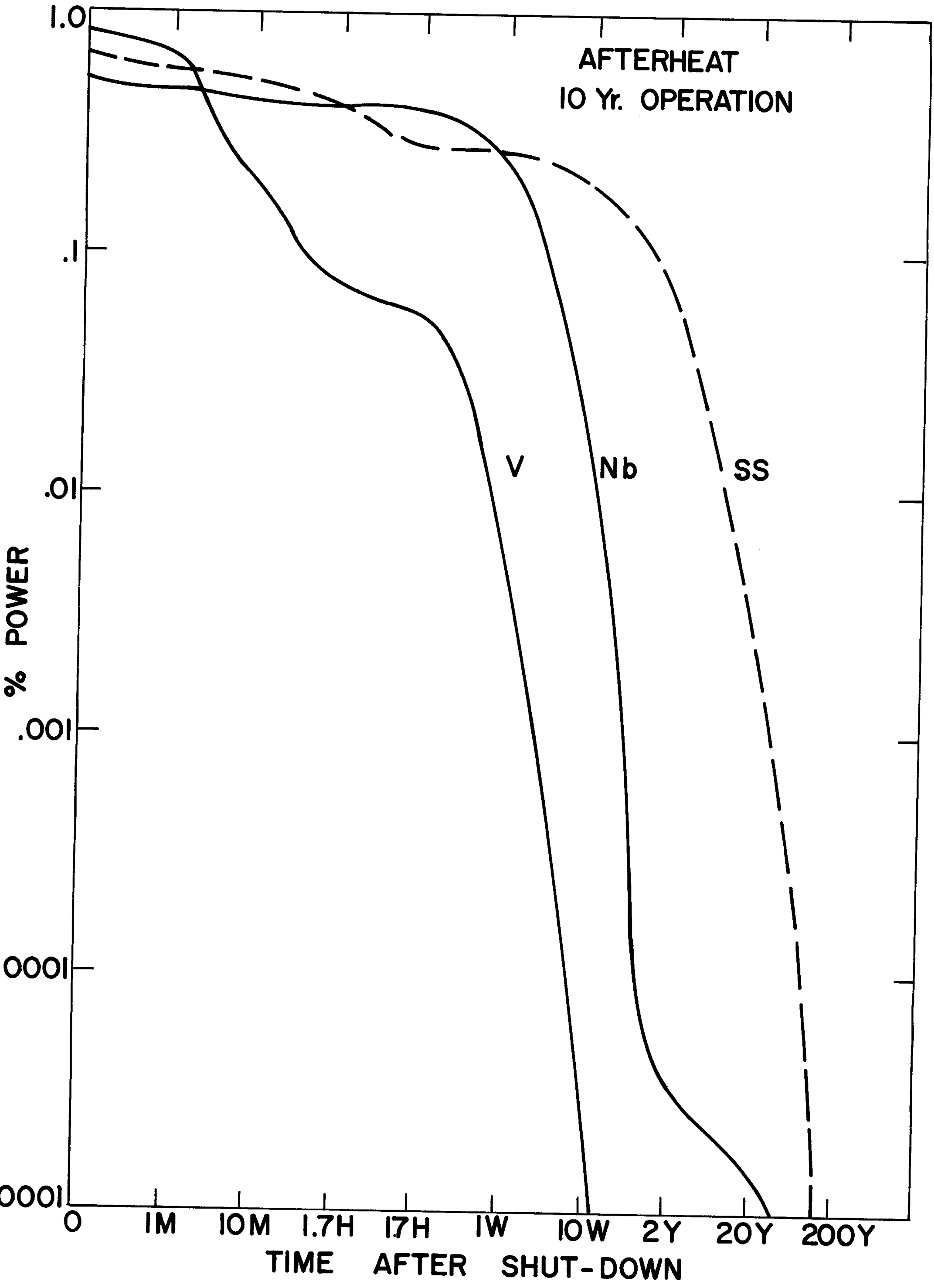

FIGURE 6 - After Heat Following Shutdoen of a Tokamak Fusion Reactor

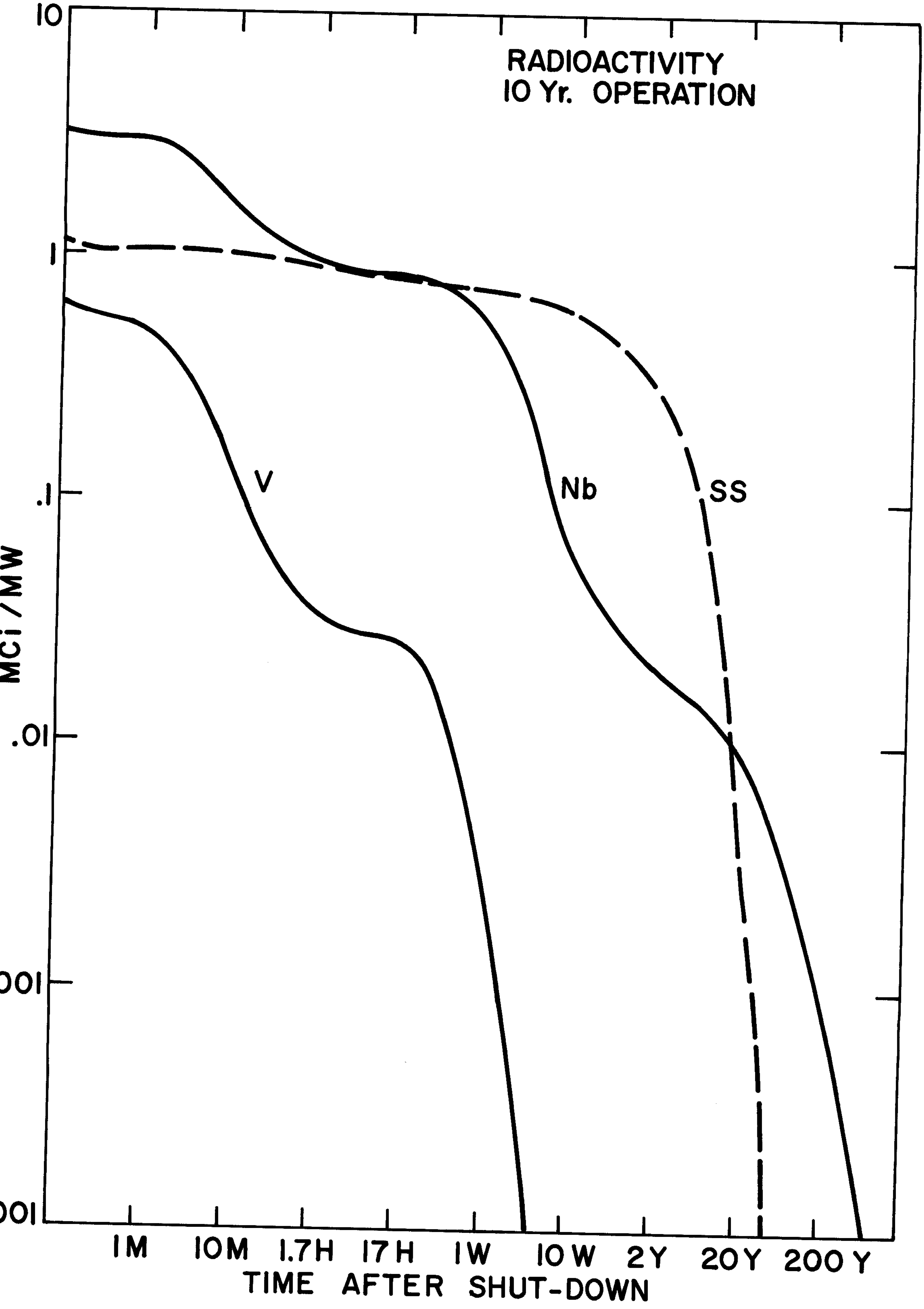

FIGURE 7 - Radioactivity Following Shutdown of a Tokamak Fusion Reactor

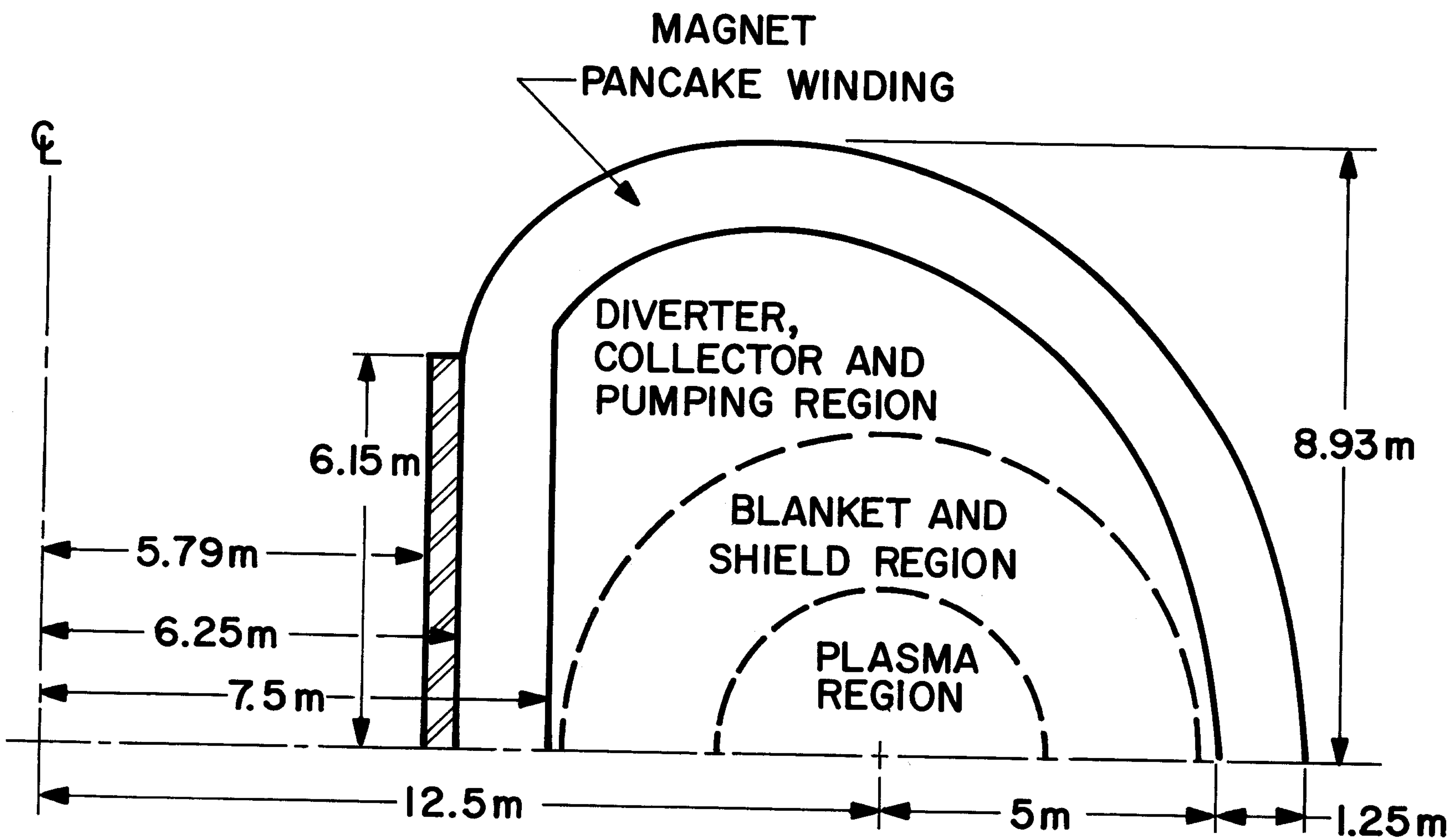

FIGURE 8 - Toroidal Magnet Cross Section