NUWMAK - A Tokamak Reactor Design Study

Chapter I (Design Philosophy)
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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

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A TOKAMAK REACTOR DESIGN STUDY

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I. DESIGN PHILOSOPHY OF NUWMAK

In many ways, the design of NUWMAK has been guided by the detailed understanding of tokamak reactor problems developed in earlier studies. The aim in NUWMAK has been to confront these key problems and to develop improvements or innovations to offset previously identified difficulties. In many (although not all) areas, such innovations or improvements have been achieved. We begin with a discussion of the key issues which confront the tokamak concept as a reactor and indicate the design approach developed in NUWMAK to deal with these issues. The design philosophy has therefore been to step back, to examine the key difficulties identified in earlier studies, and to develop solutions. The aim is to search for an end product that has the potential to be reliable, maintainable, environmentally acceptable, and reasonably economic.

I-A. PHYSICS DESIGN PHILOSOPHY

I-A-1. POWER DENSITY

The average power density in a fusion reactor is proportional to $\beta^2 B^4 S^4 f(T) g_{n,T}$ where β is the plasma beta, B is the magnetic field, S is the plasma shape factor (1 for a circle, greater than 1 for noncircles), f(T) is a function of temperature, and $g_{n,T}$ depends on the profiles of plasma density and temperature. In general, reactor costs decrease with increasing power density and in NUWMAK, we have chosen a modest total beta, ~ 7%, and a high magnetic field on axis (6T) (to provide a margin of safety against uncertainties in physics). The shape factor has been optimized using MHD calculations and a plasma height to width ratio of 1.6 has been chosen. The design philosophy has been to increase the power density by increasing the magnetic field and with this approach, the power density in the plasma in NUWMAK is ~ 10 W/cm^3. This can be compared with the power density in earlier designs which ranged from 0.5 to 2 W/cm^3.

I-A-2. IMPURITY CONTROL

The control of impurities in the plasma is key to long burn operation as well as to startup itself. A magnetic divertor is one approach to impurity control but our own and other earlier tokamak studies showed that the addition of a divertor significantly complicates reactor design, often increases the size of toroidal field magnets, and makes access and maintenance difficult.

The design philosophy in NUWMAK has been to simplify design and improve access and maintenance. We have thus developed for NUWMAK the concept of periodic gas puffing plus density-temperature profile control to simultaneously fuel the plasma, keep impurities from diffusing to the center, and maintain a sufficient impurity mantle to radiate heat that has been conducted from the plasma center. We find that such an approach has many advantages for the overall reactor design. There remain, however, key areas of uncertainty related to details of plasma transport and pumping of both recycled gas and particularly helium. This makes it difficult to conclude that the concept is feasible and further study is required.

I-A-3. DUTY FACTOR AND TIME BETWEEN BURNS

One clearly would like a steady-state burn in a fusion reactor. If this is not possible, as it may not be in a tokamak, the next feature required is a short time between burns to minimize thermal fatigue and the energy storage required to level the electrical output load. We have achieved a short time between pulses in NUWMAK (~ 15 seconds) by several techniques including a partial overlap of the current rise and RF heating phases. The duty factor is high at 0.91. In addition, a phase change blanket concept has been developed which minimizes thermal fatigue in the blanket; we will discuss this shortly.

I-A-4. HEATING

It is desirable to have an efficient plasma heating source which requires minimum access and minimum shielding. This has led in NUWMAK to the choice of RF heating at $2\omega_{CD}$ (90 MHz) using a resonant cavity located in the shadow of the limiters on the outside first wall. RF feed coaxial cables can be curved to avoid line of sight to the sources. The wave guides are constructed of V-5 Ti and are water cooled.

I-B. MAGNET DESIGN PHILOSOPHY

I-B-1. TOROIDAL FIELD MAGNETS

All earlier designs of tokamaks have a relatively large number of TF coils ($\geq$ 16) which make access difficult but which provide an acceptably small magnetic field ripple. In NUWMAK, our design philosophy is to increase access space for maintenance and other components and to accomplish this, a new approach to magnet arrangement has been developed. In essence, only a small number of primary superconducting toroidal field magnets are used (8 in NUWMAK). Access space between coils then becomes large (greater than 5 m). The field ripple is corrected with saddle coils that do not add net toroidal field. These coils are water cooled copper magnets and are located at the back of the outer blanket. They need not encircle the vacuum vessel poloidally because the field ripple is small nearest the centerline and increases in amplitude as one moves out radially. The power consumption of these coils is modest ($\sim$ 25 MW) and the improvement in access is great.

We also required in NUWMAK some additional magnetic field strength relative to earlier designs to provide a safety factor against physics uncertainties. The field on axis is thus chosen to be 6T and the peak field at the coil is then 12T. The basic design philosophy for such large high field coils is that they be fully cryostable with a reliable solid structure to avoid magnet instability. There are two technically feasible ways to design high field ($B \sim 12T$) superconductive coils. One is to use NbTi superconductor at reduced temperature ($T \sim 1.8$ K) in order to have a reasonably high current density in the superconductor at the required high field. The other is to use Nb_3Sn as the superconducting material at 4.2 K. The primary design of the TF coil uses NbTi superconductor and subcooled superfluid liquid helium at 1.8 K and atmospheric pressure. The reason for these choices is that NbTi is a ductile superconductor and superfluid helium has excellent heat transfer characteristics. As an optional design, Nb_3Sn superconductor is used in pool boiling 4.2 K liquid helium. However, there is no experience in the use of either option for large magnets at the present time.

A design philosophy in NUWMAK has been to develop a highly maintainable, accessible design. The absence of a poloidal magnetic divertor allows us to minimize the number of vertical field coils inside the main TF coils. There are only four magnets inside the TF coils and these are cryogenically cooled, normal aluminum coils. They have relatively easily made joints and any slight resistive heating at the joints will not be detrimental to coil operation. The approach is consistent with the overall design philosophy that provision be made to remove and replace a TF coil in case of failure. (A TF coil need <u>not</u> be removed for blanket replacement.)

I-C. BLANKET DESIGN PHILOSOPHY

Most of the unusual problems associated with a tokamak blanket arise from the special characteristics of the tokamak D-T reactor. These special characteristics are:

a. Cyclic behavior of the plasma

b. Tritium breeding and confinement

c. Non-uniform energy distribution

d. Complicated geometry.

The blanket design developed for NUWMAK is aimed at minimizing problems associated with the above characteristics while being inexpensive, fabricable, maintainable, and providing adequate thermal efficiency. Through this new design, we have minimized thermal cycling in the bulk blanket structure, eliminated the need for both an intermediate loop and thermal energy storage in the power cycle, and developed a double-walled tube design for added reliability and minimum tritium diffusion into the coolant. Relatively low temperature operation (300-350^{o}C) has been incorporated to extend first wall lifetime. Boiling water cooling is chosen to further minimize thermal cycling and to permit the use of the well established Boiling Water Reactor (BWR) power cycle.

The blanket utilizes the Li-Pb eutectic (62% Li, 38% Pb) as the tritium breeding and thermal energy storage material. The eutectic melts at 464^{o}C and operates in two phases within the blanket. During the down part of the burn cycle, the latent heat of fusion provides the requisite energy to maintain a constant electrical output. It also means that essentially the same heat flux is incident on the cooling tubes so that there is little temperature cycling. The tritium breeding ratio is more than adequate (~ 1.5) without breeding in the inner blanket and the total energy per fusion is acceptably high at 20.6 MeV per fusion event. The Li-Pb eutectic has other important advantages related to safety such as the fact that Li-Pb is relatively inert with respect to its interaction with water and air.

I-D. STRUCTURAL MATERIAL

The materials selection in NUWMAK is influenced by the design philosophy in other areas and by the desire to develop a reactor design with a long structural lifetime at a high neutron wall loading. The material must be compatible with various coolants and there should be a well established U.S. industrial capability.

For NUWMAK, we have selected the titanium alloy Ti-6Al-4V on the basis that it is easily fabricable and has high strength, high strength to weight ratio, excellent fatigue life and resistance to corrosion, low He production from neutron reactions and no observed void swelling as yet. The material is inherently nonmagnetic, there is a well established industry, and all the major alloying constituents are abundantly available in the United States. There are, of course, problems related to a limited operating temperature range (~ 300-450^{o}C), a very low thermal conductivity, cost, and hydriding if the temperature falls below 300^{o}C.

I-E. MECHANICAL DESIGN, ASSEMBLY, AND MAINTENANCE

The design philosophy in NUWMAK has simply been to make mechanical design and maintainability easier. The decision not to employ a poloidal divertor has led to a considerably simpler shape and mechanical design of the now compact and streamlined plasma chamber. The use of RF heating means that the launching structure becomes part of the first wall. The source and power supplies can be placed well away from the main reactor components and so are much less constrictive than are neutral beam lines and their accessories.

In the past, providing the vacuum seals between blanket modules has been one of the most difficult mechanical design problems. It is agreed that the only seal which will survive the harsh environment near the first wall is a weld. Consistent with the NUWMAK design philosophy, no seals are used between blanket modules and blanket modules are supported on rails fixed to the shield. The vacuum seals are made at the back of the shield where the seals are both accessible and maintainable. The support rails are used to guide the blanket modules during maintenance and blanket replacement.

Maintainability has been a key design philosophy behind many decisions relating to plasma chamber shape, impurity control, magnet system design, and plasma heating mechanism. Earlier studies of remote maintenance have shown that early conceptual reactors would be virtually impossible to maintain. In NUWMAK, design simplicity has been achieved, the size and weight of blanket modules has been sharply reduced (weight per module is ~ 10 tonnes of structure and reflector), access has been sharply increased, several levels of modularity have been introduced, and a maintainable design for the ohmic heating and vertical field magnet systems has been developed.

Design simplicity has been achieved both in blanket design and in access. Provision has been made for the rapid removal of vertical field coils and those coils inside the TF magnets are normal coils with joints. Space is provided around the nuclear island to allow ready access for maintenance vehicles and the number of coolant connections has been minimized. The blanket modules can be removed individually and constitute one level of modularity. In addition, the TF coils are supported from the floor rather than from a central support column so that a reactor segment, including blanket modules, shield, and one toroidal field coil can be removed. There are eight such segments at the next level of modularity. The design philosophy is that while blanket replacement is likely, the TF coils should have a lifetime exceeding plant life. Therefore, this second level of modularity involving the removal of a TF coil is not treated as a scheduled maintenance procedure.

Finally, it is crucial to the development of a maintainable tokamak concept that a design be developed which permits access and maintenance of components in the central core of the torus. A key issue is the maintainability of the ohmic heating coil system. In NUWMAK, a design approach is developed in which the OH coils are divided into two groups, one serviced from the top, the other serviced from the bottom. The separation between the upper and lower sets can be used to join a bucking cylinder (which takes up centering forces on the TF coils) to the central column. While this approach requires further development, it shows that the central core can be maintained in a reasonable way.

I-F. RESOURCE REQUIREMENTS AND ECONOMICS

The philosophy in NUWMAK has been to develop a tokamak reactor design which minimizes the impact of fusion on mineral resource requirements and has the potential to be economically attractive. Earlier studies based on the use of stainless steel led to the conclusion that chromium and nickel resources would be strongly impacted by fusion, particularly because U.S. resources in this area are inadequate even today. Other problem areas related to the use of Be and to the use of lithium as a coolant as well as a breeder. In this case, lithium metal fills not only the blanket but also the entire primary coolant circuit. The use of Ti-alloy reactor structure and high strength aluminum magnet structure, as well as increasing the power density of the reactor, has led us to the conclusion that the NUWMAK reactor design appears to place no significant burden on the materials used. The U.S. resource picture for all the materials employed is good except for Nb, W and Co.

As for economics, the aim has been to determine if tokamak reactor costs could potentially be competitive with other long term energy sources. The design philosophy has, therefore, been to increase the system power density, to employ moderately priced structural materials, and to develop design concepts which would allow the elimination of previously large cost items (e.g., a thermal energy storage unit in the power cycle). An economic analysis based upon a standardized format indicates a constant dollar (without inflation) electricity cost of approximately 35 mills/kWh for a NUWMAK type unit in 1978 dollars. Further, NUWMAK is designed to produce about 650 MWe. Advanced fission reactors are currently being designed and built in the 1100-1500 MWe range. For fusion reactors, there is every reason to believe unit costs will decrease with increasing plant size although this conclusion has not been established in the NUWMAK study.

II. OVERVIEW AND SUMMARY OF THE NUWMAK DESIGN STUDY

II-A. INTRODUCTION

The first generation of tokamak reactor designs[1-4] were aimed at providing a quantitative understanding of fusion reactor problems and identified those which are most important. In addition, quantitative analytic tools for different subsystem's performance were developed and these have proven to be especially useful in subsequent parametric studies.[5,6] The designs themselves provide a basis for beginning the development of more highly optimized reactor systems.

NUWMAK is part of a second generation of conceptual tokamak designs[7,8] aimed at maximizing the strengths of fusion while minimizing its weaknesses. Those strengths include an inexhaustible fuel supply, controllable levels of induced radioactivity, potentially advantageous safety and environmental features, and the fact that it is one of perhaps only three truly long term sources of electric power generation. On the other hand, the weaknesses of fusion include complex geometrical arrangements, complex access and maintenance procedures, a relatively low power density, and the apparent need or desire to combine a number of advanced technologies. These considerations were important motivating factors in developing the NUWMAK design. The key features of the design are presented in Sec. II-B, additional aspects are described in Sec. II-C, and a summary with comments is given in Sec. II-D. The relationship between NUWMAK and near term tokamaks such as TFTR (the Tokamak Fusion Test Reactor), is also discussed in the last section.

II-B. KEY FEATURES OF THE NUWMAK DESIGN

The major parameters characterizing the NUWMAK design are listed on Table II-B-1, a top view of the machine is shown in Fig. II-B-1, and a cross section view is given in Fig. II-B-2. The machine is small (major radius, 5.13 m) for the net power generated (660 MW_e) and has a high value of plasma power density (10 MW/m^3) and average neutron wall loading (4 MW/m^2).

II-B-1. THE TOROIDAL FIELD MAGNET DESIGN

The NUWMAK toroidal field system design is unique and consists of just eight superconducting coils (see Fig. II-B-1) supplemented by sixteen normal, water cooled, copper trimming coils. The trim coils do not add net field but lower the field ripple to less than 2% on the midplane at

Table II-B-1 NUWMAK Design Characteristics

Net Electric Power	660 MW_e
Gross Electrical Power	725 MW_e
Thermal Power	2097 MW_t
Net Efficiency	31.5%
Availability Factor	80%
Major Radius	5.13 m
Plasma Radius, a	1.13 m
Plasma (b/a) nominal	1.64
Plasma Current	7.2 MA
Toroidal Beta	6%
$n_e\tau_E$ (cm^{-3}-s)	2 x 10^{14}
q(a)	2.6
Axial Toroidal Field	6.05T
Plasma Heating Method	RF
RF Frequency ($2\omega_{CD}$)	92 MHz
RF Power to Plasma	75 MW

Structural Material	Ti-6Al-4V
Coolant	Boiling Water
Coolant Temperature	300°C
Coolant Pressure	8.6 MPa (1250 psi)
Breeding Material	$Li_{62}Pb_{38}$ Eutectic
Melting Point of $Li_{62}Pb_{38}$	464°C
Max. Structure Temperature	500°C
Max. Coolant Wall Stress	103 MPa (15 ksi)
Ave. Neutron Wall Load	4 MW/m^2
Tritium Breeding Ratio	1.54
Lithium Blanket Inventory	4 x 10^4g
Tritium Extraction Method	Molten Salt
Blanket Tritium Inventory	800 g
Toroidal Field at Conductor	11.94 T
Superconductor	NbTi
Stabilizer	Al
Conductor Current Density	6900 A/cm^2
S/C to Stabilizer Ratio	1:60
Energy Stored in Field	30 GJ
Number of TF Coils	8
Number of Cu Trim Coils	18

TOP VIEW OF NUWMAK

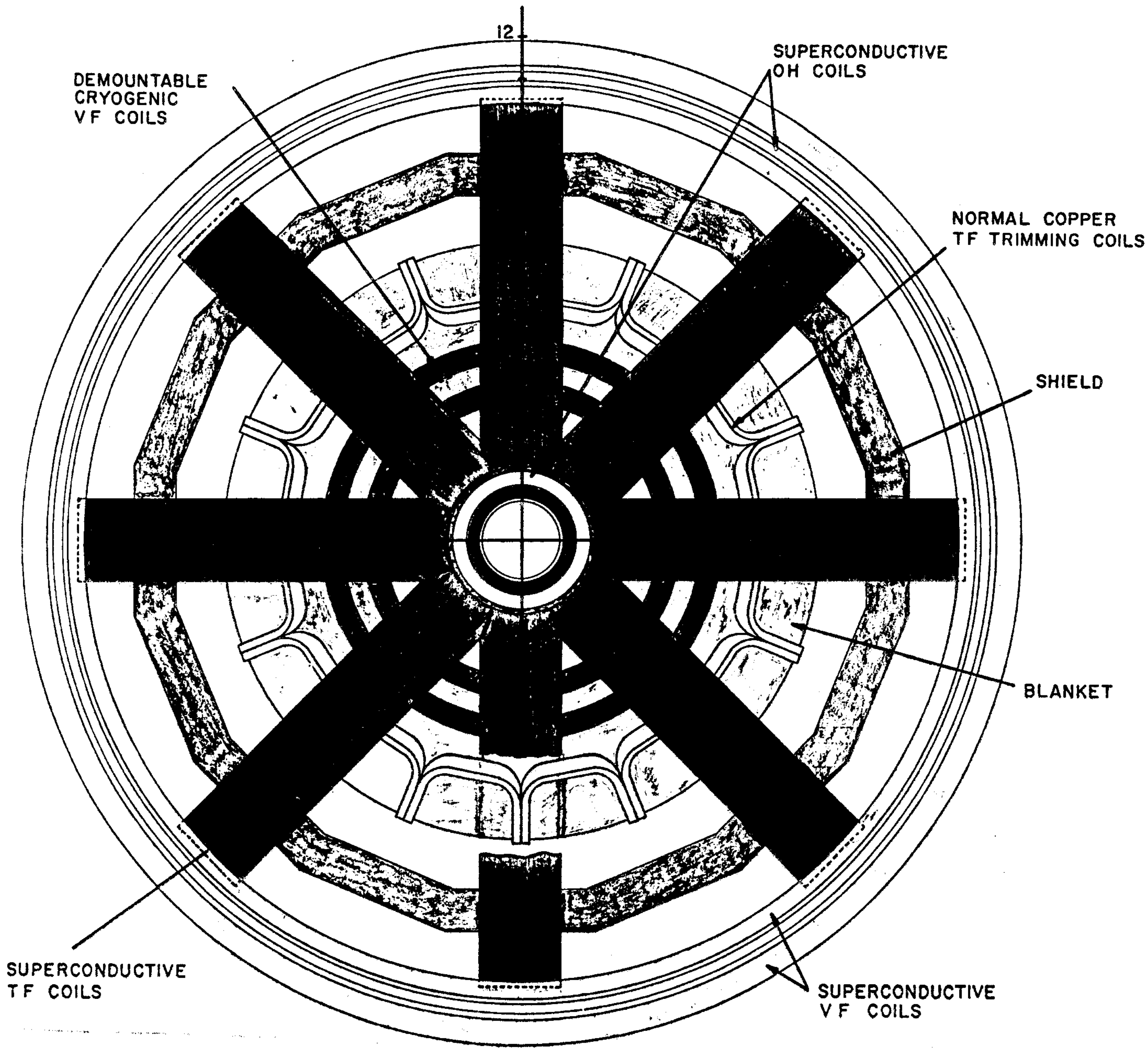


Fig. II-B-1

CROSS-SECTIONAL VIEW OF NUWMAK

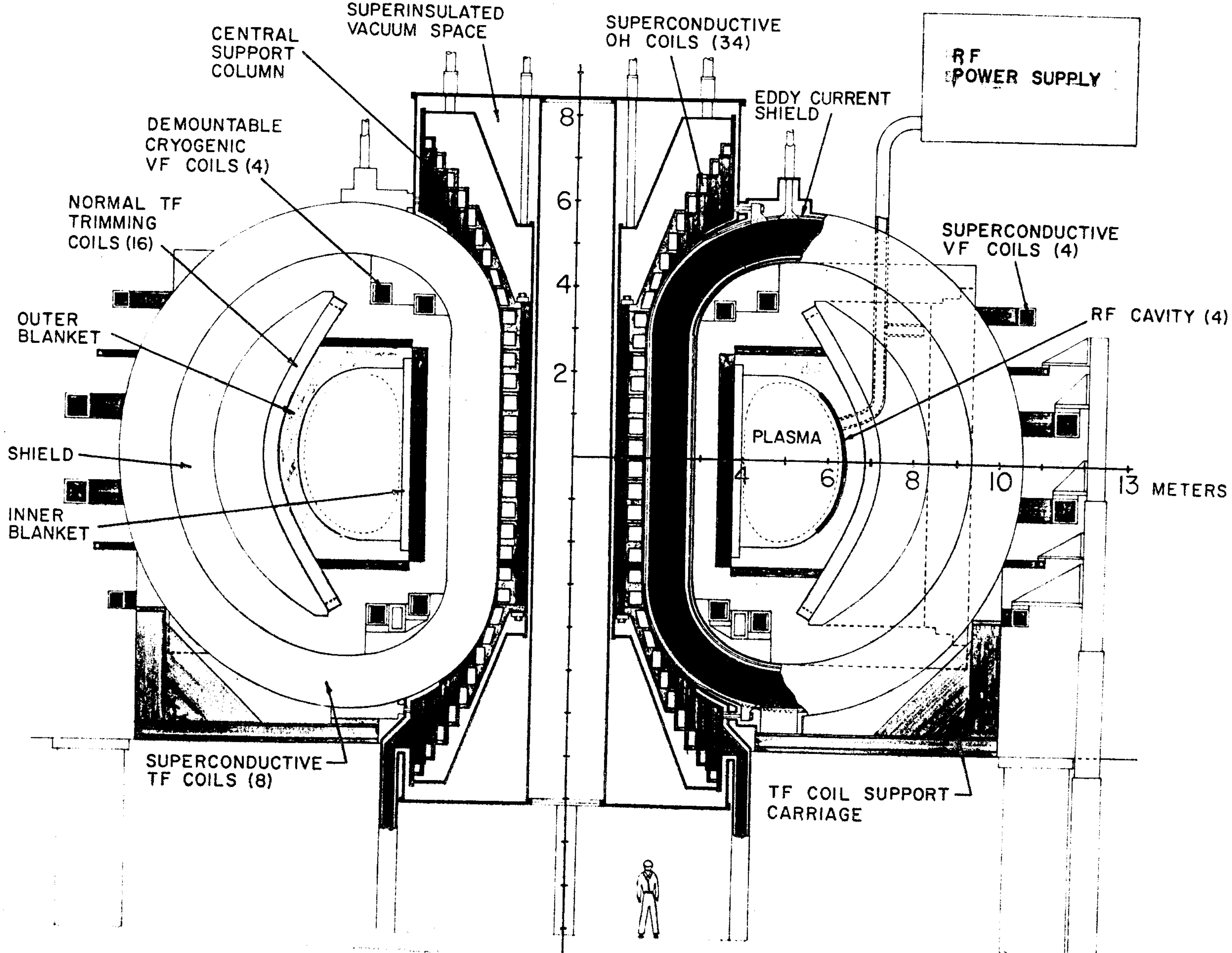


Fig. III-B-2

the plasma edge. They are located directly behind the blanket (see Fig. II-B-2). Since these trim coils do not encircle the vacuum chamber, they are readily removable.

As such, this system design represents a method to obtain the high system accessibility crucial to making maintenance feasible and practical. The distance between the outer legs of two TF coils is about 5 m.

The maximum field at the magnet is 11.9 T and the on-axis field is 6.05 T. To achieve this field, NbTi is used as the superconductor and is cooled with low pressure sub-cooled He II to 1.8 K. The advantages of this approach are that NbTi is ductile, the critical heat flux is high (0.5 W/cm^2) allowing a higher current density in the stabilizer, and the heat transfer properties of He II are excellent. The disadvantages include a high refrigeration power requirement (~60 MW), the absence of experience with this technique in large magnets, and the relatively high current density in the conductor (6900 A/cm^2)(which implies the need for fast discharging in a fault condition). High purity aluminum is used as the stabilizer and the high strength Al alloy, Al-2219, is used for the magnet structure. Other coil parameters are summarized on Table II-B-1.

II-B-2. ACCESS AND MAINTENANCE

The use of just eight superconducting TF magnets provides extensive space between each for ready accessibility. The four vertical field coils located inside the TF system (see Fig. II-B-2) are cryogenic (~18 K) aluminum (not superconducting) so that these can be disconnected and removed. A sequence illustrating the removal of a blanket segment is shown in Fig. II-B-3. The maximum weight moved per segment is just 10 tonnes.

A major advance in the NUWMAK design is the independent removability of the OH and TF coil systems. Unlike earlier studies, the TF coils are supported from the floor rather than from a central column permitting the OH system to be removed vertically without moving other elements. Likewise, an entire module consisting of one TF coil together with three blanket-shield segments can be removed independently. This design approach shows that a tokamak can have high system accessiblity and the potential for good maintainability. It need not consist of interlocking rings and an inaccessible blanket and ohmic heating coil system.

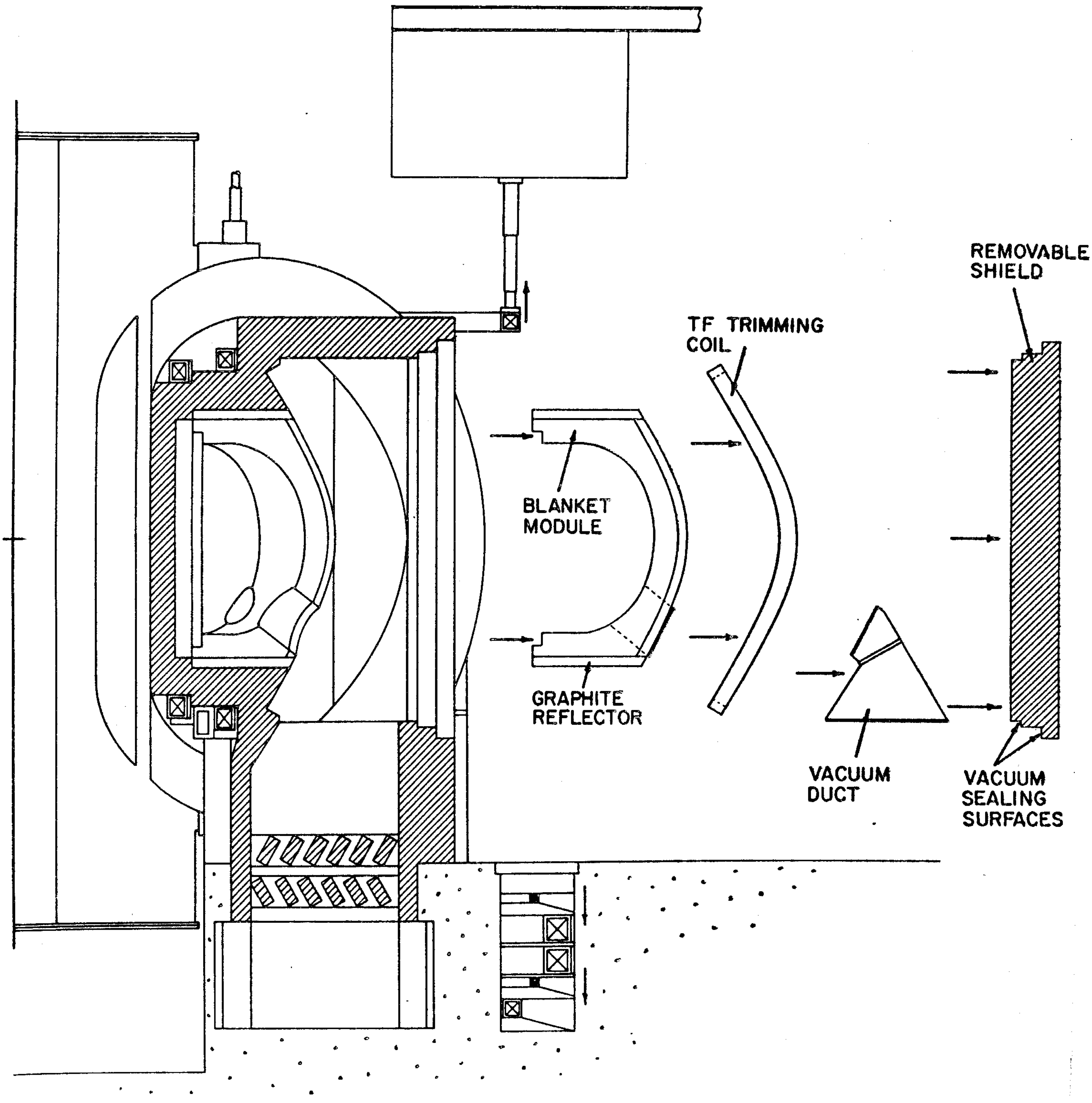


Fig. II-B-3. Sequence of steps involved in the removal of a blanket segment.

II-B-3. TITANIUM ALLOY STRUCTURE

The structural material for the reactor is the titanium alloy, Ti-6Al-4V. Titanium alloys are inherently non-magnetic and have an excellent fatigue lifetime. Also, the resistance to radiation damage appears promising and while no high neutron fluence data exist, no void swelling in either neutron irradiation or heavy ion simulations has been observed as yet. We have not determined an estimated lifetime but have used 10 MW-yr/m^2 for design purposes. Titanium does not pose any resource problems and an established industry already exists. Considerations of phase stability suggest limiting the maximum temperature to about 450°C in the high flux region while the minimum temperature is limited to 300°C to avoid hydriding. Titanium alloys have a high strength to weight ratio, good resistance to corrosion by Li or Pb, and a low neutron cross section for helium production.

Titanium alloys are also advantageous from the viewpoint of long term induced radioactivity. We find that the activity 100 years after shutdown is two orders of magnitude lower than the activity in a comparable blanket made from 316 stainless steel. The very long term activity is dominated by $^{26}Al(t_{1/2}=8x10^5y)$ but this should not prevent recycling or simple disposal.

II-B-4. ISOTHERMAL BLANKET DESIGN WITH INTERNAL ENERGY STORAGE

The blanket design is unique and is based upon the use of a breeding material which will operate at its melting point. The energy stored in the latent heat of fusion eliminates the need for an external energy storage system in the power cycle that would be needed otherwise to provide constant heat to the turbines. Further, the blanket is cooled with boiling water, thereby minimizing temperature cycling. The breeding material is the eutectic, $Li_{62}Pb_{38}$, which has excellent breeding and shielding properties and undergoes a solid-liquid phase change at 464°C.

The key to the isothermal operation of the cooling tubes and to the internal energy storage operation is shown in Fig. II-B-4. The temperature distribution from a coolant tube into the Li-Pb mixture is shown at different times during the plasma burn cycle. That cycle is summarized on Table II-B-2. The plasma current rises in 7 seconds to

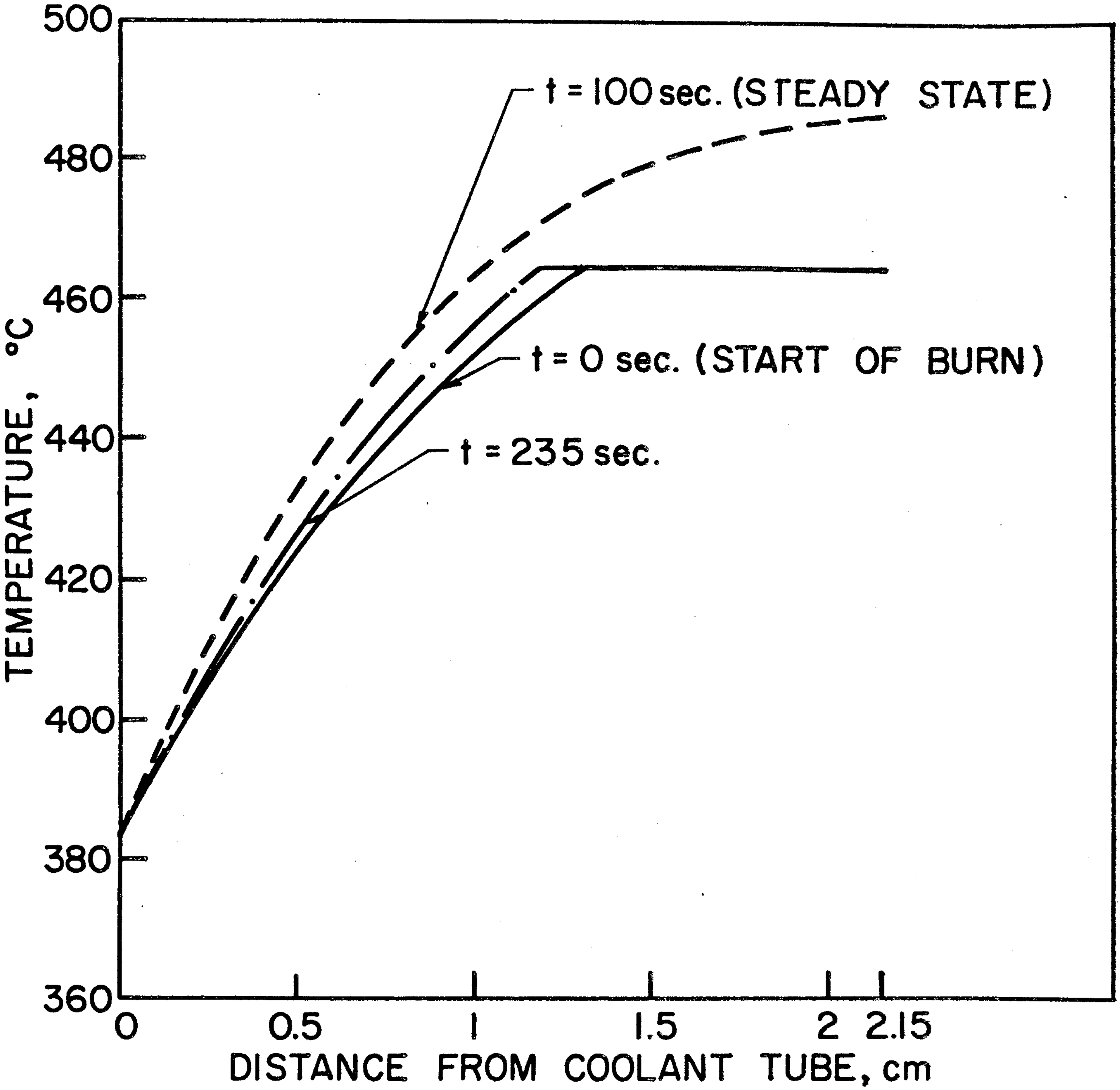


Fig. II-B-4 TEMPERATURE CHANGE OF THE BLANKET IN A BURN CYCLE (WITH PHASE CHANGE)

Table II-B-2. Burn Cycle of NUWMAK

Phase	Time (seconds)
Current Rise Time (0 to 7.2 MA)	7
RF Heating to Ignition (80 MW)	1
Plasma Burn	224
Plasma Cooling and Current Decrease	8
Additional Pumping and OH Coil Reset	5
Total Cycle Time	245
Cycle Duty Factor	0.91

7.2 MA and RF heating ignites the plasma in 2 sec. The burn time is 225 seconds. The time, t = 243 sec, on the figure is about halfway between the end of one burn and the start of another. Note that for the three quite different times during the burn, the slope of the temperature curve at the cooling tube surface changes very little. As such, both the heat flux to the coolant tube and the ΔT across the tube remain about constant during the plasma down time.

II-B-5. PLASMA HEATING BY RF AT $2\omega_{ci}$

RF plasma heating based on the fast magnetosonic mode at $2\omega_{CD}$ (92 MHz) is used in NUWMAK. This wave is approximately transverse electric (TE) with respect to the toroidal axis and is right-elliptically polarized. A cavity-backed aperture antenna is designed to couple the wave power into the plasma through the toroidal field. The wedge shaped coaxial cavity is flush mounted on the first wall as shown in Fig. II-B-2 and is fed by a coaxial line with the center conductor welded to the inner wall to form a current coupling loop.

There are four resonant cavities positioned so that they do not intersect the $\omega = 2\omega_{CD} = 3\omega_{CT}$ resonance surface over their poloidal extent. Catastrophic breakdown may occur due to anomalous acceleration of the ions if the cavity intersects such a resonant surface. The cavities have the following parameters:

Radial Width	0.1 m
Toroidal Width	1.85 m
Poloidal Width	3.5 m
Wall Thickness	0.002 m

Each cavity is water cooled and constructed of V-5Ti, chosen because of its high electrical conductivity, and each is located under a toroidal field magnet where field ripple is a minimum.

The minimum loss in a vacuum insulated coax line occurs at a characteristic resistance of 73 Ω while the maximum power handling capability occurs at about 30 Ω. Thus, a driving point resistance of about 50 Ω is highly desirable. The cavity-backed antenna designed for NUWMAK acts as an impedance transformer and, because it is resonant, nearly any driving point resistance can be found by properly locating the input coupling point to the cavity. The location of the coax feed has been determined by these considerations.

The plasma heatup phase with RF heating has been analyzed using both point and space-time plasma modeling codes. It is found from the space-time analysis that 75 to 80 MW is sufficient to ignite the plasma in about 1 second. As such, each of the four RF cavities is designed to couple in 80 MW. The overall efficiency to couple in is 80 MW. The overall efficiency of the RF driving system is estimated to be about 60% based upon an 85% efficiency for the energy store (e.g., a motor generator set), a 95% efficiency for the DC power supply, a 75% efficiency for the IPA/HPA, and a 97% efficiency for the transmission line and cavity. We thus estimate the primary power requirement during the RF pulse to be 136 MW.

II-B-6. PLASMA OPERATION WITHOUT A DIVERTOR

The operation of long pulse or steady state toroidal fusion plasmas in an appropriately clean state has been a concern from the earliest days of fusion devices. Magnetic divertors were first proposed for Stellarator reactors by Spitzer and they have been included in many recent tokamak designs,(1-4) including those of our group at Wisconsin. It has been clear that, while divertors may maintain plasma cleanliness and act as pumps, they add considerably to reactor complexity and cost. We have therefore considered an alternative for NUWMAK based on periodic gas puffing and a trapped ring of impurities which acts as a halo to radiate heat conducted from the plasma center to the chamber walls.(4)

The alpha power deposition during the NUWMAK burn is 388 MW and this must spread approximately uniformly over the first wall if it is to be a manageable heat load. The first wall area is 360 m^2 so that the average surface heating rate would be an acceptable 1.1 MW/m^2. If this heat leaves the plasma as hot ions and electrons which strike the limiter, the heat load is concentrated and would be much too high. For example, assuming escaping plasma uniformly heats two diaphragm limiters of 5 cm width, the average heat load would exceed 200 MW/m^2.

The approach in NUWMAK is based upon the assumption that impurity transport is neoclassical, as indicated by experiment. The impurities (and alpha particles) diffuse up the fuel density gradient (inward) but down the temperature gradient (outward). Periodic gas puffing maintains a relatively flat density profile (small $\partial n/\partial r$) but the alpha heating, which varies as $n^2\langle\sigma v\rangle$ and is more sharply peaked near the plasma center, drives a very sharp temperature gradient at the plasma edge. These two effects combine to effectively keep impurities at the center to a low value.

The plasma edge behavior is intimately related to plasma wall interactions and the possible presence of a Ware pinch effect. The presence of gas at the plasma boundary implies that there is a charge-exchange neutral outflux which causes sputtering and impurities. The impurities cannot penetrate to the center and periodic gas puffing maintains a relatively flat density profile. (We find an actual density inversion near the edge which we allow to relax by stopping the gas flow.) The net effect is that a ring, or halo, of impurities is maintained in steady state and radiates the heat conducted from the center to the first wall. This loading is uniform and manageable.

Fueling and pumping are key issues for divertorless operation and are not completely resolved. If fueling is accomplished solely by puffing gaseous D-T at the plasma edge, we find fuel does diffuse to the center. However, there is a very rapid turnover of plasma near the edge because the diffusion coefficient is high and the temperature gradient is steep. Some of this fuel is simply neutralized at the limiter and recycled. However, if the edge boundary density is to decrease between puffs, gas must be pumped. This leads to very large pumping speed requirements, low tritium fractional burnup (~0.6%), and thus very high tritium inventory associated with the primary fueling system (>20 kg). This situation is unacceptable.

A workable alternative is to puff only deuterium gas and to use pellet fueling[9] to deposit fuel (mostly tritium) more deeply into the plasma where diffusion rates are lower. We find the plasma can be treated as a two region model, the core region, I, with radius r_e, and an edge region, II, of thickness δ between r_e and the plasma radius a. In region I, the diffusion rates are modest and the rate of tritium loss to region II is slow. Since most of the energy (>90%) is generated in the core, we need only fuel this zone with D and T. We now find the fractional burnup to be an acceptable 10%. Region II is dominantly deuterium in this case and is refueled solely by deuterium gas puffing. In this way, we avoid the rapid turnover of tritium due to a rapid loss of particles from the edge region alone.

A second major issue is the selective pumping of helium ash. We find that the helium can be made to diffuse into the turbulent plasma edge. The reason is the fuel density profile in the central region is flat and the only driving force for alpha inward diffusion is a fuel density gradient. Once in the edge region, however, it is necessary that the helium be pumped. The helium is a small constituent of the hydrogenic gas, is at low particle pressure, and is virtually impossible to pump. What is required is selective He pumping or trapping to prevent the ash from simply recycling and building up in the plasma. We have identified the problem in a quantitative way, namely the helium is produced at the rate of 7×10^{20} alphas per second in NUWMAK and the selective pumping speed must be about this rate to prevent alpha buildup.

At present, no established technique exists to accomplish this task. An approach which deserves further attention is to operate toroidal belt limiters at a potential of approximately 500 volts negative. Alphas will then strike the surface at normal incidence with an energy of about 1 keV. Experimental results from Sandia[10] suggest that helium can be selectively trapped in stainless steel surfaces up to a fluence of $5 \times 10^{16} - 10^{17}$ cm^{-2}. This would permit only a 10-20 second burn in NUWMAK if the limiter surface is on the order of 10^5cm^2, a feasible figure. The limiters would have to be arranged in pairs and, as with cryopumps, the trapped gas would then have to be regenerated. This problem requires much further attention in light of its importance. At the moment, however, we must conclude the long burns without divertors are unlikely unless selective helium pumping is possible.

II-B-7. DIRECT BWR POWER CYCLE

The use of boiling water cooling and internal blanket energy storage permits the use of a simplified power cycle modelled after the direct Boiling

Water Reactor (BWR) approach. A comparison of the power cycle normally designed for tokamaks with that of NUWMAK is shown in Fig. II-B-5 and the average power flows are shown in Fig. II-B-6. The coolant temperature (300°C) and pressure (8.6 MPa or 1250 psi) are typical of a BWR cycle. The gross plant efficiency is 34.6% while the net efficiency is 31.5%. The largest recirculating power requirement is 60 MW_e for magnet refrigeration. It is expected that the absence of the equipment shown in Fig. II-B-6, particularly the intermediate heat exchanger and the hot and cold energy stores, will reflect favorably on system economics.

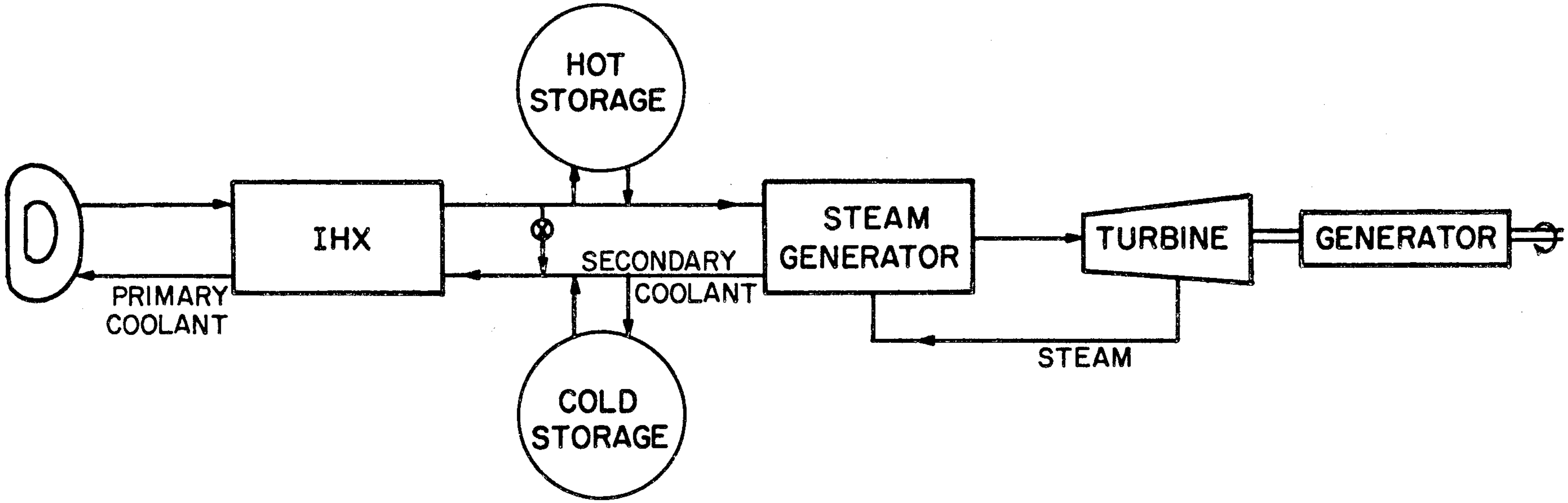
II-C. ADDITIONAL NUWMAK DESIGN CHARACTERISTICS

II-C-1. MHD PLASMA ANALYSIS AND VERTICAL POSITION CONTROL

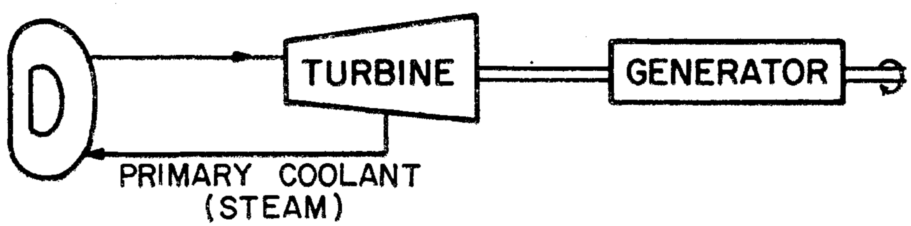
The equilibrium plasma shape for NUWMAK has been determined from MHD calculations. The final design requires just eight coils, four each above and below the plasma midplane (see Fig. II-B-2) located at the (R,Z) positions:

R(m)	Z(m)	I(MA)
3.5	±3.5	2.3
4.5	±3.75	2.0
10.5	±3.5	-2.0
11.5	±1.0	-3.5

A positive sign on the coil current signifies flow in the direction of the plasma current. The plasma shape is shown in Fig. II-C-1 and the



POWER CYCLE FOR A CONVENTIONAL TOKAMAK



POWER CYCLE FOR NUWMAK (BWR TECHNOLOGY)

Fig. II-B-5 COMPARISON OF POWER CYCLE OF NUWMAK TO A CONVENTIONAL TOKAMAK REACTOR

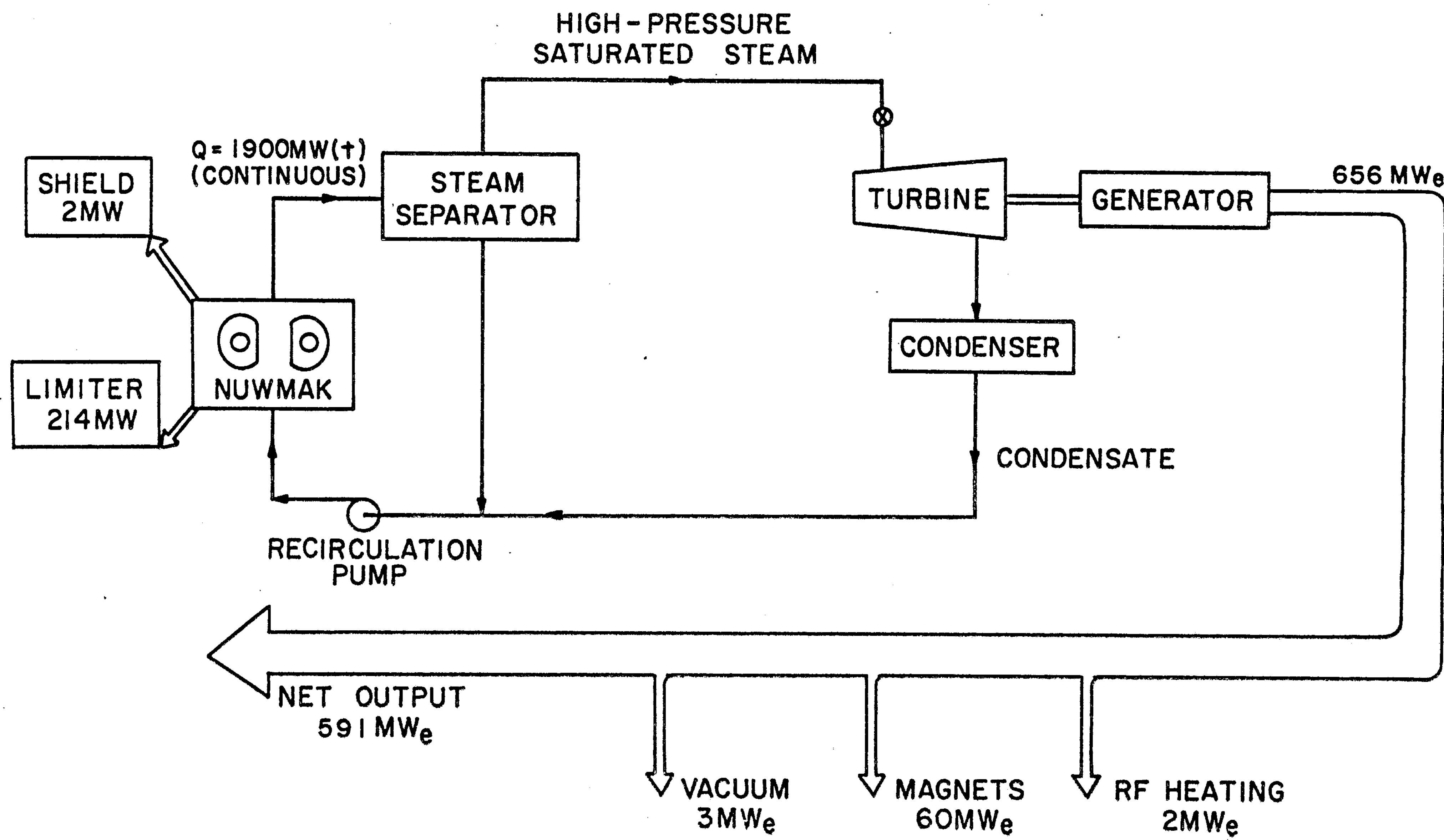


Fig. II-B-6 POWER FLOW DIAGRAM FOR NUWMAK

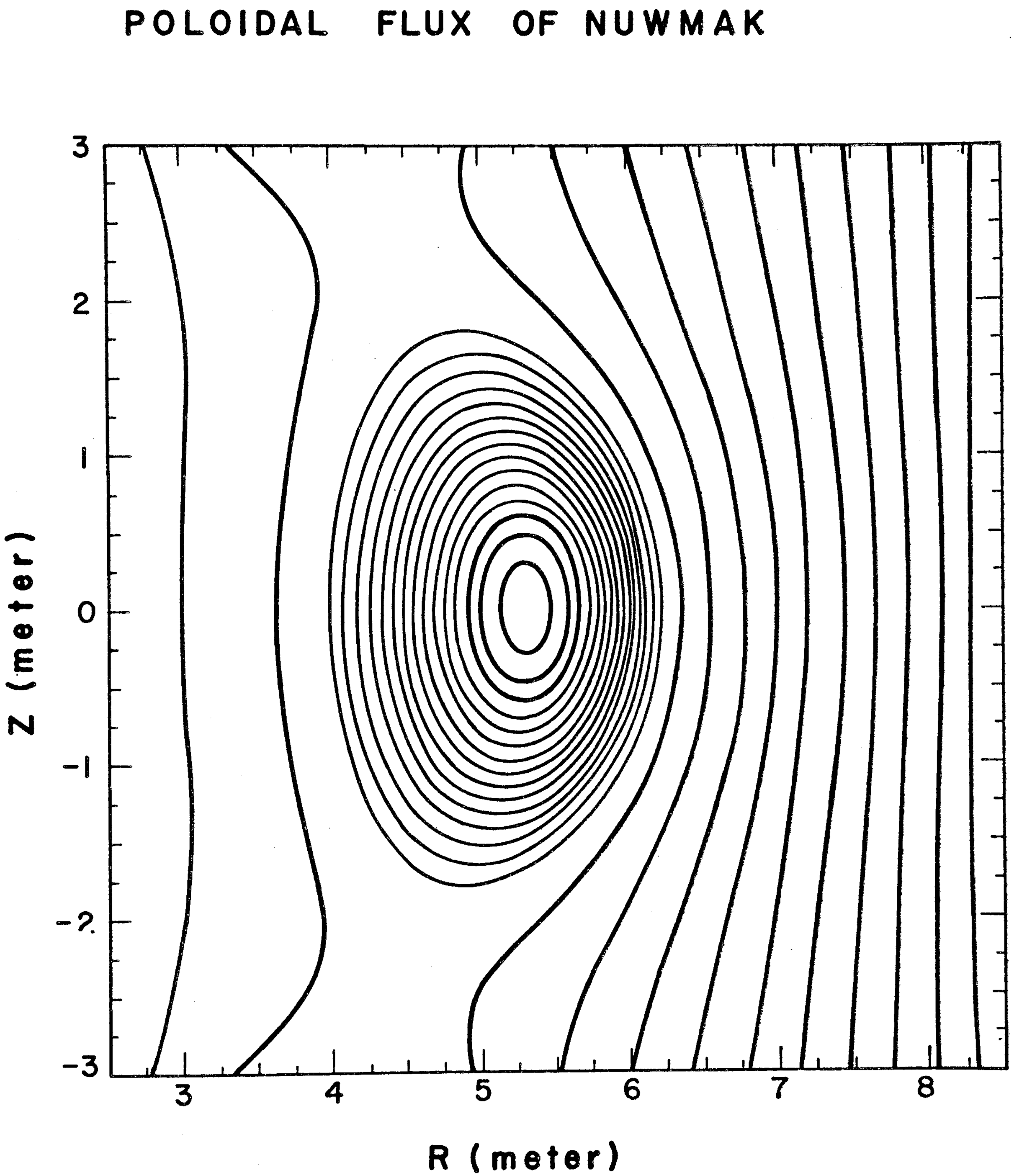


Fig. II-C-1

profile of the safety factor, q(r), as well as the stability factors, DI and DR (for ideal and resistive interchange modes), are shown in Fig. II-C-2. q(r) exceeds 1 everywhere and q(a) at the plasma edge is 2.6. The sign of DI and DR also indicates stability. The average toroidal plasma beta is 6% and the average poloidal beta ($\beta_p = \frac{2\mu_o\bar{p}}{\langle B_p^2 \rangle}$) is 3.7. We have not used the PEST code[11] to test stability against ballooning modes but 6% toroidal beta is consistent with stable β values found in other similar cases. The decay index of the vertical field, defined as $n = \frac{R}{B_\perp}\frac{dB_\perp}{dR}$, has the value of -1.13 indicating the plasma position is unstable against rigid vertical displacements. This is a familiar result found in most designs of noncircular plasmas with height to width ratios of about 1.5 or greater. In a previous study, a feedback system was designed utilizing the existing vertical field coils. The reactive power requirement was about 90 MW. The blanket in NUWMAK is more highly conducting so that the growth rate for the instability is much slower (estimated to be about 0.5 seconds). Thus, the reactive power requirement is only 1 MW.

II-C-2. BLANKET NEUTRONIC ANALYSIS

A schematic of the blanket and shield design is shown in Fig. II-C-3. The blanket has been analysed using a two-dimensional analysis to account for the poloidal variation in zone thicknesses and the different design of the inner shield. Four criteria relating to the toroidal field coils were used to design the inner shield: radiation induced changes in the critical current of the superconductor; radiation induced changes in the resistivity of the Al stabilizer; the dose limits of the super-insulation; and magnet heating. The most restrictive criterion is found to be the

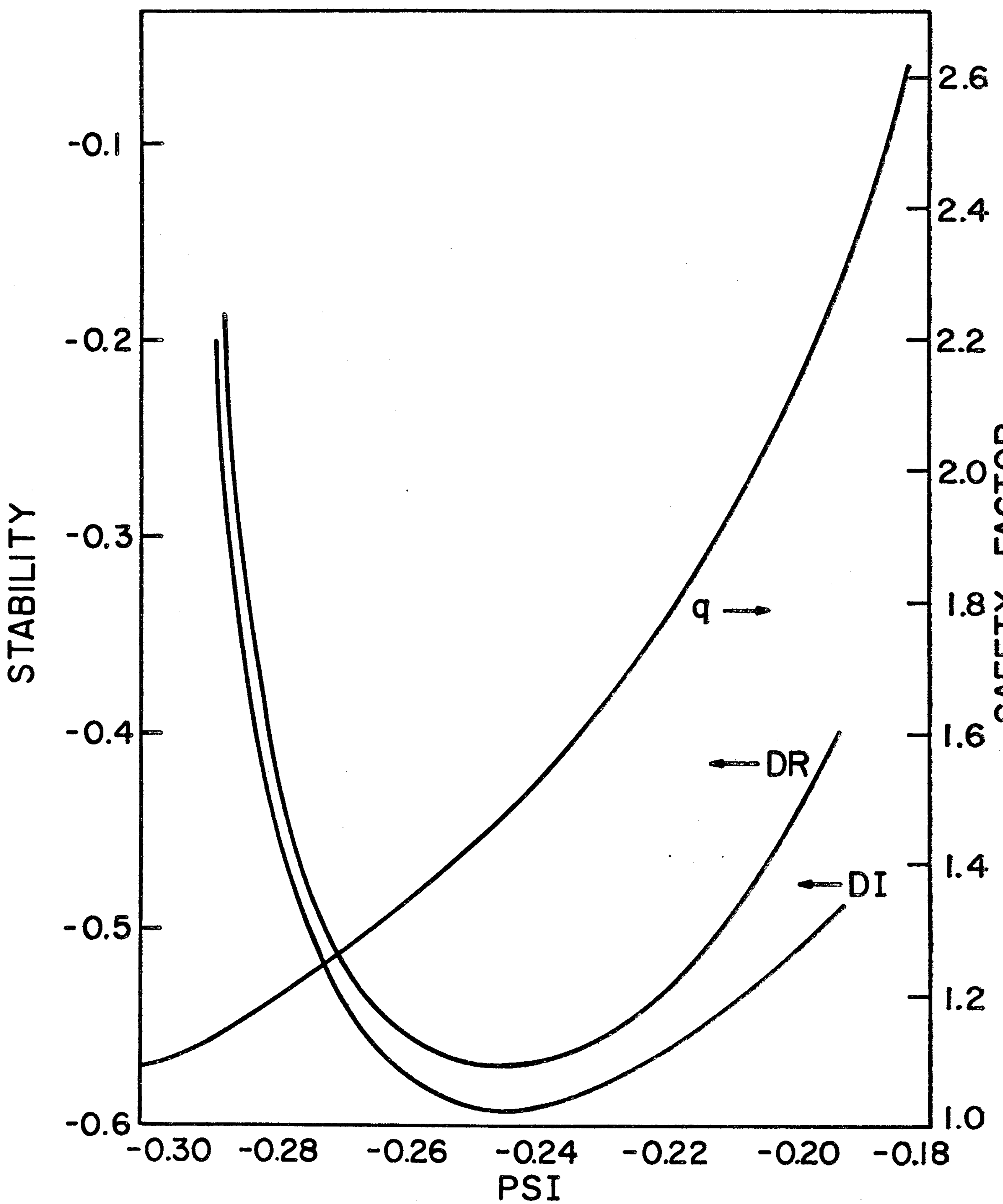
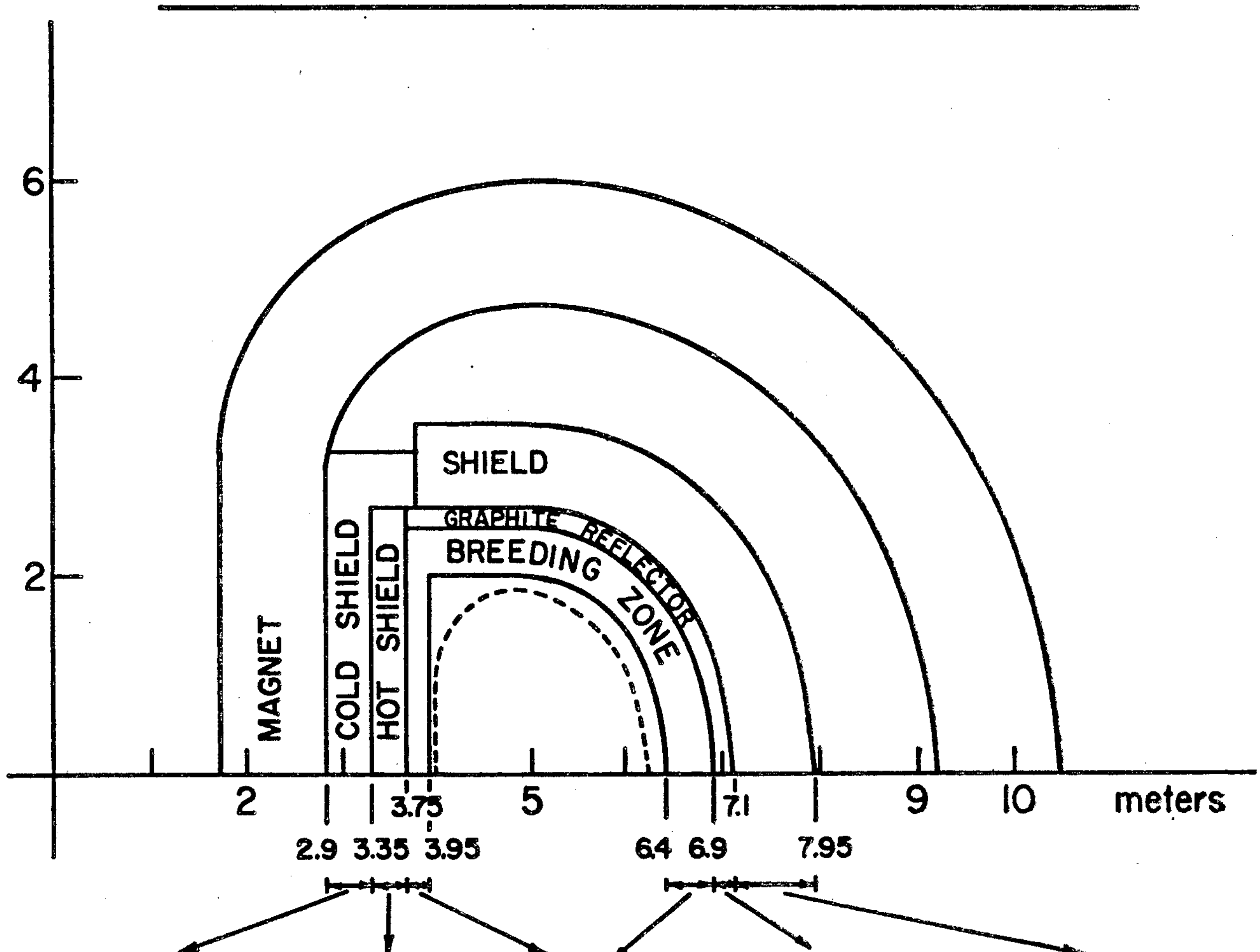


Fig. II-C-2. Plot of stability factors, DR and DI, and the safety factor, q, versus ψ surface from the plasma center to the edge.

SCHEMATIC OF THE BLANKET AND SHIELD FOR NUWMAK



COLD SHIELD	HOT SHIELD	BREEDING ZONE	GRAPHITE REFLECTOR	SHIELD
3.5% Ti alloy	4% Ti alloy	5.7% Ti alloy	3.5% Ti alloy	3.5% Ti alloy
95.25% B_4C	93% W	89.4% Pb Li	95.25% C	95.25% B_4C
1% H_2O	2% H_2O	3.7% H_2O	1% H_2O	1% H_2O
0.25% Pb	1% Pb	1.2% Pb	0.25% Pb	0.25% Pb

Fig. II-C-3

resistivity change of the Al stabilizer. The resistivity of the Al at 1.8 K is estimated to increase by 15%/year and although the design can operate with a 100% increase, it is proposed that this damage be annealed out by warming the coils approximately every two years. Enough margin exists so that this operation can be carried out while the reactor is shut down for other reasons. As such, it is not expected that this procedure will cause a decrease in the overall plant availability factor. The estimated change in the critical current, J_c, is just 0.5%/year. As for the superinsulation, it is found that the dose to mylar would exceed dose limits before plant life. An epoxy based superinsulator whose dose limit is 1-5 x 10^9 rads is therefore selected. At a dose rate of 1.6 x 10^7 rad/yr, the epoxy should last plant life. The remaining key neutronics parameters of NUWMAK are given in Table II-C-1. The quite high tritium breeding ratio is due to the presence of a Li-Pb zone in the inboard as well as the outboard blanket. In a previous study, UWMAK-III, the concept of breeding only in the outer blanket was developed to control the breeding ratio. The inboard shield combination was designed for maximum attenuation. In NUWMAK, the breeding ratio associated with the outer blanket alone is 1.24. However, we have retained the Li-Pb zone on the inside so as to maintain minimum thermal cycling of the structure. At this point, we have not found another compound or eutectic which can perform the same task as the Li-Pb in the same temperature range.

II-C-3. BLANKET TRITIUM ANALYSIS

The blanket in NUWMAK contains 8 x 10^5 kg of the eutectic 62 Li:38 Pb and has a very low steady state tritium inventory, only 800 g (1 wppm T). The resulting pressure of T_2 above the 62 Li:38 Pb is 5.9 x 10^{-4} torr. The tritium extraction system, which must remove the 380 g of T bred per day, is extrapolated from experimental work on the molten salt extraction of tritium from liquid Li. A stream of molten LiPb eutectic is continually removed from the blanket, heated to 500°C, and fed to a centrifugal contactor unit where the eutectic is brought into contact with an equal volume of molten salt having the composition 22 LiF:31 LiCl: 47 LiBr. The LiT is preferentially distributed in the salt phase by a

Table II-C-1. Key Neutronic Characteristics of NUWMAK

Tritium Breeding Ratio	1.54
Nuclear Heating (MeV/D-T neutron)	17.15
Total Energy Per Fusion (MeV)	20.67
Max. Displacement Rate in Al Stabilizer of TF Coil (dpa/yr)	1×10^{-6}
Dose Rate to Superinsulator (Rad/yr)	1.6×10^{-7}
Nuclear Heating in TF Coils (watts)	500
Energy Attenuation of the Blanket and Shield	1×10^{-9}

factor of approximately two, on a volumetric basis, and the salt and eutectic are then separated. The purified eutectic (0.3 wppm T) is then returned to the blanket. The salt is electrolyzed at an emf below its decomposition potential but above the decomposition potential of LiT (0.9 volts) for 30 minutes to remove the tritium. The fraction of tritium recovered from the salt in this period is approximately 90%.

The NUWMAK blanket and tritium extraction system are attractive for a number of reasons related to safety. Not only is the blanket lithium inventory low (4×10^4 kg) but the activity of Li in 62 Li:38 Pb at 464°C is only 0.6% of the activity of pure Li. Further, the eutectic mass in the contactor at any time is small (~40 kg). Since it is possible to remove tritium from pure liquid Li down to the 0.06 wppm level, the factor which ultimately limits the minimum tritium inventory is the number of times per day one can feasibly process the blanket eutectic. The relationship between the steady state blanket T inventory (I_{ss}) and the fraction of the blanket processed per day (X) is given by $X = \frac{0.59}{I_{ss}}$ where 0.59 is a factor incorporating the NUWMAK parameter for the volumetric distribution coefficient, efficiency of T recovery from the salt, and the breeding rate. To maintain the blanket tritium inventory at 800 g, it will be necessary to process 74% of the blanket eutectic per day. If the blanket could be processed more frequently, the tritium inventory could be further decreased resulting in a lower T_2 pressure.

II-C-4. MATERIALS RESOURCE IMPLICATIONS

The total materials requirements for a 300 GW_e installed capacity of NUWMAK-type reactors (~ 1500) are given in Table II-C-2. One can see that even such a large economy of reactors does not place a severe burden on materials resource requirements available at present prices from within the domestic U.S. market. Only three materials would be required from foreign sources, Nb, W, and Co. We recommend further that as fusion develops, the need for these materials be monitored. Overall, however, NUWMAK style reactors appear to place no severe burdens on resource requirements.

Table II-C-2

Group & Metal	Total Requirement for 300 GW_e (in metric tonnes x 10^3)
Group A - Materials available from domestic mines at market prices	
Boron	2,232
Carbon	1,093
Copper	1,183
Iron	56,362
Lead	2,829
Lithium	63
Magnesium	8
Zr	1.5
Mo	68
Group B - Materails available from domestic mines at 3X market prices	
Aluminum	2,240
Chromium	346
Titanium	1,286
Manganese	53
Vanadium	117
Ni	44
Group C - Materials available in adequate amounts only from foreign sources	
Niobium	75
Tungsten	1,040
Cobalt	68

II-C-5. ECONOMIC ANALYSIS

The economic analysis has been carried out in the format recently developed by the Department of Energy in the report "Fusion Reactor Design Studies - Standard Accounts for Cost Estimates", issued May 1978.

Two modes of economic analysis are used. The first is a current dollar mode (nominal dollar) which assumes that the purchasing value of the dollar changes over time. The second is a constant dollar mode which assumes the purchasing value of the dollar remains constant over time or that the inflation rates and component escalation rates are equal to zero. The cost of energy figures obtained by the constant dollar mode will be higher than the cost of energy today because the present dollar value is used without de-escalation to its value eight years ago (assuming an eight year construction period) and the interest during construction is based on the present day cost. This is an important factor to be kept in mind if one has to compare the cost of energy from NUWMAK obtained by the constant dollar mode with the cost of present day energy (fossile fuel, etc.).

In the current dollar mode the cost escalation on the estimated capital costs is assumed to exist and is accounted for in a single escalation during construction account. Further, the cost escalation on estimated operating and maintenance, scheduled component replacement and fuel costs is also assumed to exist, and is accounted for within the respective parent cost account. The current dollar analysis mode is, therefore, essentially a nominal first year facility cost and the cost of energy obtained in this way should be compared with the cost of energy from other sources eight years from now.

We have assumed an eight-year construction period for NUWMAK with a cash flow profile for interest during construction and escalation that follows the classic S-curve biased about 20% to the right. This profile appears to hold for major fossil and nuclear plant construction.

A summary of capital costs is given in Table II-C-3. While it is difficult to attach true significance to the numbers, they appear to show that fusion systems modelled after the NUWMAK design have costs that are within the range of costs projected for advanced energy systems. Busbar costs including operation and maintenance, annual fuel costs, scheduled component replacement costs, and an estimated plant availability are also given in Table II-C-3. In the constant dollar mode, these costs are about 35 mills/kWh. In the current dollar mode, electricity cost comes to 72 mills/kWh.

A comparison of costs between two different studies we have done is given in Table II-C-4. UWMAK-III is a 2000 MW_e conceptual tokamak reactor with major radius equal to 8 m and a neutron wall loading of 2.0 MW/m^2. The design is based upon assumptions on advanced technologies and materials, such as the molybdenum alloy structure, TZM, and the advanced direct He cycle power train. The direct costs were developed by the University of Wisconsin and the Bechtel Corp. Costs have been inflated to 1978 dollars. Two costs models were used: the basis provided in the report NUS-531 on standard nuclear power plant costs; and the costing mode provided in the previously referred to 1978 DOE Guidelines. The higher power density and lower power cycle costs are primary reasons for the lower costs of NUWMAK.

Table II-C-3

Cost Summary for NUWMAK

a. Capital Costs ($\$10^6$)

	Constant Dollars	Current Dollars
Direct Costs	844	844
Indirect Costs	295	295
Time Related Costs	194	829
Total Capital Costs	1333	1968
Capital Costs	$\$2020/kW_e$	$\$2982/kW_e$
b. Busbar Costs	34.3 mills/kWh	72 mills/kWh

Table II-C-4

Cost Comparisons Between NUWMAK and UWMAK-III

	NUS-531 (1978$)	Const. Dollars (1978$)	Current Dollars (1986$)
Plant Cost			
UWMAK-III	3317 $/kW$_e$	2743 $/kW$_e$	4039 $/kW$_e$
NUWMAK	2476 $/kW$_e$	2020 $/kW$_e$	2982 $/kW$_e$
Busbar Cost			
UWMAK-III	80 mills/kWh	48 mills/kWh	100 mills/kWh
NUWMAK	58 mills/kWh	34 mills/kWh	72 mills/kWh

II-D. SUMMARY AND COMMENTS

A new conceptual design of a tokamak fusion reactor of medium toroidal field (B_T^o = 6.05 T) shows that such systems can have high power density, high neutron wall loading, modularity, and moderate size. The design is especially attractive from the viewpoints of system accessibility, first wall lifetime, low levels of long term induced radioactivity and minimum penetrations. The power density (10 MW/m^2) and electrical power output (660 MW) of this unit are chosen as typical of a full scale power reactor operating in a base-loaded mode at the turn of the centruy. Somewhat smaller tokamaks can be designed for use in a reactor development program and larger units are feasible for longer term applications when electrical grids have expanded still further.

Overall the NUWMAK design appears to be a natural and attractive extension of moderate field, moderate size tokamaks as represented by the Tokamak Fusion Test Reactor (TFTR) and the Oak Ridge-TNS design. Parameters for the three devices are given on Table II-D-1 and a pictorial size comparison is given in Fig. II-D-1. Both NUWMAK and the ORNL-TNS are about a factor of 2 larger than TFTR in linear dimension while NUWMAK extends the toroidal field and the plasma current relative to the ORNL-TNS and includes thicker blanket-shield regions which produce major differences in design. Nevertheless, the implication is that the scale-up from TFTR to the ORNL-TNS is primarily in size and to some extent in technology. Following TNS, however, a scaleup in specific technologies can then produce an interesting reactor product.

Table II-D-1 - Comparison of Key Parameters in TFTR, ORNL-TNS, and NUWMAK

	TFTR	ORNL-TNS	NUWMAK
Major Radius (m)	2.48	5.0	5.13
Plasma Radius (m)	0.85	1.25	1.13
Aspect Ratio	2.92	4.0	4.54
Plasma Current (MA)	2.5	4	7.2
Toroidal Beta	2%	3-10%	6%
Plasma Shape	Circle	"D"	"D"
Heating Method	Neutral Beams	Neutral Beams	RF
Heating Power	20MW @ 120 keV 12MW @ 60 keV	~50 MW @150 keV	75 MW @ 92 MHz ($2\omega_{cd}$)
Axial Toroidal Field (T)	5.2	4.3	6.05
TF Coil Design	Cu	Cu/NbTi/Nb_3Sn	Al/NbTi
Inner Blanket/Shield Thickness (m)	<0.5	0.54	1.10
Average Neutron Wall Loading	---	---	4.0 MW/m^2
Number of DT Pulses in Reactor Life	4×10^3	5×10^5	5×10^6
Tritium Breeding Ratio	---	---	1.54
Tritium Inventory	<1/2 g	~190 g	$5\text{-}10 \times 10^3$ g
Duty Factor	---	~50%	.91
Expected Availability	---	~20%	~ 80%

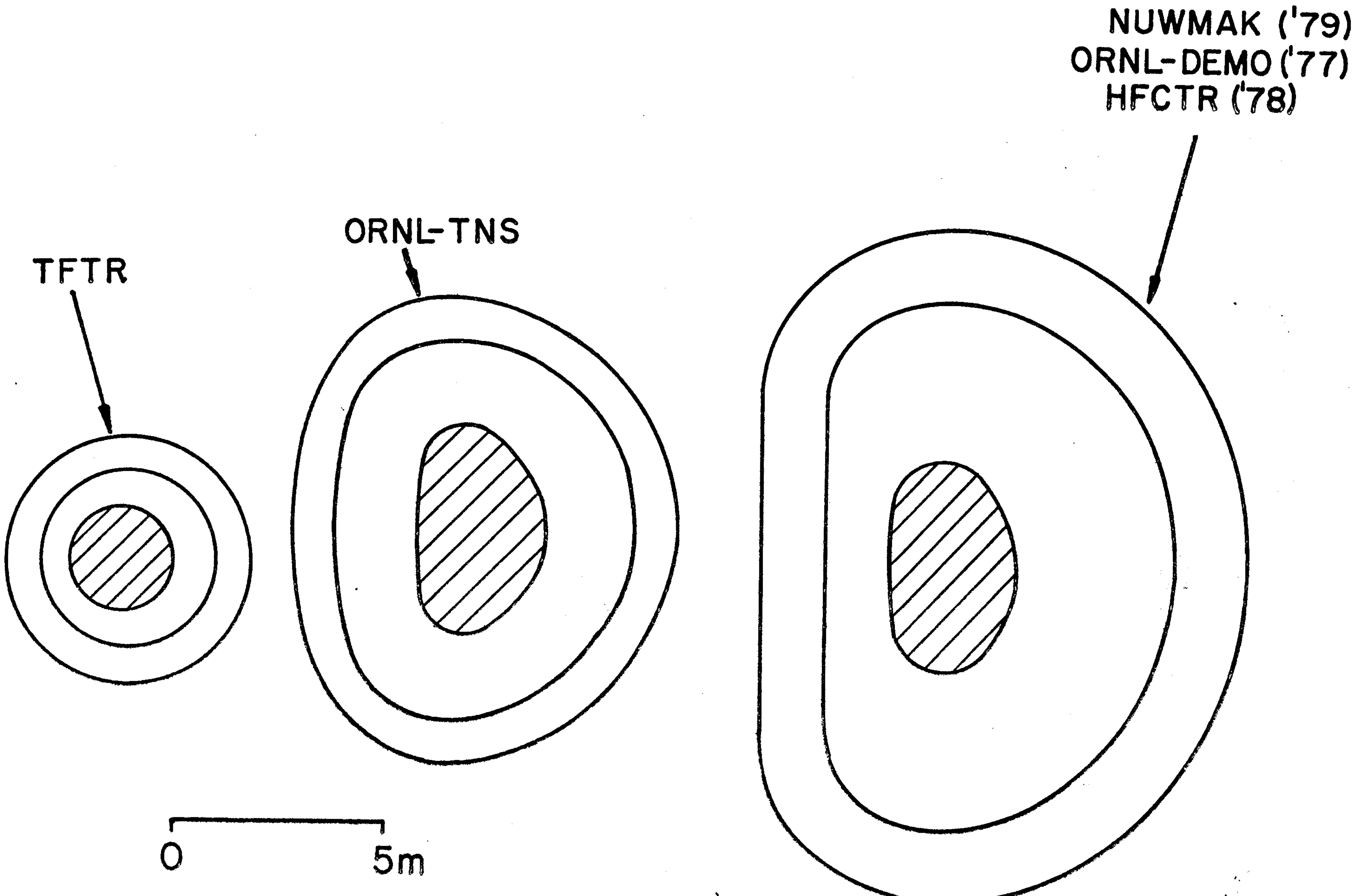


Fig. II-D-1

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