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NUWMAK: AN ATTRACTIVE MEDIUM FIELD, MEDIUM SIZE, CONCEPTUAL TOKAMAK REACTOR*

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ABSTRACT

A new conceptual design of a medium field tokamak reactor shows that such systems can have high power density, a high degree of modularity, and moderate size. The design, called NUWMAK, is especially attractive from the viewpoints of system accessibility, low levels of long term radioactivity, and minimum penetrations. The power density (10 MW/m^3) and electrical power output (660 MW) are chosen as typical of a full scale reactor operating in a base-loaded mode. The plasma has a noncircular D shape and a toroidal β of 6%. Plasma heating is by RF at $\omega = 2\omega_{CD}$ (92 MHz) based on the fast magnetosonic mode. The TF coil set is unique in that just 8 superconducting coils are used. A set of 16 small water cooled copper trim coils that do not encircle the vacuum chamber correct the field ripple to below 2%. The blanket is constructed of the titanium alloy, Ti-6Al-4V, and is designed to minimize thermal cycling, to provide internal energy storage, and to eliminate the need for an intermediate heat exchanger. A lithium-lead eutectic, $Li_{62}Pb_{38}$, with a melting point of 464°C is used as the tritium breeding and thermal energy storage material. The latent heat of fusion provides the required energy between plasma burns. Boiling water at 300°C, 1250 psi is the coolant and this further reduces thermal fatigue problems. Overall, the design appears to be a natural extension of the moderate field line of tokamaks as represented by the Tokamak Fusion Test Reactor (TFTR). NUWMAK is a factor of two larger than TFTR in linear dimension but is about the same size as several designs for reactors to follow TFTR. Thus, no sharp scale-up in size beyond TFTR appears necessary to achieve an interesting reactor product.

I. 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 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

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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 section II, additional aspects are described in section III, and a summary with comments is given in section IV. The relationship between NUWMAK and near term tokamaks such as TFTR (the Tokamak Test Reactor), is also discussed in the last section.

II. KEY FEATURES OF THE NUWMAK DESIGN

The major parameters characterizing the NUWMAK design are listed on Table 1, a top view of the machine is shown in Fig. 1, and a cross section view is given in Fig. 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).

a. The Toroidal Field Magnet Design

The NUWMAK toroidal field system design is unique and consists of just eight superconducting coils (see Fig. 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 the plasma edge. They are located directly behind the blanket (see Fig. 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 1.

b. 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. 2) are cryogenic aluminum (not superconducting) so that these can be disconnected and removed. A sequence illustrating the removal of a blanket segment is shown in Fig. 3. The maximum weight moved per segment is just 3 tonnes.

A major advance in the NUWMAK design is the independent removability of the OH and TF coil systems.[9] 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 accessibility and the potential for good maintainability. It need not consist of interlocking rings and an inaccessible blanket and ohmic heating coil system.

c. 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

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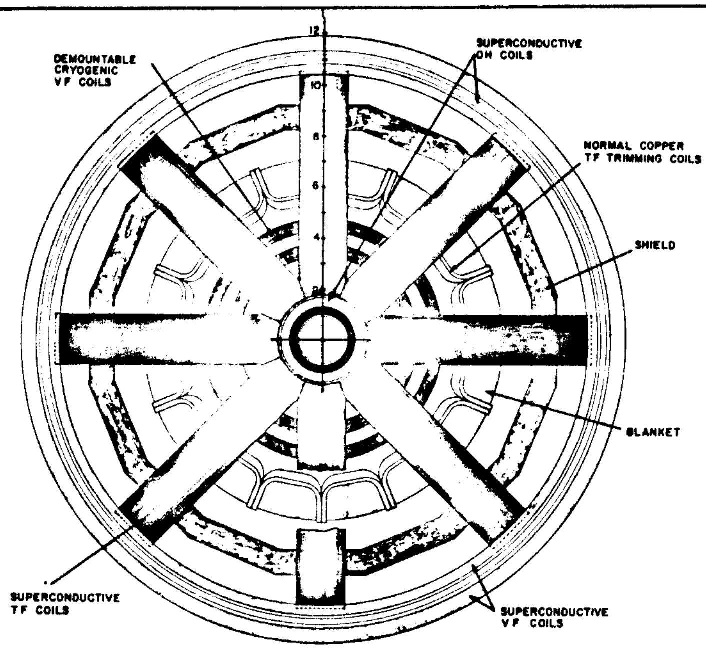

FIGURE 1. A top view of NUWMAK showing the large space between superconducting coils for access, the simple block shield design, and the location of the normal water cooled copper trim coils.

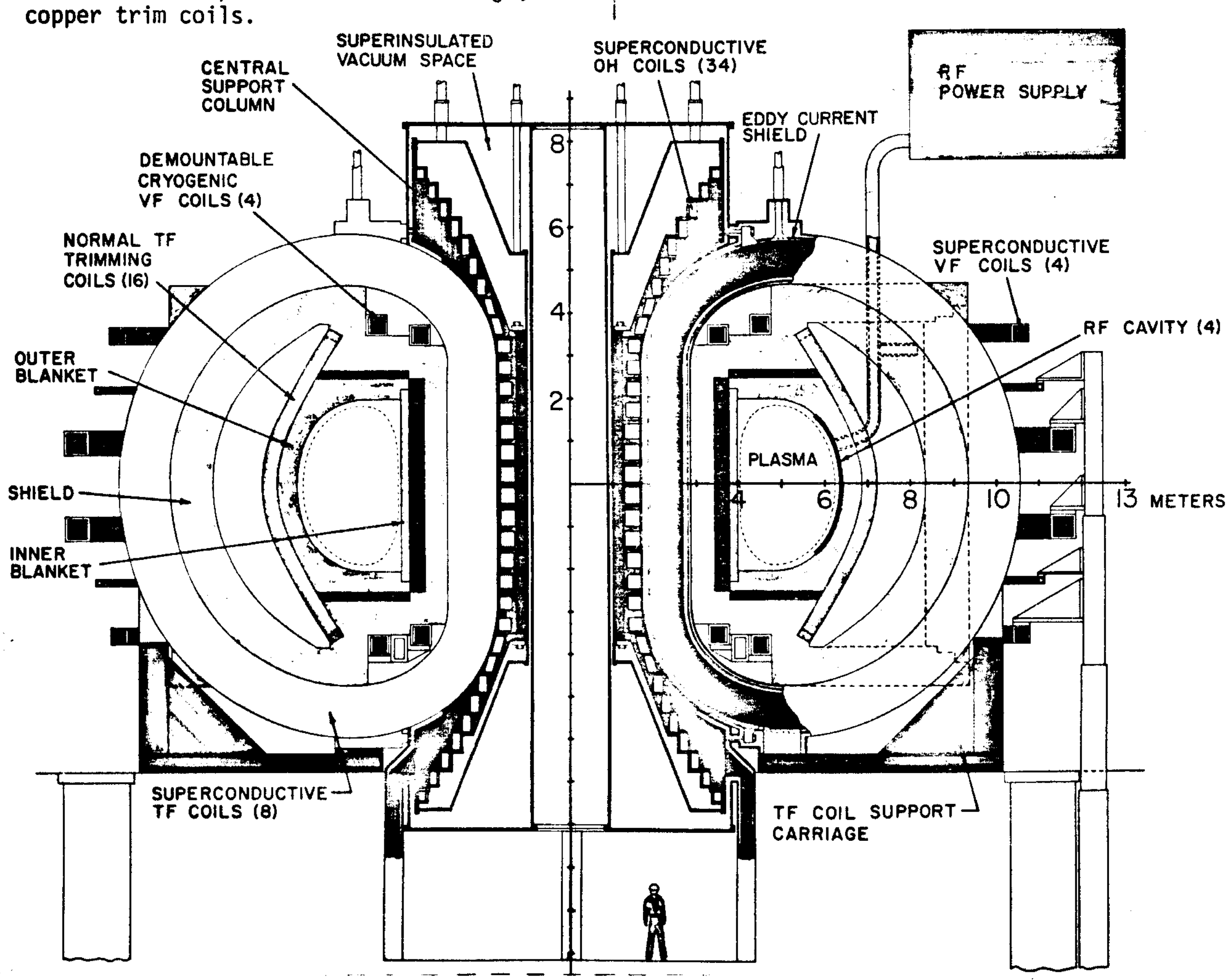

FIGURE 2. Cross section view of the NUWMAK tokamak.

TABLE 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%
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%
$n_e \tau_E (cm^{-3}\text{-}s)$	2×10^{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	4×10^4g
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	16
Max. Field Ripple	<2%

TABLE 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
Addition Pumping & OH Coil Reset	5
Total Cycle Time	
Cycle Duty Factor	0.91

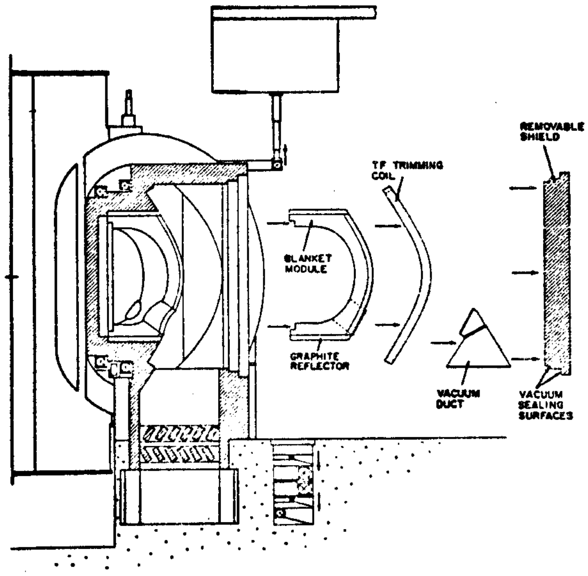

FIGURE 3. Sequence of steps involved in blanket module removal.

fatigue lifetime. Also, the resistance to radiation damage appears promising and while no high neutron fluence data exists, no void swelling in either neutron irradiation or heavy ion simulation 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 suggests 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 producion.

Titanium alloys are also advantageous from the viewpoint of long term induced radioactivity.[10] 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 time activity is dominated by ^{26}Al($t_{T/2}$=8x10^5 y) but this should not prevent recycling or simple disposal.[11]

d. Isothermal Blanket Design with Internal Energy Storage

The blanket design[12] 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. 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 2. The plasma current rises in 7 seconds

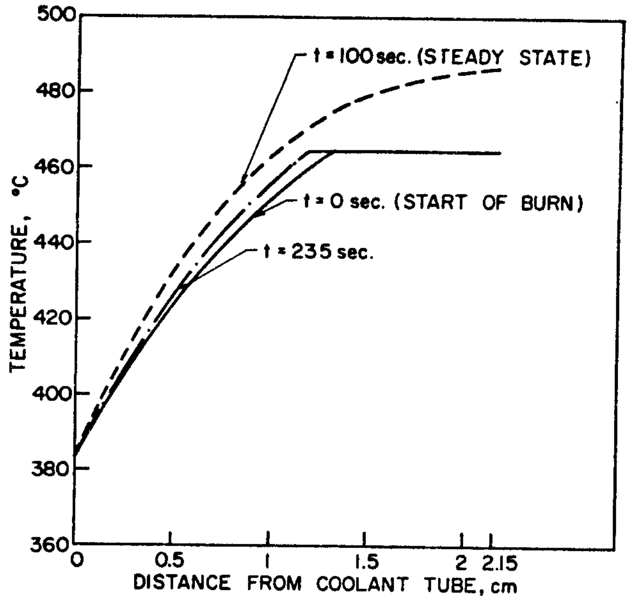

FIGURE 4. The variation in the temperature distribution in the Li-Pb eutectic from one cooling tube to the symmetry point between tubes. The key point is that the heat flux to the tube, as measured by temperature gradient, does not change much at different times during the burn.

to 7.2 MA and RF heating ignites the plasma in 1sec. 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.

e. 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-ellipitically polarized. A cavity-backed aperture antenna is designed to couple the wave power into the plasma through the toroidal field.[13] The wedge shaped coxial cavity is flush mounted on the first wall as shown in Fig. 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 anomolous 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 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.

f. Plasma Operation Without a Divertor

The operation of long pulse or steady state toroidal fusion plasma 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 act 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 is 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 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 assuming 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 sharply peaked near the plasma center, drives a very sharp temperature gradient. These two effects combine to exclude impurities from the center.

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 the density profile relatively flat. (We find an actual density inversion near the edge

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which we allow to relax by stopping the gas flow.) The next 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 is accomplished by the inward flow of gas from the edge although this may be supplemented with pellet fueling, as has recently been discussed by Houlberg.[5]

g. Direct BWR Power Cycle

The use of boiling water cooling and internal blanket energy storage permits the use of a simplified power cycle modeled after the direct Boiling Water Reactor (BWR) approach.[12] A comparison of the power cycle normally designed for tokamaks with that of NUWMAK is shown in Fig. 5 and the average power flows are shown in Fig. 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. 5, particularly the intermediate heat exchanger and the hot and cold energy stores, will reflect favorably on system economics.

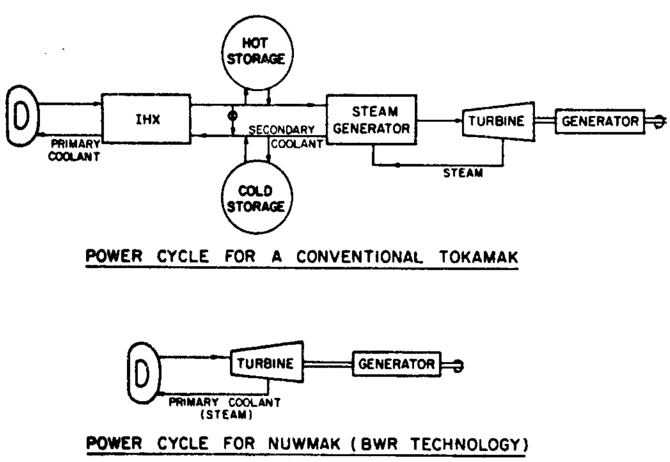

FIGURE 5. Comparison of a traditional tokamak power cycle design with that in NUWMAK.

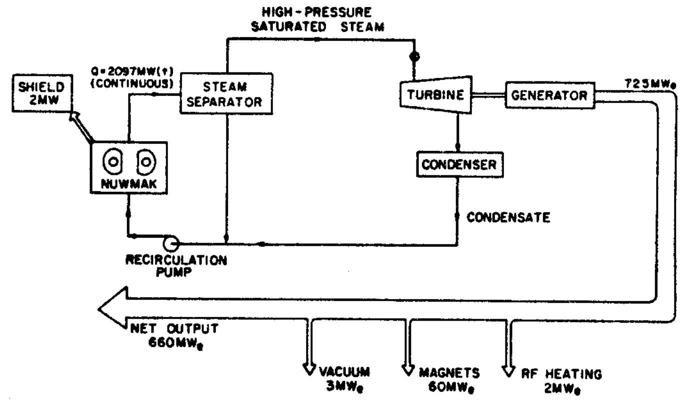

FIGURE 6. Power flow diagram for the NUWMAK system.

III. ADDITIONAL NUWMAK DESIGN CHARACTERISTICS

a. MHD Plasma Analysis and Vertical Position Control

The equilibrium plasma shape for NUWMAK has been determined from MHD calculations.[16] The final design requires just eight coils, four each above and below the plasma midplane (see Fig. 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. 7 and the 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. 8. q(r) exceeds 1 everywhere and q(a) at the plasma edge is 2.6. The sign of DI and DR also indicate stability. The average toroidal plasma beta is 6% and the average poloidal beta $\left(\beta_p = \frac{2\mu_0 \bar{p}}{\langle B_p^2 \rangle}\right)$ is 3.7. We have not used the PEST code[17] to test stability against ballooning modes but 6% toroidal beta is consistent with stable β values found in other

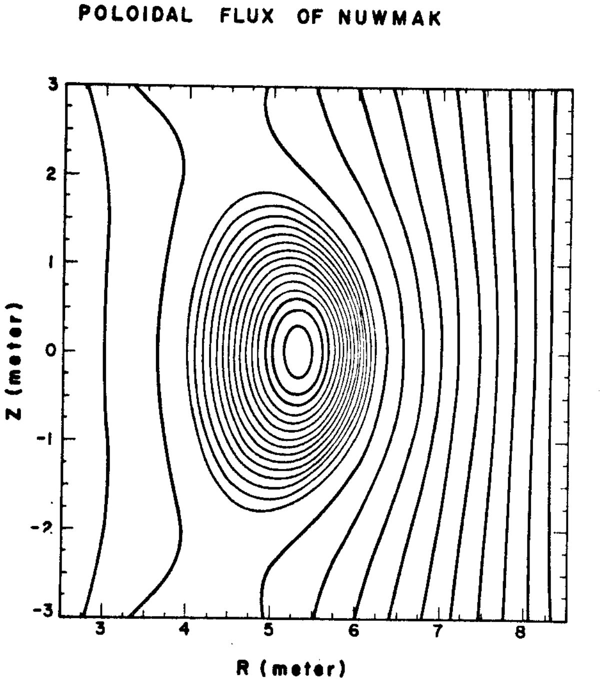

FIGURE 7. Poloidal flux surfaces calculated from MHD.

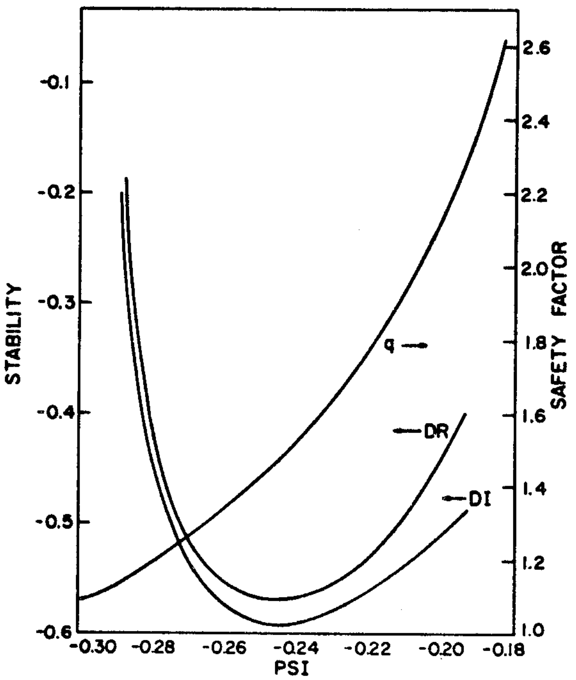

FIGURE 8. The profile of the safety factor, q(r), and the stability factors for ideal and resistive interchange modes, DI and DR as a function of plasma radius. All factors indicate stability.

similar cases.[17,18] 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,[19] 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.

b. Blanket Neutronic Analysis

A schematic of the blanket and shield design is shown in Fig. 9. The blanket has been analyzed

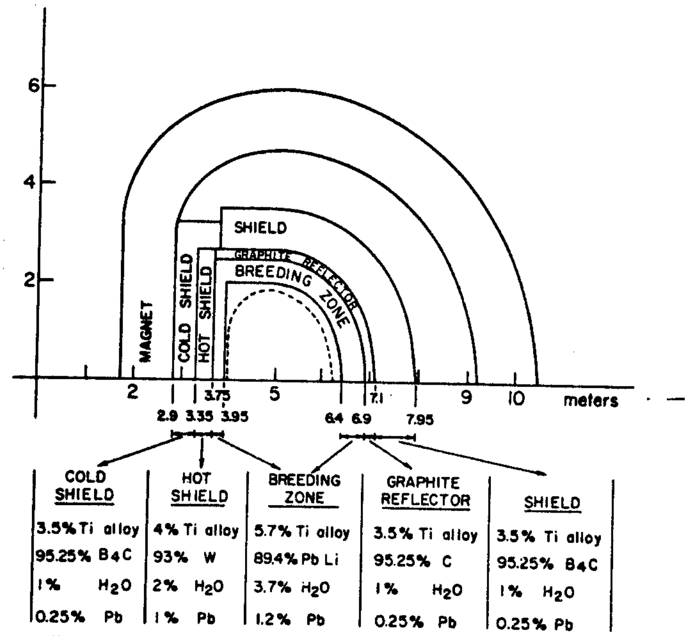

FIGURE 9. Schematic diagram of the blanket and shield design in NUWMAK.

using a two dimensional analysis to account for the poloidal variation in zone thicknesses and the different design of the inner shield.[20] 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 of the resistivity of the Al stabilizer; the dose limits of the superinsulation; and magnet heating. The most restrictive criterion is found to be the 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 shutdown for other reasons. As such, it is not expected that this procedure will cause a decrease in the overall plant availability factor. The estimated changes 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 1.6×10^7 rad/yr, the epoxy should last plant life. The remaining key neutronics parameters of NUWMAK are given in Table 3. 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,[21] 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.

TABLE 3. 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}

c. Blanket Tritium Analysis

The blanket in NUWMAK contains 8×10^5 kg of the eutectic 62 Li:38 Pb and has a very low steady state tritium inventory, only 800 g (1 wppmT). The resulting pressure of T_2 above the 62 Li:38 Pb is 5.9×10^{-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.[22,23] 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 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 (4×10^4kg) but the activity of Li in 62 Li:38 Pb at 464°C is only 0.6% of the activity of pure Li.[24-26] 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,[21] 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.

IV. 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 century. 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 tokamak as represented by the Tokamak Fusion Test Reactor (TFTR) and the Oak Ridge-TNS design.[27] Parameters for the ~~three devices are given on Table 4 and a pic~~torial size comparison is given in Fig. 10.

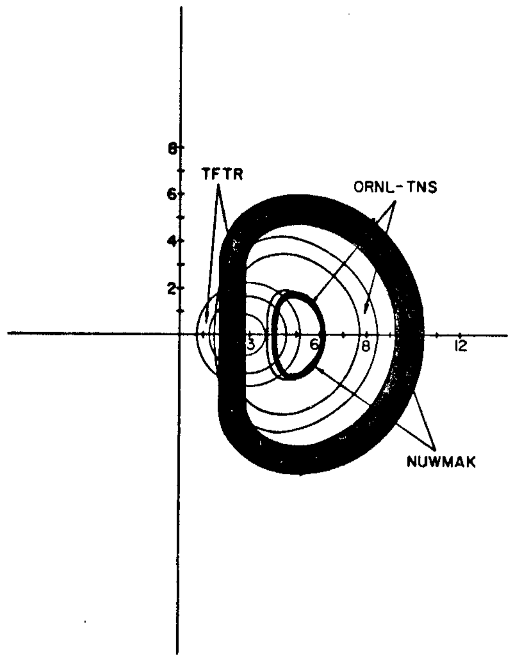

FIGURE 10. A size comparison of TFTR, ORNL-TNS and NUWMAK. NUWMAK is about twice the major radius of TFTR but no sharp size increase beyond TNS appears necessary.

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 scaleup from TFTR to the ORNL-TNS is primarily in size and to some extent in technology. Following TNS, however, a scale up in size does not appear to be necessary but a scale up in specific technologies can then produce an interesting reactor product.

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TABLE 4. 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	5-10 x 10^3 g