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CONCEPTUAL DESIGN CONSIDERATIONS FOR TOKAMAK FUSION REACTORS

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ABSTRACT

The general features of the UWMAK-I conceptual Tokamak fusion reactor are presented. UWMAK-I is a low aspect ratio (2.6), low field (B_T = 38 KGauss on axis), 5000 MW_{th} conceptual design with major radius 13m, plasma radius 5m, which is cooled with natural lithium and has 316 stainless steel as the basic structural material. An axisymmetric double null poloidal divertor is included for impurity control, and wall protection, the magnets are NbTi superconductor fully stabilized with copper and the power cycle is a Li-Na-steam system. Overall efficiency is ~30%. Specific results on neutral beam heating, microinstabilities and plasma thermal stability, neutronics, nuclear heating, materials compatibility and radiation damage, and induced activity are included. A discussion of the implications of our findings in these areas is presented.

I. INTRODUCTION

The conceptual design of a D-T fueled Tokamak fusion reactor, UWMAK-I, has recently been described in several papers.[1,2,3] We review in Section II the general features of this study. We then proceed in subsequent sections to discuss in greater detail certain specific problems and the implications of certain of the results. In particular, specific results on the following topics will be reported: in Section III, neutral beam heating of large Tokamaks; in Section IV, the impact of microinstabilities on plasma operation and thermal stability; in Section V, neutronics and photonics, including specific results on nuclear heating, gas production, and some general results and conclusions on induced radioactivity and afterheat; and in Section VI, materials compatibility and radiation damage to reactor structural materials of fusion systems. We close with a summary and discussion in Section VII.

II. OVERVIEW OF UWMAK-I

UWMAK-I (University of Wisconsin Tokamak) is a reference conceptual design of a deuterium-tritium fueled, 5000 MW_{th} (1500 MW_e) Tokamak fusion reactor. The basic system parameters are given in Table I together with specific parameters characterizing the plasma, the blanket and shield, the superconducting magnets, and the power cycle. A top and side view of the main design features are shown in Figures 1 and 2.

The system is a low aspect ratio, low field design which has an air core transformer. The transformer, divertor, and toroidal field coils are all superconducting. The reactor dimensions have been determined by optimization studies on the cost per unit power in a β-limited machine where the dominant costs are assumed to be in the toroidal field magnets. These costs were taken to scale as the energy stored in the field, which in turn varies approximate as the square of the magnetic field. The air core transformer with superconducting windings is found to be the design most consistent with the small aspect ratio demands of cost optimization. Figure 3 illustrates a typical optimization result. The maximum toroidal field at the coil is 86 KGauss and τ_B = 2.5 m is an assumed value for the size of the scrape off region around the plasma (50 cm in UWMAK) and the thickness of the blanket and shield. The results in Figure 3 do not include the constraint on core size, namely,

$$r_o + H + \tau_B + a \leq R$$

where r_o is the radius of the transformer windings, H is the combined thickness of the primary and toroidal field magnet windings, a is the plasma radius, and R is the torus major radius. For an air core transformer with superconducting windings, r_o can be computed from

$$\pi r_o^2 B_{sp} = \phi_c = L_p I_p/2$$

where B_{sp} is the superconducting primary field, and L_p and I_p are the plasma ring inductance and current, respectively. When this constraint is included, the optimum system occurs at somewhat larger aspect ratio,

TABLE I

A. General Characteristics of UWMAK-I

Power	5000MW$_{th}$ (1500 MW$_e$)
Major Radius	13 m
Plasma Radius	5 m
Fuel Cycle	D-T, Li
Divertor	Poloidal, Double Null
Coolant	Lithium
Structural Material	316 SS
Neutron Wall Loading	1.25 MW/m^2
Magnetic Field	3.8 T (on axis) 8.6 T (maximum)
Burn Time	5400 seconds
Recycle Time	390 seconds

B. Plasma Operating Parameters

Temperature	T_i = 11.1 KeV T_e = 11 KeV
Density	$n_i = 8 \times 10^{13}/cm^3$
Poloidal Beta	β_θ = 1.07
Toroidal Beta	β_ϕ = .052
Stability Factor	q(a) = 1.75
Z_{eff}	3.3
Fractional burnup	7.2%
Plasma Current	20.7 Mega-amps
Confinement Time	14 seconds
$\tau_c/\tau_{neoclassical}$	1/450
τ_c/τ_{Bohm}	400

C. Magnet Characteristics

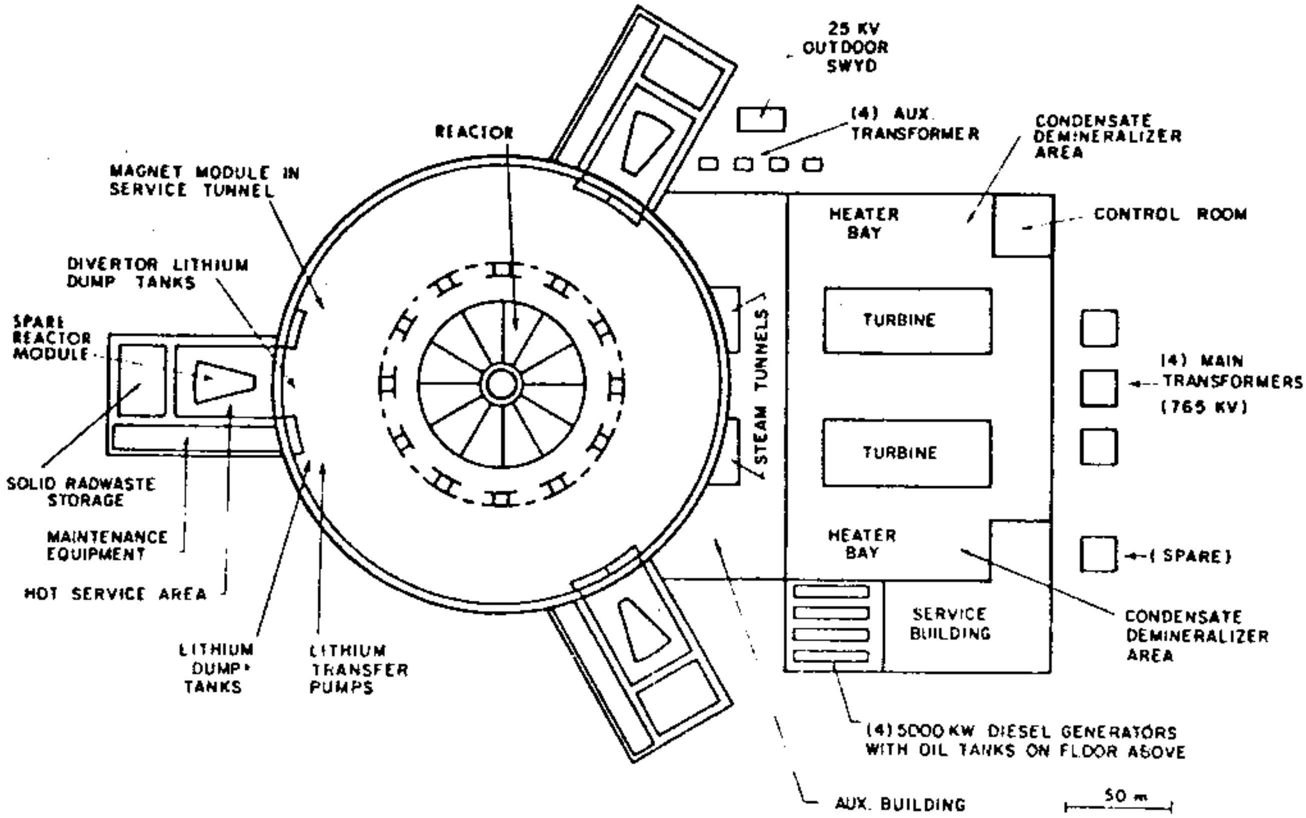
Minimum Bore Diameter	14.8 m
Maximum Field at S/C	8.66 T
Superconductor	NbTi
Stabilizer	Cu
Support Material	SS
Maximum Stress in SS	60 ksi at 4.2°K
Maximum Strain in Cu	.002
Total Amps per Conductor	10212
Conductors Per Disc	60
Discs per Magnet	34
Number of Magnets	12
Gross Current Density	1318 A/cm^2

D. Blanket and Shield Characteristics

Blanket Thickness	73.4 cm
Vacuum Gap	1.0 cm
Shield Thickness	77.0 cm
Total Energy per Fusion	20.08 MeV
Breeding Ratio	1.49
Doubling Time	2-3 mos.
Blanket Coolant	
Inlet Pressure	400 psig
Inlet Temp.	283°C
Outlet Temp.	483°C
Pumping Power	22 MW$_e$
Structure	
Max. Temperature	500°C
Max. Stress	11 Ksi
Corrosion Rate	1500-2500 kg/yr
First Wall Lifetime	2 years
First Wall Heat Load	12.5 W/cm^3
Shield Composition	30% B_4C 50% Pb, 20% 316 SS
Shield Coolant	He, 50 Atm.

E. Power Cycle

Primary Coolant	Lithium T_{max} = 483°C
Secondary System	Sodium T_{max} = 411°C
Turbine System	Steam T = 297°C
Circulating Power	125 MW
Overall Efficiency	30%



Top View of UWMAK-I Reactor Building

Figure 1

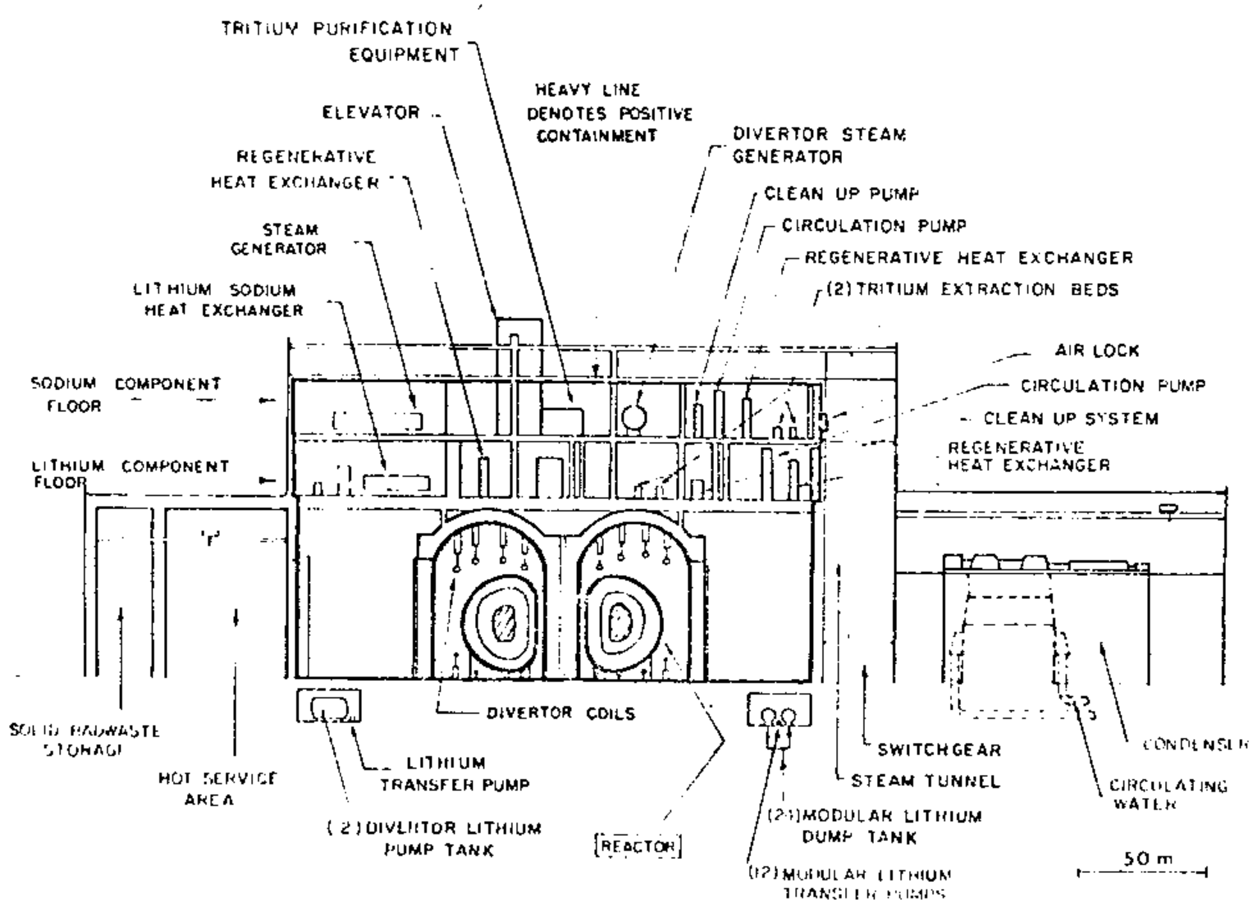


Figure 2

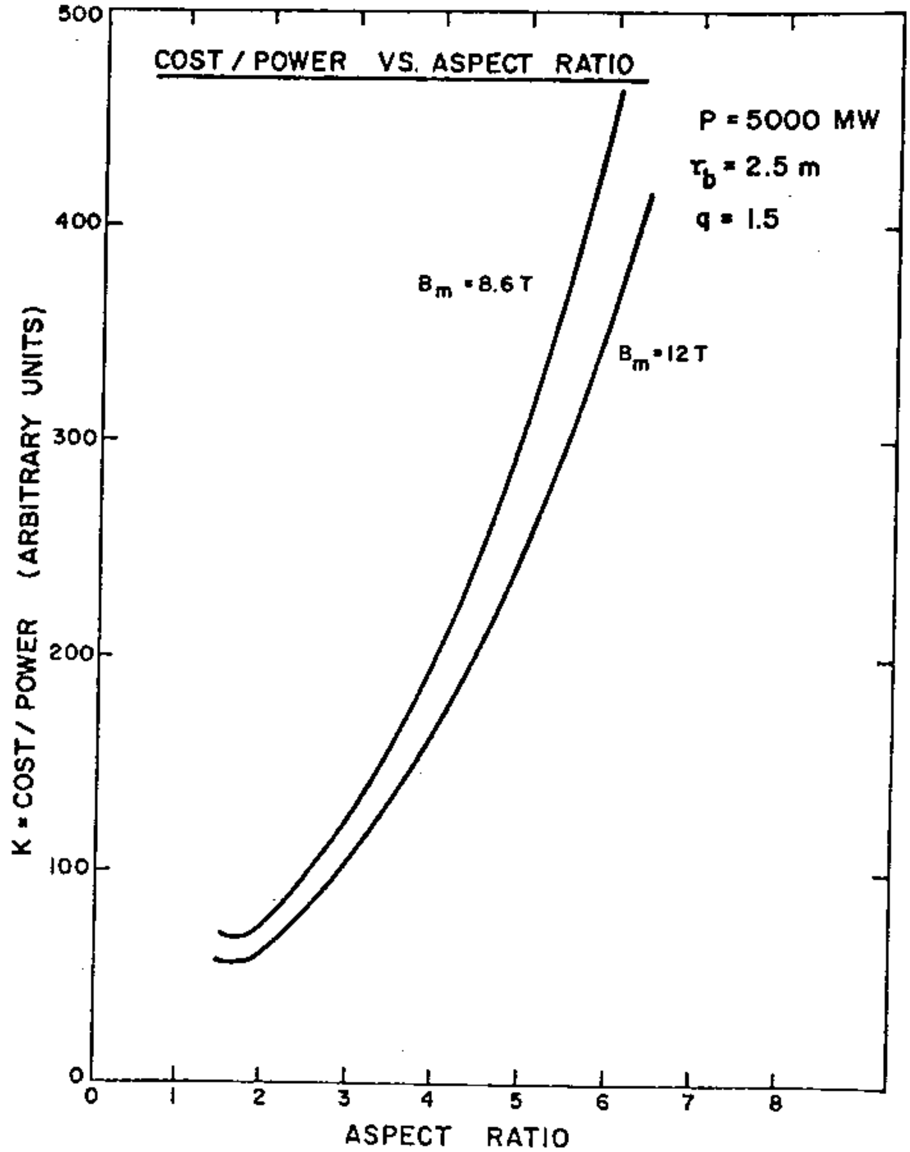
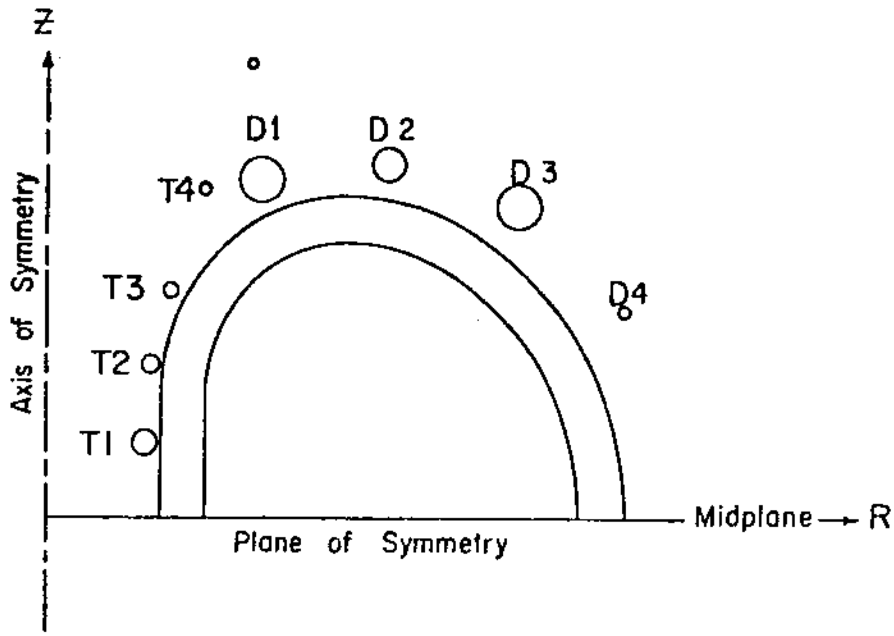


Figure 3

the curve being quite flat from 2.3 to 2.5. We have chosen A = 2.6 to provide some extra core space.

For reactor startup, the transformer and divertor coil currents are programmed to induce the plasma current by producing a time changing flux through the plane of the plasma. The placement of the transformer and divertor coils and the current carried by each coil is shown in Figure 4. For UWMAK-I, the divertor actually provides 60% of the flux needed to energize the plasma current so that the transformer proper



	Coil No.	R(m)	Z (m)	I (10^6 amp)
Divertor	D 1	8	13	+ 24.0
	D 2	13	13.5	+ 12.0
	D3	.18	12	− 24.0
	D4	22	8	− 2.4
				ΔI (10^6 amp)
Transformer	T1	3.9	3.0	− 10.47
	T2	4.3	6.0	− 9.07
	T3	4.9	8.9	− 7.07
	T4	6.1	12.7	− 6.55
	T5	8.0	17.3	− 4.97

Figure 4

need provide only 40%. The current in the plasma rises in a controlled manner to its operating value of 20.7 Mamps in 100 seconds. A total of 430 volt-seconds are required to energize the plasma current. After the poloidal field of the plasma soaks through the surrounding structure, an extra 330 volt-seconds is provided, assuming the resistivity is anomolously high by a factor of 3.5 relative to the Spitzer value, to give a burn time of 90 minutes.

The operating cycle of UWMAK-I is given in Table II. The burn time of 5400 seconds (90 min.) compares with a total recharge time of 390 seconds (6.5 min.). This gives a duty factor of 93.3% for the operating cycle. However, the plant factor is closer to 80% when scheduled and unscheduled outages are included.

TABLE II

Start Up, Burn and Shut Down Sequence for UWMAK-I

Time-Sec	Event
0-100	Gas Breakdown, Current Rise Phase, Ohmic Heating
100-111	Heating by Neutral Beam Injection to Ignition
111-120	Increase to Full Power from Ignition
120-5520	Thermonuclear Burn, Pellet Fueling
5520-5530	Plasma Cool Down by Impurity Injection
5530-5630	Shut Down Plasma Current and Reverse Transformer and Divertor Coils
5630-5680	Exhaust Chamber
5680-5780	Complete Current Reversal in Transformer
5780-5790	Purge Residual Gas - Refill with Fresh (D+T) Fuel

The coolant, moderator, and breeding material has been chosen to be lithium. Liquid metals have been shown to be efficient heat transfer fluids at high temperature and are not subject to radiation damage. It was originally thought that a major disadvantage of moving an electrically conducting fluid through high magnetic fields would be the high MHD pumping loss. However, by clever design(4), this pumping power requirement can be as little as 1-2% of the gross plant output which is actually less than is required for gas cooling. The use of liquid metals also reduces the stresses in the reactor walls (e.g. lithium pressure of 400 psi vs helium pressure of ~750 psi for helium gas cooling). Finally, the use of Li as a coolant also greatly improves the tritium breeding in a Tokamak reactor. One real disadvantage of Li is that when used with austenitic steels or nickel base alloys, lower operating temperatures are required because of excessive corrosion(5). Nevertheless, the decision was made to use Li in UWMAK-I and subsequent studies will investigate alternate coolants.

The structural material chosen for UWMAK-I is 316 stainless steel. This choice is consistent with our design philosophy to use present day technology whenever possible. The steel industry has a long established record of providing large quantitites of high quality fabricated components. Recently the quality assurance procedures of the industry have been upgraded further to produce nuclear grade components for the LMFBR program. There is a wealth of thermal, mechanical, chemical, neutronic, physical and economic data on 316 SS both in liquid metal and irradiation environments. No such extensive data exists for refractory metals nor is there an established industry for these metals at the present time or in the foreseeable future. The choice of a 316 SS-Li system appears to limit the operating temperature to 500°C because of corrosion, but if that were not the case, a maximum temperature of 650°C could not be exceeded because of excessive creep. Hence, our design philosophy has been to limit the 316 SS temperature to <500°C at all points in the reactor. Such a decision means that the efficiency of the reactor will probably be limited to ~30%.

Consistent with a conservative design philosophy, a decision was made to use NbTi superconductors because of the ductility and ease of fabrication. Such a decision limits the maximum magnetic field in the superconductor to <90 kG at 4.2°K and to <40 kG on axis of the plasma because of the geometry of the reactor. The magnets are cryogenically stabilized with copper in order to insure high realiability.

Finally, the power cycle consists of a lithium primary coolant which transfers its energy to a sodium secondary loop. The sodium in turn is coupled to a conventional steam turbine system.

III. NEUTRAL BEAM HEATING STUDIES FOR UWMAK-I

The energy and power requirements for a neutral beam injection system capable of heating a reactor size plasma such as UWMAK-I to ignition has been studied by McAlees and Conn[6] of our group. The space-time evolution of the plasma parameters during the beam heating phase is simulated by a two fluid numerical model which accounts for electromagnetic field diffusion and energy flows within the plasma. The electron-ion fluid model accounts for diffusion, heat conduction, electron-ion rethermalization, bremsstrahlung and synchrotron radiation, ohmic heating, thermonuclear alpha particle heating and heating by means of injected power. The governing equations for the system are written in cylindrical coordinates and depend only on the minor radius, r, and the time, t. Toroidal transport coefficients, accurate to first order in $\varepsilon = 1/A$, the inverse aspect ratio, are used. It is still uncertain which theory describes present day experiments and whether or not direct scaling of any existing theory to large plasmas is appropriate. We have therefore assumed the electron heat conduction coefficient is pseudoclassical[7,8] and the ion heat conduction coefficient is taken as the banana regime of neoclassical theory[9]. The particle diffusion coefficient, $D_\perp$, can be assumed zero for large plasmas. This simplification is justified by estimating the particle confinement time as $\tau_p \simeq \frac{a^2}{4D_\perp}$. Based on the initial plasma conditions and taking D to be pseudoclassical, typical particle confinement times are found to be greater than 50 seconds.

The energetic neutral beam injected into the plasma is assumed to be composed of a deuterium-tritium neutral of atomic mass 2.5. A single equivalent atom beam of zero cross sectional area (pencil beam) is considered. In practice, the required total power would be injected by several neutral beams, located symmetrically around the torus to minimize the disturbance of axisymmetry in the plasma. Rome, Callen and Clarke[10] have recently studied the injected energy density deposition rate profiles which result from finite beams. We find, using the computer code developed in their work, that the pencil beam approximation is accurate except in the region near the plasma center. The optimum choice for the angle of injection is not clear. However, injection nearly perpendicular to the toroidal field will result in fast ion production on trapped particle orbits that can have deleterious effects[9]. We have therefore chosen to inject tangent to the magnetic axis. The results of our study show that large Tokamak plasmas can be ignited at low density ($\sim 3 \times 10^{13}$ particles/cm^3) using moderate levels of neutral beam power and beam energies of several hundred KeV. In a reactor size plasma like UWMAK-I, a 500 KeV beam is adequate to ignite the plasma and yield non-inverted temperature profiles. Lower beam energies can also ignite the plasma and yield injected power deposition profiles that are peaked on axis. However, the heating rate in the plasma causes local maxima to occur in the temperature profiles in the outer zones of the plasma. The maxima develop because the injected power deposited per plasma particle depends on the density profile. Figure 5 shows beam energy depositions in the UWMAK-I plasma for three values of injection energy when the peak ion density is 3×10^{13}. This is less than the 1.2×10^{14} peak ion density during the burn time. A low density is used because beam penetration is enhanced while plasma losses are reduced. Therefore, a large system can be ignited in reasonable short times. For example, power levels on the order of 50 MW give ignition times in the 2 to 10 second range which are adequate for UWMAK-I. In smaller feasibility or reactor size plasmas, such as an a=200 cm system, approximately 10 MW of beam power is sufficient to ignite the system in about 2 seconds with 200 KeV beams, assuming the same scaling laws.

The time to ignite reactor size plasmas using a given beam power is found to be about the same where beam energies are in the range from 100 KeV to 500 KeV assuming the beam particles have an average mass. However, the final heatup rate of the plasma is sensitive to beam energy when a given power is injected for a fixed length of time. In particular, we have found that lower energy, less penetrating, neutral beams can actually produce faster plasma heating rates in some cases.(6) This is shown in Figure 6 where the heatup rate is given as a function of time for 75MW of power injected at 100, 350, and 500 KeV for 5 seconds. All three cases are ignited in the sense that the thermal content of the plasma increases in an accelerating manner when the beam energy input is terminated.

To avoid problems associated with inverted temperature profiles with shapes like the 100 KeV beam energy deposition profile shown in Figure 5, we chose a 500 KeV beam and 15 MW of beam power which will ignite UWMAK-I in 11 seconds.

IV. MICROINSTABILITIES AND PLASMA THERMAL STABILITY

In the early analysis of the plasma performance in systems like UWMAK-I, we employed neoclassical transport in the collisionless banana regime(9)

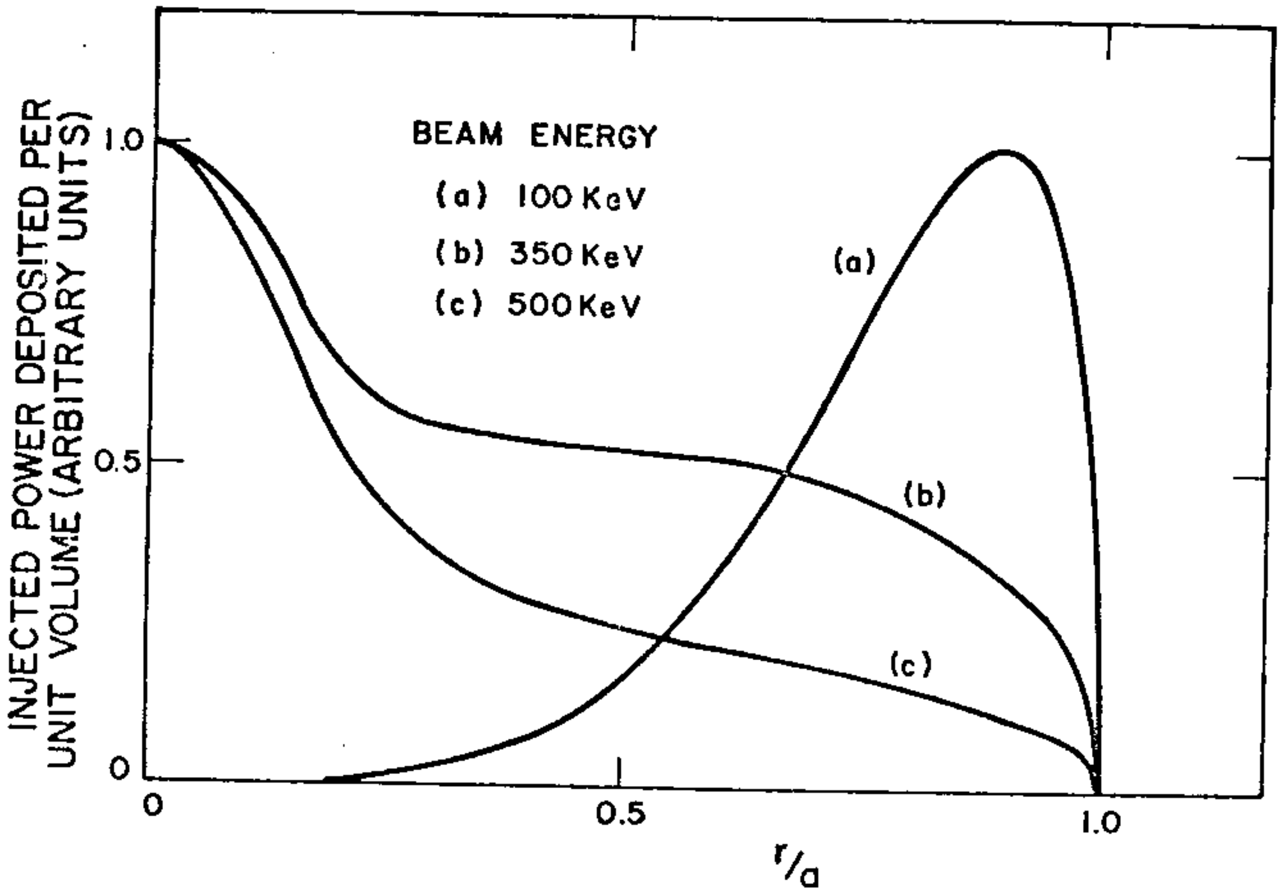


Figure 5

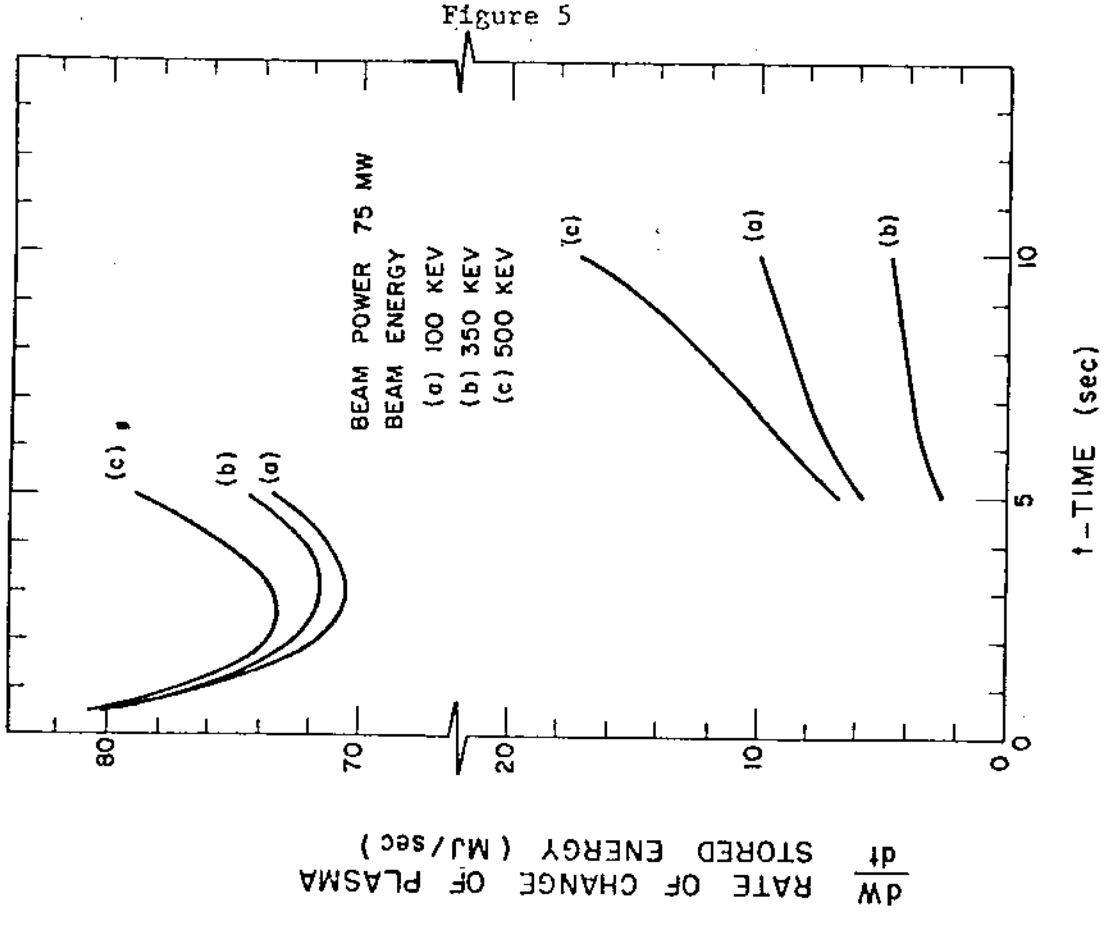


Figure 6

and found that the confinement times were much too long for reactor requirements.[11] An anomolous spoiling factor was used to scale the confinement time to lower values such that self-sustained plasma thermal equilibria could be found for temperatures in the optimum 10-20 KeV range. However, even with enhanced radiation losses, it was found that such anomolous classical scaling does not admit thermally stable equilibria in the desired temperature range[11]. The confinement time of 14.2 seconds listed in Table I, calculated from $\tau_p = a^2/4D$, is 450 times smaller than the neoclassical value but approximately 400 Bohm times.

Recently, Kesner and Conn[12] have considered the effects of trapped particle modes[13] on the thermal stability of reacting plasmas and considered the impact on UWMAK-I. It has been found that thermally stable equilibria can be found in the desired temperature range from 10 to 20 KeV.

Of the various trapped particle modes, the one most serious for reacting plasmas is the trapped ion mode. The predicted energy loss rate due to this turbulent mode is[14]

$$\frac{E}{T}\bigg|_{TIM} = 9.1 \times 10^2 \frac{b_T^2\ T^{9/2}}{I^4\ A^{13/2}\ q^4 Z_{eff}}$$

Here, I is the plasma current in mega-amps, b_T is 1/50,000 times the toroidal magnetic field in gauss, T is the plasma temperature in KeV (we have assumed $T_i = T_e$ in the reactor regime), A is the aspect ratio defined by A = R/a, a the plasma minor radius, and R the torus major radius. q is the MHD stability factor at the plasma edge and Z_{eff} is given by

$$Z_{eff} = \frac{\sum_i n_i Z_i^2}{n_e}$$

We note that this scaling law has <u>not</u> yet been verified experimentally and even if the scaling should hold, the numerical coefficients may be considerably different. The basic ideas presented here nevertheless remain qualitatively correct so long as the functional dependence of E/τ remains as in eqn. (1).

The value of the thermally stable plasma equilibrium temperature is shown in Figure 7 as a function of plasma current and machine size assuming q = 2, Λ = 3, a toroidal field of 50 KGauss, and an electron equal to 1. These points have been obtained assuming the trapped ion mode dominates all other loss mechanisms and is just balanced by alpha energy deposition. The temperature range of optimum power density is also shown. It is clear from these results that, given Z_{eff}, q, B_ϕ

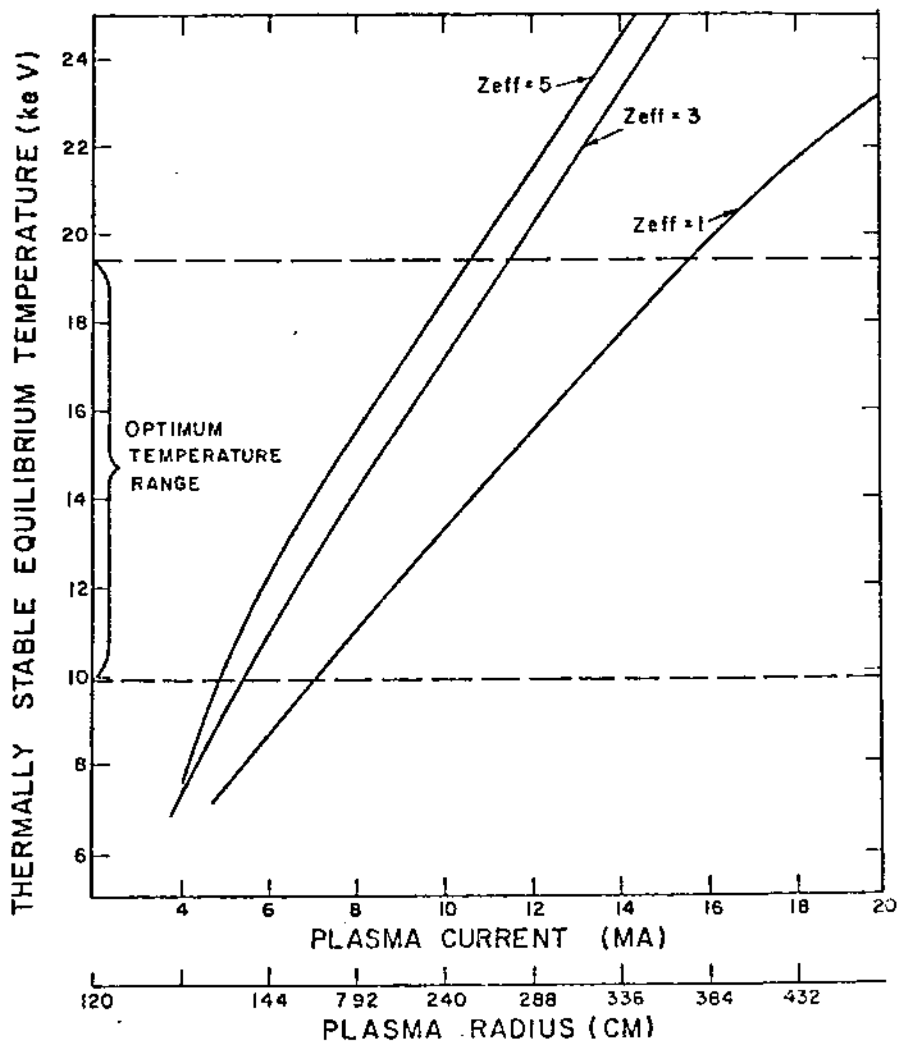


Figure 7

and aspect ratio, A, there exists only a limited range of plasma currents for which the plasma temperature lies in the optimum range from about 10 KeV to 20 KeV. This "current window" depends on the particular choice of q, B_ϕ, A, and Z_{eff}. Table III gives typical current windows for a typical choice of reactor parameters. As Z_{eff} increases, one is limited to smaller currents and thereby smaller machines. Also for given q, B_ϕ, and A, the existence of a "current window" for Tokamaks indicates a range of optimum size machines since I is proportional to $\frac{B_\phi a}{qA}$. In general, as Z_{eff} increases, the current window moves to lower currents implying the optimal sizes become smaller (and thus become lower power output machines). We note again that these quantitative results will shift if energy losses scale as the trapped ion mode formula but the numerical coefficient in eqn. (1) is different.

TABLE III

Optimum Current and Current Windows for Thermally Stable Plasmas in Tokamaks

Machine Parameters

A=3 q=2

$\beta_{pe}=1$ $B_\phi=50KG$

Zeff	Optimum Current † (MA)	Plasma Radius for Optimum Power Density (cm)	Current Window * (MA)	Plasma Radius Window (cm)
1	10	240	7.2 to 15.8	175 to 380
3	7.5	180	5.5 to 10.8	130 to 280
5	6.6	160	5.0 to 10.8	120 to 260

†Corresponding to a Plasma Temperature of 13.1 keV.

*Corresponding to a Plasma Temperature from 9.9 KeV to 19.4 KeV.

To determine the impact of such scaling on UWMAK-I, we have determined a thermally stable equilibrium for UWMAK-I values of q, β_θ A, B_ϕ(on axis) and plasma current. A thermally stable equilibrium producing 5000 MW_t occurs at a plasma temperature of 14.5 KeV for $Z_{eff}=1$. No impurities are purposely added to effect the power balance. The confinement time is approximately 3 seconds, which, since $\tau_E = \tau_p$, means an increased gas handling problem for the divertor. One can conclude that so long as the plasma can be fueled to maintain the particle density, trapped ion mode scaling can yield acceptable fusion plasmas in large Tokamaks. Also, since $n\tau_E \propto Z_{eff}$, some impurities that will inevitably enter the plasma will not necessarily be deleterious. On the other hand, the problem of impurity buildup in the plasma is difficult to assess. Collisional diffusion, such as neoclassical theory, predicts impurity buildup at the center. However, turbulent convective modes such as the trapped ion mode may take all species out at roughly the same rate. This remains to be assessed.

V. NEUTRONICS, NUCLEAR HEATING, AND INDUCED ACTIVITY

Tritium breeding in blankets cooled with liquid lithium appears to be no problem, as can be seen by the breeding ratio of 1.49 in UWMAK-I. A schematic of the blanket and shield is shown in Figure 8. Energy attenuation through the blanket and shield is ~4 x 10^{-6} MeV per incident MeV and the shield design has been optimized by considering shield costs,

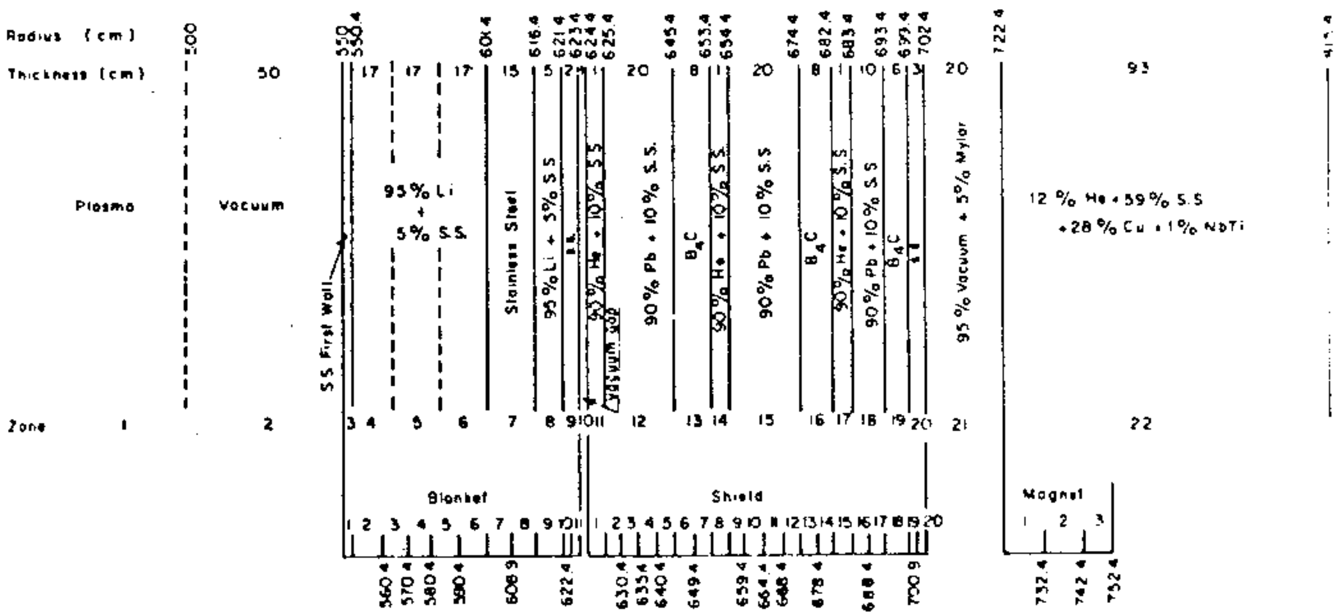


Figure 8 University of Wisconsin CTR Blanket, Shield and Magnet Structure for 5000MW$_T$ System. Note the Blanket, Shield and Magnet Zones on the Bottom. Used for Radioactivity and After Heat Calculations.

magnet costs, and refrigeration load. The blanket and shield thickness of 151 cm is thinner than most previous designs.

A comparative study of alternate structural materials, namely, Nb, V, or Mo, reveals that breeding will be more than adequate with 5% structure in the breeding zones. However, the breeding ratio drops below 1 in Nb systems at 15% structure in the breeding zones.(15)

Methods for calculating space dependent nuclear heating in fusion systems have been developed by Abdou and Maynard(16) and these results have shown that the total energy per fusion reaction is about 10% lower than the nominal value of 22.4 MeV often assumed in fusion work. This is particularly relevant since the reactor power is directly proportional to this value. The total energy production in UWMAK-I is 20.08 MeV per fusion event. This conclusion is supported by a recent comparative study by Abdou and Conn(17) in which the nuclear performance of several recently presented blanket designs is analyzed. The results on nuclear heating are given in Table IV for blanket designs presented by Fraas and Steiner of Oak Ridge(18), Price from Princeton Plasma Physics Laboratory(19), Lee from Livermore(20), and Powell et al. of Brookhaven.(21) The nominal value of nuclear heating is ~20 MeV. The somewhat higher values in the PPPL and BNL designs are due to the use of beryllium.

TABLE IV

Self Consistent Comparison of Nuclear Heating in Several Blanket Designs from Calculations by Abdou and Conn(17)

Design	Neutron Heating (MeV)	Gamma Heating (MeV)	Total Heating Including Alpha Energy (MeV)
UWMAK-I	12.43	4.13	20.08
ORNL	12.95	2.73	19.0
PPPL	12.88	4.99	21.4
LLL	12.18	3.61	19.2
BNL	15.23	4.04	22.6

From other studies reported in detail in reference 1, we have also concluded that enrichment of natural Li in ^{6}Li does not significantly effect energy multiplication and, given that it is an expensive process, such enrichment does not produce an economic gain. For UWMAK-I, enrichment to 50% ^6Li increases the energy multiplication by less than 1% over the natural lithium case. The energy produced can be improved, however, by addition of Be in the blanket and this appears economical. For example, 4 cm and 10 cm of Be increases the total energy production by 9% and 19%, respectively. The additional costs appear to be less than half the decrease in cost per unit power.

The reflector in the UWMAK-I blanket is stainless steel rather than graphite. A steel reflector improves energy multiplication and energy attenuation. It also allows for a thinner reflector zone which makes the blanket and shield thinner and brings the magnets closer to the plasma, thus saving on magnet costs. The breeding ratio is lowered slightly but 1.49 for UWMAK is perhaps too high in any case.

Another area of considerable importance which we have studied is the gas production rates as a function of position in fusion blankets. In the first wall of UWMAK, the hydrogen production rate is 636 appm/year and the helium production rate is 298 appm/year. The implications of such high production rates on the materials in UWMAK-I will be discussed shortly (see also, reference 22).

The formation of radioisotopes in the blanket represents two potential hazards; radioactivity and afterheat. Table V summarizes the important radioisotopes produced per kW_{th} in UWMAK-I and their maximum permissible concentration (MPC) in km^3 of air per curie. A biological hazards potential (BHP) was calculated by dividing the activity by the MPC. The BHP's for 316 SS in Table V are compared to alternate materials for CTR blankets. It can be seen that 316 SS is considerably better than Nb-1Zr from the standpoint of BHP but that a V-20Ti system would be even more desirable. Detailed analysis of the specific radioisotopes and their half lives are examined in References 1 and 23.

The decay of the radioisotopes mentioned above generates heat that must be dissipated to avoid severe temperature problems in the event there is a loss of flow of the coolant. For UWMAK-I, the afterheat after 2 years

TABLE V

Major Radioactive Isotopes in UWMAK-I with Various First Wall Blanket Materials(a)

System	Isotope	$t_{1/2}$	Activity Ci/kW_{th}	Maximum Permissible Concentration $\mu Ci/cm^3$	Biological Hazard Potential km^3 of air/kW_{th}
Fusion-all(c)	H^3	12.3y	60	2×10^{-7}	0.30
316 Structure only	V^{49}	331d	0.67	1×10^{-10}	6.7
	Fe^{55}	2.94y	140	3×10^{-8}	4.6
	Co^{58}	27d	29	2×10^{-9}	14.5
	Ni^{57}	1.5d	1.1	1×10^{-10}	11
	Mn^{54}	313d	24	1×10^{-9}	24
	Co^{60}	5.25	4.7	3×10^{-10}	15.6
Total(d)			~310		~80
Nb-1Zr Structure	Nb^{92m}	10.2d	152	1×10^{-10}	1,520
	Nb^{95m}	3.75d	50	1×10^{-10}	500
	Nb^{95}	35d	42	3×10^{-9}	14
	Sr^{89}	54d	38	3×10^{-10}	126
Total(d)			~300		~2,200
V-20Ti	Sc^{48}	1.83d	12.1	5×10^{-9}	2.5
	Ca^{45}	152d	2.6	1×10^{-9}	2.6
	Sc^{46}	85d	1.87	8×10^{-10}	2.3
	Sc^{47}	3.4d	1.58	2×10^{-8}	0.079
Total(d)			~56		~9

(a)Neglect all isotopes with $t_{1/2} < 1$ day

(b)10 year exposure

(c)Assume total point inventory at 30 kg (13.5 kg in reactor and 16.5 kg external).

(d)Including isotopes not listed.

of operation at 5000 MW_t is ~29 MW. The activity remains relatively unchanged for 1-2 years until the ^{55}Fe ($t_{1/2}$ = 2.94 yrs.) decays away. The overall activity then decays away quite rapidly such that the total afterheat is less than 50KW in 100 years. From these considerations, we conclude that long term solutions to the concentration and storage of spent reactor components must be addressed further. As we will discuss next, the heat removal cells (approximately the first 30 cm of the blanket) will have to be removed due to radiation induced embrittlement. If this conclusion remains, methods of handling ~250 metric tonnes of 316 SS heat removal cells per year should be studied. On site storage may be feasible but central burial facilities should be investigated.

VI. RADIATION DAMAGE AND MATERIALS COMPATIBILITY

Radiation damage studies of the UWMAK-I blanket-shield-magnet combination revealed several severe problems. Table VI lists the major information from the present work. The most severe problem stems from the fact that the uniform ductility of the 316 SS first wall will be reduced below 1% in 2 years or less at a neutron wall loading of 1.25 MW/m^2. (see also, Kulcinksi et al.[22]) Such a conclusion stems from the displacement damage alone and does not account for the effect of 298 atomic parts per million per year of helium nor the 636 appm per year of hydrogen generated in the 316 SS. This reduction in ductility extends back into the Li header and reflector region, which are 20-50 and 50-65 cm, respectively, from the first wall. It appears that the headers will have to be changed every 10 years and the reflectors every 15-20 years if one wishes to avoid costly failures during reactor operation.

TABLE VI

Major Radiation Damage Information for UWMAK-I

316 SS First Wall -	
Neutron Wall Loading	1.25 MW/m^2
Max. Displacement Rate	18.2 yr^{-1}
Max. He Production Rate	298 appm yr^{-1}
Max. H. Production Rate	636 appm yr^{-1}
Uniform Ductility After 2 Years	<0.5%
Max. Swelling for 2 Years	7.9% (ST 316 SS)
	0.25% (20% CW 316 SS)
Max. Wall Erosion Rate	0.22 mm-yr^{-1}
Max. Boron Atom Burn Up in B_4C	3.2×10^{19} $cm^{-3}yr^{-1}$
Superconducting Magnets -	
Max. Change T_c in NbTi	<1°K (30 years with periodic warm up)
Max. Change J_c in NbTi	<5% (30 years with periodic warm up)
Cu Stabilizer	6×10^{-5} dpa yr^{-1}
Max. Exposure to Mylar Insulation	2.8×10^4 Rad yr^{-1}

Swelling in a solution treated 316 SS first wall of UWMAK-I due to the production of voids was calculated to be a maximum of 7.9% after two years of irradiation. If 20% cold worked 316 SS were used, the maximum swelling value would drop to 0.25%. Hence, we have decided to use the 20% CW 316 SS in the UWMAK-I design. Detailed calculations through the heat removal cells, the headers and the blanket reflector reveal that even with the use of cold worked steel, swelling values of >20% could be experienced in 30 years at 30 cm from the first wall. Thus, the coolant headers may have to be changed every 10 years and the reflectors every 15 years due to swelling as well as embrittlement.

Sputtering and blistering effects on the UWMAK-I first wall reveal no severe problems due to wall erosion if the first wall is replaced every 2 years. The total wall removal rates should not exceed ~0.44 mm in this time period. The major contribution to wall erosion is from the 14 MeV neutron sputtering that has been recently reported by Kaminsky et al.[24]

Investigation of radiation induced swelling in the B_4C, transmutation of the structural alloy, degradation of thermal and electrical insulating material and reduction in superconducting properties of NbTi reveal minimal effects. Some concern arose about increased resistance in the Cu stabilizer due to the accumulation of point defects at low temperatures, but proper design and periodic annealing at room temperatures can alleviate those problems.

Another severe limitation on the UWMAK-I system is due to materials compatibility problems between lithium and stainless steel. High corrosion rates between 316 SS and lithium has dictated a maximum operating temperature of 500°C.[5] Even with this limitation, it has been calculated that as much as 1500-2500 kg of steel may be dissolved into the lithium per year. Such a large amount of corrosion product could represent a problem in the fouling of heat transfer surfaces, the deactivation of tritium extraction beds or the actual plugging of tubes in heat exchangers. Even more serious is the fact that a large amount (~10%) of the corrosion product will come from the first wall and therefore is highly radioactive. High radiation levels in loops outside the reactor may severely hamper normal maintenance.

It must be noted that even those materials which exhibit good corrosion resistance may cause high radioactivity levels in the coolant. Such activity could come from neutron sputtering of the first wall into the coolant. It has been calculated, strictly on the basis of high 14 MeV sputtering yields(24), that this mechanism could contribute up to 50% as much radioactivity as chemical corrosion alone. This needs to be investigated experimentally.

Finally, there is clearly room for ingenuity in the blanket and shield design. Clever assembly and disassembly schemes, methods of detecting leaks once they form, and mechanisms for shutting the reactor down quickly and safely are required.

VII. SUMMARY

We have presented a synopsis of the UWMAK-I conceptual Tokamak reactor design(1-3) and presented specific details on analyses in the following areas: neutral beam heating; microinstabilities, scaling, and thermal stability; neutronics, nuclear heating and induced activity; and radiation damage. A number of important topics in fusion technology which were considered for UWMAK-I but not described here can be found in reference 1. Such areas include structural design, magnet design, tritium handling, safety, divertor design, startup and other plasma physics considerations, and so on.

We would, however, like to conclude by noting that, overall, most of the technological problems posed by Tokamaks as fusion reactors appear to be solvable within reasonable extensions of existing technology. The two general problem areas which cannot be categorized this way and which have large remaining uncertainties relate to materials, particularly first wall problems, and plasma physics and plasma technology, including scaling, impurity control, and fueling. A list of problem areas is given in Table VII which fall in these two general categories. We would conclude, therefore, that while many of the identified technological problems appear solvable, major advances are required in the state of plasma physics and certain reactor technology problems before a reactor such as UWMAK-I could be built. On the other hand, it is noted that the real usefulness of such a conceptual design effort lies not with the hope that such a system will actually be built, but rather in focusing attention on areas of technology that require further work before meaningful reactor studies can be truly completed.

TABLE VII

Areas Within Extendable Technology	Areas with Large Uncertainties
. Multi-Ampere, Megawatt Neutral Beams	. Plasma Startup and Scaling
. Lithium-Stainless Steel Systems	. Impurity Control
. Tritium Breeding, Extraction and Leakage	. Fueling, Long Burn Times
. Modular Design; System Disassembly	. First Wall Life; Materials
. Large NbTi S/C Magnets	. Large Nb_3Sn S/C Magnets
. Energy Storage and Transfer	. Unstable Magnets
. Afterheat and Radioactivity	
. Power Cycle	

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