The Conceptual Design of a Tokamak Fusion Power Reactor, UWMAK-I

G.L. Kulcinski and Robert W. Conn; Reported for the University of Wisconsin Fusion Feasibility Group

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Abstract

The design details of a low β, D-T fusion reactor based on the Tokamak confinement concept are described. The thermal output of the plant is 5000 MW_{th}. The basic structural material is 316 stainless steel and the coolant, moderator and breeding medium is liquid lithium. Materials compatibility limits the maximum coolant temperature to 500°C and the electrical output to 1500 MW_e. The ion temperature of the 5 meter radius plasma is 11.1 keV and the mean confinement time and fractional burnup are 14.2 seconds and 7.2% respectively. A double null poloidal divertor is used to protect the plasma from impurities. Cryogenically stabilized niobium-titanium superconducting magnets are used to provide a 3.82 Tesla field on the plasma axis. Neutron and photon transport calculations indicate the breeding ratio in UWMAK-I is 1.49 and doubling times may be as low as 2-3 months. The tritium leakage is 10.1 curies per day. The total energy per fusion neutron, including the 3.52 MeV alpha particle, is calculated to be 20.08 MeV. Radiation embrittlement of the stainless steel limits the first wall lifetime to 2 years while swelling and/or surface erosion limits the wall life to ~5 years. Radioactivity and afterheat calculations reveal that after 10 years of operation there will be 1.6 x 10^9 curies of activity and 31 MW_t of afterheat. It is concluded that even though the UWMAK-I is a relatively conservative design, major advances in the state of plasma physics and materials technology would be required before such a plant could be built.

I. Introduction

Scientists have recently become more and more optimistic about achieving a positive power balance from controlled thermonuclear reactions. However, such a momentous achievement does not automatically mean that the road to economic power generation will be assured. In order to aid in the assessment of the technological problems associated with fusion power, a group of scientists and engineers at the University of Wisconsin initiated a design study of a large electrical power generating station based on the Tokamak concept and fueled with deuterium and tritium. The goal has been to conduct a self consistent study from the standpoint of plasma physics, neutronics, materials, magnets, power cycle, environment, resources and cost. In this paper, we summarize the design features of a 5000 MW_{th} D-T Tokamak conceptual power reactor called UWMAK-I (University of Wisconsin Tokamak). A subsequent paper(1) in this volume will emphasize the major conclusions, implications and recommendations of this work. A much more detailed description of this study is described in a University of Wisconsin report(2).

II. Reactor Description

A. General Features

The UWMAK-I reactor has been designed with the philosophy that whenever possible, decisions should be made on the basis of a reasonable extension of present day technology. Such a constraint has produced a rather conservative design which may appear less efficient and perhaps more expensive than more advanced concepts[3-5]. The major design features of UWMAK-I are listed in Table 1.

Table 1

UWMAK-I Operating Characteristics

POWER	5000 MW_t 1500 MW_e
FUEL CYCLE	(D-T), Li
DIMENSIONS	R=13m, a=5m
DIVERTOR	POLOIDAL, DOUBLE-NULL
COOLANT	LITHIUM
STRUCTURAL MATERIAL	316 STAINLESS STEEL
NEUTRON WALL LOADING	1.25 MW/m^2
MAGNETIC FIELD	$B_t^\circ = 3.82$ T $B_t^{max} \cong 8.66$ T
MAGNETS(SUPERCONDUCTING)	NbTi (CRYOGENICALLY STABILIZED WITH Cu)
POWER CYCLE	Li-Na-Steam

The power level was limited to 5000 MW_{th} even though the electrical generation costs in the Tokamak reactors may be somewhat cheaper at higher power levels. It was felt that when fusion reactors might be introduced into electrical networks (~ the year 2000), units as large as 1500-2000 MW_e would be acceptable.

The choice of a D-T fuel cycle (as opposed to a D-D of $D-He^3$) stems from the belief that we will achieve the D-T reaction first because of its lower ignition temperature and because it returns more energy per unit of energy invested. Such a decision has a significant impact on the technological problems that need to be faced (e.g. radiation damage, need for lithium, tritium handling, etc.).

The size of the reactor was dictated by optimizing the cost per unit power in a β-limited system. The costs were assumed to scale as the superconducting magnet costs. Subsequent work reveals that when all of the non-nuclear component costs are included, this may be a very conservative constraint tending to make the unit power costs somewhat high. When the 5000 MW_{th} power level is coupled with a radiation damage limitation of 1.25 MW/m^2 neutron wall loading, an optimum aspect ratio of 2.6 is indicated. This aspect ratio is best satisfied with a plasma radius of 5 meters and major radius of 13 meters.

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 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, this pumping power requirement can be as little as 1-2% of the gross plant output which is actually less than 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

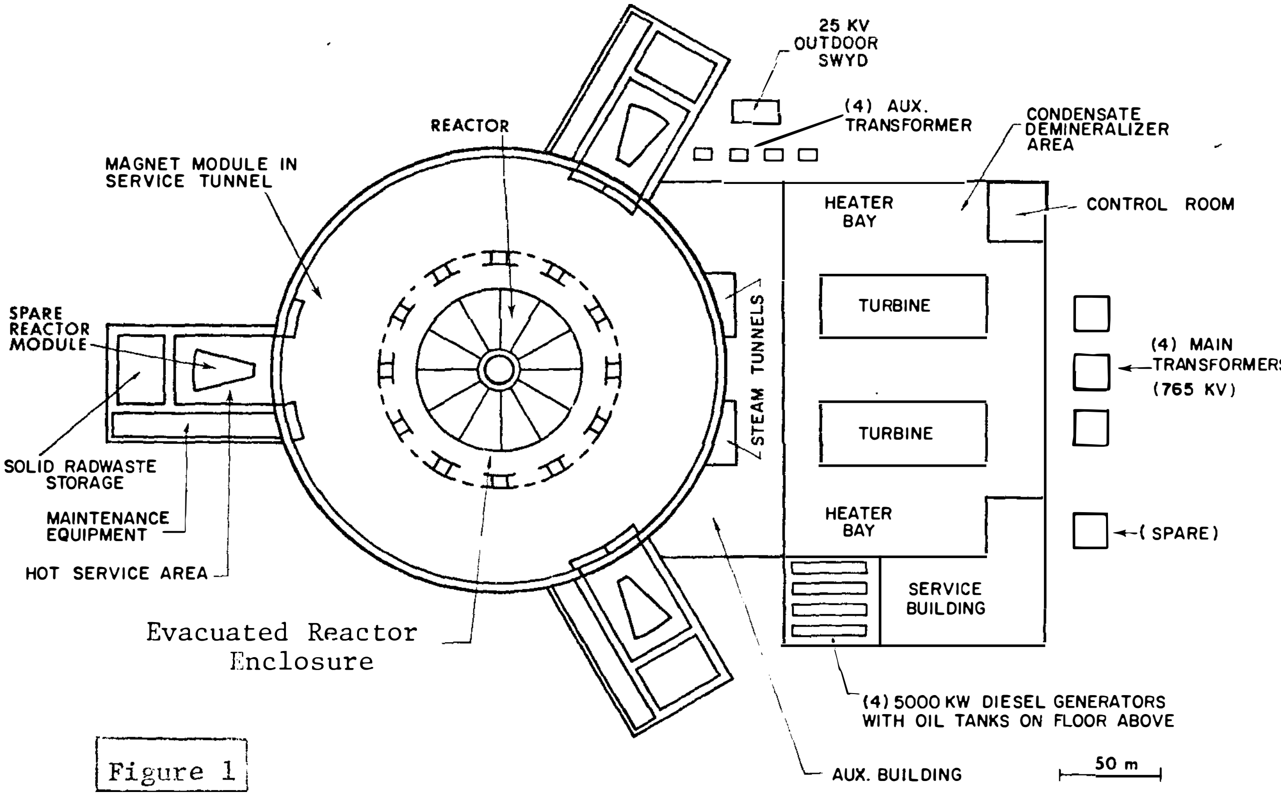


Figure 1

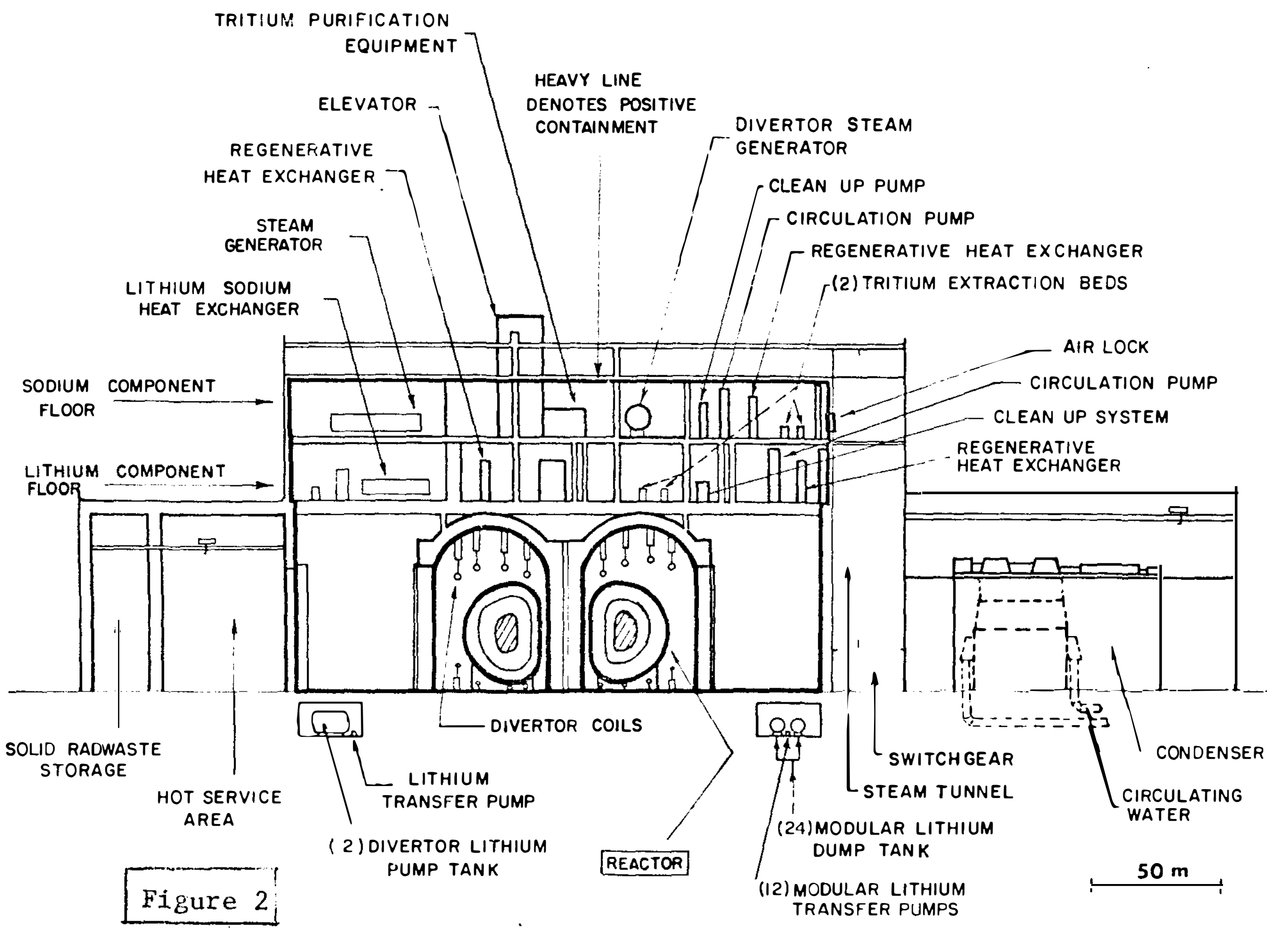


Figure 2

corrosion.[6] 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 quantities 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 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 their 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 the axis of the plasma because of the geometry of the reactor. The magnets are cryogenically stabilized with copper in order to insure high reliability.

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.

Overall plant views of the reactor building are shown in Figures 1 and 2 while Figure 3 shows a cross section view of the reactor and its associated transformer and divertor coils. The fine points of these figures will become apparent in the subsequent discussion.

B. Plasma Properties

The operating cycle of UWMAK-I is given in Table 2. 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 2

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

Reactor startup makes use of an air-core transformer with superconducting windings, (see Figure 3) a configuration most consistent with the small aspect ratio demands of the cost optimization. The transformer and divertor coil currents are programmed to rise with the plasma current producing a time changing flux

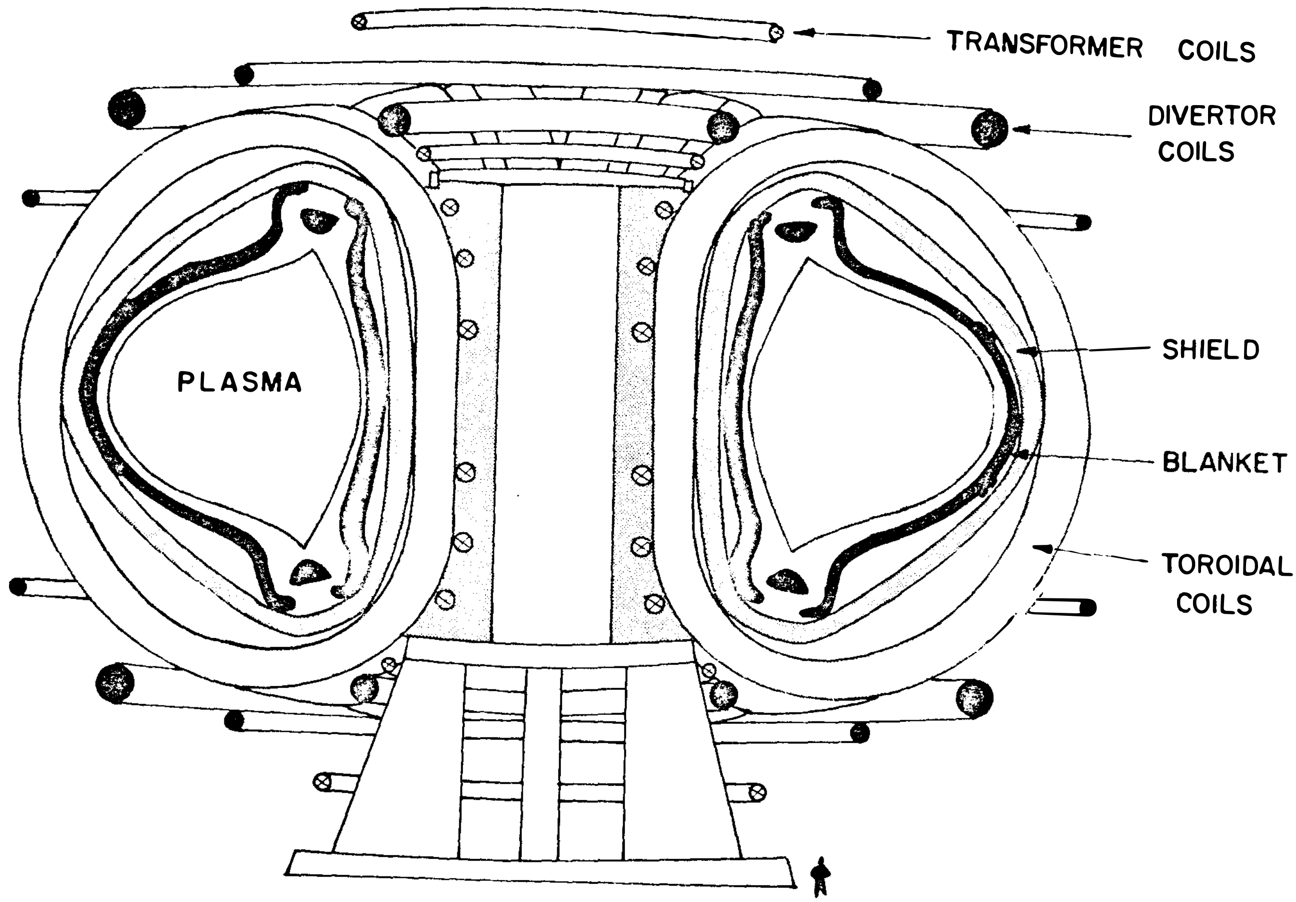


Figure 3 - Cross Section View of UWMAK-I Fusion Reactor

through the plane of the plasma. For UWMAK-I, the divertor actually provides 60% of the flux needed to energize the plasma current so that the transformer proper 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 current soaks through the surrounding structure, the core flux is held constant if there is a bootstrap current[7]. However, this has not been assumed in this work. Rather, the resistivity has been assumed to be anomolously high by a factor of 3.5 relative to the Spitzer resistivity. This implies an extra 330 volt-seconds for a 90 minute burn time and a total volt-second requirement of 760.

Plasma heating to ignition is via the use of neutral beams. Ohmic heating alone is insufficient. Neutral beams of 500 KeV injected tangent to the magnetic axis, penetrate the UWMAK-I plasma when a low density startup is used. The initial ion density on axis is $3 \times 10^{13}/cm^3$. With tangential injection, all beam particles are on circulating orbits following ionization. The profile of power deposition per plasma particle is peaked on axis. The beams are turned on immediately after the plasma current has risen to its final value. Using 500 KeV beams and 15 MW of power, the plasma ignites in 11 seconds. Faster start-ups can be achieved by using more power but this is not advantageous in UWMAK-I. In the 500 KeV beam case, 99.5% of the beam is trapped in the plasma. Thus, neutral beam heating appears to be an effective way to ignite a large, power producing reactor such as UWMAK-I.

Once ignited, the plasma is assumed to rise in ~10 seconds to the operating conditions listed in Table 3. If the scaling is quasi-classical (that is, the diffusivity varies as $T^{-1/2}$ but contains an anomolous multiplicative coefficient relative to the classical value of the diffusivity,) then plasma operation under these conditions is thermally unstable and requires feedback control. The anomolous factor, S = 450, in Table 3 is relative to the neoclassical value of $D_\perp$ at the plasma conditions listed. The confinement time has been obtained from $\tau = a^2/4D_\perp$.

Table 3

Operating Plasma Parameters for UWMAK-I

T_{ions} = 11.1 KeV	q(a) = 1.75
T_{el} = 11.0 KeV	a = 5m
$\bar{n}_{D+T}$ = 0.8 x $10^{14}/cm^3$	R = 13m
$\bar{n}_\alpha$ = .0295 x $10^{14}/cm^3$	r_w = 5.5m
$\bar{\tau}_c$ = 14.2 sec	A = 2.6
Confinement Spoiling Factor = 450	B^o_ϕ = 38.2 kG
Z_{eff} = 3.5	B_θ(a) = 8.4 kG
f_b = 7.2%	Plasma Vol. = 6400 m^3
$n\tau_c$ = 11.35 x 10^{14}sec-cm^{-3}	Chamber Vol. = 7750 m^3 (nominal)
$\bar{\beta}_\theta$ = 1.07	Wall Area = 2830 m^2 (nominal)
$\bar{\beta}_\phi$ = .052	I_ϕ = 20.7 x 10^6 Amps.

The UWMAK-I design imposes a conservative limit on $\bar{\beta}_\theta$ of one. Present experiments achieve a β_θ of about one-half and the recent low-aspect ratio, MHD equilibrium studies of Callen and Dory(9) give, as a best case, $\bar{\beta}_\phi$ ~0.1 and $\bar{\beta}_\theta$ ~ 2. For UWMAK-I, we have chosen values intermediate between these and somewhat arbitrarily used $\bar{\beta}_\theta$ ~ 1 and $\bar{\beta}_\phi$ ~0.05.

To achieve favorable operating conditions with quasi-classical scaling, energy losses from the plasma have to be increased via the addition of 0.95% argon impurity atoms. Further, as noted above, the average confinement time of ~14 sec is 2 orders of magnitude shorter than is predicted by neoclassical theory. Such reduction in confinement time, relative to neoclassical scaling, is required to both achieve a favorable power balance at T_i = 11.1 KeV, as listed, and to remove spent fuel (α-particles) so that a respectable D+T ion density can be maintained. For these operating conditions, the plasma is a low β ($\bar{\beta}_\phi$=0.052, $\bar{\beta}_\theta$=1.07), low field (B°_ϕ = 3.82 Tesla) reactor producing 5000 MW_T, based on a total of 20 MeV per fusion event. If the bootstrap current exists, the plasma is assumed to operate at these conditions until impurity buildup from wall erosion (because the divertor is not 100% efficient) causes excessive losses and requires shutdown and purging. Otherwise, the burn time is determined by available core flux to be 90 minutes.

The plasma characterized in Table 3 is assumed to be fueled during operation by injecting solid (D+T) pellets to make up for losses due to fusion and diffusion. The use of neutral beams for this purpose is highly questionable. Beam penetration is more difficult at the average operating density of 0.8 x $10^{14}/cm^3$ and further, the leakage rate of 3.6 x 10^{22} (D+T) ions/sec means that ~3000 MW_e of power are required when 500 KeV beams are used. Higher energy beams imply even larger power requirements are clearly not economical. Fueling is therefore assumed to be via pellet injection, using 20 micron radius pellets injected at the rate of 20 x 10^6 pellets per second, or 2mm pellets at the rate of 20 pellets per second. The former requirements are closer to current technology, assuming the plasma can withstand pellet injection in the first place.

At the end of the burn cycle, the plasma is quenched by injecting impurities for 10 seconds. After the power level is lowered, the currents are reversed in the transformer and divertor coils 100 seconds. The chamber will then be purged to remove unburnt fuel, helium "ash", and impurities over a 50 second period. Another 100 seconds is used to complete the current reversal in the transformer. A final 10 seconds is used to purge any residual impurities that have been collected during the current reversal phase. Refueling with fresh D+T will also be accomplished near the end of this 10 seconds.

UWMAK-I utilizes a double neutral point poloidal divertor generated by superconducting coils outside the toroidal D-magnets. (Fig. 3) The coil locations, currents, and separatrix (plasma boundary) are shown in more detail in Fig. 4. The particles diffusing from the plasma are collected by a flowing lithium surface with a trapping efficiency of 96%. The lithium flow down the face of a stainless steel plate, under gravity alone, and the flow rate of 10 kg/sec is such that no additional cooling of the backing plate is required. More details of this system can be found in Reference 2.

C. Magnet Design

The main toroidal field magnets are superconducting using NbTi cryogenically stabilized with copper. We have concluded that such fully stabilized magnets are the most feasible and that there is no need for unstabilized magnets. The NbTi filaments are contained in a large 2 cm x 2 cm conductor and the conductor is mechanically mounted, not loosely wound. Winding with wire or tape is very difficult for such large bore magnets. A list of the magnet characteristics are given in Table 4. It is concluded that gross current densities of ~1000 Amps/cm^2 are acceptable for at least 24T and that there is therefore no reason for the magnets to be unstable. Unstable magnets save only on the copper and would require a more expensive filament design.

Table 4

UWMAK-I Toroidal Magnet Characteristics

Minimum Bore Diameter	14.8 meters
Maximum Field at Superconductor	8.66 T
Superconductor	NbTi
Stabilizer	Cu
Support Material	Stainless Steel
Maximum Stress in Steel	4220 kgf/cm^2 (60,000 psi) at 4.2°K
Maximum Strain in Copper	0.2%
Total Amps per Conductor	10212 Amps
Conductors Per Disc	60
Discs per Magnet	34
Number of Magnets	12
Gross Current Density	1318 Amps/cm^2

The power supply for the transformer and divertor coils is a major cost item and has not yet been designed in detail. However, energy storage for 100 second pulses will probably be via superconducting magnets. The energy storage unit must supply 16 MW-hr and this will be coupled with a Graatz Bridge System to transfer this energy.

D. Blanket and Shield

The blanket of UWMAK-I is shown schematically in Figure 5 and the operating characteristics are listed in Table 5. It is 73.5 cm thick and separated from the 77 cm thick magnet shield by a 1 cm vacuum gap to allow for thermal insulation. The blanket is cooled with Li and the shield is cooled with helium gas.

UWMAK-1 DOUBLE NULL, POLOIDAL DIVERTOR

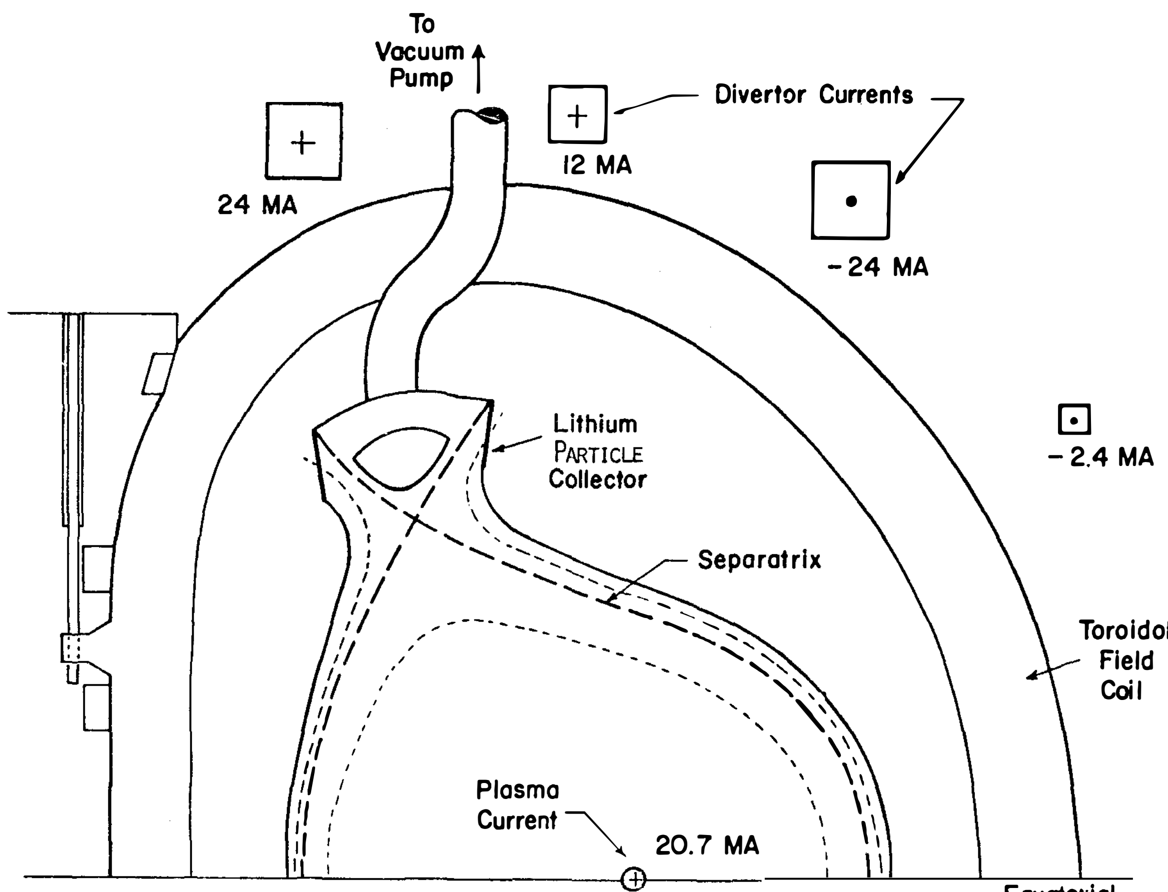


Figure -4

Table 5

Blanket and Shield Chacteristics

Dimensions -	
Blanket	73.4 cm
Vacuum Gap	1.0 cm
Shield	77.0 cm
Blanket Coolant -	Lithium
Pressure	28.1 kgf/cm^2 (400 psig)
T_{in}	283°C
T_{out}	483°C
Pumping Power	22 MW_e
Structure	316 Stainless Steel
T_{max}	500°C
Maximum Stress at t=0	914 kgf/cm^2 (13,000 psi)
Corrosion Rate	1500-2500 kg/yr
First Wall -	
Lifetime	2 years
Neutron Wall Loading	1.25 MW/m^2
Nuclear Heat Load	12.5 $watts/cm^3$
Shield -	
Composition	B_4C, Pb, 316 SS
Coolant	He, 50 atm, 200°C

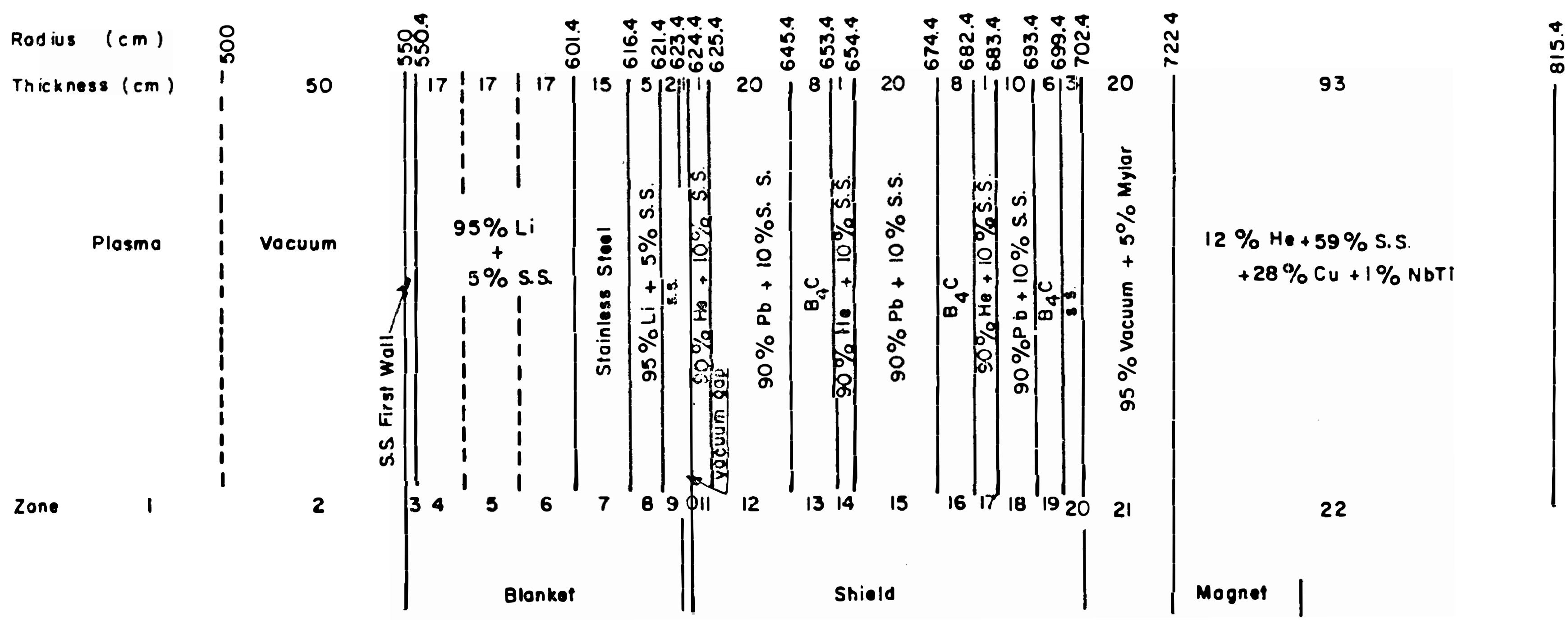


FIGURE 5 - Schematic of UWMAK-I Blanket, Shield and Magnet

The general flow pattern of the Li in the heat removal cells, which constitute the first 20 cm of the blanket, is perpendicular to the plasma as shown in Figure 6. The lithium enters the reactor at 283°C and leaves at 483°C. As stated previously, this relatively low temperature is dictated by the corrosion rate of Li on the structural material, 316 SS. The maximum operating temperature of the 316 SS is limited to <500°C and this means that 1500-2500 kg of metallic corrosion product must be removed from the primary lithium circuit per year. The coolant cleanup is necessary to avoid plugging the primary heat exchanger and high radioactivity levels in the maintenance areas(6). The maximum pressure in the Li coolant is 28 kgf/cm^2 at the reactor inlet and drops to 21 kgf/cm^2 at the first wall of the blanket. The total power required to pump the Li is 22 MW_e, or ~1.5% of the plant output. This number is quite low due to the present flow design which reduces the average coolant velocity and avoids excessive eddy current losses.

The first wall of the UWMAK-I blanket has been designed to be replaced every two years because of radiation induced embrittlement.(10) The first 20 cm has been designed so that they are easily removed and a new section replaced in suitable hot cell facilities. The decision to replace this wall every two years causes a 6% reduction in the plant factor if such an operation takes no more than six weeks each time. Approximately 500,000 kg of 316 SS must be removed and disposed of each time the entire heat removal cells are replaced.

A complete plan for reactor disassembly has been developed and included in the overall plant layout. The reactor torus has been divided into 12 modules which can be disassembled and withdrawn into the module repair track (Figures 1, 2). Figure 7 shows an isometric view of one module on its motorised vehicle. This module will be transported to a hot cell where the heat removal section (including the first wall) can be safely removed and replaced. The details on the blanket and shield disassembly can be found in Reference 2.

Finally, the shield composed of layers of B_4C and Pb in a stainless steel structure. The shield is cooled with helium gas. (Figure 5) The B_4C is used to slow down and absorb thermal neutrons, and the lead serves to absorb the high gamma fluxes from the blanket. The total heat generated in the shield is 50 MW_T.

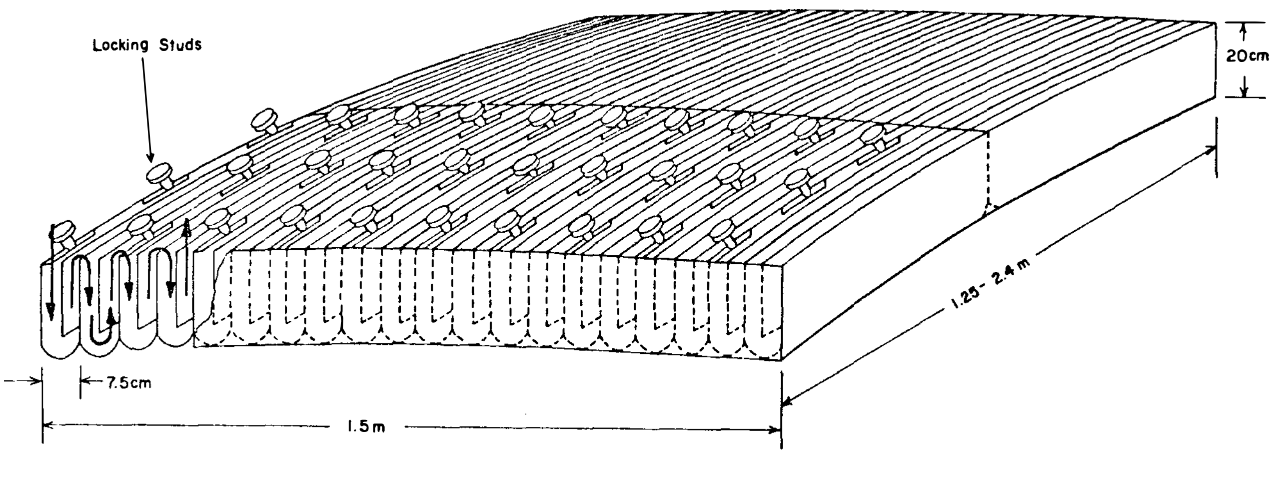
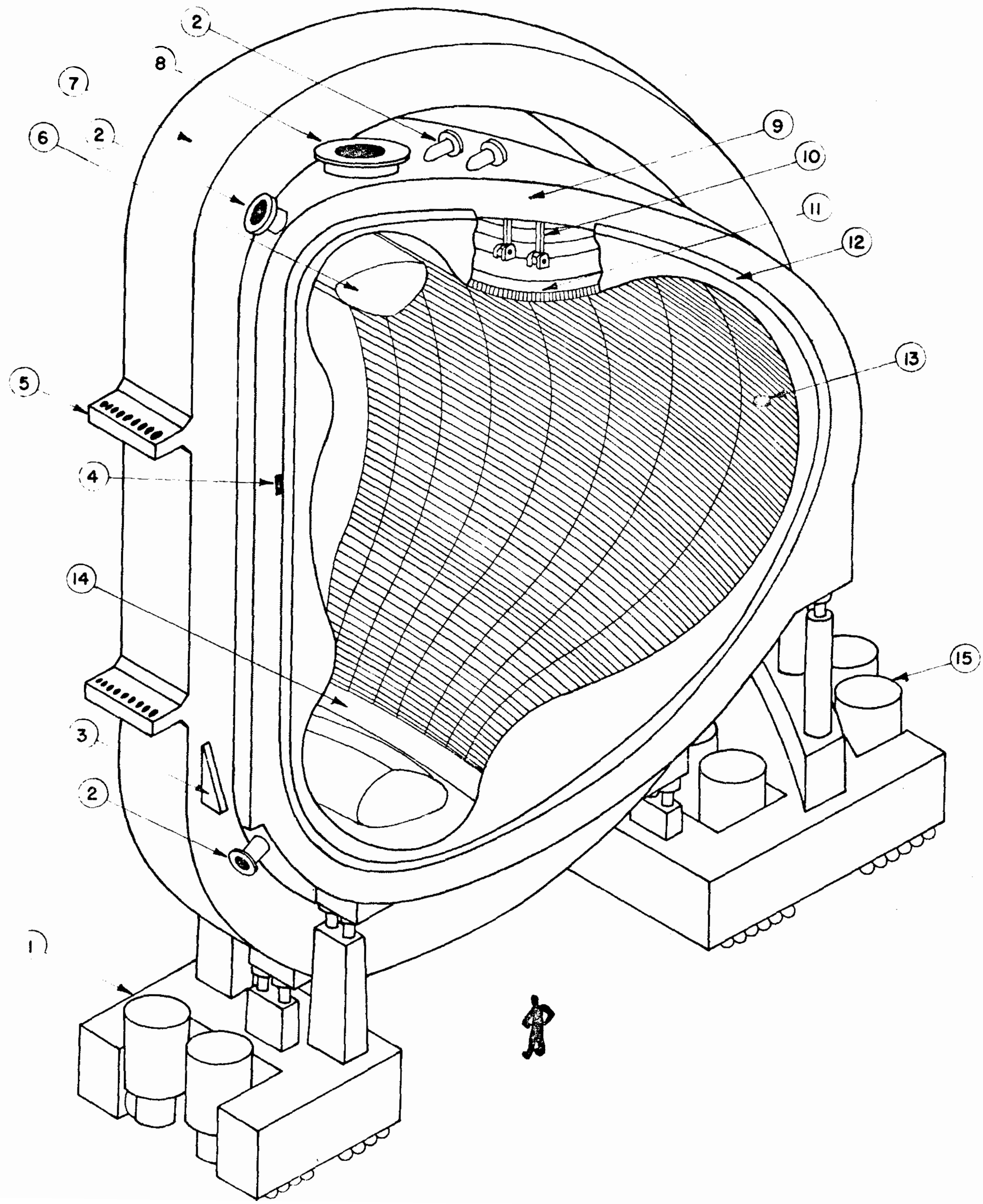


Figure 6 - Isometric View of a Complete Section of Heat Removal Cells
(Locking studs are shown on one half of the section only)



1- Front motorised caterpillar
2- Lithium inlet or outlet
3- Front magnet dewar support
4- Front blanket support bar
5- Magnet support shear beam
6- Vacuum port shield
7- Toroidal magnet in its dewar
8- Vacuum connection
9- Shield
10- Rear blanket support rods
11- Heat Removal cells
12- Blanket seal flange
13- Neutral beam injection port
14- Particle collection plate
15- Rear motorised caterpillar

FIGURE 7

E. Neutronics

Neutron and photon transport calculations give a breeding ratio in UWMAK-I of 1.49 with a doubling time on the order of 2-3 months. The tritium breeding is likely to be adequate for all uncertainties in nuclear data or design. The energy attenuation through the blanket and shield is $\sim 4 \times 10^{-6}$. Detailed heating calculations, based on kerma factors from the MACK program(11), were performed and reveal that the energy amplification of the blanket is ~17%. It is found that 16.55 MeV of the energy are produced per 14.06 MeV neutron incident on the blanket. Thus, the total energy per fusion reaction, including the 3.52 MeV alpha energy, is 20.08 MeV. This is in contrast to values of 22-27 MeV which have been used in computing power output for fusion plants.

F. Radiation Damage

Radiation damage studies of the UWMAK-I blanket-shield-magnet combination revealed several severe problems. Table 6 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.(10) 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. (Figure 8) 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. 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.

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 ans 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. 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.(12)

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.

G. Tritium

The extraction of tritium from the Li coolant is accomplished with yttrium traps. The breeding ratio of 1.49 is so high that doubling times of 3 to 4 months are indicated. However, when fueling, heating and vacuum ports are included in the design, it is expected that the breeding ratio may drop to a lower level. It still may be desirable to "spoil" breeding in UWMAK-I and breed more energy. Such possibilities are being investigated.

ANTICIPATED UNIFORM ELONGATION REMAINING
IN 316 SS AFTER IRRADIATION IN UWMAK-1

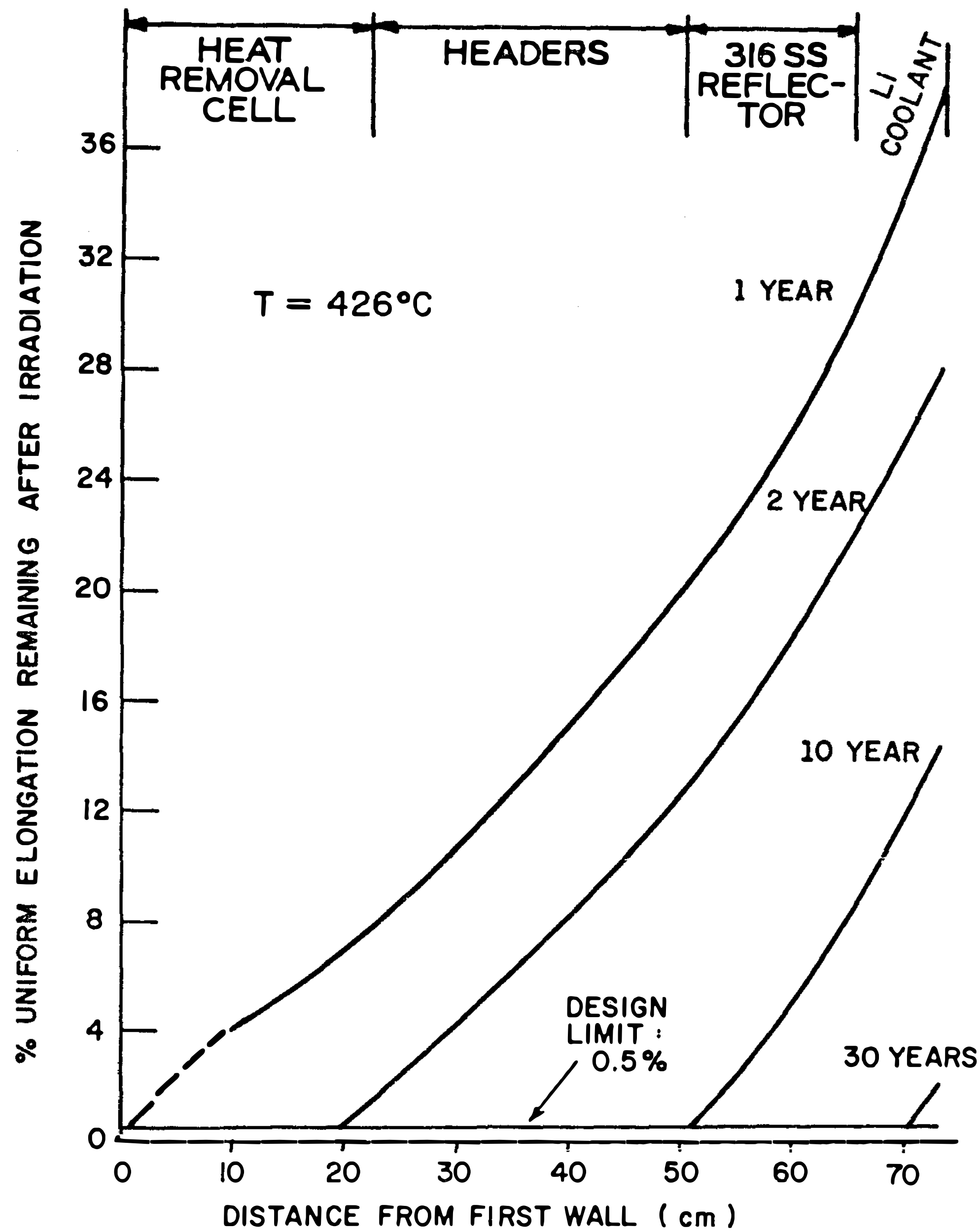
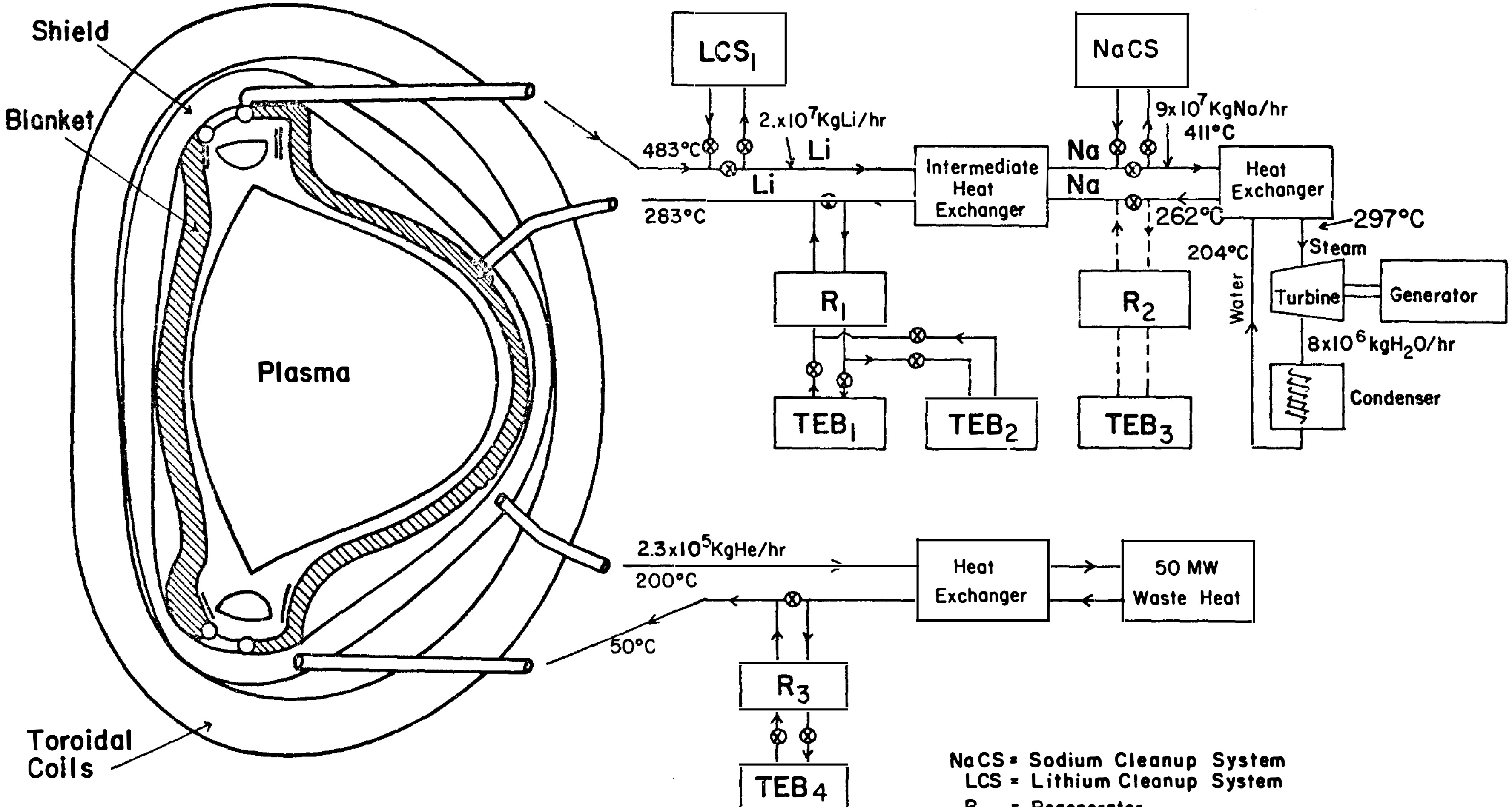


Figure 8

A diagram of the tritium removal scheme is shown in Figure 9 with appropriate liquid metal flow rates and temperatures. It is noted that a small amount of lithium is removed from a primary coolant loop, the temperature lowered to ~300°C and the lithium passed over a yttrium extractor bed. There are two extractors for the primary loop such that the tritium can be extracted from one unit while the other is in service. Only one extraction unit is required for the sodium secondary loop. The pertinent parameters for the tritium system are listed in Table 7. Note that the tritium leakage rate into the steam is ~10 curie per day.(13)

H. Radioactivity

The formation of radioisotopes in the blanket represents two potential hazards; radioactivity and afterheat. Table 8 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



NaCS = Sodium Cleanup System
LCS = Lithium Cleanup System
R = Regenerator
TEB = Tritium Extraction Bed

Flow Rotes are for Whole Reactor

Coolant Loops for
Wisconsin Toroidal Fusion Reactor — UWMAK-I

FIGURE 9

Table 6

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 $mm\text{-}yr^{-1}$
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}

dividing the activity by the MPC. The BHP's for 316 SS in Table 8 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 2 and 14.

The decay of the radioisotopes mentioned above generated heat that must be dissipated to avoid severe temperature problems in the event there is a loss of flow of the coolant. Pertinent information on afterheat in UWMAK-I with heat removal cells of three different materials is shown in Figure 10. The afterheat after 10 years of operation at 5000 MW_T is ~31 MW for 316 SS, ~30 MW for Nb-1Zr and 23 MW for V-20Ti at shutdown. This radioactivity drops off quite rapidly for the vanadium system but remains rather stationary in 316 SS and Nb-1Zr for 1-2 years. Both of these latter systems show a considerably drop in the 2-20

Table 7

Summary of Tritium Extraction System Characteristics[(a)]

System	Temp. Range°C	Extraction Method	Tritium Accumulation per Day (kg)	Tritium Leakage Ci/day	Tritium Concentration ppm (wt.)	Tritium Inventory (kg)
Primary Lithium	283-483	Yttrium Metal Bed	1.05(b)	10.1	5	in Li 8.7 in beds 1.0
Secondary Sodium	261-411	Yttrium Metal Bed	~0	---	3.3×10^{-4}	in Na 2.5×10^{-4} in beds ~0
Divertor		Yttrium Metal Bed				in Li 8×10^{-3}
Lithium	200-325		7.4 T + 5.0 D	2×10^{-4}	0.24	in beds 3.5
Sodium	190-265		--	--	3×10^{-4}	in Na 2×10^{-5}
Divertor Vacuum	25	Charcoal cooled liq. He	0.3 T + 0.2 D	1×10^{-4}	N.A.	0.3
Helium	50-200	Metal getter	1.1×10^{-6}	low	N.A.	low
			Total	10.1	Total	13.5

(a) Based upon thermodynamic calculations; no kinetic considerations
(b) At maximum breeding ratio of 1.49
N.A. - Not Applicable

Table 8

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

System	Isotope	$t_{1/2}$	Activity Ci/kW(b)	Maximum Permissible Concentration $\mu Ci/cm^3$	Biological Hazard Potential km^3 of air/kW(b)
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 plant inventory at 30 kg (13.5 kg in reactor and 16.5kg external).

(d)Including isotopes not listed.

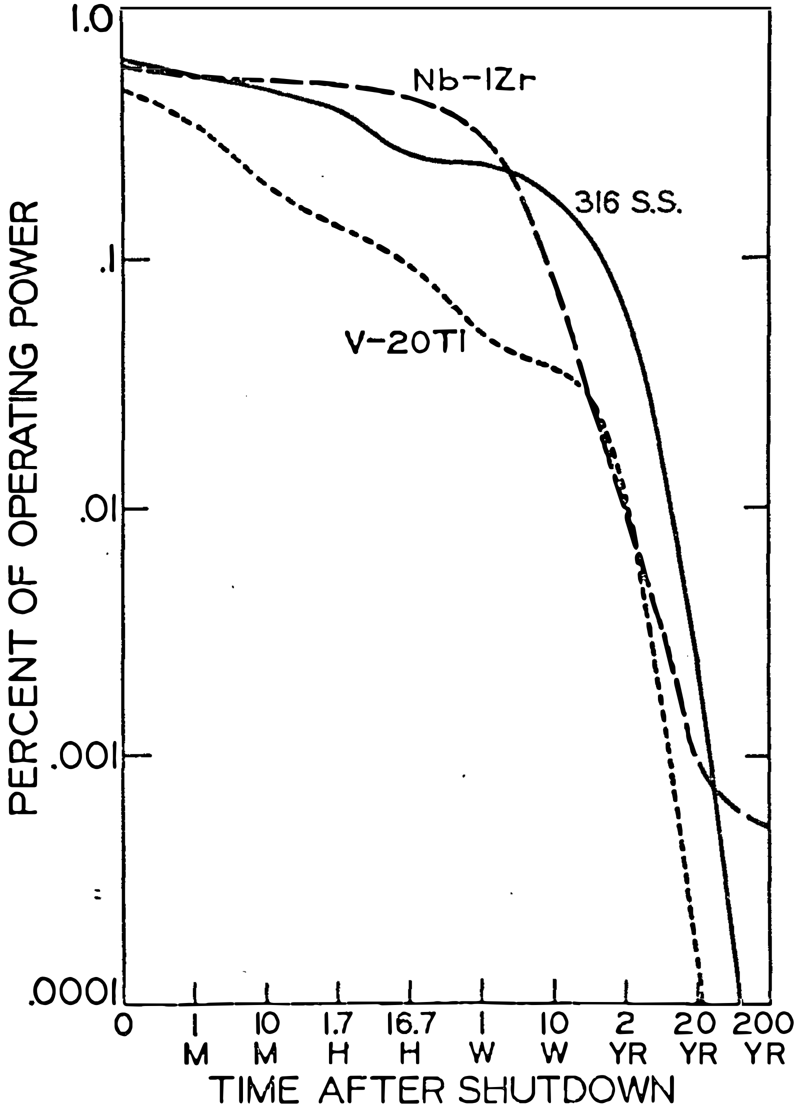
year period decaying to less than 50 kW in 100 years. Calculations of the maximum temperature rise rate under adiabatic conditions reveal values on the order of ~0.1°C sec^{-1}. More realistic approximations of the rate of heat leakage reveal the maximum value is unlikely to exceed 0.01°C sec^{-1} indicating that emergency cooling requirements are minimal.

I. Power Cycle

The pertinent temperature and flow rates for Li, Na and steam are shown in Figure 9 for UWMAK-I. Detailed analysis of the steam cycle will be reported elsewhere[15] but an overall efficiency of ~30%(including circulating power requirements of 8.4%) has been calculated.

J. Cost Analysis

A preliminary cost analysis of the UWMAK-I system has been completed[16]. The basic assumptions that have been used are an 80% plant factor, 8% interest during a five year construction time and 15% return on capital. The resulting analysis reveals that the overall plant costs could be as much as $900-1000 per kW_e and the cost of generating electricity may be in the neighborhood of 20 mills/kw-hr. Further optimization of the UWMAK-I reactor costs is in progress and it is hoped that the cost maybe reduced by 10-20%. It is encouraging that these preliminary estimates of fusion reactors are not particularly out of line with first generation fission reactors.



Afterheat in UWMAK-I

Figure 10

III. Concluding Remarks

Even though we have attempted to minimize the amount of extrapolation that would be required to construct a reactor like UWMAK-I, it is certainly recognized that there are areas which still contain large unknowns. These areas will be more clearly delineated in another paper in this volume(1) but two major areas stand out; plasma physics and materials technology. A great deal of investigation is still required to understand the behavior of D-T plasmas containing helium, the effects of impurities, fueling, and loss modes. It is also imperative that we understand the mechanisms of radiation damage of CTR materials if we ever expect to build safe, economical fusion reactors.

Finally, it should be especially noted that the real usefulness of the design effort which we have just summarized 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 completed. We fully expect that some features of UWMAK-I design will be changed as new discoveries are made in plasma physics, material behavior, and reactor technology in general. Hopefully, other laboratories will also complete detailed studies, and by noting the best features from many systems, we will be able to begin the design of the first real fusion power plant in the 1980's.

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