An Overview of TASKA - A Tandem Mirror Fusion Engineering Facility

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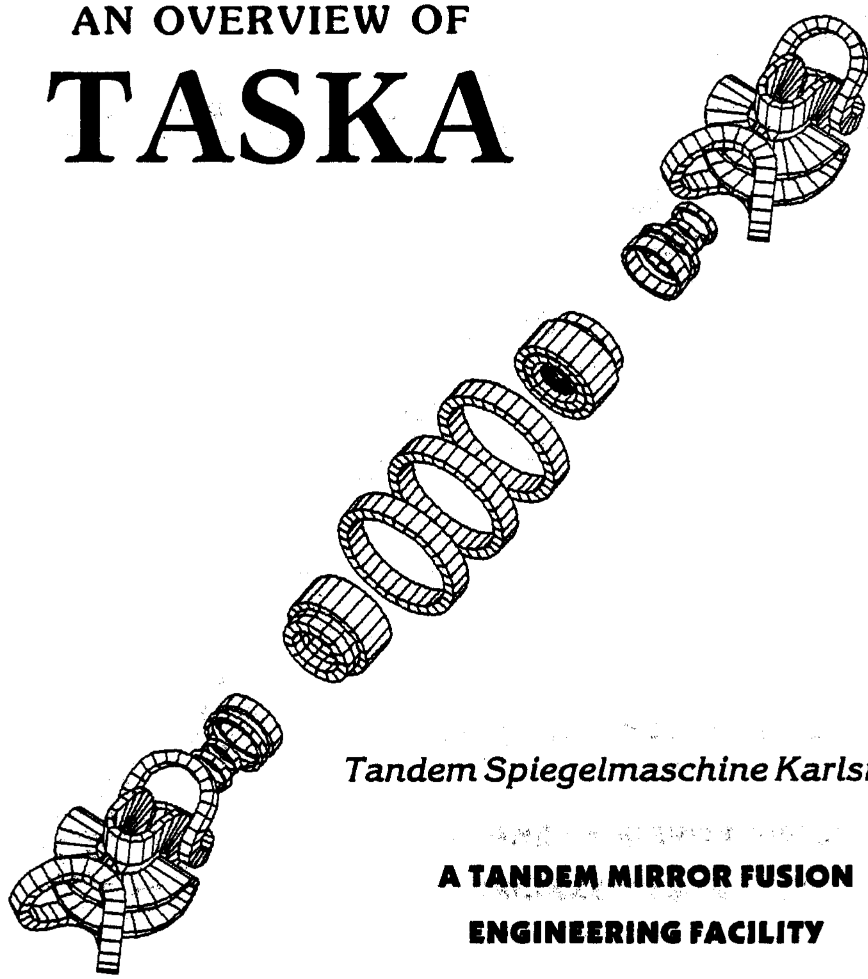
AN OVERVIEW OF

TASKA



Tandem Spiegelmaschine Karlsruhe

A TANDEM MIRROR FUSION ENGINEERING FACILITY

UWFDM-462

An Overview of the TASKA Fusion Engineering Test Facility

Presented by

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for the Design Groups from

- University of Wisconsin
- Fusion Power Associates
- Kernforschungzentrum Karlsruhe

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Please Note:

The following is the Overview chapter from the preliminary TASKA Report (UWFDM-500, FPA-82-1, KfK-3311). Please see the full report for details of the reactor design. The TASKA study has received major financial support from the Kernforschungszentrum Karlsruhe (KfK) in the Federal Republic of Germany, with significant additional contributions from the University of Wisconsin, the Wisconsin Electric Utilities Research Foundation and Fusion Power Associates.

II. Overview of TASKA

II.1 Introduction

The rapid progress in plasma physics during the past 10 years and the expectations of positive results from the major experiments to come into operation this decade (e.g., TFTR, JET, T-15, JT-60, MFTF-B) suggest that the next large device to be built before the Demonstration Reactor (DEMO) operates will be a DT Technology Test Facility. This point of view has initiated many studies directed towards the next step in the world fusion program which is envisaged to be an engineering test facility where all of the key technologies required for a Demonstration Reactor can be successfully integrated into, and tested in, one machine. One such worldwide endeavor for the conceptual design of a tokamak is the study of the International Tokamak Reactor, INTOR.(1) Indeed, tokamaks presently represent the most advanced fusion concept and are expected to demonstrate ignition and the behavior of an ignited DT-plasma in the late 1980's. Nevertheless there are some doubts that tokamaks may in fact lead to a commercial power reactor mainly because of their complex and toroidally interlinked magnet structure.(2)

In principle, a linear device could avoid such complexity. It can lead to a device which gives better access and the linear geometry allows for modular construction of the major components. This configuration is also a definite advantage for the exchange or repair of key components within the reactor vessel. The physics concept with the best chance for a linear geometry is the mirror and recent advances in the physics of mirrors give rise to the expectation that the difficulties in the plasma physics performance of minimum B mirror machines can be overcome by the tandem mirror concept with thermal barriers.(3) Conceptual designs of power plants have already shown such configurations to be economically competitive with tokamaks.[4] In addition to the favorable possibilities of the tandem mirror, it was also evident that such a device might be a very attractive engineering test facility. Thus, the TASKA study was initiated in late 1980 to see if our optimistic expectations were justified from an engineering point of view.

II.2 TASKA Objectives

The main objective of TASKA is to provide an engineering test bed to qualify and test materials and blanket concepts for a Demonstration Fusion Power Reactor. TASKA must also demonstrate that superconducting magnets, heating technologies, tritium handling equipment, remote handling equipment, etc., can all operate in an intense neutron environment with reliabilities that will allow ~ 50% availabilities to be achieved. It must do all of this in a timely, but yet cost effective manner which is consistent with the safe operation of a nuclear facility. To be more specific, TASKA must be the maximum reasonable physics and technology step beyond the next generation of large mirror machines (AMBAL,(5) TMX-Upgrade,(6), GAMMA-10,(7) TARA,(8) and MFTF-B(9)). It should be able to operate in the early 1990's (similar to INTOR(10)) and provide at least 5 MW-y/m^2 of large scale test volume in no more than 10 years of full power operation (exclusive of check-out and initial low power tests). Finally, the overall direct cost of TASKA should be $\lesssim$ 800 million dollars and the yearly operating cost (including personnel, power, T_2, etc.) should be less than 50 million dollars.

II.3 Physics Basics for TASKA

The tandem mirror physics concept has been previously verified on GAMMA-6[11] and TMX.[12] Some aspects of electron heating with ECRH in the end plugs of TMR's have been recently demonstrated on Phaedrus[13] and ICRH heating of plasmas has been demonstrated in PLT.[14] The key experiment to demonstrate operation with thermal barriers on a tandem mirror will be performed in 1982 on TMX-U.[6] This device will also advance the understanding of electron heating and the central cell region will be operated in the collisionless diffusion regime.

The MFTF-B[9] and its axicell upgrade[15], currently under construction, should demonstrate long pulse operation (30 seconds) in the TMR-thermal barrier mode in the 1985-1986 time period. The limits on central cell beta will also be investigated in that device. High power, continuous (30 sec) 80 keV neutral beams will be used to achieve a D-T equivalent $Q \sim 1$ in the same time period. MFTF-B will be the first tandem mirror machine to use all superconducting magnets, including high field barrier and yin-yang coils.

The physics relationship of TASKA to past, present, and future devices is shown in Fig. II.3-1. The anticipated performance of WITAMIR-I[4] is also included and the collection of parameters shows that TASKA lies on a reasonable projection of the aforementioned devices. More discussion on the physics basis of TASKA is given below and in Ref. 16. It is important to note that while the optimism about achieving the TASKA physics goals is high, the success of any device after MFTF-B depends on the degree to which current physics models can be verified. Progress through the TARA/AMBAL/TMX-U/GAMMA-10/MFTF-B series must therefore be closely monitored.

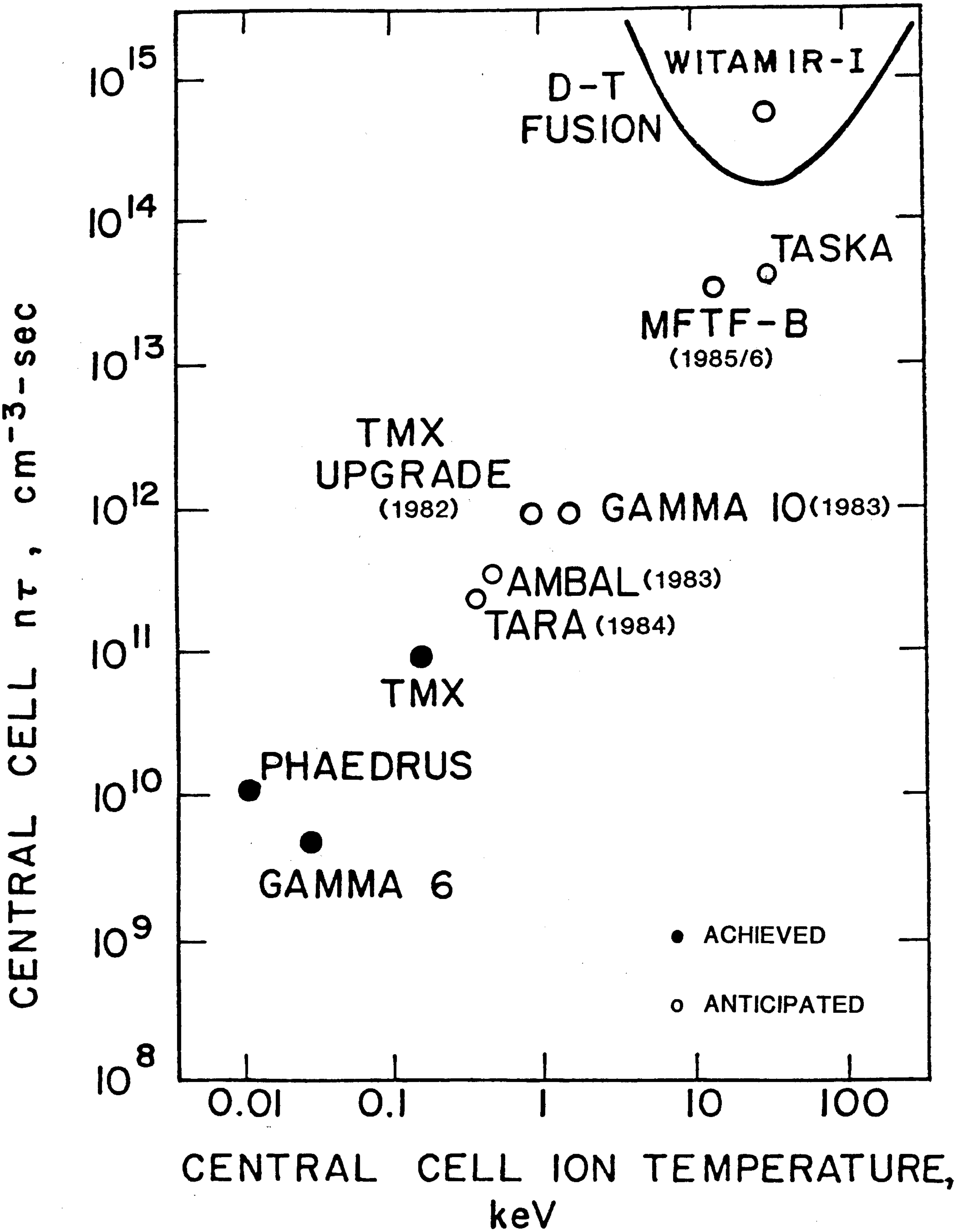


Fig. II.3-1 Critical physics parameters for present and future tandem mirrors.

II.4 General Survey and Basic Reactor Parameters of TASKA

II.4.1 Design Philosophy

TASKA is based on the concept of a tandem mirror with an inside thermal barrier. The design uses existing technologies or those which may be expected to be available in the near future. A net power gain is not required, therefore Q is not an important parameter and will be slightly less than unity. However, a main consideration is that the neutron wall loading should be high enough to achieve a significant neutron flux and fluence for materials and blanket tests. The central cell length is minimized because of the modest requirements of the test blankets, thus reducing costs without losing scalability. A tritium breeding ratio of 1.0 or more is foreseen so that there will be no net tritium consumption over the lifetime of the machine. Electric power production, direct energy conversion, or fission fuel breeding are options that can be examined during the life of TASKA.

II.4.2 General Survey and Parameters

Schematic views of TASKA are shown in Figs. II.4-1 and II.4-2. The positions of the magnets, the test blankets, the neutral beam injectors and the generators for ECRH and ICRH are indicated along with the power and energy levels for NBI power and frequency for the RF heating systems. A selective list of TASKA general operating parameters is given in Table II.4-1. In Fig. II.4-3 the confining magnetic fields and electric potentials are shown. The end plugs consist of an inside thermal barrier, and a minimum-B yin-yang coil set. There are 3 central cell solenoids.

Some key features of TASKA are listed below:

- The DT power level is 86 MW, far below the 620 MW of INTOR[1] or the 180 MW of FED.[10] This lower power level greatly eases the tritium requirements

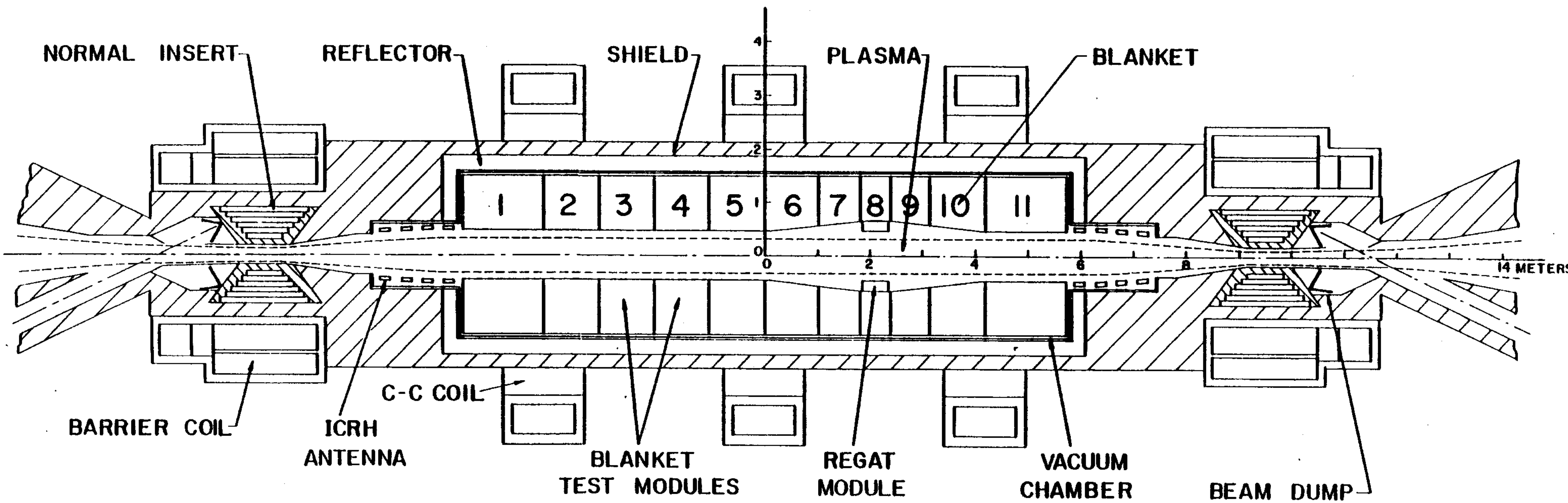


Fig. II.4-1 TASKA central cell layout.

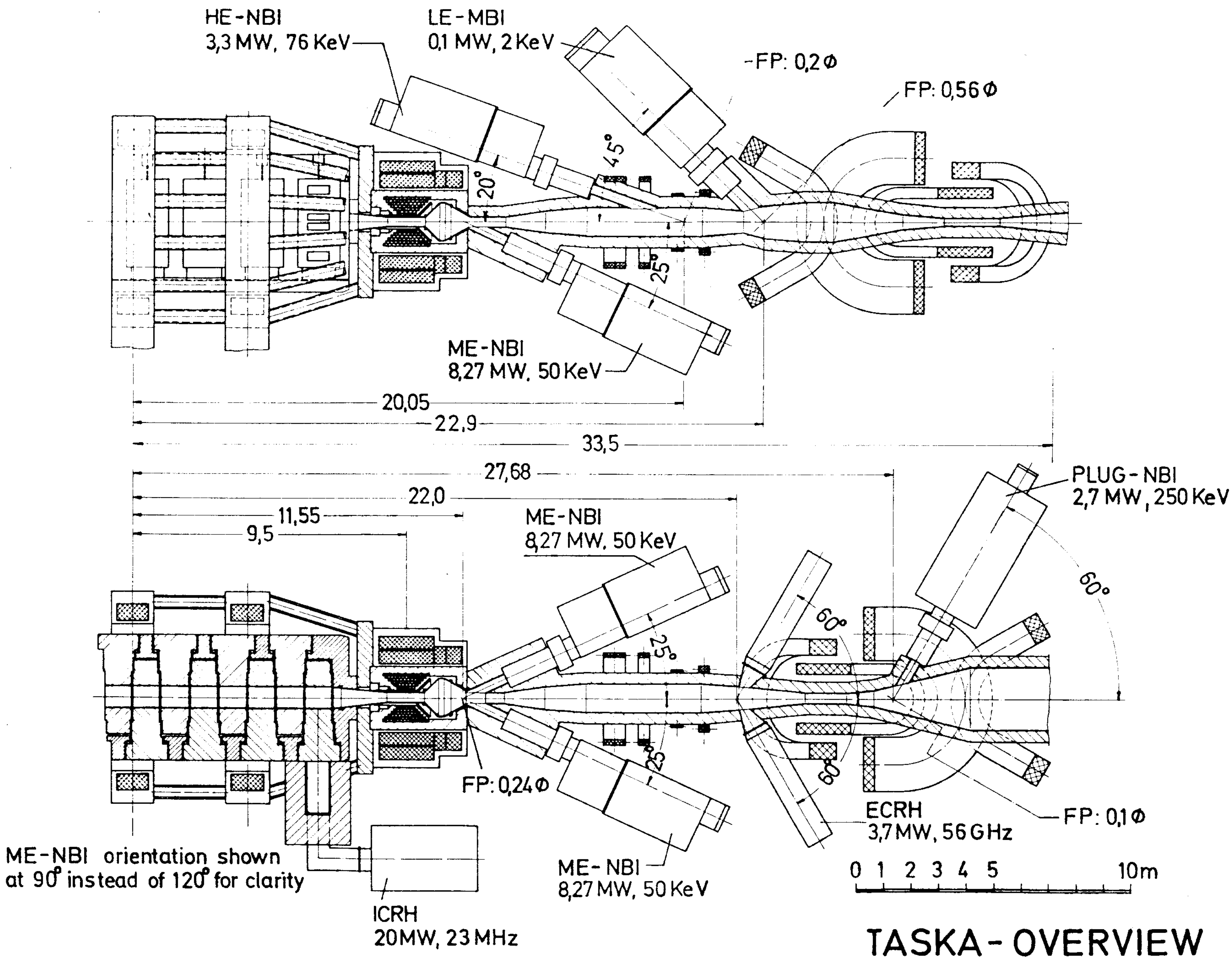

HE-NBI
3,3 MW, 76 KeV
LE-MBI
0,1 MW, 2 KeV
-FP: 0,2 Φ
FP: 0,56 Φ
45°
20°
25°
ME-NBI
8,27 MW, 50 KeV
20,05
22,9
33,5
27,68
22,0
11,55
9,5
PLUG-NBI
2,7 MW, 250 KeV
ME-NBI
8,27 MW, 50 KeV
60°
25°
FP: 0,24 Φ
ECRH
3,7 MW, 56 GHz
FP: 0,1 Φ
ME-NBI orientation shown
at 90° instead of 120° for clarity
ICRH
20MW, 23 MHz
ME-NBI
8,27 MW, 50 KeV
0 1 2 3 4 5 10m
TASKA - OVERVIEW

Fig. II.4-2

Table II.4-1. General Operating Parameters - TASKA

DT Power Level		86 MW
First Wall Neutron Wall Loading		1.5 MW/m^2
Total Heating Power		110 MW
Central Cell Magnetic Field (On-Axis)		2.7 T
Central Cell Length		21 m
Structure/Breeder		HT-9/$Pb_{83}Li_{17}$
Number/Total Volume of Test Modules		1-Material/493 liters
		2-Blanket/5700 liters
Operating Lifetime		15 years
Operating Scenario	Year	% Availability
H_2 Check Out	1	10
DT Check Out	2	15
Short Term Test Phase	4	25
Long Term Test Phase	8	50

MAGNET and ELECTROSTATIC CONFIGURATION of TASKA

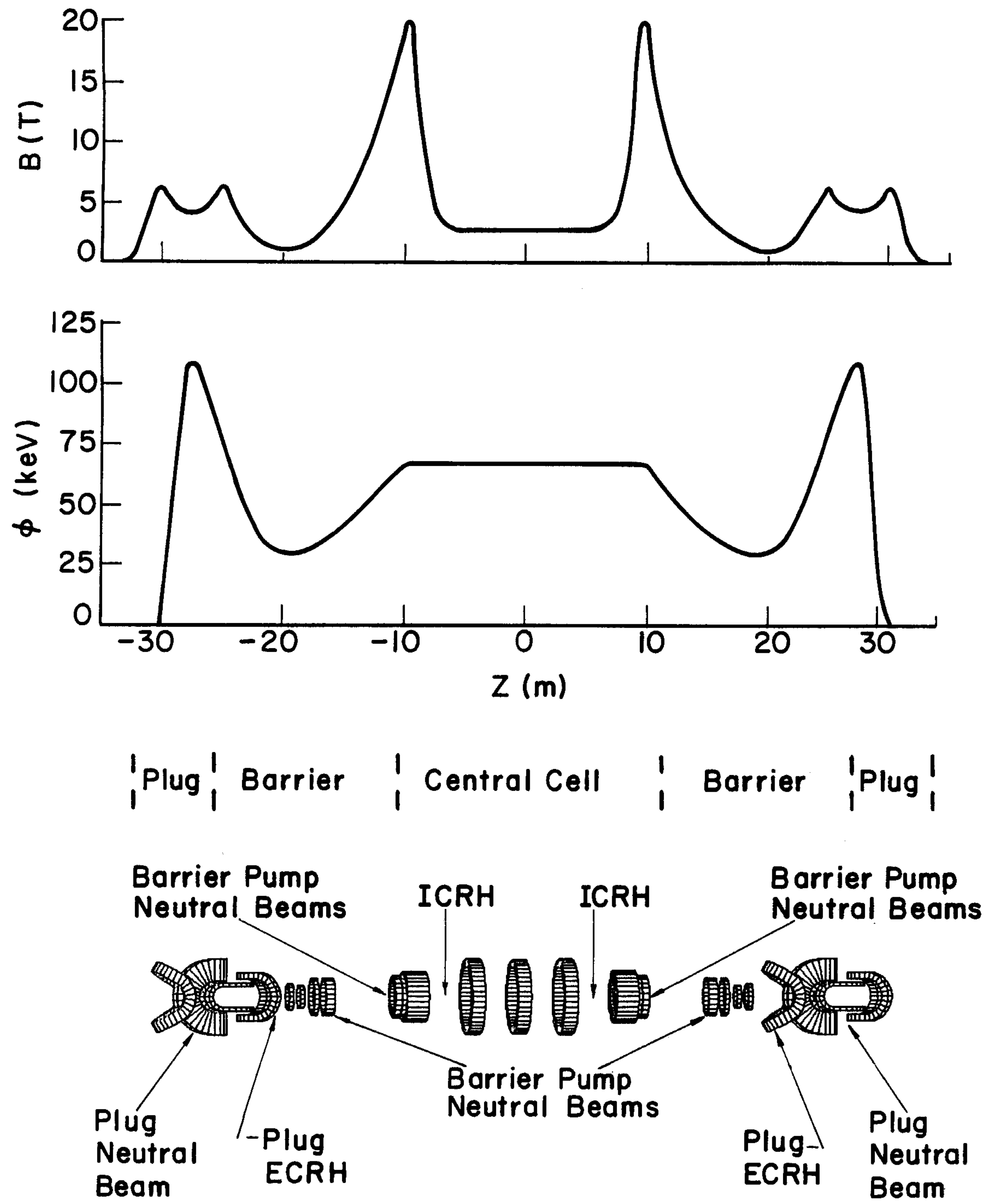


Fig. II.4-3 Magnet and electrostatic configuration of TASKA.

and reduces the overall costs compared to previous test devices.

- The neutron wall loading is 1.5 MW/m^2. This relatively high wall loading will allow reactor relevant testing to be performed in both blanket and materials modules. Coupled with reactor availabilities of 25 to 50%, this flux will also allow reactor relevant fluences to be obtained.
- The barrier region is pumped with neutral deuterium and tritium beams and the electrons in the end plug region are heated with ECRH at 56 GHz. The plug ions are sustained by H^0 beams of 250 keV. The use of the very high barrier magnetic fields and ECRH requires selective ion pumping and the proposed design uses two stage charge exchange pumping(17) to reduce these requirements.
- One of the key features of the machine that allows such a favorable performance is the use of a high field, room temperature copper insert which raises the field in the barrier coil from 14 T produced by the superconducting coil to 20 T. The life limiting feature of this coil is radiation damage to the ceramic insulation conservatively assumed to be 10^{12} rad. The projected life is then 10 years at 25% availability or 5 years at 50% availability.
- The tritium for this device is provided by circulating a $Pb_{83}Li_{17}$ alloy in HT-9 ferritic steel tubes (see Fig. II.8-1). The localized breeding ratio is 1.65 and the overall breeding ratio of the machine (including test sections as well as leakage) is 1.0 so that no net tritium consumption is incurred over the life of the machine. The low solubility of T_2 in $Pb_{83}Li_{17}$(18) results in only a 20 g inventory in the blanket.
- There are two modules devoted to blanket testing and one module devoted to materials testing. These test modules are placed between the central cell

coils for ease of access and maintenance.

- The secondary heat transfer loop contains an organic material, HB-40. Normally, the approximately 60 MW from the central cell breeding blanket are dumped to cooling towers but provisions have been made to generate electricity with 350°C steam. Roughly 15 MW_e can be generated in this manner.
- Normally, the energy of the plasma ions and electrons leaking from the plasma is deposited in heat dumps at either end of the machine but provisions have been made to test various direct convertor modules on one end. The operation of TASKA does not depend on the successful operation of the direct convertor.

II.5 Plasma Physics

The end plug configuration used in TASKA consists of an inboard thermal barrier, generated by a high field hybrid solenoid, and the electrostatic plug located in a min-B yin-yang magnetic mirror (see Fig. II.4-3). The potential peak in the plug provides axial confinement of the central cell ions; the good magnetic curvature of the min-B mirror provides MHD stability of the entire system. The thermal barrier provides thermal isolation of the plug and central cell electrons and allows the plug electrons to be heated substantially without heating the central cell electrons. This also allows the positive confining potential of the plug to be achieved at lower density, which thereby reduces the required neutral beam power to sustain the plug. The central cell ion temperature is maintained by ICRF heating and the power input from the barrier pump beams. This reduces the power requirements for "pumping" of the thermal barriers.

The physics parameters of TASKA are given in Table II.5-1 and the heating parameters are given in Table II.5-2. The central cell beta of 50% is an assumed value, but is considered to be conservative in light of recent theoretical developments concerning finite Larmor radius stabilization of ballooning modes; this is discussed further in Section III.1. Microstability of the mirror-confined plug plasma is an unresolved issue with the TASKA configuration. The TASKA design utilizes "sloshing" ions in the plug to create a local electrostatic well and trap warm plasma. This can, in principle, provide microstability against the drift cyclotron loss cone (DCLC) mode and the Alfvén ion cyclotron mode, but stability against the axial loss cone mode (which has not yet been observed experimentally) is harder to obtain.

Table II.5-1. TASKA Plasma Physics Parameters

Central Cell	
Magnetic field	2.7 T
Density	1.94×10^{14} cm^{-3}
Alpha particle density	1.6×10^{12} cm^{-3}
Ion temperature	30. keV
Electron temperature	11.5 keV
Beta	0.5
$(n\tau)_{ic}$	5.4×10^{13} cm^{-3} s
$(n\tau)_{ec}$	5.3×10^{13} cm^{-3} s
Potential, ϕ_c	42.8 keV
Barrier	
Barrier peak magnetic field	20 T
Barrier minimum magnetic field	.8 T
Potential, ϕ_b	37.5 keV
Pumping parameter, g_b	2.
Plug	
Midplane magnetic field	4 T
Vacuum mirror ratio	1.56
Midplane density	6.3×10^{13} cm^{-3}
Mean ion energy	388. keV
Electron temperature	59.3 keV
Beta	0.64
$(n\tau)_{ip}$	2.9×10^{13} cm^{-3}s
$(n\tau)_{ep}$	7.5×10^{11} cm^{-3}s
Potential, $\phi_c+\phi_e$	109. keV
Cohen parameter, ν_c	0.5

Table II.5-2. TASKA Heating Parameters

Neutral Beams		
Plug:	power	5.4 MW
	energy	250. keV
	angle	60°
	species	p
	trapping fraction	0.21
Barrier:	power	6.6 MW
	energy	76 keV
	angle	20°
	species	d
	trapping fraction	0.42
Barrier:	power	49.7 MW
	energy	50 keV
	angle	25°
	species	0.44 d/0.56 t
	trapping fraction	0.95
Barrier:	power	0.2 MW
	energy	2. keV
	angle	45°
	species	d
	trapping fraction	0.99
ECRF		
Plug:	power	14.9 MW
	frequency	56. GHz
	absorption efficiency	1.
ICRF		
Central cell:	power	40. MW
	frequency	30 MHz
	absorption efficiency	0.8
Total Injected Power		117. MW

NB: Plug and barrier powers are total powers for both sides.

Maintaining the thermal barrier requires removal ("pumping") of the ions which become trapped in the barrier. TASKA utilizes neutral beam pumping for this purpose; this process occurs by charge exchange between the barrier trapped ions and the neutral atoms which have been injected with the appropriate energy and angle relative to the magnetic field. The required energies and power for neutral beam pumping of the barrier and for sustaining the plug are given in Table II.5-2.

Alpha particle accumulation in the central cell is a general problem with tandem mirror reactors. Accumulation in the central cell of TASKA is not a problem because the ion confining potential is relatively low compared with the ion temperature ($\phi_c/T_{ic} \simeq 1.4$); the steady state alpha concentration in the central cell is about 1%. Alpha accumulation in the thermal barriers is a potential problem that requires further study. Fueling of the central cell is done entirely by ionization of the neutral beams which pump the thermal barriers; a separate fueling mechanism is not required, except perhaps during startup.

II.6 Magnet System of TASKA

The total magnet system of TASKA consists of:

- 3 solenoids in the central cell to give the required central cell field;
- 2 barrier mirror hybrid coils to provide the magnetic mirror field;
- 2 transition coils for plasma cross section shaping;
- 2 yin-yang systems to provide plasma stability;
- 2 recirculating coils for plasma cross section shaping; and
- 8 coils for field shaping in the thermal barrier region.

The (arrangement) position of the coils is given in Figs. II.4-1, II.4-2, and II.6-1, and the magnetic field generated by those magnets is shown in Fig. II.4-3. Table II.6-1 gives the general operating parameters of the magnet system.

The three central cell magnets have an inner radius of 2.8 m and a winding cross section of 1.2 x 0.58 meters. The technology for these coils is available and is based on the experience with large coils already existing. The current density in the two outside coils is 1440 A/cm^2 and it is 1345 A/cm^2 in the center coil which is necessary to reduce the field ripple to 5% or less. The maximum field at the conductor is less than 6.0 T and the conductor consists of NbTi with copper and/or aluminum stabilizer and stainless steel reinforcement.

The most complicated coil is the barrier mirror hybrid coil. It consists of a superconducting outer part and a normal conducting inner part; each of these is built up by six solenoids with different current densities and different winding cross sections. The design goes to the limits of the technology which can be expected in the near future; the majority of the field is provided by the Nb_3Sn superconductor with a maximum field of ~ 15 T at the

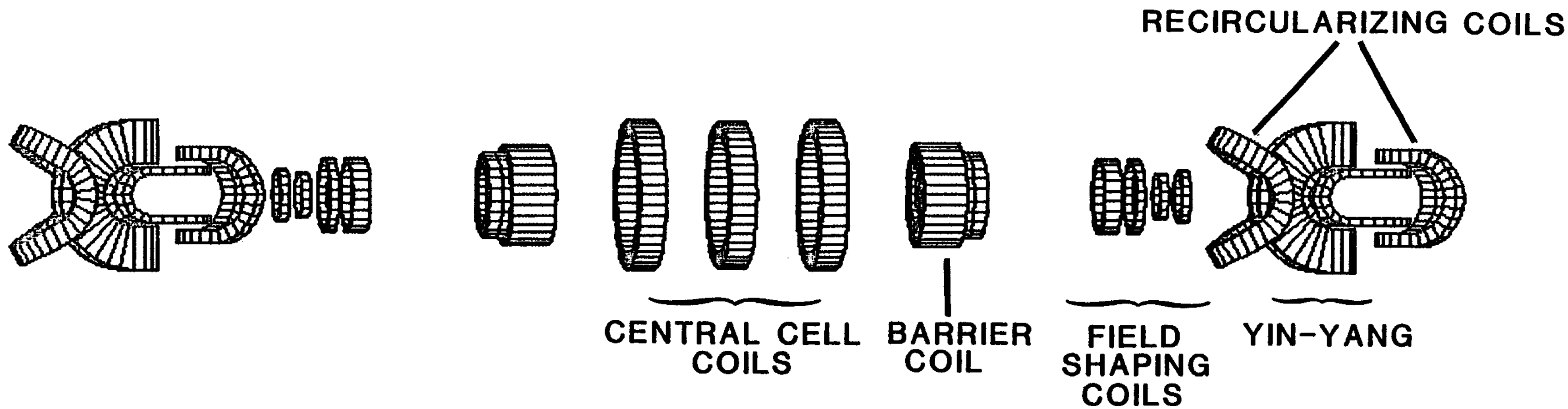


Fig. II.6-1 TASKA magnet configuration.

Table II.6-1. Main Parameters of the TASKA-Magnet System

	Central Cell Solenoids	Barrier Coil S.C. Part	Barrier Coil N.C. Part	Transition and Recirculating Coils	Yin-Yangs	Field Shaping Coils
Conductor	NbTi, Al-stabilized	NbTi/Nb_3Sn Cu and Al-stabilized	Hard Cu	NbTi, Cu-stabilized	NbTi, Cu-stabilized	Hard Cu
Overall current density in the winding (A/cm^2)	1350/1160	1600/2400	418-3070	1900	1630	450-795
Maximum field at the conductor (T)	6	15	20.7	7	7.9	0.5
Stored energy (MJ)	368/202	2600	12	487	411	0.013-2.25
Weight of the winding (tonnes)	68/72.5	177	20.5	84	117	1-12.9
Operating temperature (K)	4.2	4.2/1.8	300	4.2	4.2	300

coil winding and a stored energy of ~ 2 GJ. The design of the normal conducting part is made to be most power effective and is based on the experience of high field coils of the Bitter or polyhelix type already in operation at various High Magnetic Field Laboratories.

The general design of the normal Cu insert coils includes six nested cylinders, each 10 cm thick, but with a length which increases with increasing radius. Figure II.6-2 shows a cross section of the coil with the lines of constant magnetic field superimposed on it. The inner radius of the coil is 0.3 m to provide space for radiation shielding. The current density drops from 3070 A/cm^2 in the inner cylinder to 418 A/cm^2 in the outermost cylinder. The field contribution of the normal copper coil is about 6 T. The outer superconducting coil is limited by stress requirements and by the maximum allowable magnetic field at conductor of 15 T. The coil is graded in the NbTi region for conductor fields of about 8 T and in the Nb_3Sn region for higher fields. The current densities vary from 1600 A/cm^2 to 2200 A/cm^2 due to the stress limitation.

The end plug magnets (transition coil, yin-yang, recircularizer) are C-shaped with current densities less than 1900 A/cm^2. The design of these magnets was straightforward because they are similar in geometry and electrical data to those of the MFTF-B machine which has already operated under similar conditions. Characteristic dimensions for the yin-yang system are an overall height of 7.0 m and for a transition coil about 5 m. These are comparable with the MFTF-B dimensions of ~ 6 m overall height for the yin-yang and ~ 12 m for the outside A-cell coil. This coil was successfully tested in February 1982.

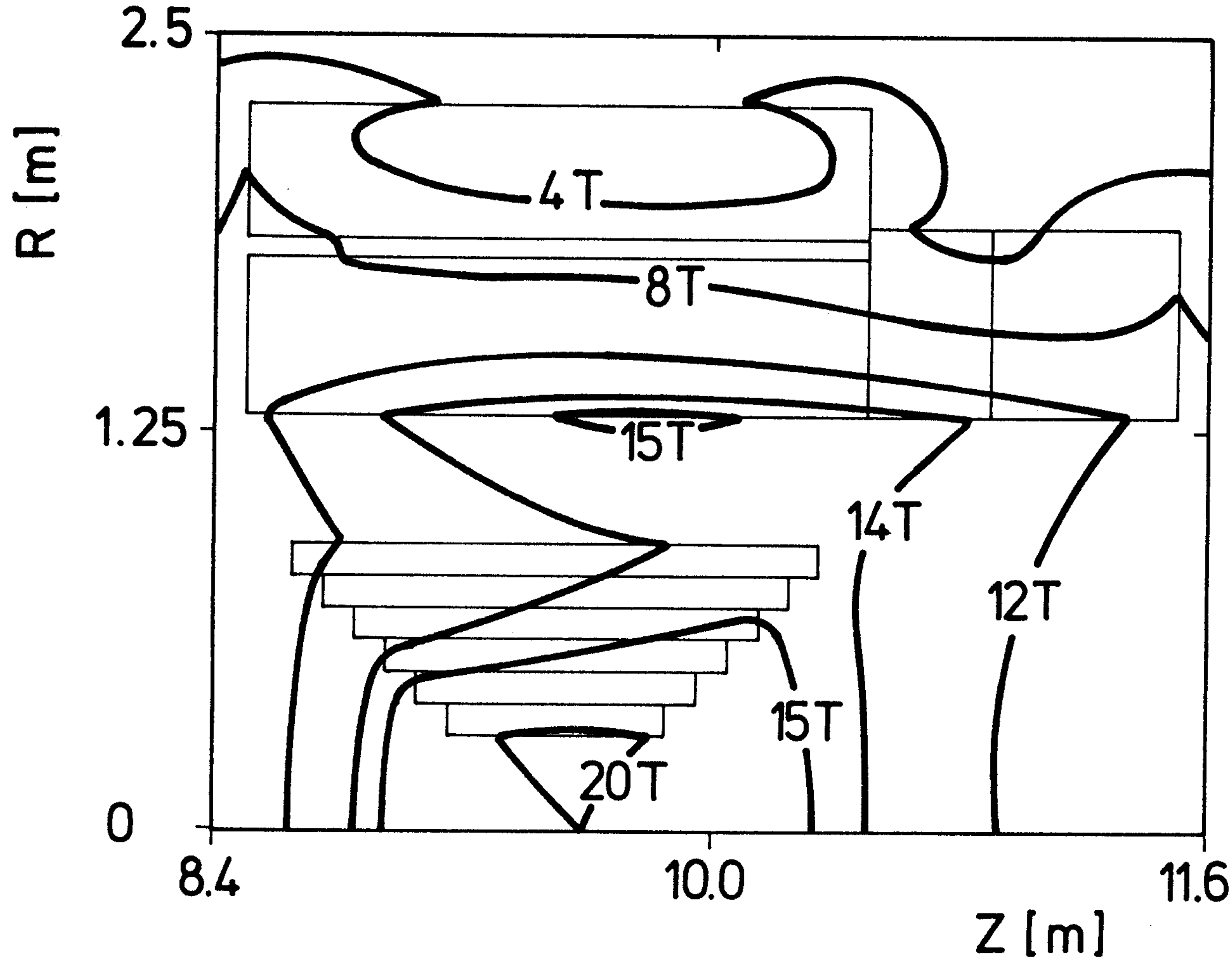


Fig. II.6-2 Cross section of the barrier coil with 4 T, 8 T, 12 T, 14 T, 15 T, and 20 T B-contours.

In addition, access for neutral beam injectors which provide the barrier pumping has to be included. The neutral beam injection angles, dictated by plasma physics requirements, are small which means that the present magnet design is the result of a trade-off between the magnetic fields from the plasma physics requirements and the access requirements for neutral beam injection. To fulfill these requirements, the barrier coil is built up by several parts with different thicknesses and different current densities. In addition, the end plug has been moved away from the barrier coil to enhance NBI access. However, the minimum field in the thermal barrier region is then lower than the required 0.8 T. This requires that field shaping coils (in this case normal conducting) be placed on each end of the device to increase the field to the required level. These coils are integrated in the shield as shown in Fig. II.4-2.

II.7 Plasma Heating Technology

II.7.1 Neutral Beam Injection

Neutral beam injection (NBI) is used as the primary means for plasma heating, plasma fueling, and selective ion charge exchange pumping in the TASKA materials test tandem mirror reactor design. Computational studies[19] of the equilibrium plasma parameters needed to attain the desired neutron wall loading of 1.5 MW/m^2 in the central cell yield the preliminary NBI design and heating requirements (see Table II.7-1). For simplicity in present parameter studies, each neutral beam is assumed to consist only of the full energy component.

The NBI performance parameters (listed in Table II.7-1) are based upon a present capability or scaling of existing ion source technology. However, the application to steady state D-T operation for TASKA will require a further level of special technological development particularly in the following areas:

- The design of high power level steady state NBI/ion sources with high reliability and compatibility with remote NBI component changeout. Operation of NBI hardware in a high neutron fluence with a tritium loaded system will also require some form of remote handling for maintenance (the aim is for a minimum of 1 year normal lifetime before required maintenance).
- Special cooling technology will be required because of locally high beam power loading on the charged ion dump, on the remnant neutral beam dump, on associated diagnostics, on the ion source grids, and on the machine end walls. Solutions such as thin channel-cooled surfaces[20] or direct energy recovery for ion dump and end walls[21] are feasible.

Table II.7-1. TASKA Neutral Beam Injector and Heating Requirements

Location	Injection Angle	V_o (kV)	NBI Power Per Injector (MW)	# Ion Sources Per Injector	Total # Injectors	I^o (Equiv.) Per Injector	$I^\pm$ (EST) Per Injector
P-NBI (plugs)	60°	250	2.7	1/H^- est.	2	10.8 AH^o	29 AH^-
HE-NBI (barriers)	20°	76	3.3	1	2	43 AD^o	108.8 AD^+
ME-NBI (barriers)	25°	50	8.3	3	6	3 x 65 A $D^o + T^o$	3 x 362 A $D^- + D^+$
LE-NBI (barriers)	45°	2	.1	1	2	50 AD^o	97.5 AD^+
ECRH (plugs and barriers)	~ 56 GHz 4 units each 3.7 MW to plasma						
ICRH (central cell)	~ 21 MHz 1 unit yielding ~ 40 MW to plasma						

- The development of steady state vacuum pumping schemes for the H_2, D_2 or D_2/T_2 gas flow in the ion source and neutralizer is required. Sufficient local pumping speed is required to reduce the line density of gas beyond the ion dump to low enough values to limit re-ionization loss to less than 10% and eliminate duct choking. The low injection angles for the high energy and medium energy pump beams tend to require long ducts and careful baffling to avoid direct beam impingement on the walls. The cooling of duct walls (to avoid any thermal desorption) is also essential. Initial studies[22] with a long duct NBI system possessing a small thermal desorption term of .005 T-ℓ/s-kJ, revealed that we may have a duct choking problem. To overcome this, present plans call for H_2, D_2 and T_2 gas pumping using panels of solid getter material arranged in a full surface folded panel configuration which allows cyclic regeneration. A short cold wall/hot exit neutralizer is being considered to reduce the neutralizer gas flow.[23]
- The relatively high plug-NBI energy requirements and the need to avoid neutron production in the plugs call for the use of H^0 injection at 250 keV. This will require H^- ion source technology for a reasonable neutralization efficiency. Such a source is also desirable for other fusion devices.
- Magnetic shielding for the NBI's in the high fringe magnetic field from TASKA (particularly for beam lines at low injection angles) is required. While such shielding is difficult to include in the small space allowed, it is feasible.

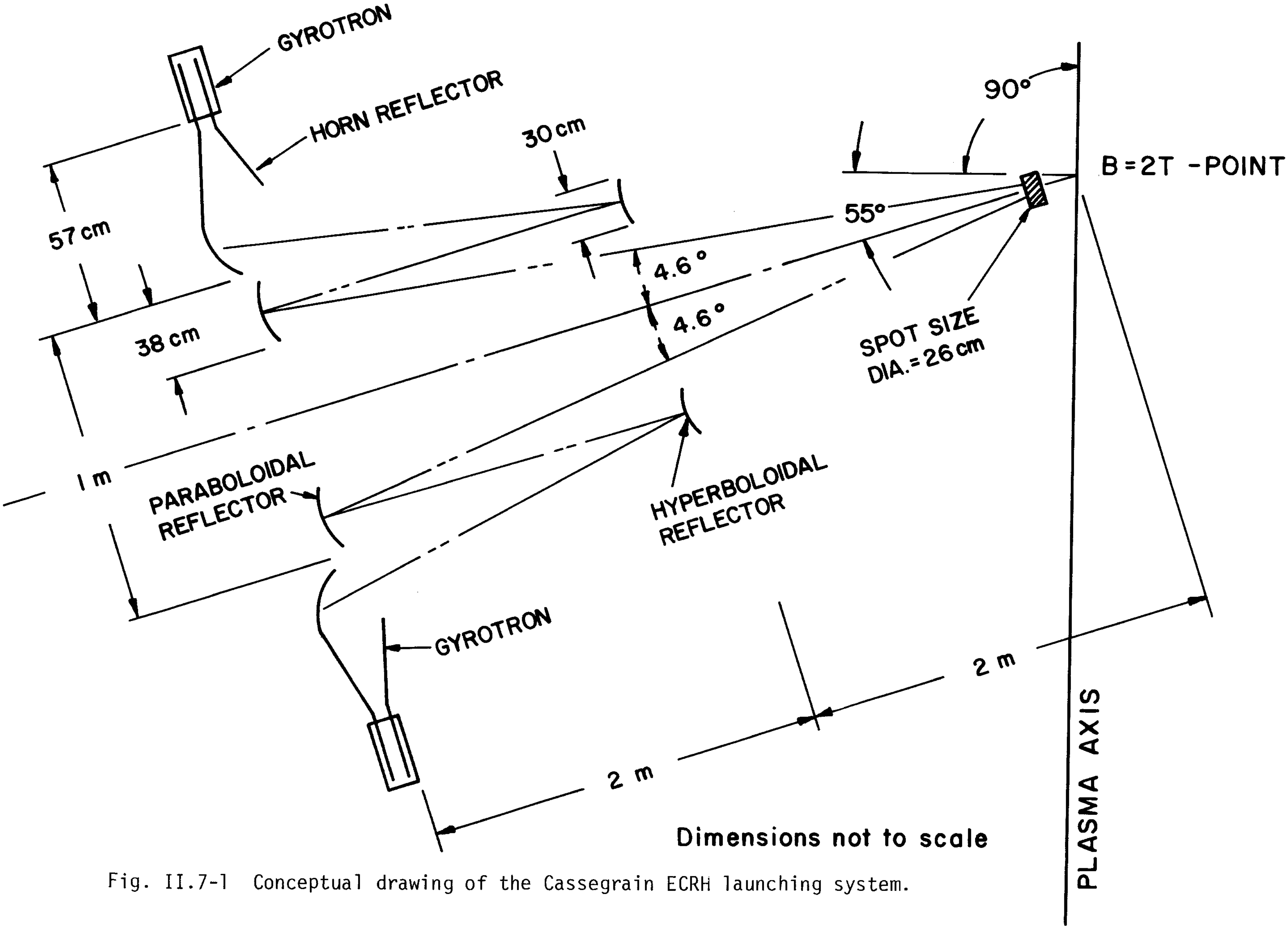
It is obvious that TASKA represents a challenge to NBI technology, but no insurmountable problems have been identified. Testing of advanced neutral beam injectors and heating systems in an integrated system can be one of the key applications for TASKA.

II.7.2 ECRH and ICRF Heating

The plug electrons are maintained at a temperature of 59 keV with 7.5 MW of ECRH power per plug. The frequency chosen is 56 GHz, which corresponds to resonance at a magnetic field of 2 T. The resonance surface is located between the minimum field point in the barrier and the mirror throat of the plug. Electrons reaching the resonance surface are primarily plug electrons; heating the plug electrons there heats the entire plug electron population because of their bounce motion along B, drift motion in the flux surface, and collisional transfer to electrons which don't reach the resonance surface. The 56 GHz frequency corresponds to the upper limit of high power cw gyrotron sources considered to be available on the TASKA time scale.

The ECRH power is delivered to the plasma using a quasi-optical offset Cassegrain beam waveguide transport system, as shown in Fig. II.7-1. Using a set of hyperbolic-parabolic mirrors, the microwave power is reflected and focussed onto the plasma at the desired angle. An array of gyrotrons feeds a single launcher system. Up to 4 MW can be focussed onto a reasonable spot size at the plasma with reasonable electric field intensity. Consequently, two launcher systems are required per plug.

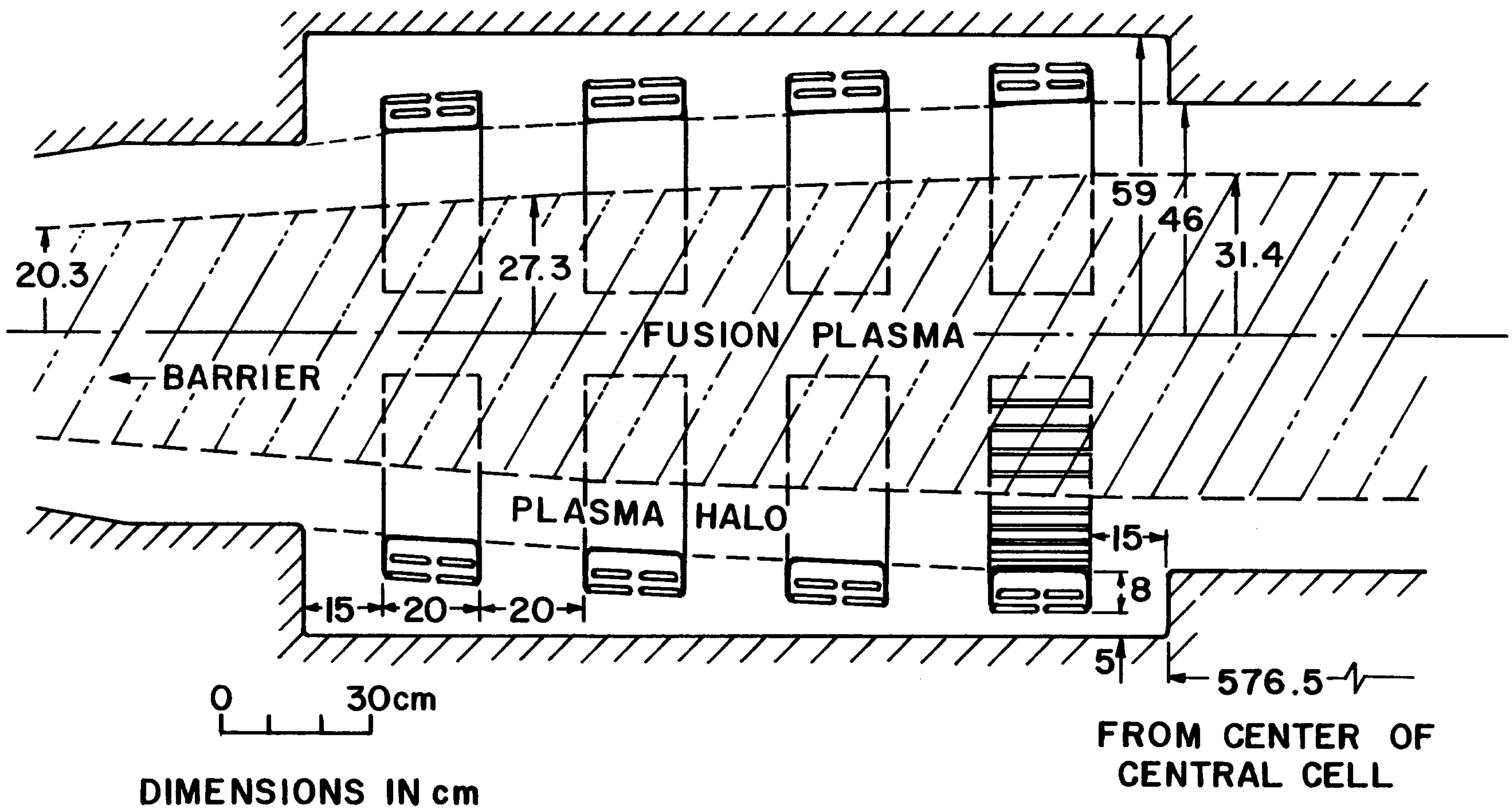
Forty megawatts of ICRF heating of central cell ions is used to maintain the ion temperature at 30 keV; this allows a considerable reduction of the neutral beam energy and power required for pumping of the thermal barrier. The fundamental deuterium frequency at the beta-corrected magnetic field in the central cell is 15 MHz. In this frequency range, and because of the 32 cm hot plasma radius, we are constrained to using antennas to couple the ICRF power to the plasma. In order to improve antenna coupling, second harmonic heating (at 30 MHz) is used. To protect the antennas from alpha particle



Dimensions not to scale

Fig. II.7-1 Conceptual drawing of the Cassegrain ECRH launching system.

bombardment and to improve the coupling to the hot plasma, a warm plasma halo between the hot plasma and the antennas is proposed. The antennas are located at each end of the central cell in order to leave the central region free for test modules. The four 2-coil sets (see Fig. II.7-2) take up 1.4 m of axial length at each end. The antennas are austenitic stainless steel with a high conductivity copper surface layer and cooled by water. The Faraday shields are made of molybdenum and radiation cooled.



CENTRAL CELL ICRF ANTENNA LAYOUT

Figure II.7-2

II.8 Blanket Design

The TASKA central cell region has two main types of blankets: (1) the permanent tritium breeding and heat removal blanket, and (2) test blanket modules. The first blanket system is designed to last the lifetime of TASKA (15 years), while the second blanket system is designed to be changed rather frequently to test a variety of breeding materials. There are completely separate coolant systems for each system, but they are based on the same design principles as shown in Fig. II.8-1.

II.8.1 Permanent Breeding Blanket

The coolant-breeder is $Pb_{83}Li_{17}$ which enters the U-shaped tubes at 300°C and leaves at 400°C. The tubes are made from a martensitic alloy, HT-9, which has displayed a great resistance to radiation damage in fission reactor tests. The design of the blanket is such that all welded joints are protected by roughly 1 meter of $Pb_{83}Li_{17}$/HT-9 material which reduces the radiation damage in the weld region.

The localized tritium breeding ratio is calculated to be ~ 1.65 which more than compensates for the lack of breeding in the materials test modules and the loss of neutrons out the ends of the machine. When the overall tritium breeding ratio is calculated, it is ~ 1.0 (including a nominal breeding ratio of 1 from the test blanket region). The low solubility of tritium in the $Pb_{83}Li_{17}$ alloy gives an inventory of only ~ 20 grams. This low inventory, coupled with the reduced chemical activity of this liquid metal, makes it very attractive from a safety standpoint.

II.8.2 Test Blanket Module

A breeder test module with liquid lithium as coolant and breeding material has been designed (Fig. II.8-2). On the basis of neutronic calculations,

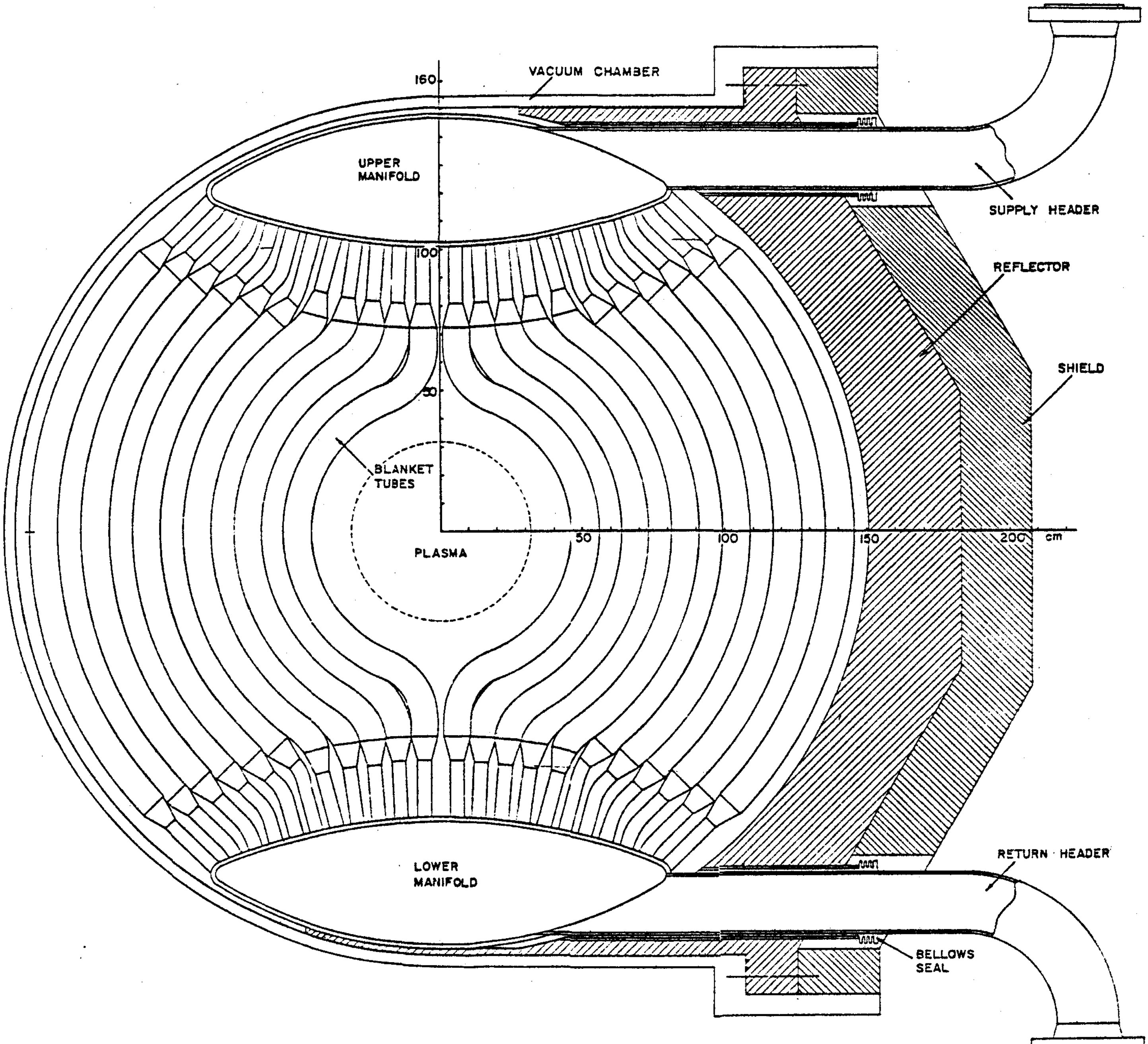


Fig. II.8-1 Vertical section of TASKA blanket

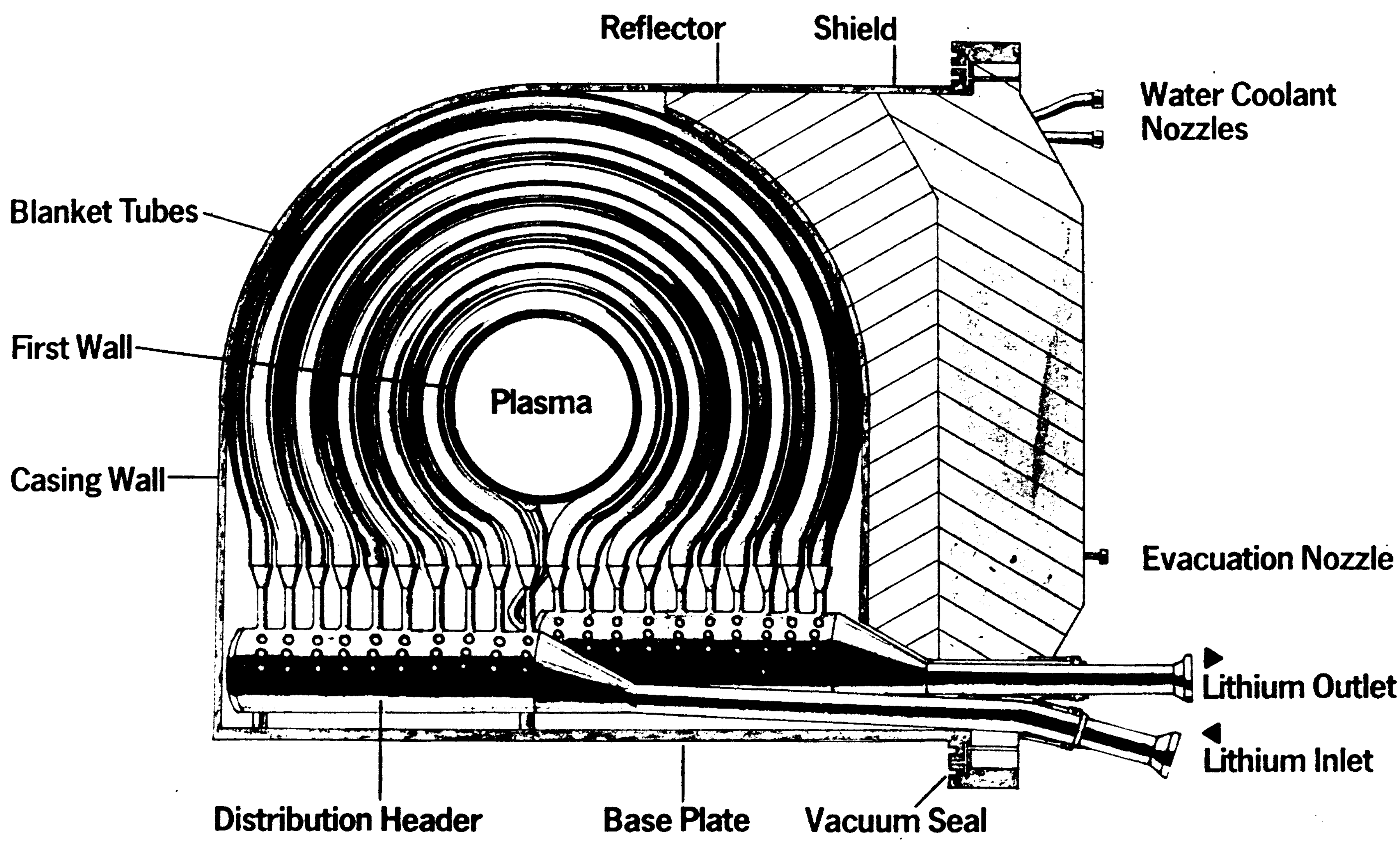


Fig. II.8-2

Taska-Test Module

the test module will be provided with a liquid lithium blanket using natural lithium as breeding material. This will result in a blanket power of about 3 MW (design value) at a maximum neutron wall loading of 1.5 MW/m^2. The operation target of one test module is expected to be 4 years at a load factor of 25% or 2 years at 50%.

The test module consists of three main parts: casing, blanket with headers and coolant pipes, and reflector and shield. The blanket module is constructed such that the vacuum vessel wall is shielded from the direct 14 MeV neutron flux.

Liquid lithium is circulated in tubes bent around the first wall cylinder. The tubes are fed from headers connected by nozzles of the required size and length to connect all tube ends by one inlet and one outlet header. To keep the tubes a fixed distance from each other they are provided with wire or helical finned spacers. The main coolant pipes are stacked one above the other. Headers and main coolant pipes are heat isolated by ceramic materials. Reflector and shield are designed as water-cooled plug units.

II.9 Materials Testing

One of the main functions of TASKA is to test structural materials for the fusion Demonstration Power Reactor which should operate shortly after the turn of the century. To satisfy this function, we require three main features of TASKA. The first is a high neutron wall loading to reduce the time needed to accumulate significant damage levels; TASKA is designed to give 1.5 MW/m^2. The second is a high reactor availability to make the most effective use of the irradiation time. In this respect we used the proposed operating sequence for INTOR [1] (see Table II.4-1), but because (1) the duty cycle of TASKA is 1 versus 0.7 to 0.8 for INTOR, (2) the wall loading is higher (1.5 versus 1.3 MW/m^2), and (3) the samples can be placed closer to the vacuum surface in TASKA than in INTOR, we obtain even higher cumulative damage levels in TASKA than in INTOR. It should also be noted that maintenance of TASKA is much simpler than for a tokamak so that if INTOR can attain an availability of ~ 50%, TASKA should be able to attain an even larger value (however, we did not take credit for that in this study). The third requirement for the materials test program is for a large testing volume and in that respect we have designed for more than 3×10^5 cm^3 of high flux test volume in TASKA.

Analyses of the special test module REGAT (Reduced Damage Gradient Test) design as well as types and numbers of samples to be irradiated are given elsewhere[24,25] and we will only present the results of that discussion here. Figure II.9-1 shows the general design of the test module and one of the 354 test capsules that can be used to irradiate over 27,000 specimens in 10 years (see Table II.9-1) The REGAT modules are either He or H_2O cooled and provide test environments ranging from 300 to 600°C at damage levels up to ~ 100 dpa.

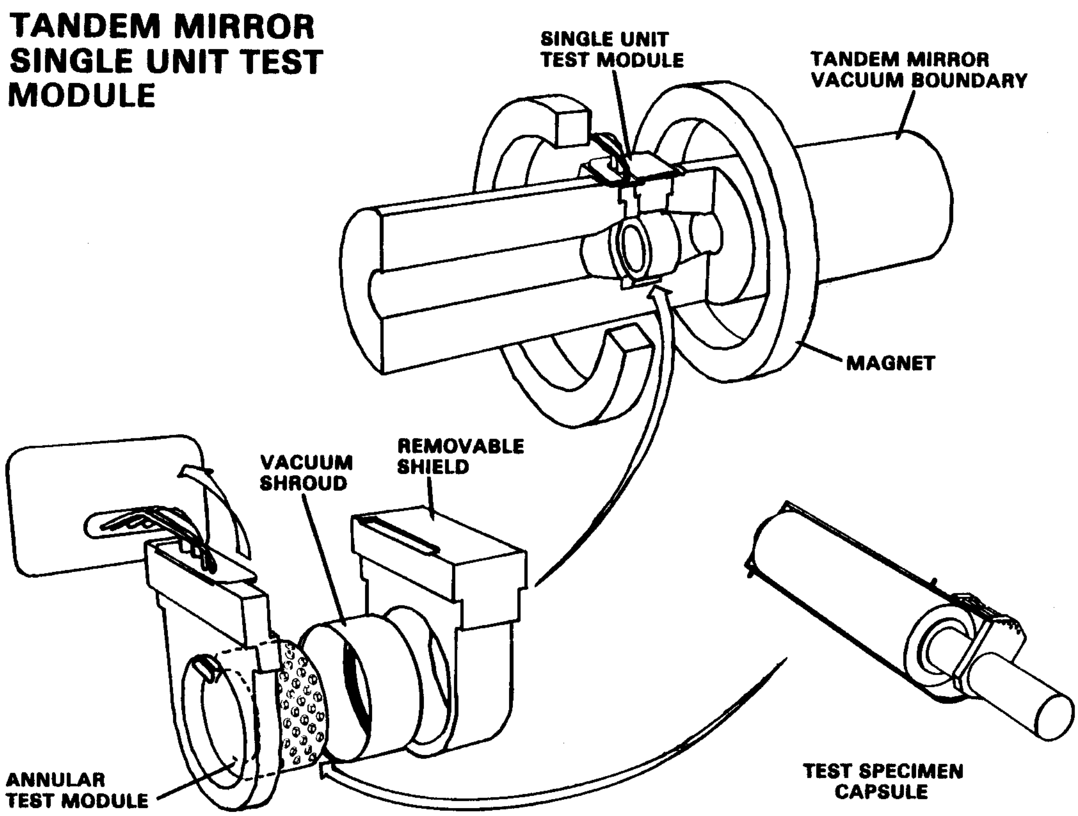

TANDEM MIRROR
SINGLE UNIT TEST
MODULE
SINGLE UNIT
TEST MODULE
TANDEM MIRROR
VACUUM BOUNDARY
MAGNET
VACUUM
SHROUD
REMOVABLE
SHIELD
ANNULAR
TEST MODULE
TEST SPECIMEN
CAPSULE

Fig. II.9-1

TABLE II.9-1

Proposed Materials Test Matrix -TASKA

	Mat. Var.[a]	Dup.[b]	Temp.[c]	Fluence[d]	Conditions	Total Specimens Mirror[e]	Total Specimens Tokamak[f]	Total Capsule[g] Mirror[e]	Total Capsule[g] Tokamak[f]
Materials Surveillance									
Tensile	3	2	2	2	2 rate/temp.	48	48	3	3
Fatigue	0(3)	0(2)	0(2)	0(2)	0(4) stress	0	96	0	4
Crack growth	1(2)	2	2	3	3 stress levels	36	72	1	2
Fracture	2	2	2	2	2 temp.	32	32	4	4
					Subtotal	116	248	8	13
Structural Materials									
Tensile	5	3	6	5	6 rate/temp.	2700	2700	10	10
Fatigue (High Cycle)	0(8)	0(3)	0(2)	0(4)	0(4) stress	0	768	0	29
Crack growth	3(6)	2	4	4	3 stress levels	288	576	3	6
Fracture	4	3	4	2	2 temp.	192	192	5	5
Swelling	10	5	10	5	4 post irr. tests	10,000	10,000	5	5
Stress relax.	6	4	6	-	5 stresses	720	720	3	3
Creep-rupture	6	2	6	-	5 stresses	360	360	2	2
In situ-cyclic	0(4)	0(2)	0(2)	-	0(4) stress levels	0	64	0	64
					Subtotal	14,260	15,380	28	124
Other Materials[h]									
Fatigue	5	3	4	4	2 strain range	480	960	11	22
Tensile	15	3	6	4	4 rate/temp.	4,320	4,320	15	15
Dimensional stab.	15	5	6	4	4 post tests	7,200	7,200	4	4
Creep	10	2	6	-	4 stresses	480	480	2	2
In situ-cyclic	0(6)	0(2)	0(2)	-	0(4) stresses	0	96	0	96
Fracture	3	2	2	2	6 temp.	144	144	7	7
Elect. prop.	6	3	2	4	3 tests	432	432	18	18
Therm. Cond.	6	3	4	4	---	288	288	12	12
					Subtotal	13,344	13,920	69	176
					Total	27,720	29,548	105	313

[a]Materials x variations
[b]Duplication
[c]Number of irradiation temperatures
[d]Fluence levels
[e]Specifically for the Mirror Program
[f]Required for both Mirror and Tokamak Programs
[g]Capsule volume-390 cm^3
[h]Ceramics, electrical, and heat dump materials
( ) Addition for tokamak program

In order to compare the performance of TASKA to other test facilities we show in Fig. II.9-2 the cumulative damage in four devices of interest to fusion materials scientists: the RTNS-II at LLNL, the proposed FMIT device at HEDL, TASKA, and the INTOR test reactors. The main points from this figure are:

1. The accumulated damage rate and test volume is too small in RTNS to be of importance for the Demo.
2. The FMIT will produce high damage levels by the early 1990's, but the test volumes are rather small, 10-100's of cm^3.
3. If TASKA and INTOR have exactly the same starting dates and operating schedules, reactor relevant damage levels (~ 50 dpa) can be achieved in TASKA by the year 2000, whereas it will take 5-10 years longer to achieve such levels in INTOR. The test volume in both devices is reasonably large (~ 10's of liters).

There is an even better way to represent the testing capabilities of fusion materials test devices and this is by multiplying the damage level times by the test volume at that damage level. Mathematically, this can be stated by:

$$\text{dpa-}\ell = \int \text{dpa}(v)\, dv \quad ,$$

where the volume, v, of test space that can give a dpa level in a given time is represented by dpa(v).

A graphical representation of the dpa-ℓ values for the test devices is given in Fig. II.9-3. It clearly shows, along with the previous figure, that if one wants to achieve the largest damage times volume product, then clearly

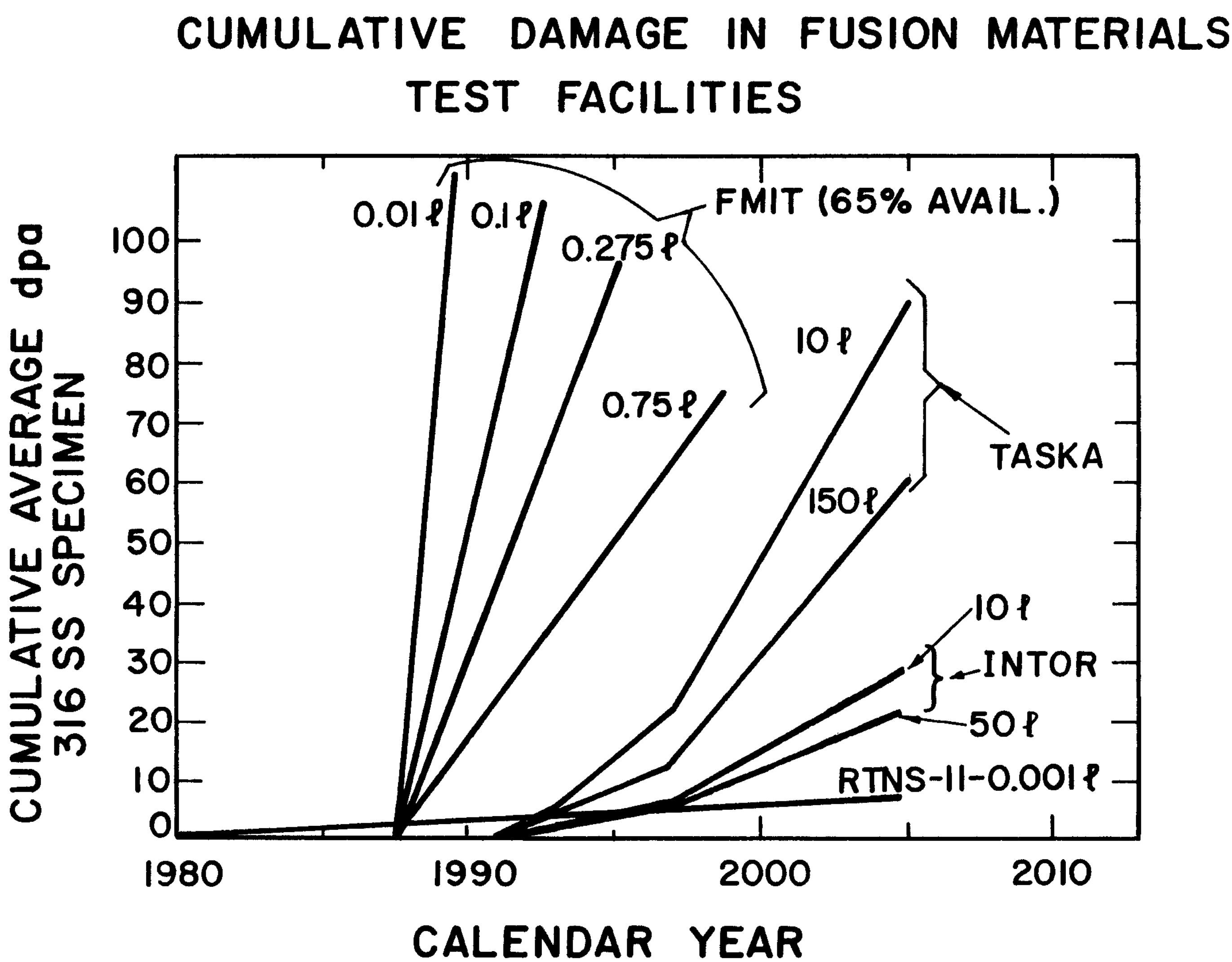


Fig. II.9-2 Cumulative damage in fusion materials test facilities.

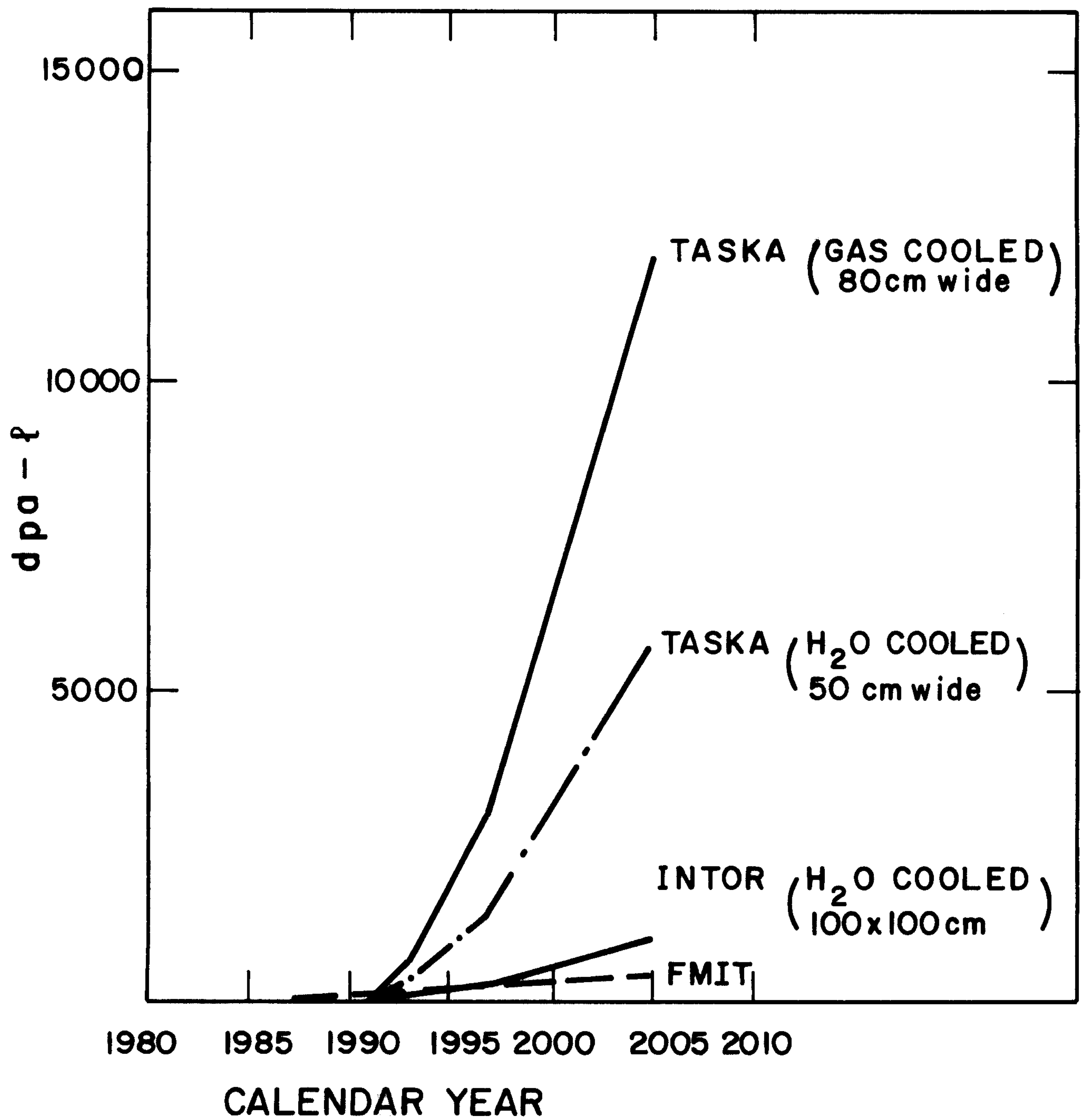


Fig. II.9-3 Cumulative damage times test volume for fusion material test facilities.

the TASKA device is superior to INTOR or FMIT (RTNS data is not discernible on this scale).

II.10 Maintenance

Successful operation of TASKA can be achieved if the downtime can be maintained at a level consistent with the assumed availability. The TASKA reactor equipment is divided into four classes, depending on the anticipated replacement or repair frequency.

Class 1 - Designed for full lifetime such as buildings, support structure and parts of the vacuum vessel.

Class 2 - Lifetime $\geq$ 5 years, such as shield, magnets, etc.

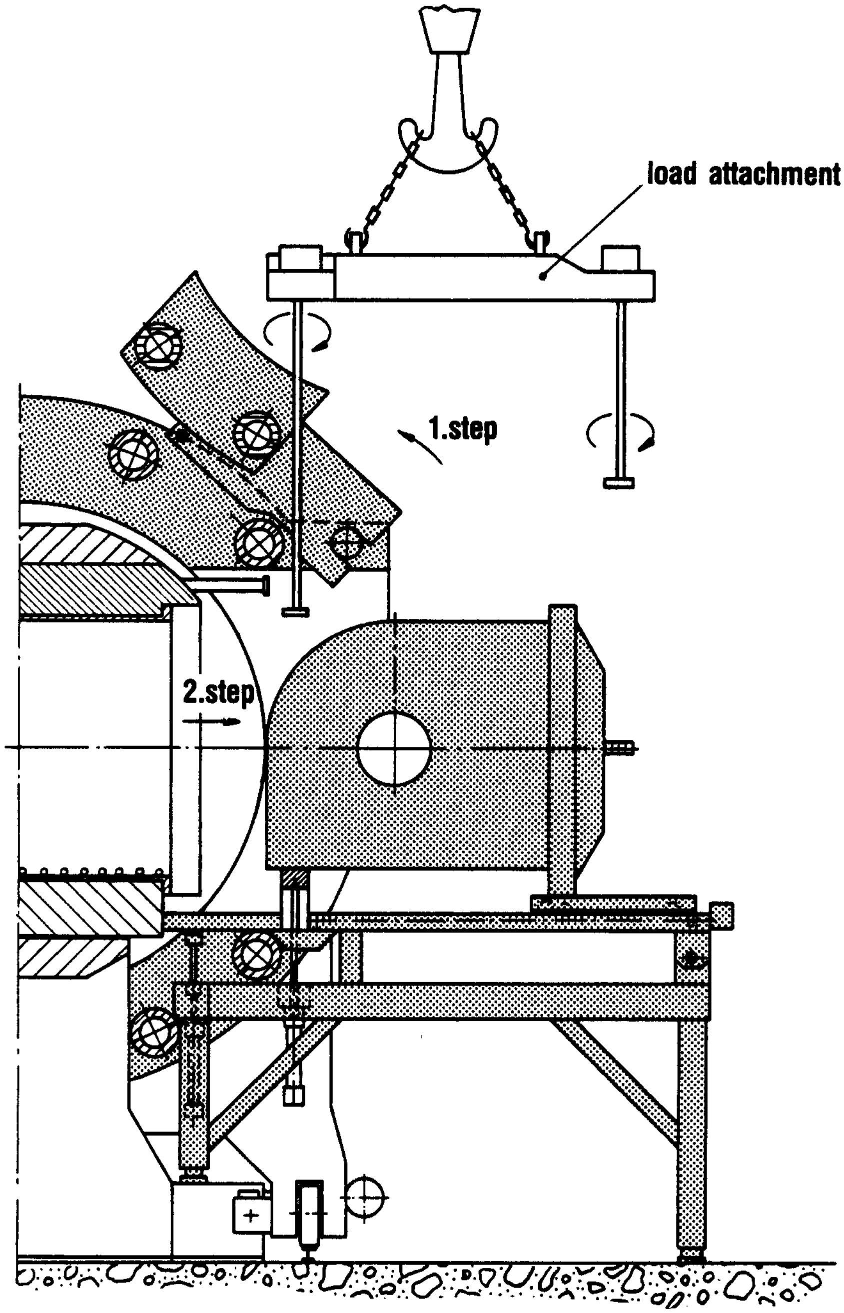
Class 3 - Average lifetime, such as blanket and material test modules, neutral beam components.

Class 4 - Short lifetime, such as handling and experimental equipment.

It is felt that at the minimum the following general purpose remote handling systems will be required:

1. Component handling machine and manipulator carrier attached to the overhead bridge crane.
2. Shielded cabin with manipulator.
3. Elevated work platform.
4. Stereo television viewing system.
5. Various tools adapted for remote handling use.
6. Moveable shields.

The maintenance concepts also address the changeout and repair of blanket modules (as shown in Fig. II.10-1), neutral beam injector components such as ion sources and getter panels, central cell coils and the barrier coils. Displacement of the barrier coil perpendicular to the axis of the reactor (as shown in Fig. II.10-2) is needed to provide access for maintaining the normal insert



Blanket exchange

Fig. II.10-1

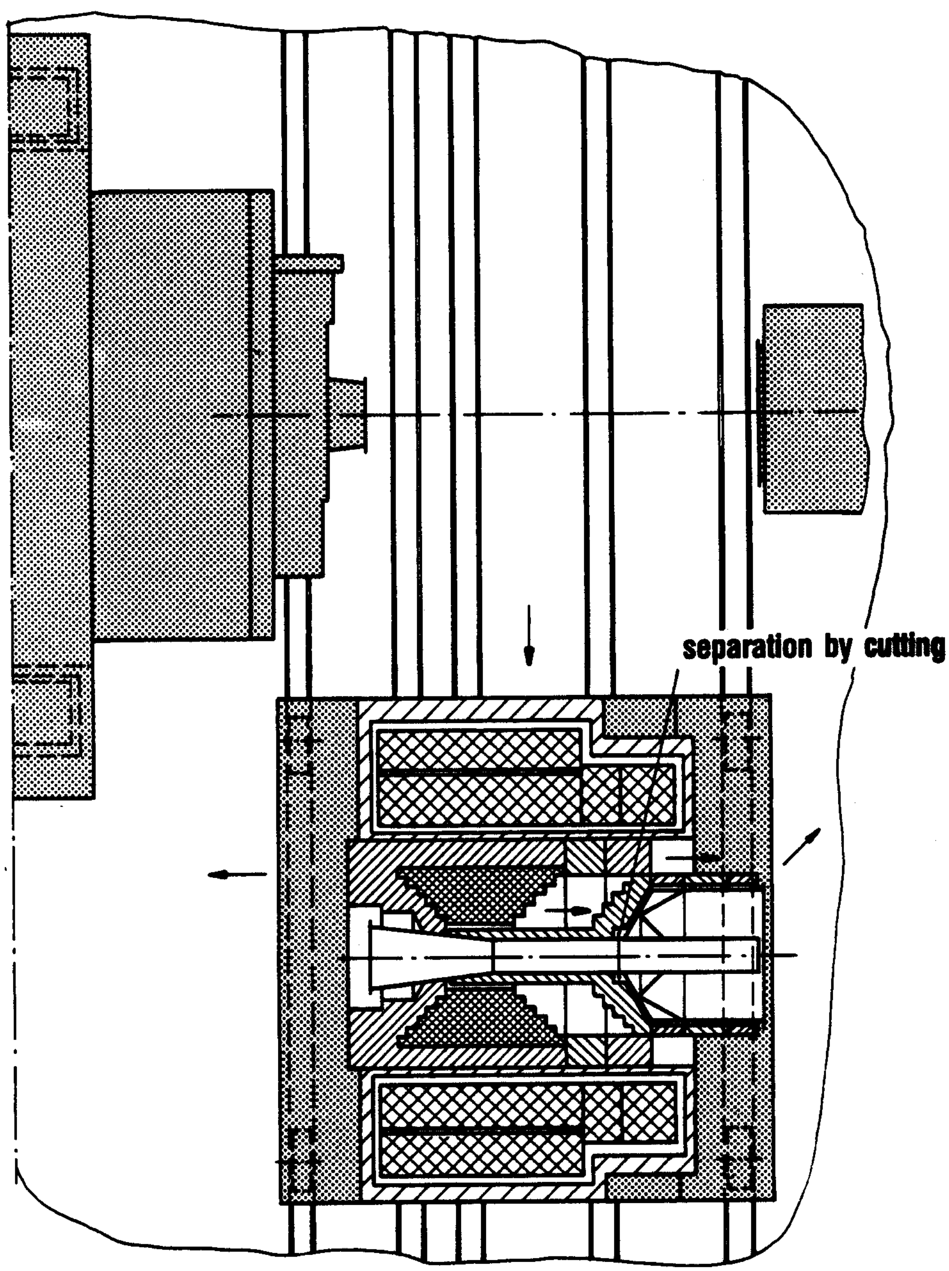
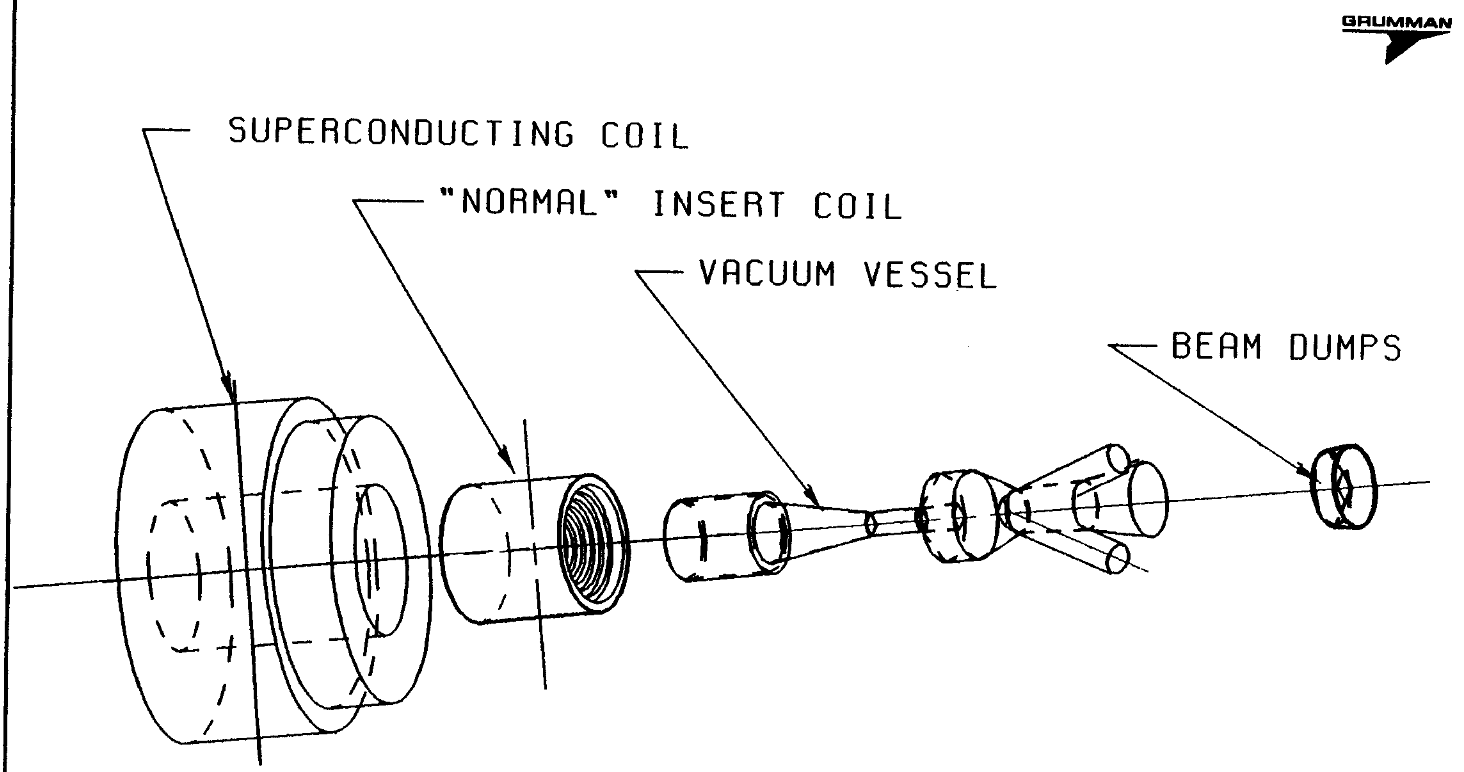


Fig. II.10-2 **Components exchange at barrier region-components dismantling** and the thermal barrier dumps (an exploded view of the barrier coil and vacuum vessel is shown in Fig. II.10-3). This operation requires the following special purpose remote systems:

1. Special transportable carriage support structure with hydraulic adjustments and a lifting traverse.
2. Turnover device for use in maintaining getter panels.
3. A cutting and welding machine adapted for separating or joining vacuum chamber sections.
4. Auxiliary support structure used in removing the barrier coil.

Although only several critical maintenance operations have been addressed, it is felt that the remaining numerous maintenance tasks can be performed with the general purpose equipment provided and some additional special purpose fixtures.

Fig. II.10-3



BARRIER COIL MODULE, MAJOR COMPONENTS

II.11 Cost Analysis

The costs developed for TASKA follow the format adopted for INTOR. The accounts are divided into blanket/shield, magnets, plasma heating, reactor support systems, and buildings. Indirect costs (ID) are engineering (45% of direct costs (DC)), installation/assembly (15% of DC), and contingency (30% of DC and IC). Unit costs and cost algorithms were taken from INTOR (FEDC-M-81-SE-062), PNL-2987, and ORNL (WFPS-TN-057) in that order of information availability. A summary of the costs for TASKA are given below in Table II.11-1:

Table II.11-1. Summary of Direct Costs for TASKA

	$\$ \times 10^6$ (1981$)
1.1 Blanket/Shield	46.3
1.2 Magnets	227.9
1.3 Plasma Heating	269.6
2.0 Reactor Support Systems	163.8
3.0 Buildings	80.4
Total Direct Costs	788.0

It can be seen from Table II.11-1 that we were able to meet our objective of < 800 million dollars in direct costs. The main cost drivers are the high costs of ECRH and neutral beams. If some improvement in the ECRH costs can be made, the total cost of TASKA would be proportionately reduced. The other major cost driver is the magnets with the end plug and barrier coils accounting for roughly 1/3 each of the total cost. The intercoil support structure accounts for ~ 28% of the total coil costs. It is obvious that more intense effort to reduce the magnet costs would also be important to reducing the overall cost of TASKA.

In addition to the direct costs, certain percentages for indirect costs such as engineering, assembly and contingency have to be accounted for. As an example, in INTOR these consisted of 45% and 15% of the direct costs for engineering and assembly respectively, and 30% of the direct and indirect costs for contingency.

The operating costs for TASKA are composed of three main items:

1. Annual O & M (including salaries, administrative expenses, etc.).
2. Costs for continuously required power.
3. Additional electrical power costs needed during reactor operation.

The first item is usually taken as 3% of the direct costs, or 24 million dollars per year. It is important to note that this does not include the experimentalists or special equipment used in the blanket or test modules. The second item amounts to 8.7 MW_e continuously or ~ 3.4 million dollars per calendar year. The third item includes 189 MW_e of power during the burning plasma phase and that is ~ 37 million dollars per year (at 50% availability).

The total O & M cost for 15 years is 360 million dollars and the total electrical power costs are 455 million dollars. The levelized annual costs are 54 million dollars per year and will be below our target of 80 million dollars per year.

II.12 Conclusions

The purpose of the TASKA study was to identify the potential of a tandem mirror device as a technology test bed in a next generation of fusion experiments. This preliminary conceptual design has shown that TASKA can provide meaningful tests of heating technologies, superconducting magnets, remote maintenance equipment, etc., as well as blanket and material tests and that all these reactor relevant technologies could be integrated into one machine of moderate size and with relatively low costs. In particular, the materials testing capabilities are very attractive. A large volume (> 300 liter) of high damage level (up to ~ 100 dpa) testing space is available in TASKA and it can accommodate all the specimens needed to qualify alloys and non-metallic materials for a demonstration plant operating shortly after the turn of the century.

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