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TANDEM MIRROR REACTOR SYSTEMS CODE (TMRSC)*

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ABSTRACT

This paper describes a computer code developed to model a tandem mirror reactor. This is the first tandem mirror reactor model to couple the highly linked physics, magnetics, and neutronic analysis into a single code. Results from this code for two sensitivity studies are included in this paper. These studies are designed (1) to determine the impact of center cell plasma radius, length, and ion temperature on reactor cost and performance at constant fusion power and (2) to determine the impact of reactor power level on cost.

II. INTRODUCTION

A computer code was developed to provide self-consistent determination of configuration, performance, and cost of a tandem mirror reactor as a function of plasma, magnetic, and engineering parameters. The first version of the TMRSC models a configuration similar to MARS [1] and FPD [2], which incorporates a solenodial center cell and an end cell consisting of a choke coil, a "c" coil transition region, an anchor "c" coil set, a plug "c" coil set, and a recircularizing coil. The thermal barrier in this configuration is located in the plug. (Also, see Reference 3, Physics-magnetics Trade Studies for Tandem Mirror Reactors by R. B. Campbell, L. J. Perkins, D. T. Blackfield, these proceedings).

The modules comprising the TMRSC were provided by various sources within the fusion community; the physics, magnetics, magnet, and facility modules were the responsibility of LLNL. Neutronics, shielding, and tritium modules were modeled by ANL. Blanket thermal hydraulics, heat transport/power conversion, cryogenics, direct convertor, and plasma heating systems were provided by TRW. Magnet electrical, AC power, vacuum vessel, fueling, maintenance equipment, and I&C modules were modeled by the FEDC. The integration of the modules into the TMRSC was the responsibility of the FEDC.

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III. TMR MODEL

Code Architecture

The Tandem Mirror Reactor Systems Code consists of modules, each describing a reactor component or system, connected by a driver. The flow diagram for the TMRSC is shown in Fig. 1. Three feedback loops are indicated by the dashed lines. These loops are necessary due to the strong coupling between the plasma physics, the magnetics, neutronics, and magnet design parameters.

The calculational procedure used in the TMRSC is to start at the plasma center line of the center cell and proceed radially. The center cell length and plasma radius are determined primarily from the desired fusion power, field on axis, beta, and plasma temperature. The center cell blanket thickness is determined consistent with the desired energy multiplication and tritium breeding ratio. The shield thickness is set consistent with nuclear response limits in the superconducting solenoidal coils. The center cell solenoidal coil radius is then determined from the summation of the plasma radius, blanket and shield thickness, and assembly gaps. Coil currents and conductor areas for the solenoidal coils are determined as a function of the coil radius, desired field on axis, and allowable coil current density.

The code now proceeds axially to the choke coil and end cell regions. The plasma radius at the choke coil is determined from the desired field on the choke coil axis and the requirement to pass the center cell magnetic flux. Knowing the plasma radius at the choke coil, a choke coil (superconducting portion

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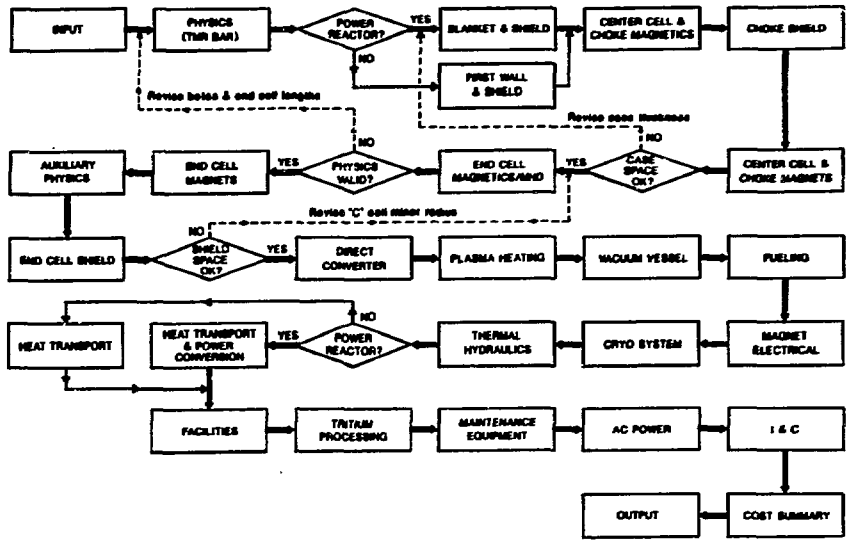

Fig. 1. Tandem Mirror Reactor Systems Code flow diagram.

plus copper insert portion) is sized, based on required currents and allowable current densities, to deliver the desired field on axis. Space for shielding of the choke coil is accounted for.

The "c" coil radii in the end cells are consistent with the plasma boundary, the desired field on axis, requirements for shielding, desired sweep angle, and allowable current densities. Axial positions of the coils are chosen consistent with recircularizing the flux in the anchor and plug wells and reducing to zero the average geodesic curvature. As previously noted, a feedback loop assures compatibility between coil geometry, neutronics, magnetics, and plasma stability.

Modules downstream of the iteration loops are executed in a once-through manner according to the sequence shown in the flow diagram.

Module Descriptions

A brief summary of the modules of the tandem mirror reactor follows.

Physics

The physics module computes the steady state plasma power and particle balance and the plasma supplemental heating requirements for tandem mirror reactors by solving multiple nonlinear linked equations. Quasineutrality is maintained at several cardinal points in the end cell region. Volumes, densities, potentials, and fusion power values are determined. Options to find minimum length, maximum power, or maximum Q are available. The center cell may be specified to be ignited or driven.

Neutronics

Options are available to select from vari breeding, reflector, and structural materials in the center cell blanket and shield module. Tritium breeding ratio, energy deposition, and nuclear response in the coils are determined consistent with the neutron wall loading and material composition and thickness. End cell shielding is based on the neutron source strength. Costs of the blanket and shield are estimated.

Blanket Thermal Hydraulics

Coolant inlet and outlet temperature, pressure drops, pumping power, and structural temperatures are determined for liquid metal and gas-cooled components.

Magnetics

Magnetics for the center cell, solenoidal coils, the choke coil, and the end cell "c" coils are determined. Required currents are computed based on the magnetic field profile, the coil radii, and the coil axial location. The center cell coils may be descrete coils or a current sheet. Conductor current density and coil dimension or coil aspect ratio are input items. The end cell "c" coils are sized and

positioned to provide (1) the desired magnetic field profile (2) flux tube circularity in the magnetic wells and (3) zero average geodesic curvature. This module runs the EFFI magnetic field code and the tandem equilibrium and stability code (TEBASCO). Allowable value of beta in the center cell, anchor, and plug are determined consistent with MHD equilibrium and stability. These values of beta are coupled to the plasma physics through an external feedback loop.

Magnet Module

Center cell and end cell magnets are modeled. Magnet designs are consistent with limitations of current density, maximum field, cryostability, and fluence for various conductor types. Coil case thickness is based on allowable stress. Cost for each magnet is estimated.

Neutron Source (Auxiliary Physics)

This module determines the neutron source strength in the end cells (needed to determine shielding requirements), frequency requirements for the plasma rf heating and drift pumping systems (ECRH, LHRH, ICRH), and magnetic flux, heat flux, magnetic field profile, and net electrical power associated with the direct convertor.

Direct Convertor

The direct convertor is based on a gridless design, and consists of four concentric collectors at each end. Radial drift pumping forces most of the ions in the plasma onto the halo, which is kept at ground potential by the outer two collectors. Electrons flow axially through the middle of the magnet sets and are deposited on the inner two collectors which are biased on the order of -100 kV. Direct electrical power is produced by the electrons; heat deposited by the ions and alphas can be recovered by a thermal cycle.

The model calculates the collector area required for each of the four regions based on a maximum energy flux allowed (input parameter). The electrical power produced, effective radii of the collectors, length of the direct convertor, and the size of the enclosing vacuum tank are also calculated. The thermal power is sent to the heat transport module. Costs are computed based on collector area for each region, direct electrical power for inverting equipment, and vacuum pumping requirements.

Plasma Heating

This module will size rf heating or neutral beam heating systems to supply the required plasma supplemental heating in the center cell and end cell plasma regions. The rf system computes required circulating power, efficiency, cost, and component sizes consistent with available space for access and required power at the launcher. The negative ion neutral beam system computes the circulating power, efficiency, cost, and the number of sources and associated currents to deliver the required power to the plasma. Heating system component characteristics, such as power supplies, amplifier, waveguide, launchers, and neutralizers are determined. Positive ion heating systems are not currently included in the module but may be added later.

RF systems for drift-pumping application are also included in this module. The purpose of the drift-pump system is to remove ions by the process of induced radial drifts which have become trapped in the end cells as they pass to the potential peaks. The model is based on the MARS system and produces a perturbation field normal to the ambient B field. Physics requirements of ion-pumping speed, frequency, and geometry are used to calculate required RF frequency, current required in the coils, and number and width of individual driver frequencies. Total power consumption and system cost are estimated.

Vacuum Vessel

A vacuum vessel exterior to the solenoidal coils, end cell "c" coils, and direct convertor is sized and costed.

CRYO System

The cryogenic system model accumulates cryogenic loads from each of the subsystems requiring cryogens and generates the required electrical power and capital cost of the cryoplant.

Heat Transport/Power Conversion

The heat transport and power conversion module sizes and costs the power conversion system. The blanket/reflector inlet and outlet temperatures and flow rates determine the cycle parameters. Thermal input from the end cell is also incorporated. The module consists of a heat transport routine to generate steam conditions, a turbine efficiency routine, and a costing routine. An option is available to dump the thermal power for experimental TMR designs (nonelectrical power producers).

Tritium Processing

The tritium module determines mass flow rates for the primary tritium/deuterium fuel cycle based on input from the physics module. In the fueling section, an option of using tritium neutral beams during the burn is included. Tritium inventories in all major

systems are calculated. The cost of the tritium needed per year is calculated both with and without a breeder blanket. An atmospheric tritium recovery system is assumed in four areas (reactor hall, hot cell, tritium building, and rad-waste building). Capital costs for the major tritium processing and tritium recovery systems are computed.

Fueling Module

The fueling module computes pertinent design requirements and cost data for the gas injectors, first-stage pellet injectors, second-stage EM rail gun accelerators and their support systems. The pellet velocity, pellet size, pellet rate, vacuum power, helium/nitrogen refrigeration, and cost of the major equipment are determined.

AC Power Module

The ac power system code module calculates characteristic design and cost data for the electrical power systems needed to operate the reactor. This module identifies and computes the cost for major equipment such as circuit breakers, switches, transformers, lightning arrestors, diesel generators, load control centers, and power feeders. This module does not include the turbine generator nor the dc direct convertor in the end cells, but it does include the switch gear and dc-to-ac inverters that interface with the main substation. An electrical power summary is generated.

Magnet Electrical Module

The magnet electrical module computes design and cost data for the power supplies and coil protection equipment of the central cell and end cell magnets. in specific, design and cost data for power supplies, bussing, load centers, dump resistors, dc current breakers, and associated local controls and instrumentation are determined.

I&C Module

This module determines the costs of process I&C, plasma diagnostic instrumentation, data transmission, data processing, and consoles located in the control building. The cost of each I&C process and diagnostic will include both hardware and software.

Instrumentation and control defined in this module refers to the supervisory control and data system located in the main control building and the associated data links to local control and instrumentation. It does not include the local process control and instrumentation located in the proximity of the reactor vault.

Maintenance Equipment Module

This module consists of a compiled list of reactor cell and hot cell equipment and their unit costs. The user chooses the appropriate equipment for a particular device configuration from the comprehensive listing. The equipment either scales with reactor parameters or is fixed in size and cost.

Facility Module

The facility module estimates the size and cost of buildings based on reactor size, thermal power from the blanket and other components, gross electrical power output, and number and capacity of each turbine generator. Facilities considered include reactor building, hot cell building, tritium building, steam generator building, power supply building, cryogenics building, and central building.

Also, the costs of radwaste systems equipment, miscellaneous reactor and balance of plant equipment, and special materials are estimated in this module.

IV. TRADE STUDIES

The tandem mirror reactor system code was used to perform the following studies:

(1) to determine the relationship between reactor center cell length, plasma radius, ion temperature, and cost at a given value of fusion power.

(2) to determine the impact of reactor power level on cost.

Major Constraints or Assumptions

1. Magnetic Field Profile

These studies were conducted with a magnetic field profile similar to that of MARS, which is presented in Table 1.

Table 1. Magnetic field profile.

Location	Value
Center Cell Field	2.5
Choke Mirror Field	24
End Cell Mirror Field	7.5
Anchor Well Field	3.75
Plug Well Field	2.5

2. Beta

Values of beta were consistent with MHD stability. For this study, average values of beta were able to be maintained at 0.6 in the

center cell and 0.3 in the plug region for all cases presented. The value of beta in the anchor region varied from case to case.

3. Ignited Center Cell

The combination of plasma parameters for all cases were maintained consistent with an ignited center cell. All the heating was applied to the end cells.

4. Neutronics

Adequate shielding was provided to limit the nuclear heating in the center cell solenoidal coils to 0.1 MW/cc. Shielding of the end cell coils was not considered in this study.

5. Capital Costs

The costs estimated by the Tandem Mirror Reactor Systems Code are costs for equipment and installation labor only. Component engineering, indirect costs, and contingency are not included. The unit capital cost values ($/kg, $/kW, $/m^3, etc.) used in this study was derived from cost estimates for the FPD II reactor study [2].

Study Results

1. Trade study to determine the impact of center cell plasma radius, length, and ion temperature on reactor cost and performance at constant fusion power (1000 MW).

There are as many combinations of center cell length, plasma radius, and ion temperature that will provide the same value of fusion power. (Recall that the magnetic field profile and beta are fixed.) From the viewpoint of plasma power density, one would choose low values of ion temperature (10 to 20 keV at constant beta) but in a tandem mirror reactor the transport losses scale inversely with temperature, therefore limiting the minimum temperature at which an ignited center cell can be achieved. Figure 2 shows the relationship between center cell length, ion temperature, heating power, and capital cost for a constant radius plasma (45.8 cm) producing 1000 MWs of fusion power. The minimum length reactor is achieved at the limiting ion temperature of 29 keV. Figure 2 shows that as temperature and length decrease at constant plasma radius, the required heating power increases. However, the net effect on cost is for cost to decrease with decreasing temperature and the minimum cost is achieved at the minimum ion temperature. Recall that this analysis was for a constant value of center cell plasma radius. This analysis was repeated for additional values of plasma radius, the minimum temperature points found, and the parameters corresponding to the minimum temperatures were plotted in Figures 3 and 4. Figures 3 and 4 show that as plasma radius is increased at constant fusion power, the length decreases while the plasma heating power and minimum ion temperature for ignition increases. The capital cost initially decreases with increasing plasma radius (decreasing length and increasing plasma heating power), goes through a minimum and then increases as plasma radius is further increased. It is noted that capital cost is not a strong function of the combination of plasma length and radius at constant fusion power. Changing the length and radius combination from 145 m length, 42 cm radius to 115 m length, 52 cm radius shows a capital cost reduction of approximately 5%.

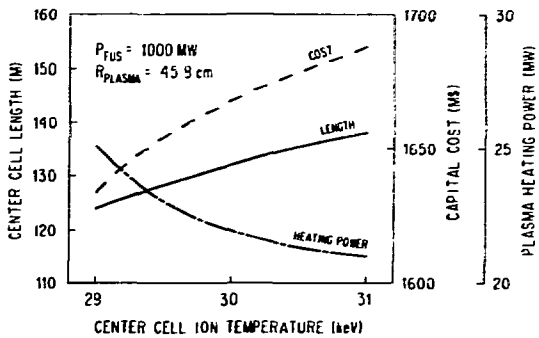

Fig. 2. Length, cost, and heating power vs. ion temperature at fixed fusion power and plasma radius.

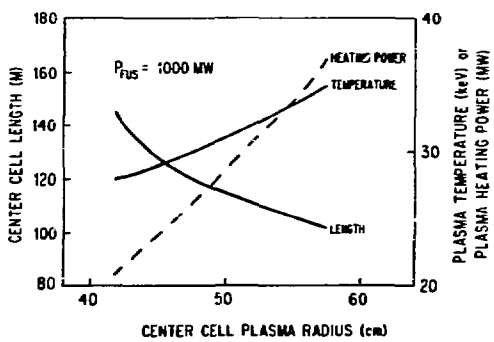

Fig. 3. Length, ion temperature, and heating power vs. plasma radius for fixed fusion power.

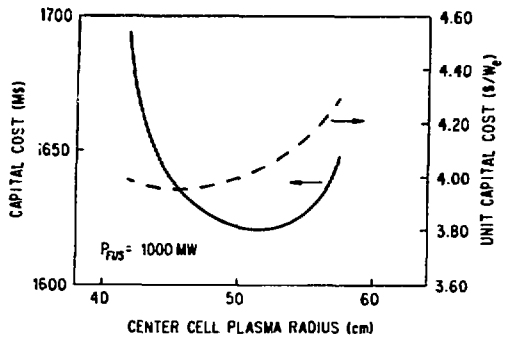

Fig. 4. Costs vs. center cell radius at fixed fusion power.

The unit capital cost, $\$/W_e$ optimizes at a smaller plasma radius, longer center cell length, lower plasma temperature and heating power than does the optimium point based on total capital cost (see Figure 4). A comparison of the TMR parameters at minimum capital cost and minimum unit capital cost, $\$/W_e$, is presented in Table 2. The variation in cost between these two points is slight; approximately 1% in capital cost and 2.5% in $\$/W_e$.

Table 2. TMR parameters at 1000 MW fusion power.

Parameters	Min. Cost	Minimum $\$/W_e$
Plasma Radius, (cm)	52	46
Length, (m)	115	124
Ion Temperature, (keV)	32	29
Heating Power (mw)	31	25
Capital Cost (m$)	1620	1635
Unit Capital Cost (W_e)	4.05	3.95

2. Trade study to determine the impact of reactor power level on cost.

The procedure described in Trade Study 1 was repeated at various fusion power levels. The minimum capital cost point at each power level was determined and the results are presented in Table 3. As indicated in this table, the minimum ion temperature to achieve an ignited center cell decreases as power level increases. Length and radius both increase with fusion power. This study shows that there is a significant ecomony of scale for tandem mirror reactors. The unit capital cost, $\$/W_e$, decreases from approximately $\$8/W_e$ to $\$3/W_e$ as fusion power increases from 500 MW to 1500 MW.

Table 3. TMR parameters as a function of fusion power.

Parameter	Fusion Power, MW		
	500	1000	1500
Length, (m)	94	108	120
Radius, (cm)	45.8	53.7	57.6
Ion Temperature, (keV)	40	33	29
Heating Power, (MW)	22	32	43
Capital Cost, (m$)	1278	1622	1917
Unit Capital Cost ($\$/W_e$)	8.45	4.10	2.95

V. CONCLUSIONS

1. A tandem mirror reactor systems code has been developed with support from the fusion community and is now operational.

2. Initial trade study using this code suggests the following:

   For a fixed value of fusion power, the center cell plasma length and radius combination is not a strong cost driver. Changing the length and radius from 145 m, 42 cm, to 115 m, 52 cm respectively shows a capital cost reduction of 5%.

3. At fixed fusion power, the unit capital cost, $\$/W_e$, minimizes at a longer center cell radius, smaller plasma radius, lower ion temperature combination than the minimum associated with total capital cost.

4. There is a strong economy of scale for a tandem mirror reactor. Increasing the fusion power from 500 to 1500 MW results in decreasing the unit cost from approximately $\$8/W_e$ to $\$3/W_e$.

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