CONF-811040--99

OVERVIEW OF THE FUSION ENGINEERING DEVICE (FED) DESIGN*

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Summary

The U.S. Magnetic Fusion Engineering Act of 1980 calls for the operation of a Fusion Engineering Device (FED) by 1990. It is the intent of the Act that the FED, in combination with other testing facilities, will establish the engineering feasibility of magnetic fusion energy. During 1981, the Fusion Engineering Design Center (FEDC), under the guidance of a Technical Management Board (TMB), developed a baseline design for the FED.[1] This design is summarized herein.

The device has a major radius of 5.0 m with a plasma minor radius of 1.3 m elongated by 1.6. Capability is provided for operating the toroidal field coils up to 10 T, but the bulk of the operations are designed for 8 T. At 8-T conditions, the fusion power is ~180 MW (neutron wall loading ~0.4 MW/m^2) and a plasma Q of ~5 is expected. At 10-T conditions, which are expected to be limited to about 10% of the total operations, the fusion power is ~450 MW (~1.0 MW/m^2) and ignition is expected.

In developing the device configuration, maintenance and cost were the key non-physics drivers. The plasma chamber is assembled by inserting ten shield sectors into a spool support structure. Ten toroidal field (TF) coils (7.4- by 10.9-m bore) are employed and produce a 3.6 T field (8 T) or 4.6 T field (10 T) on axis. Options for the TF coils include superfluid-cooled NbTi, sub-cooled NbTi and a hybrid coil consisting of both NbTi and Nb_3Sn. The poloidal coil system incorporates both normal copper coils (inside the TF coils) and superconducting NbTi coils (outside the TF coils). Plasma bulk heating is accomplished using 50 MW of ion cyclotron resonance heating (ICRH). Electron cyclotron resonance heating (ECRH) is used for startup assist. A mechanical pump limiter, located at the bottom of the plasma chamber, establishes the plasma edge and is used to pump hydrogen and helium particles. The first wall consists of water-cooled stainless steel panels complemented with passively cooled graphite armor on the top and inboard walls and on each side of the limiter. The inboard shield is 60 cm thick and the outboard shield is 120 cm thick. This design provides the basis upon which a full conceptual design effort can be initiated.

Introduction

During FY 1981 a baseline design was developed for the FED. Although not optimized, it represents a reasonable design with feasible concepts for all the major systems and components. This paper summarizes the FED design as developed by the Fusion Engineering Design Center (FEDC) under the guidance of the FED Technical Management Board (TMB). A comprehensive discussion of the FED design, the supporting analyses, and the options considered can be found in ORNL/TM-7948.[2]

The development of the FED baseline design was an evolutionary process. Initially, the TMB established a set of working parameters and design guidelines; these are summarized in Table 1 and reflect the FED mission. The TMB also specified that the FED should incorporate toroidal field coils designed to operate nominally at a maximum field of 8 T at the conductor, but which would be capable of limited operation at 10 T. The 10-T capability does not drive the design; only about 10% of the total machine operation is at the 10-T level. The 10-T capability allows for enhanced plasma performance and provides for additional engineering scaling tests, if needed.

Table 1. Initial FED Working Parameters and Design Guidelines

Fusion power (MW)	~200
Neutron wall loading (MW/m^2)	~0.5
Burn time (s)	~100
Plasma elongation	~1.6
Plasma radius (m)	~1.3
Plasma burn mode	Driven, Q ~ 5
Startup technique	RF assist
Bulk heating technique	ICRH
Particle and impurity control	Pump limiter

Trade and design studies were performed using a full set of system parameters and configuration layouts developed from the parameters and guidelines given in Table 1. The studies focused on cost and performance implications of variations about the working parameters and on the engineering feasibility of systems. Emphasis was given to major cost drivers, major performance drivers, and major engineering drivers. These trade and design studies were reported in ORNL/TM-7777.[3]

Machine Configuration

An elevation view of the FED baseline configuration is given in Fig. 1. Table 2 lists key parameters of the baseline for both the 8-T and 10-T operating modes.

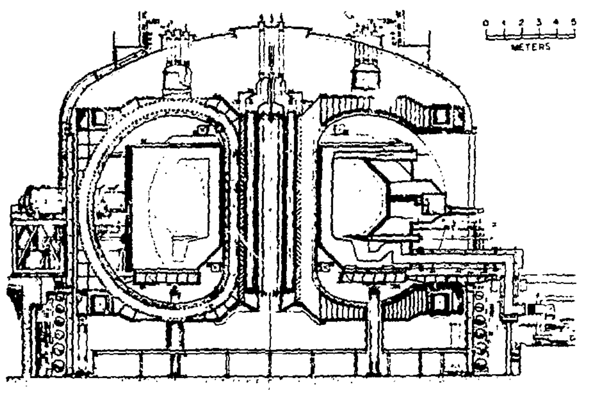

Fig. 1. FED Baseline Configuration, elevation view.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with Union Carbide Corporation.

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Table 2. Key Parameters for the FED Baseline

	8 Tesla	10 Tesla
Major radius (m)	5.0	
Plasma radius (m)	1.3	
Plasma elongation	1.6	
Fusion power (MW)	180	450
Neutron wall loading (MW/m^2)	0.4	1.0
Heating power (MW)		
Initial	50	
Burn	36	0
Q	5	Ignited
Burn time (s)	$\geq$100	50
Duty factor	0.65	0.5
Average D-T density (m^{-3})	0.8×10^{20}	1.2×10^{20}
Average total beta (%)	5.2	
Plasma current (MA)	5.4	6.5
Clear bore, width × height (m)	7.4 × 10.9	
Field on axis (T)	3.5	4.6
Number of full field pulses	2.5×10^5	2.5×10^4
Availability (%)	10-20	10-20

Maintenance was a significant consideration in developing the FED configuration. The maintenance approach for FED consisted of the following key elements.

- Modularity — Where possible, modularity was a design goal for all components which are expected to require replacement or frequent maintenance; an example of this is the pump limiter blade.

- Accessibility — Good access has been a central design consideration of the overall configuration and has strongly influenced the design of the TF coils (size and number) and the design of the torus.

- Hands-on capability — For all device components external to the shield, hands-on access appears to be a practical necessity for many operations and was adopted as a design requirement. Hands-on capability is available approximately one day after shutdown. Providing this capability has strongly influenced the design of the outboard shield.

- Component lifetime categories — Two categories were established. Long-lifetime components are those that are expected to operate the lifetime of the device without replacement, e.g., the TF coils. Short-lifetime components are expected to require relatively frequent replacement, e.g., the pump limiter blade. This designation has been important in developing the FED maintenance needs including maintenance equipment.

Access was the dominant consideration in the selection of a 10-coil arrangement for the TF coil system. These ten coils react against a central bucking cylinder. The TF coils have a 7.4- by 10.9-m bore. Together they produce a 3.6 T field on axis when operating at 8 T and a 4.6 T field on axis when operating at 10 T. Sufficient access is provided so that a torus sector can be either inserted or withdrawn solely by radial motion between the outer legs of the TF coils.

Magnetic Systems

The magnetic system components consist of: the superconducting toroidal field coils; the poloidal field coils which include the superconducting ohmic heating (OH) solenoid, superconducting equilibrium field (EF) coils external to the TF coil bore, and normal copper coils located internal to the TF coil bore; and the cryostat.

TF Coils

A conductor capable of operation to 10 T is required for FED. Three candidate coil technology approaches are capable of achieving the required 10-T field; these are NbTi pool-boiled superfluid-cooled to 1.8 K, NbTi forced-flow sub-cooled to 3 K, and a Nb_3Sn/NbTi combination cooled to 4.2 K. There is no clear technical basis for a preferred option at this time. For purposes of illustrating design considerations, the NbTi forced-flow sub-cooled (3 K) option was selected as the FED baseline.

An overall winding current density of 2200 A/cm^2 has been used in assessing 10-T operation at 3 K. The coils are pancake wound with a total of 444 turns and use NbTi strands in a steel conduit cooled by supercritical forced-flow helium. The over-turning moments are reacted by an intercoil support structure at the top and bottom of the TF coils. The deadweight of the TF coils is supported by a series of outboard pedestal supports designed to also withstand a 1-g-seismic load.

PF Coils

The design of the superconducting (NbTi) OH and EF coils is scaled from the Los Alamos National Laboratory (LANL) design for the 20 MJ Pulsed Coil Program. The design of the interior normal copper EF coils is dominated by the requirement for demountable mechanical joints to facilitate assembly and coil replacement. These coils are structurally supported from the torus permanent spool.

Cryostat

A common vacuum cryostat contains all of the superconducting coils. The cryostat has separate individual enclosures for the outboard legs of the TF coils. This approach maintains the good access between the TF coils and requires no penetration of the cryostat boundary for torus access. This approach also separates the warm and cold components of the FED configuration.

Nuclear Systems

The nuclear systems include the torus (spool assembly, shield sectors and support), the first wall (actively cooled outboard panels and inboard armor) and the mechanical pump limiter.

Torus

The assembled torus constitutes the plasma vacuum chamber. It is made up of ten sectors which are inserted into a spool structure. Each sector is assembled into the spool solely by radial motion (see Figs. 3 and 4). Maintainability has been a dominant consideration in the design. The spool structure provides high vacuum integrity and high electrical resistance. The shield sectors: attenuate nuclear radiation; convert neutron kinetic energy into heat; provide for the removal of this heat; and support the first wall and limiter components. The spool is constructed of Inconel, selected because of its high electrical resistance. The shield sectors are constructed of Nitronic 33 which was selected because it is highly corrosion resistant, exhibits low levels of long-life radionuclides, and is commercially available. The

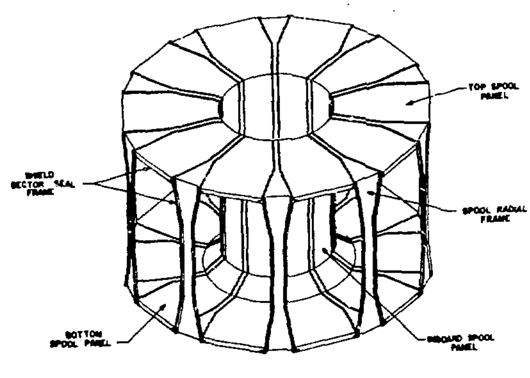

Fig. 3. Torus support spool.

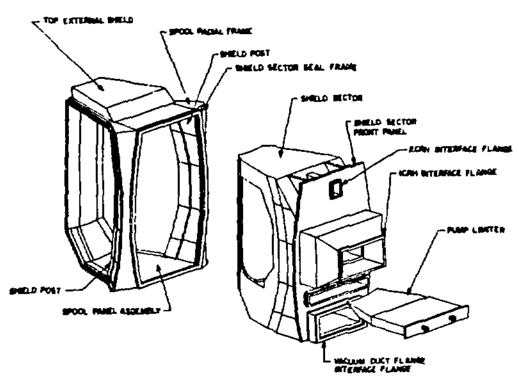

Fig. 4. Torus sector assembly.

shield is cooled with pressurized water. The shield is 60 cm thick on the inboard side and 120 cm thick on the top, outboard, and bottom sides. The shield limits radiation damage at the TF coil insulation to $<10^9$ rads and allows hands-on maintenance by limiting the activation level external to the shield to <2.5 mrem/h about one day after shutdown.

First Wall

The FED first wall system consists of actively cooled stainless steel panels on the outboard wall and passively cooled graphite armor tiles on the inboard and top wall. This design has the capability of accommodating the nominal startup and burn heat loads and the anticipated disruption energy without replacement for the design life of the device (10 years). The outboard first wall panels are of 316 stainless steel. There are six panels on each torus sector so that each panel is about 2 m on a side and 7 cm thick. The vertical facet serves also as a startup limiter. The armor tiles are attached to the torus chamber with graphite bolts. Each tile is 5 cm thick and 15 cm on a side. About 5,300 tiles are required in the device. The tiles are coated with titanium carbide to limit chemical erosion.

Mechanical Pump Limiter

The FED baseline has a mechanical pump limiter for particle and impurity control. The limiter is located at the bottom of the vacuum chamber and is continuous in the toroidal direction. The limiter establishes the plasma edge, pumps helium ash and hydrogen particles and helps protect first wall components from large particle and energy fluxes. The limiter is divided into ten removable segments, one in each torus sector of the device. Each limiter sector is removable independent of the shield sector. Each limiter segment consists of a reusable core structure consisting of an internally stiffened Nitronic 33 box and a replaceable protective surface consisting of surface armor tiles attached to substrate copper. The segment is water cooled. Limiter segments are electrically connected with metal bellows and copper bus plates along one edge of each segment. Analysis indicates that the limiter will provide the desired particle pumping (at least 5% of the total ion flux leaving the plasma). Depending on the assumed plasma edge condition (which is highly uncertain at present), the predicted erosion of the armor tiles varies from ∿0.3 cm/yr to ∿7.0 cm/yr. This results in a variation in predicted tile lifetime of from ∿4 years to ∿2 months. The alternative to the pump limiter is a single null poloidal divertor for particle and impurity control.

Plasma Heating Systems

Systems for plasma initiation and startup and for plasma bulk heating comprise the FED plasma heating systems. An rf system is used for initial heating of the plasma. This consists of ∿1 MW of ECRH [90 GHZ (8 T) and 113 GHz (10 T)] launched through waveguides on the high field side of the plasma using the extraordinary mode of wave propagation. The FED bulk heating is based on ICRH. Second harmonic deuterium species used for majority heating is the baseline approach for both bulk heating and during burn (8 T). The frequencies required are ∿54 MHz (8 T) and ∿68 MHz (10 T). A total of 50 MW is provided for the bulk heating phase. The alternative to ICRH for bulk heating is 150 keV positive ion neutral beams.

Reactor Support Systems

The reactor support systems consist of the following: tritium; fueling; diagnostics, information and control; power handling and conversion; electrical energy storage; vacuum pumping; cryogenics; and remote maintenance equipment.

Tritium Systems

The tritium systems must provide fuel for the device, provide tritium handling in a safe manner and provide an integrated test of tritium handling technology. The system is comprised of primary systems to handle the primary fuel cycle requirements (fuel cleanup, isotope separation, tritium analysis) and secondary systems to provide for safe operation of all systems involving deuterium and tritium (waste treatment, glovebox detritiation, tritiated water recovery). The tritium system will have a tritium inventory of 825 grams for continuous 8-T operation or 1470 grams for continuous 10-T operation.

Fueling Systems

The FED fueling system consists of gas puffers and pellet injectors. Two independent gas puffing systems (one for redundancy) are available to provide fuel gas (deuterium, tritium or a mixed species) to each of 10 inlet ports. The gas puffing is used to backfill the torus prior to startup and continues until a plasma of 1 keV is established. Frozen deuterium and tritium pellets are then injected to control plasma density. Two pellet fuel injectors are located on one torus sector. Each can inject 4-mm pellets at a velocity of 2 km/s at an injection rate of up to 20 pellets/s. Either pneumatic or centrifugal pellet injectors, which are now being developed, can be used.

Diagnostics, Information and Control Systems

The diagnostics system must provide instrumentation for developing physics understanding, for machine performance verification and optimization, for control, for safe, reliable operation, and for component and reactor-relevant testing. The diagnostics will dominate the use of two torus sectors of the machine and additional diagnostic information will be present in all torus sectors. Many of the instruments will have to be replaced on FED once D-T operations commence because of the radiation environment. The Information and Control System for FED consists of the hardware and software to perform all programmable processes for the entire FED complex.

Power Handling and Conversion

The electrical power handling and conversion system includes the ac power system and the TF and PF coil power conversion systems. The ac power system provides both pulsed and steady-state power for the FED loads. The required maximum ac power system capacity is 350 MVA for pulsed power loads. The TF coil power conversion provides for charging the ten TF coils (in about 4 hours with two 65-V power supplies) and for discharge through dump resistors (in about 2 hours). During a quench, the large stored energy (∿23 GJ for 10-T operation) is dissipated through external dump resistors with a time constant of ∿40 s and limits the maximum TF coil temperature to <200 K. The PF coil power convertors are used to make ac power from the motor-generator-flywheel (MGF) units (or utility line) and convert it to pulsed dc power needed for the PF coils during each operating cycle. The system also provides for PF coil protection in case a quench occurs.

Electrical Energy Storage

The electrical energy storage requirements are met in FED with two MGF units. Energy storage is required for the PF coils and for the rf systems. A total of ∿6 GJ of energy is required during startup with a peak MVA load of ∿1850. The MGF units satisfy these requirements. Each is a wound-rotor induction motor with 15,000 HP. They provide variable frequency, 13.8 keV pulsed power. These units are safe, reliable, economical and easy to control. Voltage can be regulated to within $\pm 1\%$ with conventional controls.

Vacuum Pumping

Twenty large turbomolecular pumps, two at the end of each of the 10 vacuum ducts, backed by 20 scroll pumps are used as the vacuum pumping system for FED. This system is used to pump down the torus initially and between burns and to remove the gas load from the pump limiter during the burn. The initial base pressure is 10^{-7} torr. The pumpdown pressure between burns is 10^{-5} torr. The evacuation time between burns is 30 s. The high vacuum turbomolecular pumps are of the Balzer TPH 5000 type or equivalent which have a pump speed of 6.2 m^3s^{-1}. The scroll pumps are used to back the turbomolecular pumps and for rough pumping of the plasma chamber. These are sealed pumps which have no heavy lubricant in contact with the pumped gas. A first stage pump backs each turbomolecular pump and pumps at 33 ℓ/s exhausting at a pressure of 25 torr. The exhaust of all 20 first stage pumps is combined and fed to a single small second stage pump that operates at ∿2 ℓ/s and exhausts at about atmospheric pressure.

Cryogenic System

The crogenic system for FED provides for an entropy generation rate which is several times larger than that of any existing or planned cryogenic refrigeration system in the world. The system must be capable of performing 63 MW of work on helium at room temperature. This system must produce and transfer cryogens at a sufficient rate to sustain normal operations of the superconducting magnet systems of FED. The FED syst- -onsist of forced-flow closed coolant loops for the TF coils and coil cases and a separate loop for the PF coils.

Remote Maintenance Equipment

An extensive list of remote maintenance equipment required for FED has been developed. It includes both general purpose equipment, such as manipulators and cranes, and special purpose equipment for specific applications.

Facilities

A complete facility for FED has been developed, including the reactor building, hot cell facilities, necessary additional support buildings and a site layout.

The reactor building is a rectangular building approximately 60 × 50 × 40 m with a small (3-5 psi) overpressure capability. The walls and roof are 2-m thick to provide for adequate shielding. The building has been designed to mitigate and reduce the consequences of postulated accident conditions. The hot cell facilities provide the capability to support the maintenance and operation of the reactor building and those other facilities involving radioactive operations. The hot cell facilities are of a controlled ventilation construction and require a size of ∿80 × 50 × 30 m. Walls and roof construction are of up to 2-m-thick concrete.

Concluding Remarks

This baseline design represents a workable tokamak design concept that satisfies the FED objectives. Physics analyses indicate that the device can achieve the required plasma performance goals under a range of reasonable assumptions and eventualities.[1] A feasible approach has been developed for all of the major device systems and components. A machine configuration has been developed which incorporates the important needs of maintenance and access. Reactor support systems, facilities and a site layout have been developed. This baseline design provides the basis upon which a full conceptual design effort can be initiated.

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