6.0 Evaluation of the FY 01 Design

In the previous studies, FIRE considered a range of machine and operating parameters. A bucked/wedged TF design was considered in FY01 as an alternative to the baseline wedged design. *One of the major accomplishments this year was the selection of a single set of parameters and design options from the several which were being considered*. This set of parameters will permit engineering to proceed more efficiently as the project progresses towards and begins the Conceptual Design Phase in FY 03. This selection evolved from feedback gained from the fusion community and from tradeoff studies performed by the FIRE project. The basic parameters and features of FIRE that were chosen for FY02 work are presented in Table 3.0-1. The most significant choices made and the background on these choices are discussed below:

- **The machine size parameters were adjusted to permit increased plasma current.** The major radius, R, was increased from 2.0 to 2.14, the minor radius, a, was increased from 0.525 to 0.595, and Ip increased from 6.5 MA to 7.7 to improve FIRE's margin to the global plasma energy confinement scaling provided by ITER $H_{98}(y,2)$. This is provided by the increase in the plasma current and results in a slight decrease in the plasma aspect ratio from 3.8 to 3.6. The fusion power is determined by the operating β; the β_N decreased from 2.4 to 1.6
- **A wedged TF configuration was chosen.** Although the bucked/wedged design study indicated a number of potential advantages, the most significant being a possible 45% reduction of peak power, the wedged design was selected in October to be the baseline TF design structural configuration. The major factors which led to this choice are:

  - *Experience with Wedged Machines:* There is great deal of worldwide operating experience with wedged machines and none yet with bucked / wedged machines. IGNITOR is a bucked / wedged machine, and has done an impressive job of design and engineering analysis. However, it has not yet been constructed and operated. Since FIRE is a fairly large burning plasma experiment and will quickly become activated, it was determined that FIRE is a poor candidate to be the first bucked/wedged demonstration.

  - *Robustness of the Wedged TF Coil Design*: FIRE must have a robust design to routinely operate at its design rating and achieve its physics mission. The wedged design is judged to be more robust against manufacturing uncertainties and variations in operational conditions. The bucked / wedged design requires a fit-up tolerance of +2/-0 mm for the TF / CS interface. If these clearances are not achieved, the load sharing will not be as projected by the analysis. Another concern of the bucked / wedged design is the potential limitations on operational flexibility. In the bucked/wedged design, a portion of the "excess" centering force (ie, the portion not needed to generate wedge friction between the TF inner legs to react the overturning loads) is reacted (bucked) against the CS coil. A portion of the expansive stress generated in the CS by its self-field is reacted by the pressure on its OD by the TF legs. This mutual support requires synchronization of the TF and CS, and therefore will limit operating flexibility.

  - *BeCu Copper plate availability* - Another major factor that led to the choice of the wedged design is the availability of the C17510 "Hycon 3" plate made by Brush-Wellman that is needed for the inner legs. Discussions with Brush-Wellman indicate that BeCu could be produced with the mechanical properties required. They indicated that there is also a high probability that the electrical conductivity would be a minimum of 70% IACS (compared to the 68% assumed in calculations).

- **The maximum operating field of the machine is set at 10T.** 12T was previously considered as a potential upgrade operating mode because it would provide margin for advanced tokamak performance or the achievement of the desired Q at 10T. However, since the forces scale as B^2, the forces would be 1.44 times higher. Providing this margin results in a fairly high cost, in both the engineering and monetary sense.

Results of the design work continue to be very encouraging. The design meets or exceeds all of the major performance objectives that were set for FIRE at the beginning of the study in FY 99: B_T=10 T; I_p=6.4 MA; minimum flat top time=10 s; minimum full power pulses=3000. The new baseline FIRE design can operate at 10T with a plasma current of 7.7 MA and a flat-top time of 20 s for a minimum of 3000 full power pulses.

The main features of the FIRE design are:

- Sixteen LN2 pre-cooled, wedged TF coils with C17510 beryllium copper inner legs and C10200 OFHC copper for the balance of the TF coils
- LN_2 pre-cooled, C10200 OFHC copper, free standing, 5 section, modular central solenoid
- Four LN_2 cooled, C10200 copper PF coils
- A double walled vacuum vessel with integral shielding, passive stabilization system and active control coils
- Shielding with water and steel within the double walled vacuum vessel to reduce activation to allow

hands-on maintenance outside the TF coils.

- Plasma Facing Components using Be for the First Wall and W for the Divertor.
- Double null radiative divertors.

The status and assessment of specific systems is as follows:

6.1 TF Coils and Global Structure

The TF coil peak conductor membrane plus bending stresses are 529 MPa. This is within the static 724 MPa allowable stress for C17510 beryllium copper. Stress limits for a mission lifetime of 3000 cycles at full field and 30000 cycles at 2/3 field are expected to be acceptable for the TF coil since the loading in the peak stress areas is primarily compressive, which inhibits crack growth. **Factor of Safety (peak stress /allowable) = 1.4**

The TF coil temperature excursion for a 10 T, 18.5 s DT pulse or for a 26 s DD pulse is from 80K to 370K. The excursion is the same for a 12 T, 12 s DT pulse or 15 s DD pulse. The peak temperature allowable is 373K. **(TF conductor temperature rise is at the allowable)**.

One of the design issues for tokamaks with highly shaped plasmas and "external" PF coils is the support for the overturning moment on the inner TF coil leg. This moment is due to the fields from the central solenoid and PF coils crossing the legs of the TF coil. This moment causes shearing stresses in the insulation between the turns in the inner leg. In FIRE, the maximum calculated shear in the inner leg of the TF coil, at the mid-plane, is ~50 MPa. Using a conservative coefficient of friction of 0.3 and the calculated wedging pressure of ~200 MPa, the allowable stress would be 60 MPa. **(Insulation shear stress in the throat region is at 83% of allowable).**

In wedged TF coils, the wedging pressure has a tendency to decrease at the top and bottom of the inner leg so the allowable shear stress on insulation decreases. However, the large compression rings in FIRE compensate for this effect by providing a preload and load augmentation as the TF coil temperature increases during a pulse.

Cool down analyses indicate that cooling on the inside edge of the inboard leg of the TF coil is sufficient to achieve a pulse repetition rate of 3 hours. The space required for manifolds and cooling have been incorporated into the design, but detailed stress analyses have not been done. Consideration will be given to adding cooling to the inboard edge of the TF coil so as to decrease the time needed between pulses.

6.2 Central Solenoid and PF Coils

Work has begun on the CS and PF coils for the 2.14 m baseline design. As with the 2.0 m design, stress and thermal analyses indicate that all of the CS and PF coils can use liquid nitrogen cooled OFHC copper conductor. The maximum von Mises stress in CS1 is 322 MPa has been calculated for one scenario; the factor of safety is 1.07. Current studies to optimize the design are considering the allocation of radial space between the CS, vacuum vessel, diagnostics, and PFCs. OH biasing is also being adjusted to find the optimum stress and thermal profiles for the coils. If necessary, consideration will be given to the use of a Cr Cu (Elbrodur) to raise the allowable stress for the CS.

6.3 Vacuum Vessel

The double walled Vacuum Vessel has 16 sets of ports including large mid-plane ports, angled ports above and below the mid-plane, and vertical ports. The combined water and steel shielding allows hands-on maintenance outside the TF coils. Port plug shielding concepts, passive stabilization plates and active control coils have been incorporated into the vacuum vessel. Seismic and VDE loads have been estimated to allow vertical and lateral supports to be sized for the VV. Support and cooling concepts are being analyzed for the passive stabilization plates, active control coils, and PFC's. This will continue in FY02. Since the use of carbon inside the vessel is avoided, high temperature bakeout and operation is not needed. The vessel will operate at 100 C.

The vessel is fabricated in octants from Type 316 LN stainless steel. When all the octants are in place within the TF coils, they are welded together from the plasma side of the torus. The field joint for the double wall structure uses splice plates to accommodate assembly tolerances. It also allows accessing the coil-side, face-sheet from the plasma side of the torus. This type of joint has undergone significant, full scale testing using remote welding equipment as part of the ITER R&D program.

6.4 Divertor and Plasma Facing Components

The divertor design is required to be open to accommodate the short distances from the x-point to the plate and the spreading of the field lines. The connection lengths are short and the scrape-off layer (SOL) thickness is small.

The actively-cooled, outer divertor module design is based on fabrication technologies developed for the ITER divertor and consists of 24, modular, copper-alloy "finger" plates that are mechanically attached to a stainless-steel support structure that spans the toroidal width of the module. The support structure includes machined distribution and collection pathways and manifolds that route coolant to the individual finger plates. Concepts for remotely attaching the modules to the vacuum vessel have been developed.

Passive cooling of the inner divertor plate and baffle components is sufficient for the baseline pulse lengths of 20 s at 10 T . To accommodate longer pulses, the baffle now uses active cooling and the inner divertor is conduction cooled to the baffle. Passive cooling is adequate for the first wall for pulse lengths of about 2 minutes at full power.

Analyses of the PFC designs have begun based on initial specifications for projected disruption and thermal loading conditions to assure that the structures and attachments are sufficient. Work to date has considered halo current loads and disruption eddy current loads on the inner and outer divertor modules. Further analyses are underway to develop the attachment requirements and details of interface conditions.

In general, reliable, yet easily detachable electrical contact must be provided between the plasma facing components and / or plasma facing components and the vacuum vessel. Grounding straps and Multilam® contacts were proposed for this in ITER, since each can accommodate thermal cycling and relative motion. Similar design concepts are being considered for FIRE.

6.5 Thermal Shield

The thermal shield or cryostat provides the insulating environment for the liquid nitrogen cooled coils. The cryostat consists of a stainless steel structure with a thin shell of stainless steel covered by insulating panels and sprayed-on insulation. Penetrations will be sealed with rubber or fabric bellows that accommodate the relative motion between the VV and thermal shield. The result is a cost-effective concept that is relatively easy to maintain and modify.

6.6 Ion Cyclotron Heating

The ICH system requirements were updated to match the needs of the new baseline. The ICH system is designed to support heating at 10T for full burning plasma operation and 7T operation for setup shots. It operates at 80-120 MHz, delivering 20 MW at 90-110 MHz, with modest falloff allowed at the high and low frequency ends of the operating ends. Four adjacent ports with 2 straps in each port will be used. Each strap will have 2 feed points, giving a total of 16 feeds. 20 RF sources will be used, with each having the capability to deliver ~1.25 MW to the plasma.

6.7 Fueling and Vacuum Pumping

Pellet injection is used in FIRE from the outside mid-plane, vertically and also from the inside lower quadrant aimed towards the plasma center. This will be accomplished by three sets of injectors. The initial sizing and integration of the pellet injector components into the vessel has been done.

A tritium-rich pellet source will be used for core fueling and a deuterium-rich gas source for edge fueling. The fueling system includes: a conventional gas puffing system, using all-metal electromagnetic valves, (four toroidal stations at two poloidal locations at each divertor level), and a pellet injection system using two identical (redundant) injectors. The technology to deliver intact pellets at the highest possible speeds around curved surfaces (guide tubes) is under development.

The design vacuum pumping speed is 200 torr-liter/s for a 20 s pulse length. The base pressure prior to discharge is 10^{-7} torr for fuel gases (H, D, T) and 10^{-9} torr for impurities; operating pressure is~10^{-4} to 10^{-3} torr. There will be a total of 16 cryopumps with 8 each on the top and bottom (at alternate divertor ports), close coupled to the torus in the pumping duct directly from the double null divertor. The interface issues for these elements will continue to be addressed together with the impact on the requirements for other possible operating scenarios. Sufficient pumping speed will be assured by providing additional pumping capacity through a section of one of the midplane ports.6.8 Tritium

The on-site tritium inventory has been set at 30 g to allow sufficient operational flexibility without introducing additional restrictions. However, the inventory can be reduced if a tritium reprocessing system is added to recycle the tritium daily.

6.9 Neutronics and Shielding

Nuclear heating has been computed for the major components (e.g., magnets and PFC's) as input to the cooling design. The largest nuclear heating values in the different components were calculated for the 200 MW fusion power DT pulses. During these pulses the average neutron wall loading is 3 MW/m^2 with values at the outboard (OB) midplane, inboard (IB) midplane, and divertor being 3.6 MW/m^2, 2.7 MW/m^2, and 1.8 MW/m^2, respectively. Radiation damage estimates have also been done to size shields and estimate lifetime for sensitive components. Evaluations are underway to determine the impact of radiation on the electrical resistivity and, in turn, on the electrical and thermal performance of the TF coil materials.

The insulation dose is computed to be 1.3-1.5 x 10^{10} rads for 3000 full power DT pulses (fusion energy of 5 TJ) and 30, 000 DD pulses (fusion energy of 0.5 TJ). This is the peak, end of life, value and occurs at the magnet surface at the inboard mid-plane. This value drops to 9.8x10^8 rads in the divertor region and 7-12.6 x 10^6 rads in the outboard region at mid-plane.

The commonly accepted dose limit for epoxies is 10^9 rads. Polyimides and bismaleimides are more radiation resistant with experimental data showing only a small degradation in shear strength at dose levels in excess of 10^{10} rads. However, they are difficult to process due to their high viscosity and requirement for high temperatures to fully cure. Newly developed insulations, such as cyanate esters, should provide radiation resistance with easier processing requirements.

The vacuum vessel jacket/shield thickness has been sized so that it, in conjunction with the shielding provided by the TF coils and port plugs, will permit "hands on" ex-vessel maintenance. This will require further consideration of shielding details.

6.10 Activation, Decay Heat and Radiation Exposure

The plasma facing components, first wall on the inboard and outboard sides and the divertor, experience the highest levels of specific activity and decay heat. However, the operational schedule allows short-lived radio nuclides to decay between pulses resulting in low levels of activity and decay heat at shutdown.

The biological dose rates behind the vacuum vessel and the divertor remain for several years following shutdown, however, the dose rates outside the magnet and at the mid-plane are acceptable for hands on maintenance within a few hours after shutdown. At the top of the machine the dose rate drops to an acceptable level within one day after shutdown.

Dose rate calculations have indicated that port plugs 1.1 m long would provide adequate shielding and have led to the addition of shielding outside the magnets on the top and bottom of the machine.

At the end of the machine life, calculations indicate that all components would qualify for disposal as Class C low level waste.

6.11 Remote Maintenance

The strategy is to employ hands-on maintenance to the fullest extent possible in order to minimize remote handling operations and equipment while achieving acceptable machine availability. Activation levels outside the vacuum vessel are low enough to permit hands-on maintenance in the ex-vessel region. Remote handling (RH) is required for in-vessel components including the divertor, FW and limiter modules, and the port mounted systems including heating, diagnostics and cryopumping systems.

When in-vessel maintenance or modification is required, the affected components are removed from the vessel and transferred to the hot cell where they are refurbished or processed as waste. Divertor, FW and limiter modules are accessed through the midplane ports and are handled with an articulated boom equipped with a specialized end-effector. The boom can access the complete in-vessel region from 4 of the 16 midplane ports. Port mounted system assemblies are located in both the mid-plane ports and the upper and lower auxiliary ports and are removed by a vehicle and manipulator system operating at the closure plate of the related port. A boom and manipulator built for RH R&D and demonstrations will serve as a back-up for the single boom built for machine service.

RH operations are performed from sealed transfer casks that dock to the ports via a double door system to contain and prevent the spread of in-vessel contamination. Casks carry components between the reactor and the hot cell and are transported by a vehicle or the facility overhead

Components have been classified according to their required maintenance frequency and their designs will be standardized and optimized for RH. Preliminary time estimates to complete the more frequent maintenance tasks are consistent with the required machine availability. Replacement of a port assembly requires approximately 3 weeks of maintenance operations. A complete divertor changeout, 32 modules, is completed in about 6 months. Individual divertor, limiter and first wall modules can be replaced in about one month. The time target to perform a complete changeout of the divertor and FW components is 1 year

Studies have begun and will continue in FY02 on kinematics and end-effector design for the in-vessel manipulator to assure that sufficient space has been allocated in ports and around the machine. Analysis shows that the 800 kg combined divertor module (32 module configuration) can be supported and transported through the vessel and ports. Studies will also continue in FY02 on the port assembly and handling equipment design, cell layout and cask design to assure adequate building size and layout for component transport for repair or disposal.

6.12 Power Supplies

The conceptual design of power supplies for FIRE magnet systems seeks to minimize capital cost by leveraging existing capabilities of the local electric utility, which are assumed to be robust. Therefore, all of the FIRE device's time-varying power (peak demand of

800MW) for TF and PF magnets as well as the RF systems are provided directly by the utility's "stiff grid" without requiring any power demand ramp rate limiting equipment, or energy storage equipment, at the FIRE device site. However, provision for reactive power (MVA) support up to 300MVA is included in the design baseline. The grid's ability to supply the required time varying active and reactive power demand will be evaluated when a specific FIRE site is chosen and the above assumptions adjusted as necessary.

If the local electric utility is not capable of powering the pulsed load directly from its ac power line, MG energy storage devices could still be installed, but at additional cost.
We plan to survey grid capabilities to determine if direct pulsing from the grid would seriously restrict site selection options before choosing between direct grid powering or combined grid/MG set powering.

Power equipment for TF and CS/PF magnets includes thyristor rectifiers, resistor banks, and switching/interrupter circuits. The required total pulse rating of the rectifier complement is approximately 1000 MVA for the 10 T pulse. For the DD long-pulse scenario at 4 T, 2 MA the total 243 second long-pulse rectifier rating required is 345 MVA. By way of comparison, these total rectifier MVA ratings are similar to the total ratings of existing rectifiers, that were used to operate the TFTR magnets. Resistor banks and interrupter switching circuits are used in FIRE for plasma initiation in a fashion similar to TFTR and JET. Some of the magnets require current reversal during a pulse and therefore incorporate dc polarity switching in their rectifier circuits, as done for TFTR.

6.13 Cryoplant

The FIRE cryoplant and nitrogen distribution system is a modified form of the design developed for CIT and BPX.

Major design features of the cryoplant:

- Large liquid nitrogen storage tanks are used on site. The FY99 concept for nitrogen deliveries by truck has been replaced by pipeline delivery from a new on-site or near site air liquefaction plant. Commercial suppliers recommended the latter.
- The amount of radioactive N^{13} generated in FIRE is small and would be within allowables for most site boundaries. A helium purge has been added before each pulse to displace any remaining nitrogen in the passage prior to the pulse, thus eliminating N^{13} generation and the need for a gas holdup circuit.
- FIRE uses the Alcator C-Mod method of one pump and cool down and which has proven to be very reliable.
- A subcooler is used to provide 80 K liquid nitrogen to the coils.

The magnets are kept cold overnight and weekends, and only warmed up to room temperature during maintenance periods. This provides considerable flexibility for adjusting shot scenarios.

6.14 Facilities and Siting

A conceptual layout and building design has been developed for a "green field" site. For example, the deletion of the central tie rod system from the tokamak has allowed a decrease in the test cell height. In the future, candidate sites should be identified and evaluated for their technical acceptability and their influence on the cost and schedule of the project since significant savings may be available in the form of "site credits".

The test cell size is determined by space required to maneuver and dock remote handling casks at ports. Because of the length of the port inserts, remote handling casks are expected to be approximately 8 m in length and about 1.9 m in width. There are several strategies under consideration for the design of remote handling cask vehicles. A tentative routing for the vehicles to other parts of the facility has been selected.

Some components, for example port inserts ("plugs"), will require enough shielding to make it impractical for the casks and remote handling vehicles to include shielding. Therefore, transfer of objects of this type are planned as remote handling activities. The special requirements on the facility for routing and storage of these items are being evaluated.

The hot cell concept is based on the expectation that some port mounted objects can be repaired and returned to the tokamak. The extent and nature of these hot cell processes are not yet well developed, but it is expected that they will include divertor repair, tritium recovery from beryllium, size reduction by sawing or cutting, and encapsulation of radioactive material for subsequent shipment to a waste repository.

Some building requirements are not yet well developed, but a preliminary allowance has been made. For example, the cryogenics systems building is used to house indoor parts of the liquid nitrogen system for the FIRE magnets. It also houses a liquid helium refrigerator that provides liquid helium to cryopumps in the tokamak vacuum vessel and in the diagnostic neutral beam, and to the isotopic separation system in the fuel process.

6.15 Safety

Radiological release targets for tritium, activated tungsten (e.g. tokamak dust) and activated air and nitrogen have been established to meet regulatory dose limits in the DOE fusion safety standard taking account of the ALARA principle.

A goal for the FIRE design is to keep the total on-site tritium inventory below 30 g, so that it can be classified as a low hazard nuclear facility based on current DOE hazard classification rules. For off-normal events, as long as the total facility tritium inventory remains below 100 g, then complete release of that inventory would not threaten the ability of FIRE to meet the no-evacuation objective.

The vacuum vessel will be a highly reliable primary confinement barrier for the in-vessel inventories. The thermal shield will serve as a moderately reliable secondary barrier. Double confinement (e.g. a combination of valves, windows or other barriers of moderate reliability) will be implemented in all penetrations attached to the FIRE vacuum vessel.

Acceptable leak rates for these boundaries will be established as the design progresses.

Examination of the potential safety concerns associated with the different energy sources in FIRE has not yet revealed any events that pose a serious challenge to the radiological confinement function. A preliminary analysis has been done for:

- Long term thermal response and passive decay heat removal capability under a complete loss of coolant condition for the divertor and VV following a pulse--Results indicate that decay heat is not a serious concern and that oxidation of the activated PFC surfaces will not be significant.
- Break in the divertor or VV cooling lines inside of the VV—Results indicate that pressure within the VV does not rise to a level expected to compromise its radiological confinement integrity. Further-more, because of the low VV steam pressures and low FW temperatures (below 350°C), insignificant amounts of hydrogen are generated from Be-steam and W-steam interactions. Thus, the chemical energy from these reactions does not threaten the radiological confinement function of the vacuum vessel.
- Deflagration and/or detonation of hydrogen upon mixing with air. From the accident perspective, hydrogen from Be/steam and W/steam reactions was not of concern, however the tritium on the cryopumps must be controlled. The deflagration limit of 30 g-moles translates into a deflagration limit of ~ 300 g DT. Regeneration will be scheduled frequently enough to stay well below this limit.

The control of plasma energy, magnet energy, loss of vacuum events, and potential cryogen/water interactions has not yet been analyzed. As the design matures, this examination will continue such that confinement is adequately ensured in FIRE.

In summary, all of the major subsystems for FIRE have been addressed to a level that provides confidence that the mission requirements can be achieved. Several design improvements have been incorporated to produce greater physics flexibility or resolve engineering issues. First round cost estimates have been completed and are being reviewed to determine design changes, which can reduce costs. Modest changes to machine parameters were specified at the end of FY01 and work has started to modify the design as required for the selected baseline of a wedged TF system. This work will continue in FY02.