FIRE Engineering Overview

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for the FIRE Team

Presented at
External Review of FIRE Engineering
PPPL, Princeton, NJ

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http://fire.pppl.gov

FIRE ***Lighting the Way to Fusion***

The FIRE Design effort has addressed all major subsystems & issues:

- TF Coils & Global Structure
- Central Solenoid & Poloidal Field Coils
- Vacuum Vessel
- Plasma Facing Components
- Thermal Shield
- Ion Cyclotron Heating
- Fueling & Pumping
- Tritium Systems
- Neutronics & Shielding
- Activation, Decay Heat & Radiation Exposure
- Remote Maintenance
- Magnet Power Systems
- Cryoplant
- Facilities & Siting
- Safety

Design goals have been met or exceeded.

Several options & issues have been identified.

Initial cost estimates have been prepared.

Guidelines for FY01 Engineering Tasks

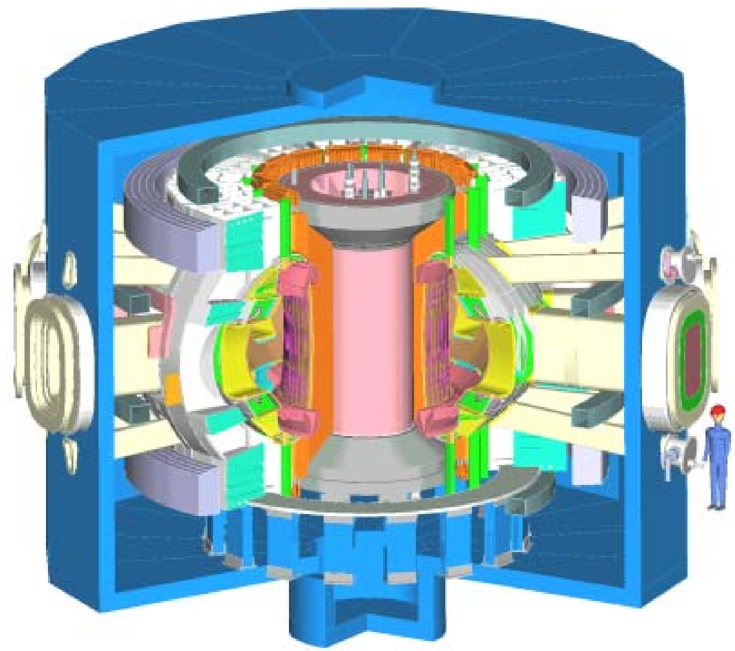
- Evaluate design alternates:
  - Sensitivity of cost to performance, aspect ratio, and size
  - Modifications to wedged baseline
  - Bucked and wedged, all OFHC Cu TF coils
- Identify R&D issues
- Carry out peer reviews of critical systems
- Complete the baseline cost estimate

FY01 Meetings and Milestones

item	where	date
FY01 Kick-off Meeting	ANS, Park City	Oct 18, 00
Design Point Subgroup	PPPL	Nov 29-30, 00
Cost Subgroup	PPPL	Dec 1, 00
Review of Physics & Engineering Status	NSO PAC, MIT	Jan 17-18, 01
Project Peer Reviews:		
TF/PF/Structures	PPPL	June 5-7, 01
VV, PFC's, Fueling & Pumping	PPPL	June 5-7, 01
Nuclear Effects and Activation	By mail	June, 01
Facilities & Siting	By mail	June, 01
Power Supplies	TBD	FY02
ICRF Systems	TBD	FY02
Remote Handling & Tritium	TBD	FY02
Physics & Engineering Update	TBD	July 15, 01
Final FY01 Engineering Report	------	Sept, 01

Features of FIRE Baseline

- 16 Wedged TF Coils
- Two Pairs of External Divertor Coils
- Two Pairs of External Ring Coils
- Free-standing, Segmented CS
- Vacuum Vessel Filled with Steel/Water for Shielding
- Plasma Facing Components:
  - -Be coated Cu 1st Wall
  - -W pin-type Inner Divertor, Baffle, & Outer Divertor
- 2 Outboard Poloidal Limiters
- Internal Passive & Active Stabilization Coils
- Remote Maintenance

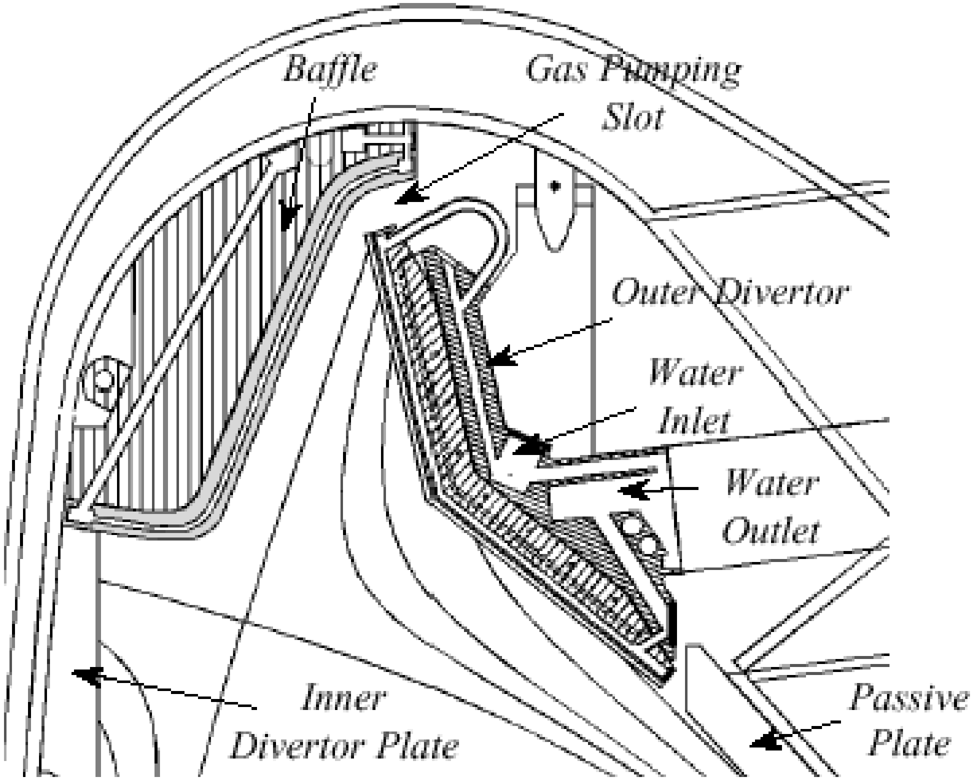


Cutaway Through Thermal Shield

- 16 Large Midplane Ports
- 32 Angled Ports
- 32 Vertical Ports
- Thermal Shield:
    - SS Frame with SS skin
    - Insulated Exterior
    - Provides 80-90 °K Inside

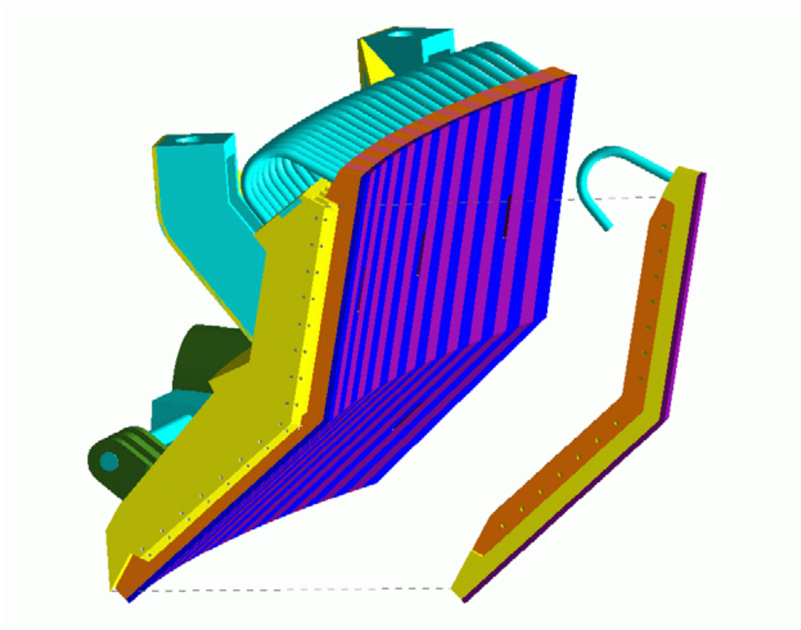
Divertor & Plasma Facing Components

- The divertor design is open due to the short distances from the x-point to the plate and the spreading of the field lines.
- The outer divertor & baffle are actively cooled; inner divertor & FW are cooled by conduction to the actively cooled Cu clad VV



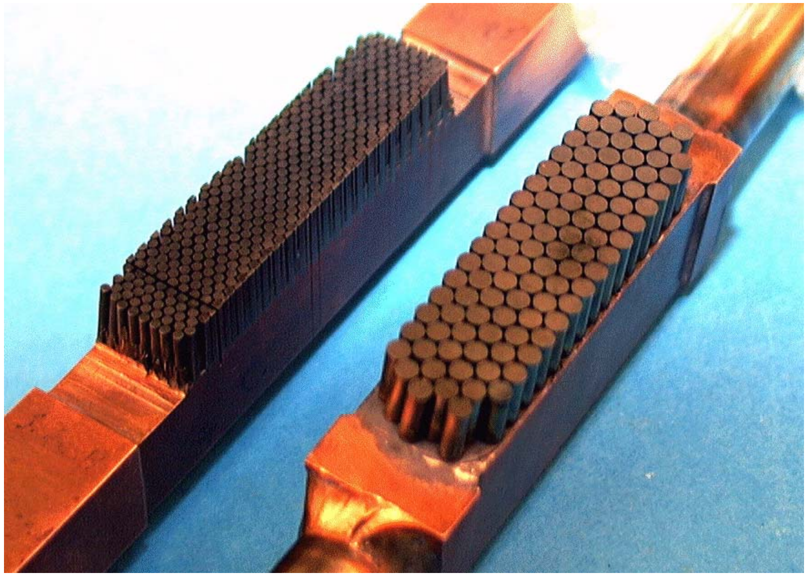
Cross-section Through
Divertor Module & Baffle

Divertor Module Components



Finger Plate for
Outer Divertor Module

Two W Brush Armor Configurations Tested at 25 MW/m^2



TF Coils-Baseline

- wedged coils, inertially cooled using LN2
- Inner legs: C17510 BeCu (68% IACS)
- Outer legs: C10200 OFHC (100% IACS)

Pulse Flat Top Time Based on TF Coils

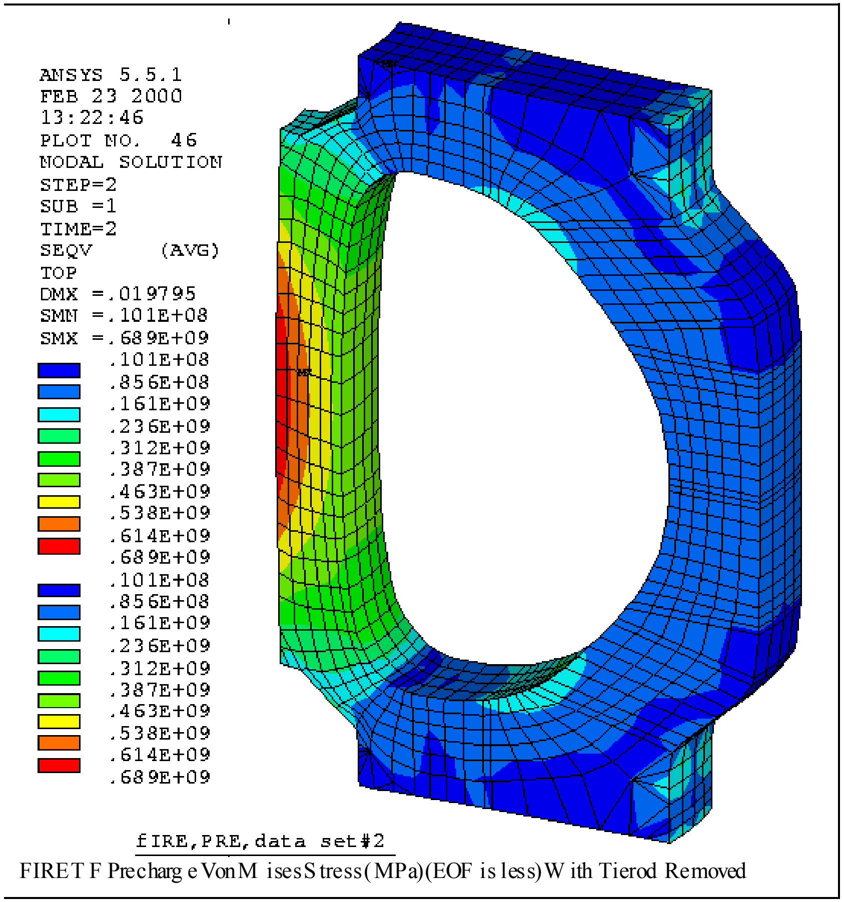
initial temperature=80°K

peak allowable temperature = 373°K

Field	DT Operation	DD Operation
12 T	12 s	15 s
10 T	18.5 s	26 s
8 T	31 s	46 s
4 T	---	214 s

Baseline TF Coil Von Mises Stresses

- **The peak conductor VM Stress of 689 MPa for 12 T (7.7 MA) is within the static allowable stress of 724 MPa**



TF Coil Von Mises Stress Contours at 12 T

TF Coils-Stresses

- **Peak conductor Von Mises stresses of 469 MPa for 10T and 689 MPa for 12T (7.7 MA) are within the static allowable stress of 724 MPa.**
- **Stress limits for a mission of 3000 cycles at full field & 30000 cycles at 2/3 field are expected to be acceptable since the loading in the peak stress areas is primarily compressive, which inhibits crack growth.**

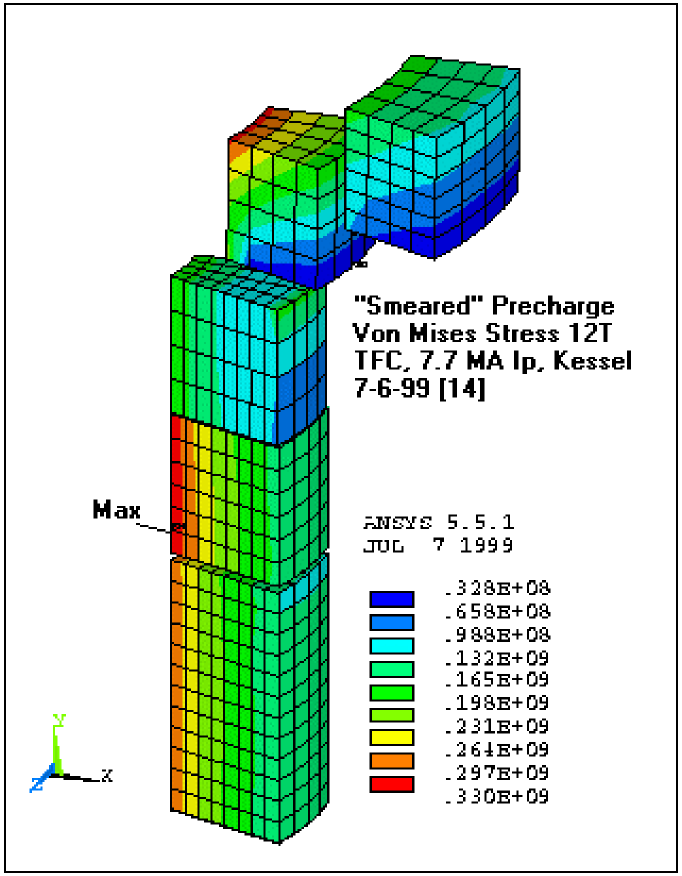
Support for the overturning moment on the inner coil leg:

- **This moment causes shear stresses in the insulation between the turns in the inner legs as they are twisted**
  - **~30 to 40 MPa at midplane**
  - **~50 to 65 MPa at top and bottom of inner leg**
- **In wedged TF coils, the wedging pressure tends to decrease at the top and bottom of the inner leg so the allowable shear stress on insulation decreases. In FIRE, large rings add compression in these corners and compensate for this effect.**
- **Using a coefficient of friction of 0.3 and the calculated wedging pressure of ~200 MPa, the allowable stress would be 60 MPa**

Central Solenoid & PF Coils

- All of the CS and PF coils use LN_2 cooled OFHC copper conductor
- The max temperature in a CS or PF coil occurs for the 12 T, 7.7 MA scenario:

  161 K in CS1, and 183 K for PF2
- For the baseline 10T or 12 T pulses, the pulse length is limited by the temperature rise of the TF coils.
- Pulse length is also limited by the temperature related reduction in the stress allowable for the CS and PF coils.
- The baseline 10T scenario & others will meet stress and temperature limits; the highest field scenario (12 T & 7.7 MA) needs additional work



Sector of top half of CS & PF1,2

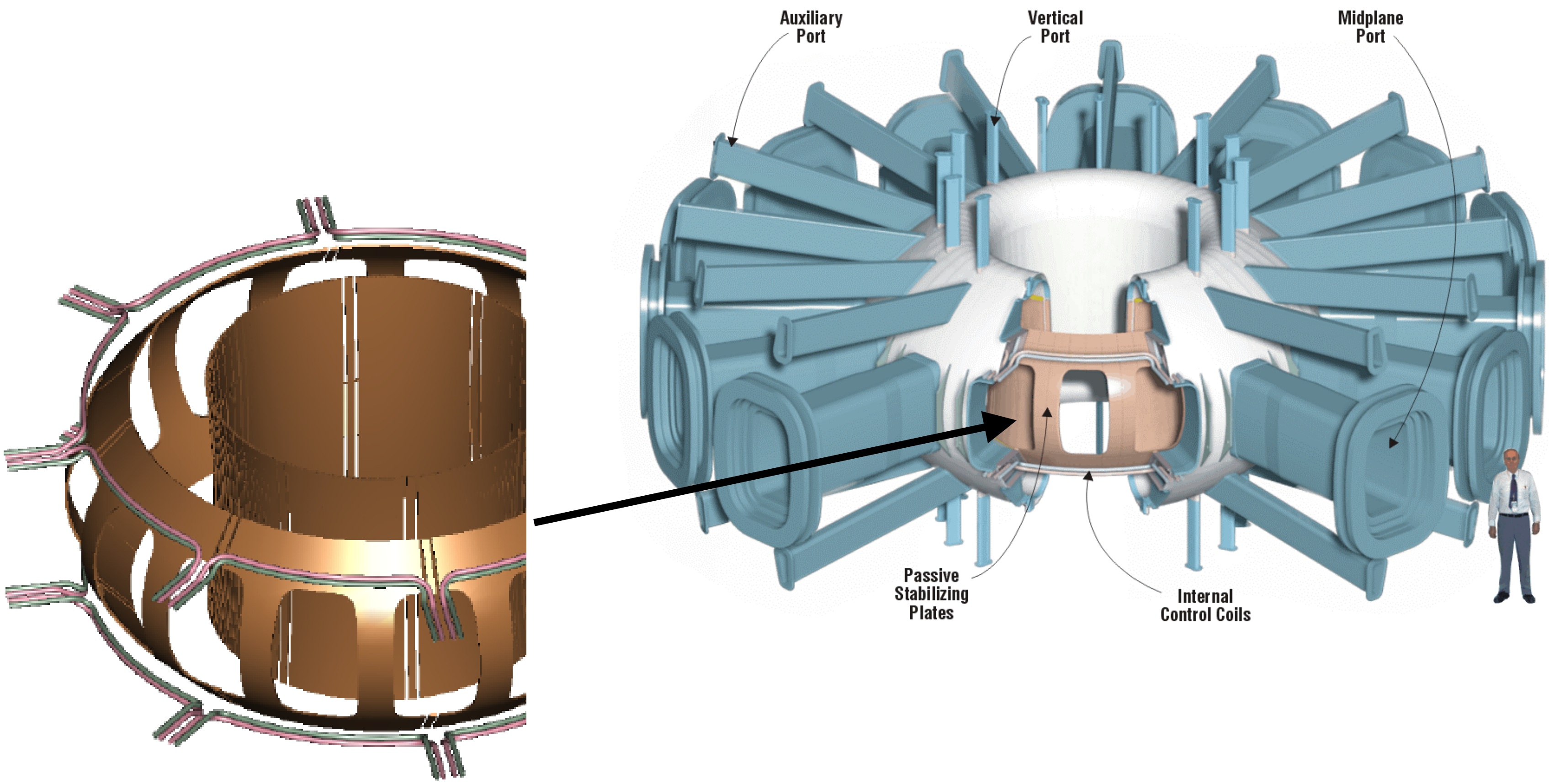
TF Coils—Bucked and Wedged Option

- An all OFHC, Bucked and Wedged, TF configuration is an option
- Max Field is 11.5T to remain within the OFHC copper allowable stress limit
- Longer pulses are possible at a given field level
- Lower power requirements may increase number of possible sites
- TF material costs will be reduced and R&D for a BeCu to OFHC joint in TF plates will not be required
- TF fabrication & assembly will be more complex to assure proper bucking & wedging

FIRE Design Variations

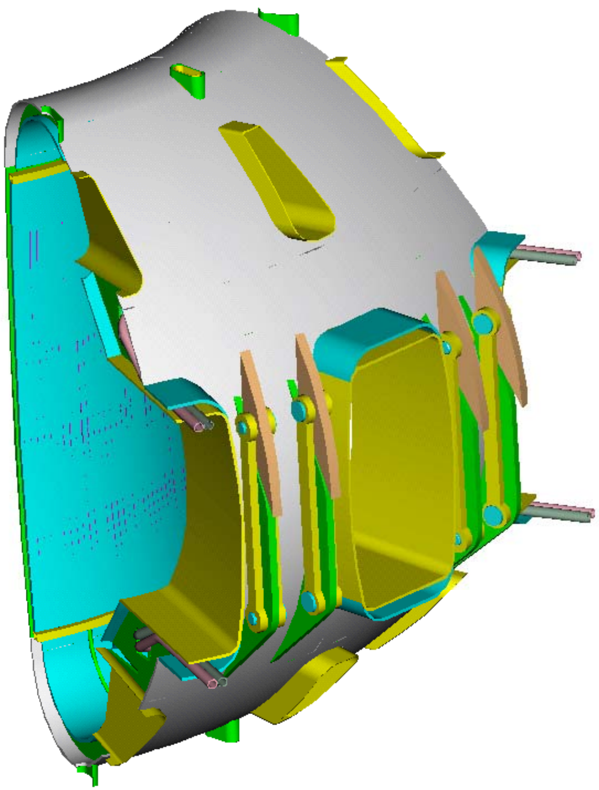
	FIRE baseline	FIRE	FIRE*	FIRE*
	Wedged	B & W	Wedged	B & W
Inner Leg Mat'l	BeCu	OFHC	BeCu	OFHC
Radii: R(m), a(m)	2.0, 0.525	2.0, 0.525	2.14, 0.595	2.14, 0.595
Field: B_t at R, (T)	10 (12)	10 (12)	10 (12)	10 (12)
Plasma Current: I_p, (MPa)	6.44 (7.7)	6.44 (7.7)	7.7 (8.25)	7.7 (8.25)
Flat-top time, (sec)	~20 (12)	31 (23)	~20 (12)	~31 (23)
TF Allowable Stress, MPa	700	300	700	300
TF VM Stress, MPa	466 (666)	230 (326)	529 (762)	230 (326)
Allowable/Actual Stress	1.5 (1.05)	1.3 (0.92)	1.3 (0.92)	1.3 (0.92)

Vacuum Vessel- double walled vacuum vessel with water & steel shielding

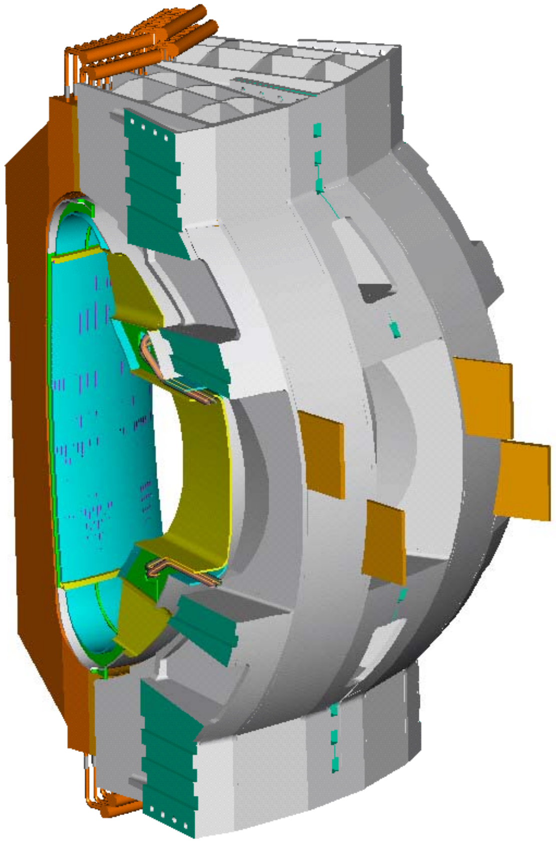


- Integral active and passive stabilization coils

Vacuum Vessel is Fabricated in Octants and Assembled into TF & Structure in Octants



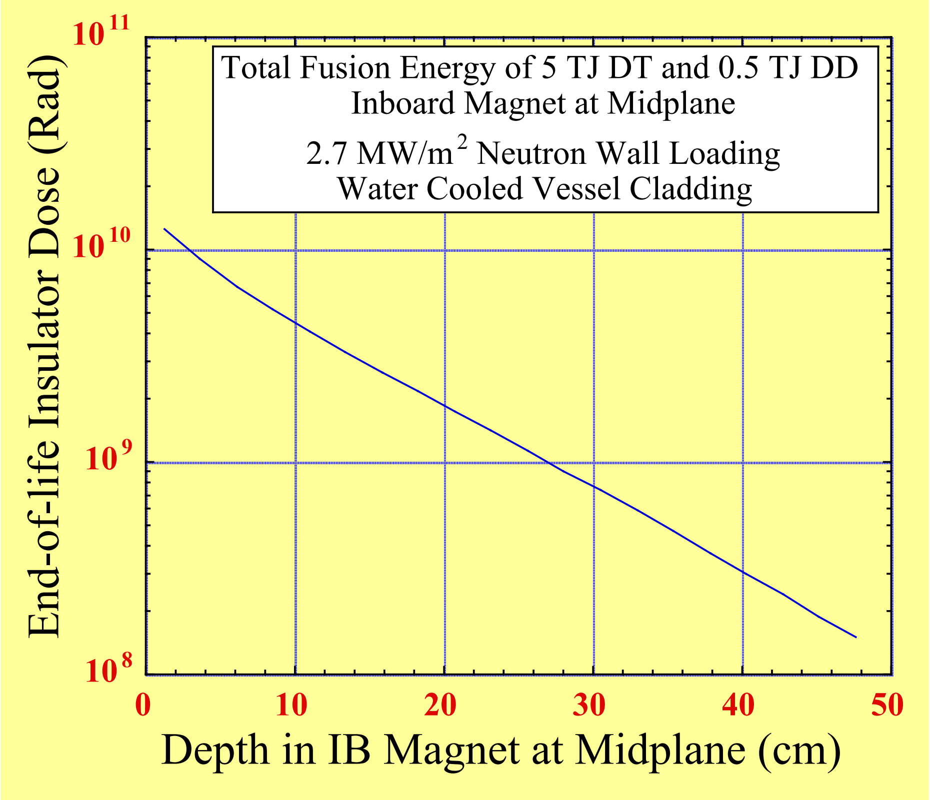
Vacuum Vessel Octant



VV Sector Rotated Into TF Assembly

Neutronics & Shielding

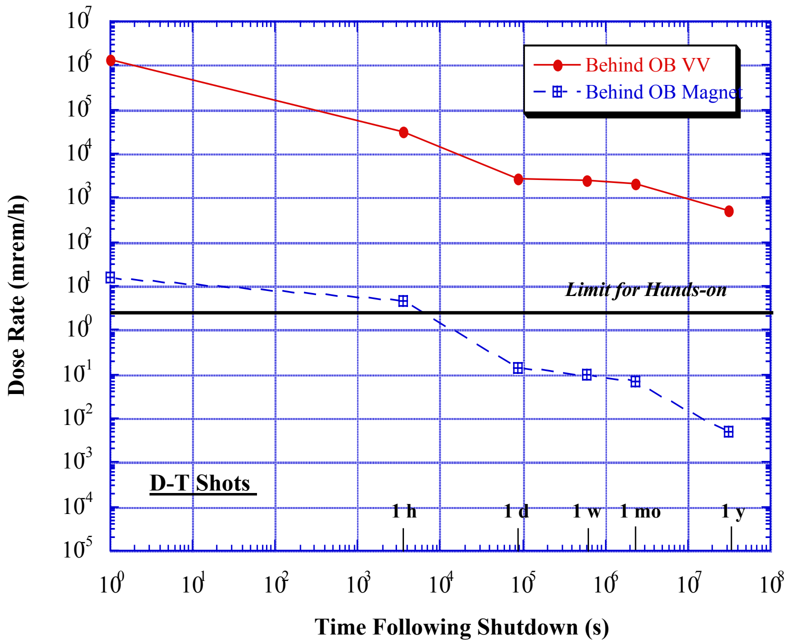
- Nuclear heating has been computed for the major components (eg- magnets, vacuum vessel and PFC's) and can be accommodated.
- The TF coil insulation must tolerate ~1.5 x 10^{10} rads for a cumulative fusion energy of 5 TJ DT and 0.5 TJ DD. *It is expected that insulation materials can be identified that can meet the exposure limits.*



Radial variation of insulator dose in inboard leg of TF coil

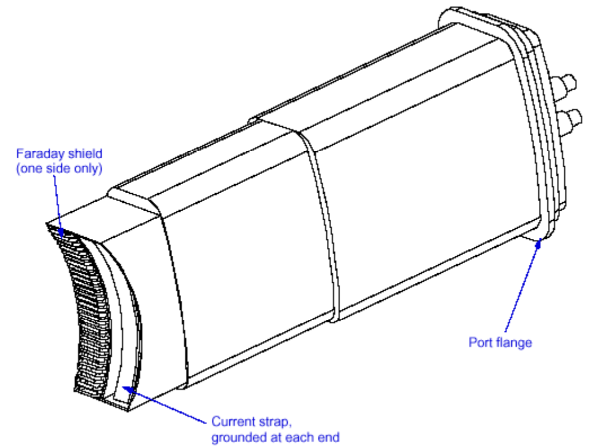
Activation & Radiation Exposure

- **The PFC's produce the highest levels of specific activity and decay heat,** ***but the operating schedule allows for the decay of short-lived radionuclides between pulses.***
- **The vacuum vessel jacket/shield thickness, together with the shielding provided by the TF coils and port plugs, is such that "hands on" ex-vessel maintenance can be done within a few hours after shutdown.**
- **The biological dose rates behind the vacuum vessel and the divertor remain high.**
- **At the end of the machine life, all components qualify for disposal as Class C low level waste.**

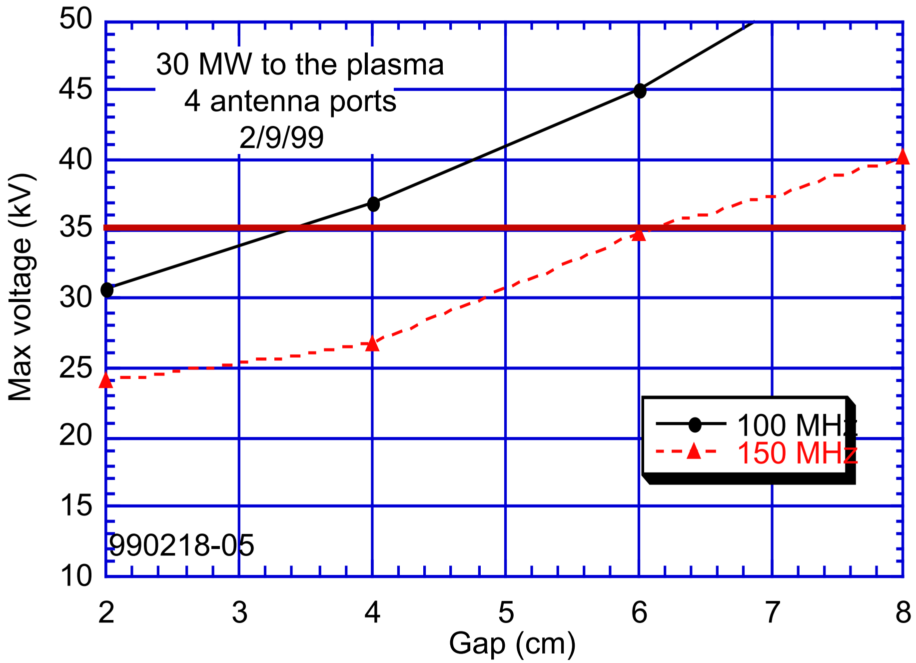


Biological dose rates at the midplane as a function of time following shutdown.

Ion Cyclotron Heating

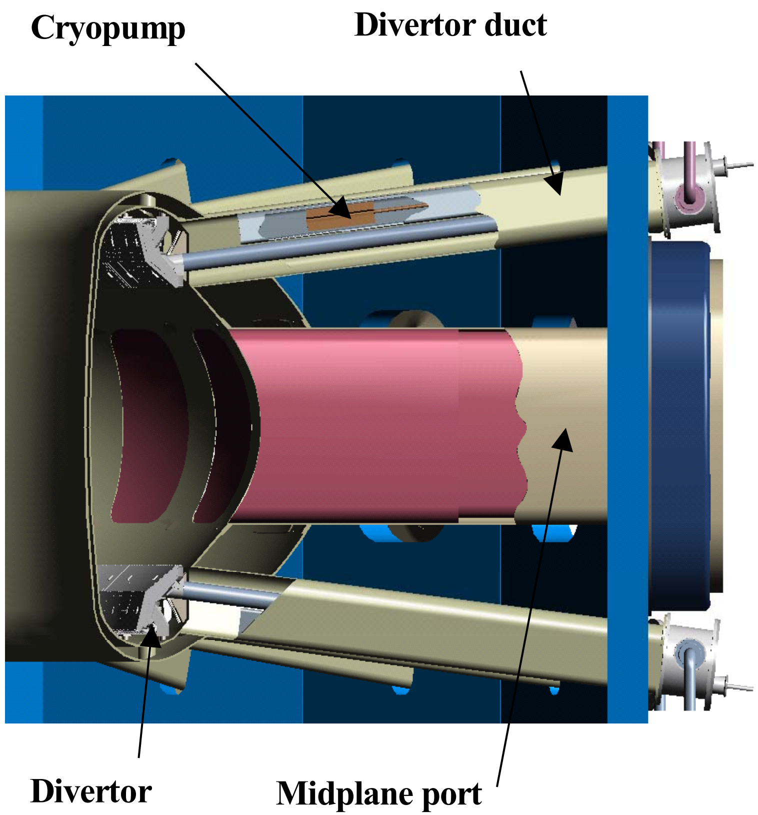


- Plasma transport calculations indicate the need for 30 MW of ICRH.
- A 4 port system with 2 antennae per port will be used.
- With a 6 cm gap to the plasma, the 30 MW can be delivered at 150 MHz using 35 kV. The design gap is 3-4 cm and calculations indicate that 30 MW can be delivered at 100 MHz with a 3.5 cm gap.

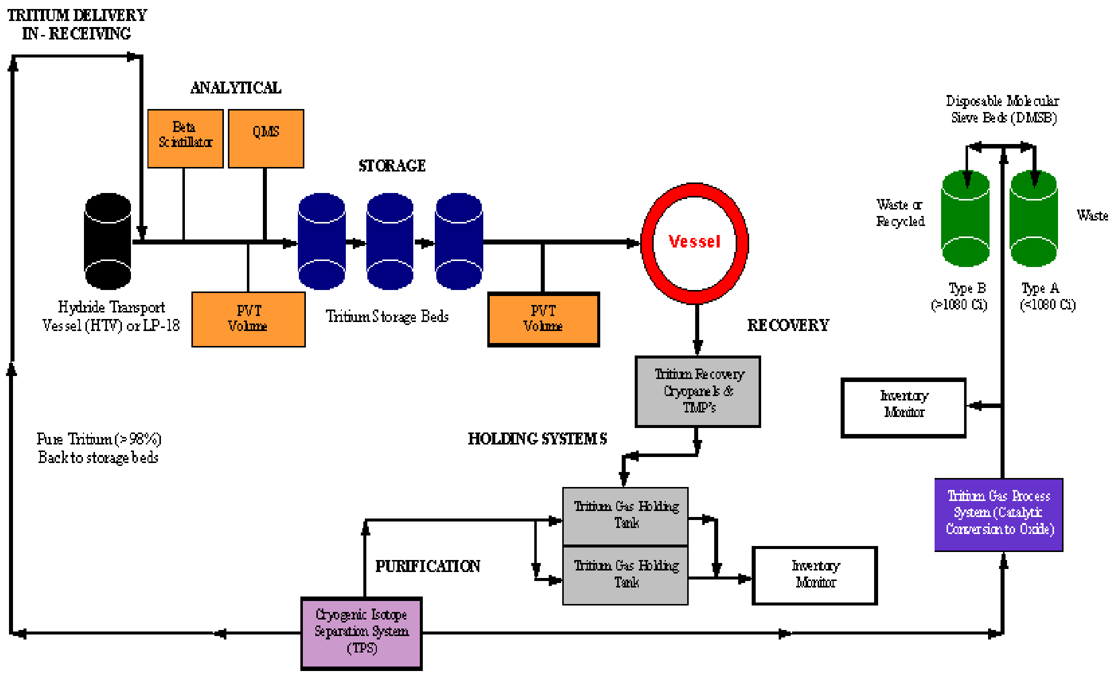


Fueling & Vacuum Pumping

- Pellets will be injected from multiple guide tubes including low-field and high-field-side launch.
- A tritium-rich pellet source will be used for core fueling and a deuterium-rich gas source for edge fueling.
- The divertor pressure is ~0.01 torr at a throughput of 200 torr-liter/s. The base pressure is 10^{-7} torr for fuel gases (H, D, T) and 10^{-9} torr for impurities.
- 16 pumping stations are used: 8 each top & bottom at alternate divertor ports
- Each station has a 30K duct liner with an internal impurity & DT cryopump & an external He ash dump



PPPL
Tritiuim Delivery and Process System

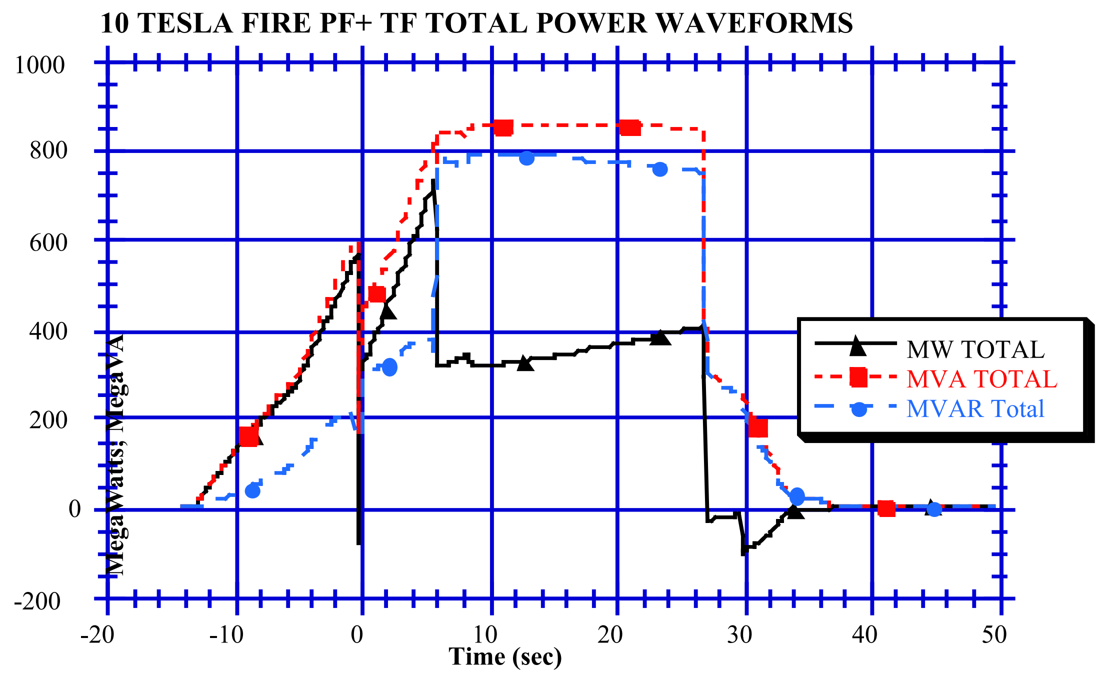


- The on-site tritium inventory has been set at 30 g to allow sufficient operational flexibility without introducing additional restrictions.
- The inventory can be reduced if a tritium reprocessing system is added to recycle the working tritium:
  - 30g if monthly; 5-6 g if weekly; 1-1.5g if daily

Cryoplant

- **FIRE magnets obtain ntrogen from a specially built, "leased" LN2 production facility**
  - **No upfront plant installation costs**
  - **~10M$/year nitrogen cost**
- **FIRE uses the Alcator C-Mod method of one pump and individual regulator valves for each flow circuit.**
- **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**
- **The storage requirements are higher than they were in the CIT design:**
  - **The energy dissipated is higher than in CIT (18.7 GJ vs. 12 GJ)**
  - **The number of pulses is higher than in CIT (40/week vs. 20/week) note: if 7,000 gallon trucks are used, this would require 60 trucks/day**
- **The amount of radioactive nitrogen-13 generated is small and would be within allowable limits for most site boundaries, but a cold He purge is used before a pulse to allow compatibility with any site.**

Power Supplies



- A 10 T pulse will require ~12 GJ for the TF system and 2 GJ for the CS/PF magnets; the Peak power is 542 MVA and 412 MVA, respectively.
- Power Requirements could be reduced significantly if all Cu TF coils are used

POWER REQUIREMENTS FOR FIRE

	BeCu TF Inner Legs				All Cu TF Coils			
Field Flat-top	**10T 20s**	**10T 20s**	**12T 12s**	**12T 12s**	**10T 45s**	**10T 45s**	**12T 25s**	**12T 25s**
	Peak Power (MW)	**Peak Energy (GJ)**	**Peak Power (MW)**	**Peak Energy (GJ)**	**Peak Power (MW)**	**Peak Energy (GJ)**	**Peak Power (MW)**	**Peak Energy (GJ)**
TF	**490**	**11.5**	**815**	**11.5**	**267**	**12.6**	**345**	**13.2**
PF	**250**	**2.2**	**360**	**3.7**	**250**	**5**	**360**	**4.6**
RF	**60**	**1**	**60**	**0.6**	**60**	**2.3**	**60**	**1.3**
Sum	**800**	**14.7**	**1235**	**15.8**	**577**	**19.9**	**765**	**19.1**
Grid	**550**	**12.5**	**600**	**10.9**	**577**	**19.9**	**404**	**14.5**
MG	**250**	**2.2**	**635**	**4.9**	**0**	**0**	**360**	**4.6**

Remote Maintenance

- **The strategy is to employ hands-on maintenance to the fullest extent possible.** ***The activation levels outside the thermal shield are low enough to permit hands-on maintenance; temporary local shielding will be necessary when the duct shield plugs are removed.***
- **In-vessel components will generally be removed as integral assemblies and transferred to the hot cell for repair or processing as waste.**
- **In situ operations will be limited to inspection, vacuum window replacement, leak testing and, if necessary, dust removal.**
- ***Remote maintenance will continue to be a driver for design of interfaces. Components have been given a classification and preliminary requirements are being accommodated in the layout of facilities and the site.***
- ***Remote Maintenance R&D needs are being identified.***

Safety

- ***Release targets for tritium, and activated tungsten, air and nitrogen have been established.***
- **A goal is to keep the total on-site tritium inventory below 30 g**
  - ***Site can be classified as a low hazard nuclear facility***
- **Confinement barriers:**
  - **double-walled vacuum vessel is a highly reliable primary barrier**
  - **thermal shield will serve as a moderately reliable 2nd barrier**
  - ***double confinement will be implemented in all penetrations attached to the vacuum vessel***
- ***Examination of the potential safety concerns associated with the energy sources has not yet revealed any events that pose a serious challenge to the radiological confinement function.***

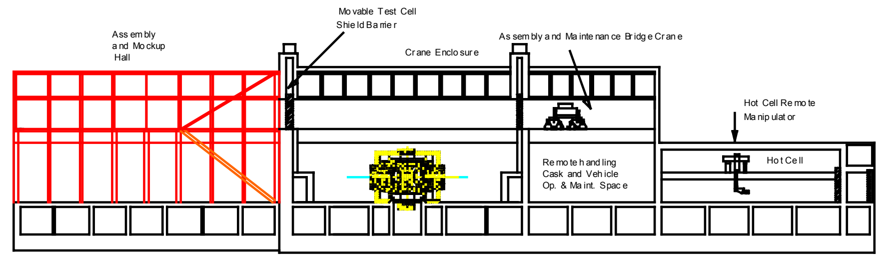
Safety Analyses

Preliminary analyses have been done for:

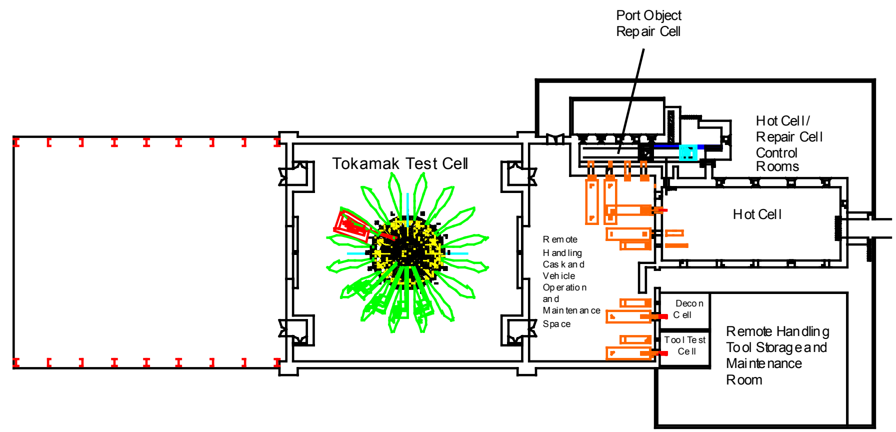
- **Long term thermal response and passive decay heat removal under a complete loss of coolant condition for the divertor and VV --** ***decay heat is not a serious concern and oxidation of the activated PFC surfaces will not be significant*.**
- **Break in the divertor or VV cooling lines inside of the VV—*pressure does not rise to a level expected to compromise the VV radiological confinement integrity. Furthermore the chemical energy from Be-steam and W-steam interactions does not threaten the radiological confinement function of the VV.***
- **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, or potential cryogen/water interactions have not yet been analyzed.***

Facilities- Tokamak Building

- The test cell size is determined by the size of the cryostat and space required for remote handling casks (casks are 8 m in length and about 1.9 m in width). *A tentative routing for the vehicles to other parts of the facility has been selected.*
- Shielding is provided by the vacuum vessel and the magnet system. Port objects will also provide shielding, making them both long and heavy, but the outboard end of the port objects will not become radioactive. The plasma facing end will be a strong radiation source, however the size and spacing of the ports make it impractical to include shielding in the casks. *The remote handling requirements on the facility for routing and storage of these items is being evaluated.*



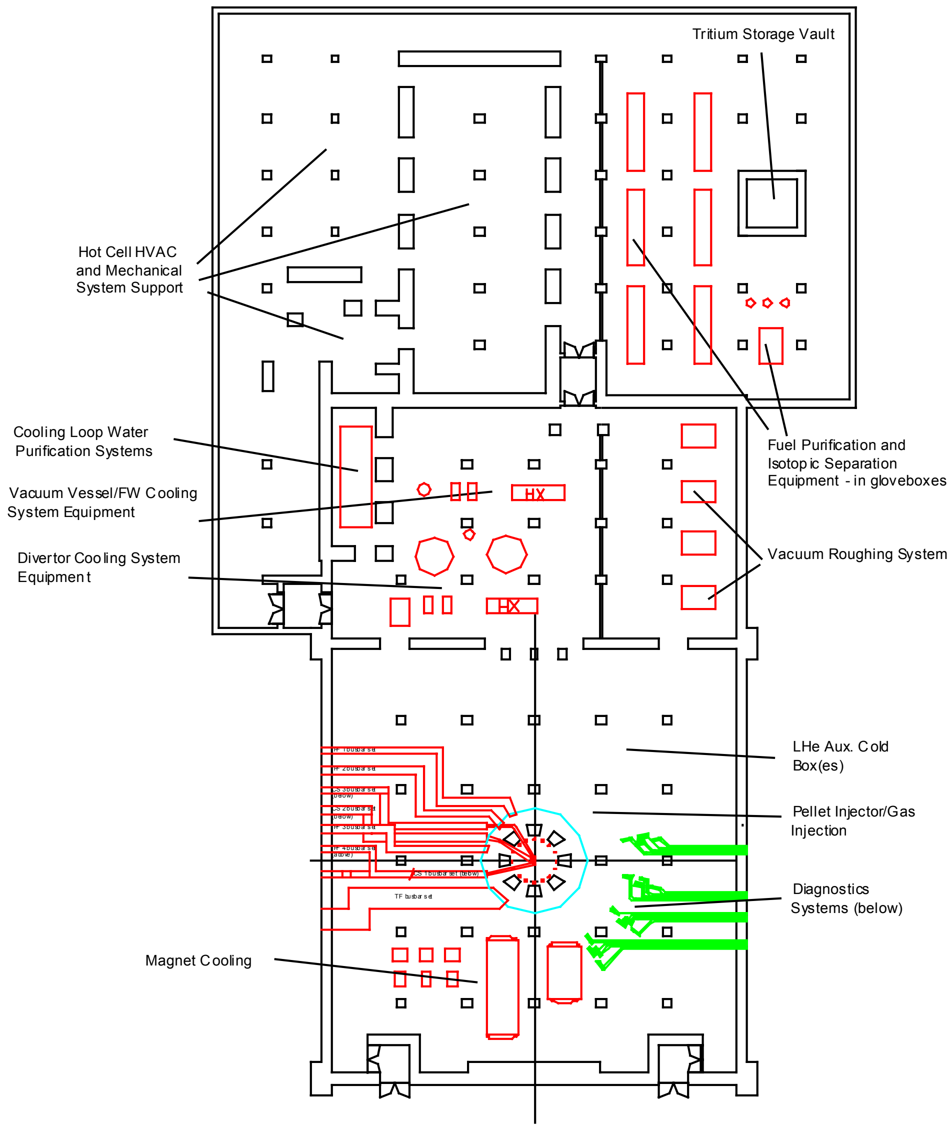
Assembly Hall, Tokamak Building, and Hot Cell - NS Section



Assembly Hall, Tokamak Building, and Hot Cell - Plan View

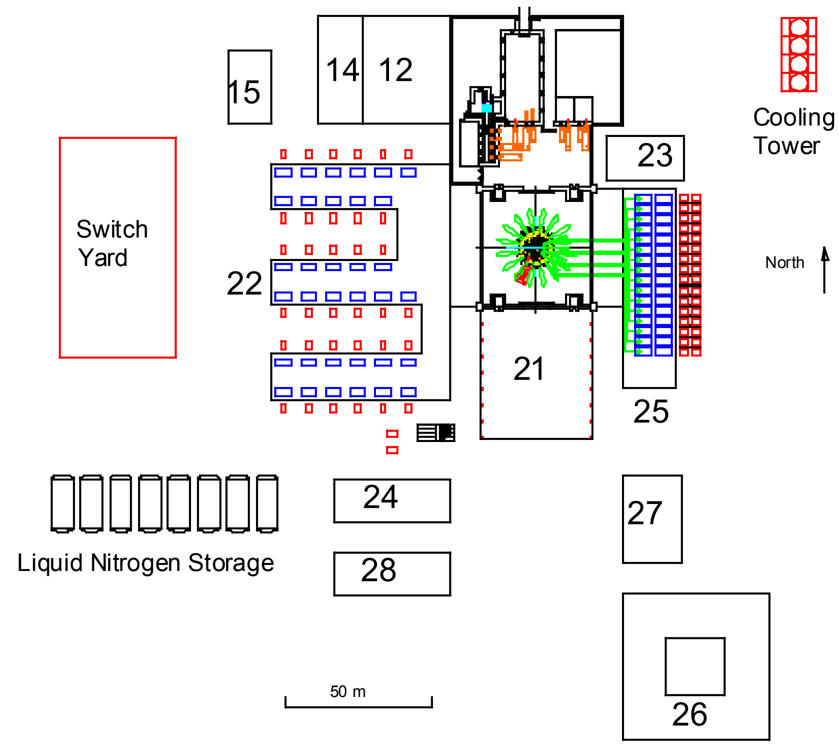
Facilities- Hot Cell Concept

- The hot cell concept assumes that some port mounted objects can be repaired. *The extent and nature of these processes are not yet well developed,* but they will include replacement of divertor strike plates, and repair of diagnostic and plasma heating devices.
- Radioactive materials which cannot be returned to the tokamak will be processed in the hot cell to recover tritium from beryllium and will then be size reduced and encapsulated for subsequent shipment to a waste repository.



Facilities & Siting Layout

- A conceptual layout has been developed for the safety and non-safety related buildings based on a "green field" site. It may also be possible to adapt an existing facility to the FIRE project.
- *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. It also houses a liquid helium refrigerator for the cryopumps in the vacuum vessel and in the diagnostic neutral beam.
- Magnets will be cooled before each operating pulse, using liquid nitrogen, supplied commercially.



Legend:

Safety Related Buildings
11 - Tokamak and Hot Cell Building
12 - Radioactive System Support Building
14 - Radwaste Systems Building
15 - Emergency Power Supply Building

Non-Safety Related Buildings
21 - Assembly and Mock-up Hall
22 - Magnet Power Conversion Building
23 - Cooling Systems Building
24 - Cryogenic System Building
25 - ICRH Power Supply Building
26 - Laboratory Office Building
27 - Control and Operations Building
28 - Utility Services Building

FIRE Engineering R&D

- **State-of-the-art materials and manufacturing processes will allow the highest performance to be achieved cost effectively.**
- **Several R&D areas have been identified to:**
  - **-complete the material property data base to assure consistency with design criteria for materials procured in the size required for the device,**
  - **-test design concepts for component manufacture or assembly to assure processes are sufficiently developed and specified, or**
  - **-validate the design of prototype components through fabrication and test to assure that performance, cost or remote handling features have been adequately considered.**

List of Engineering R&D Areas

- TF Conductor and Design Criteria
- TF Conductor Joints
- Radiation Resistant Electrical Insulation
- High and Low Friction Materials
- High Force, High Reliability Jacking System for TF coils
- Power Supply System
- First Wall and Divertor Components
- Vacuum Vessel
- Remote Handling
- Fueling and Pumping
- ICRH Antenna

FIRE Baseline Operation Summary

Configuration	TF Coils[a]: Flat-top time, s	CS Coils: Max Temp, K	PF Coils: Max Temp, K
Baseline: 10T; 6.44 MA DT Power: 200 MW	18.5 s with DT 26 s with DD	152	173
Higher B mode: 12T, 7.7 MA DT Power: 250 MW	12 s with DT 15 s with DD	161	183
TPX mode: 4T; 2 MA DD Power: 5 MW	~214 s	144	169
AT/BP mode: 8T; 5 MA DT Power: 150 MW	31 s with DT[b] 46 s with DD	TBD	TBD

Note: a) BeCu for TF coil inner leg; OFHC for balance of TF coils, CS and PF coils
b) AT mode pulse length with DT may be limited by VV or PFC thermal limits

Conclusions

- Design has addressed all major systems, facilities and safety
  - FY99 and FY00 reports are available
  - Cost estimate available now
- Baseline design meets or exceeds initial requirements for 10 T, 6.4 MA, flat-top > 10 s
- Possibility exists for higher fields (eg 12 T, 7.7 MA) and longer pulses at lower fields (eg 8T, 5 MA, 46 s)
- Specific issues are being addressed, eg-
  - For a bucked and wedged design, and B limited to 11.5 T, TF coils could be entirely OFHC copper; <u>this would reduce power and TF coil costs</u>
  - For B limited to 10 T, compression ring cross-section could be reduced, TF inner leg for the wedged design could change to a lower resistivity BeCu, and pulses could lengthen slightly
  - Disruptions are the life limiting events for the PFC's. The design is evolving to tolerate disruptions
  - PFC and Vacuum Vessel thermal limits are TBD for AT modes with DT