Nuclear Analysis of FIRE

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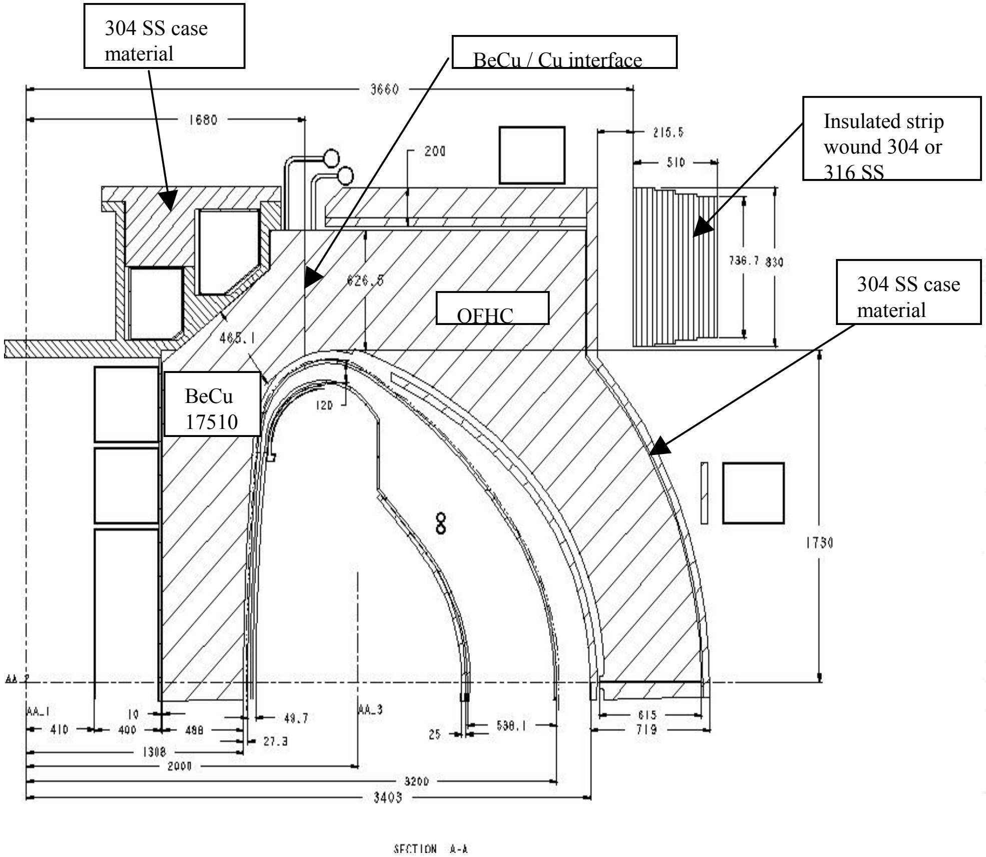
Background

- FIRE design is in pre-conceptual phase with different design options and operation scenarios being considered
- DT pulses with widths up to 20 s and fusion powers up to 200 MW produce a total of 5 TJ of fusion energy
- DD pulses with different widths and fusion powers up to 1 MW yield total fusion energy of 0.5 TJ
- A double walled steel VV with integral shielding adopted
- VV thickness varies poloidally from 5 cm in inboard region to 54 cm in outboard region
- The PFC include Be coated Cu FW and divertor plates made of tungsten rods mounted on water-cooled Cu heat sink
- Two design options considered for FW/tiles:
  - ☐ Option 1 with passive cooling
  - ☐ Option 2 with active water cooling of vessel cladding
- Nuclear analysis performed to assess if major performance objectives of project can be met without jeopardizing performance of radiation sensitive components

FIRE Configuration

Cross Section of FIRE



304 SS case material

BeCu / Cu interface

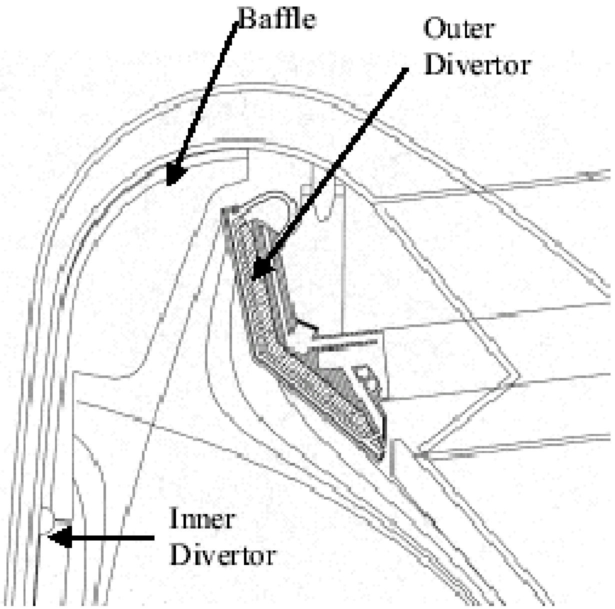
Insulated strip wound 304 or 316 SS

304 SS case material

OFHC

BeCu 17510

FIRE Divertor



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Calculation Procedure

- Neutronics and shielding calculations performed using the ONEDANT module of DANTSYS 3.0
- Activation calculations used the DKR-PULSAR2.0 code system
- FENDL-2 evaluated nuclear data used
- IB and OB regions modeled simultaneously to account for toroidal effects
- Flux dependent parameters (e.g., nuclear heating and decay heat) determined for worst case of 200 MW DT pulses. In these pulses average neutron wall loading is 3 MW/m^2 with peak OB, IB, and divertor values of 3.6, 2.7, and 1.8 MW/m^2, respectively
- Fluence dependent parameters (e.g., cumulative radiation damage, insulator dose, and radwaste classification) determined for the combined total fusion energy of 5 TJ DT and 0.5 TJ DD

Radial Build of FW/Tiles

- Radial build and composition of FW/tiles in IB side

  Option 1: 5 mm Be PFC (90% Be)
  43 mm Cu tiles (80% Cu)
  2 mm gasket (50% SiC)

  Option 2: 5 mm Be PFC (90% Be)
  18 mm Cu tiles (80% Cu)
  2 mm gasket (50% Cu)
  25 mm water cooled Cu vessel cladding
  (80% Cu, 15% water)

- In OB side same radial build used except that total thickness is increased to 100 mm in option 1

Peak Nuclear Heating (W/cm^3) for 200MW DT Shots

	Option 1		Option 2 (Baseline)	
	IB	OB	IB	OB
Be PFC	34.7	36.8	33.3	35.6
Cu Tiles	44.9	43.6	46.9	46.3
Gasket	19.6	11.0	40.6	40.6
Cooled Cu Vessel Cladding	NA	NA	40.2	40.1
H2O FWCoolant	NA	NA	27.6	30.9
SS Inner VV Wall	35.9	19.6	33.8	30.9
SS VV Filer	37.5	20.6	32.9	28.5
H2O VV Coolant	17.5	11.1	14.9	15.5
SS Outer VV Wall	35.1	0.04	30.3	0.07
Microtherm Insulation	11.4	0.01	9.8	0.02
SS Inner Coil Case	NA	0.021	NA	0.038
Cu Magnet	23.1	0.010	19.5	0.019
SS Outer Coil Case	NA	1.5x10^{-5}	NA	2.8x10^{-5}

For DD pulses with largest fusion power (1 MW), neutron wall loading is a factor of 0.0021 of that for the DT pulses

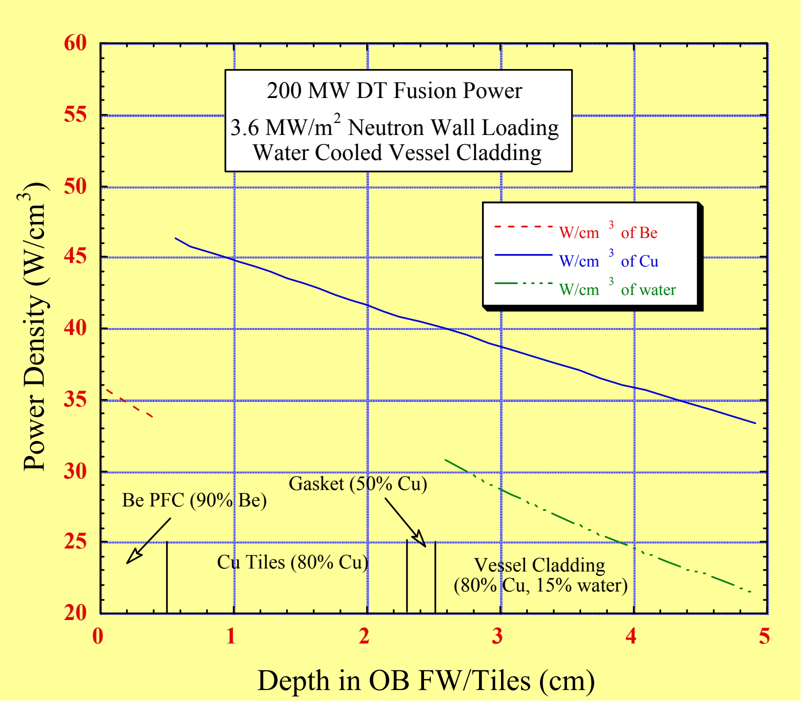
⇒ Nuclear heating values are at least two orders of magnitude lower

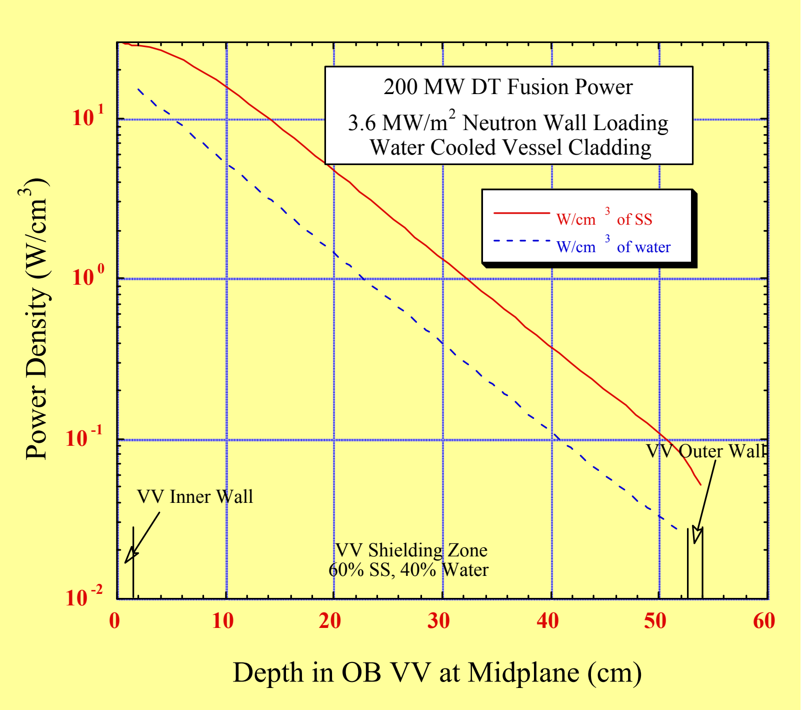
Impact of FW/Tiles Design Options on Nuclear Heating

- Nuclear heating values in FW/tiles are comparable for two design options
- IB VV and magnet heating decreases by ~15% in the baseline design (option 2) due to added water coolant and using Cu in gasket in place of SiC
- OB VV and magnet heating increases by a factor of 1.5-2 in option 2 due to the 5 cm reduction in FW/tiles thickness

Nuclear Heating in OB FW/Tiles

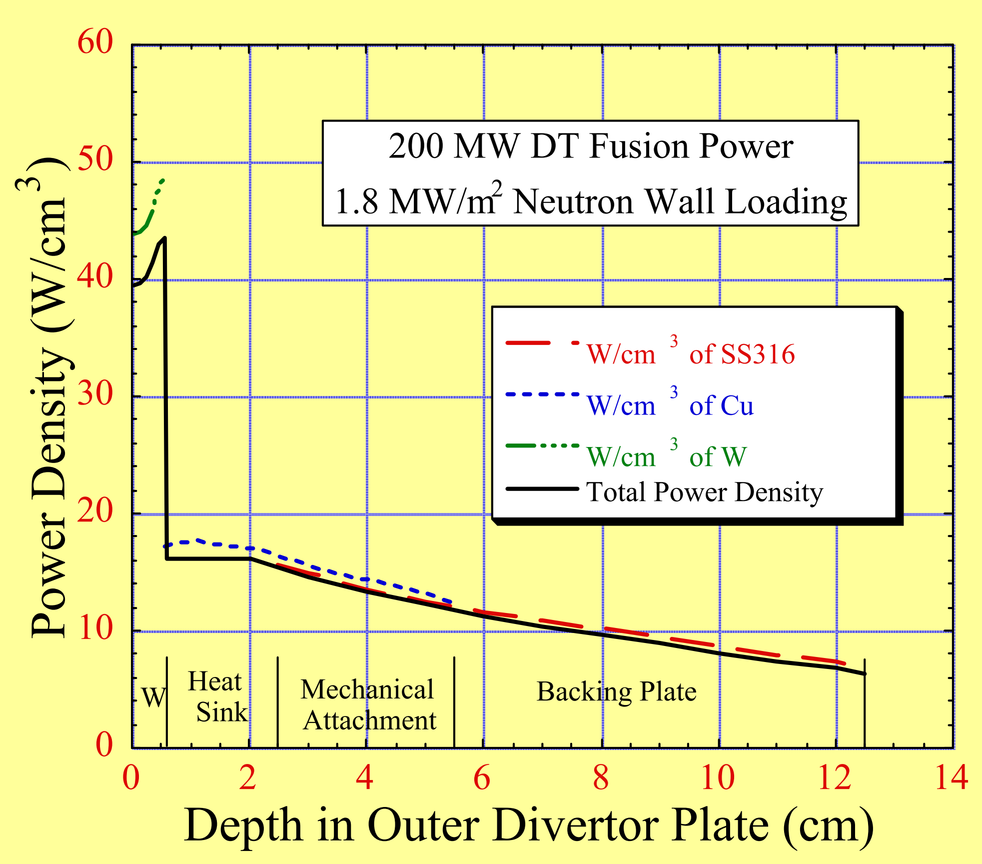
Nuclear Heating in VV Drops by an Order of Magnitude in ~18 cm





Relatively High Nuclear Heating in W PFC of Outer Divertor Plate

	Peak Nuclear heating (W/cm^3)
W rods in divertor	49.0
Cu heat sink in divertor	17.2
SS structure in divertor	14.9
SS VV	6.7
Cu Magnet	1.7



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Total Magnet Nuclear Heating in 16 TF Coils for 200 MW DT Shots

- Variation of neutron wall loading and shielding thickness taken into account

	Magnet Nuclear Heating (MW)	
	Option 1	Option 2 (Baseline)
IB region	27	22.9
OB region	0.03	0.05
Divertor region	2.1	2.1
Total	*29.13*	*25.05*

- Total heating is dominated by contribution from lightly shielded IB legs

- Total magnet heating decreases by 14% in the baseline case (option 2) compared to the passive cooling option (option 1)

Cumulative Damage in FIRE Components is Very Low

Peak end-of-life cumulative radiation damage values in FIRE components are very low < 0.05 dpa

Peak end-of-life He Production in VV

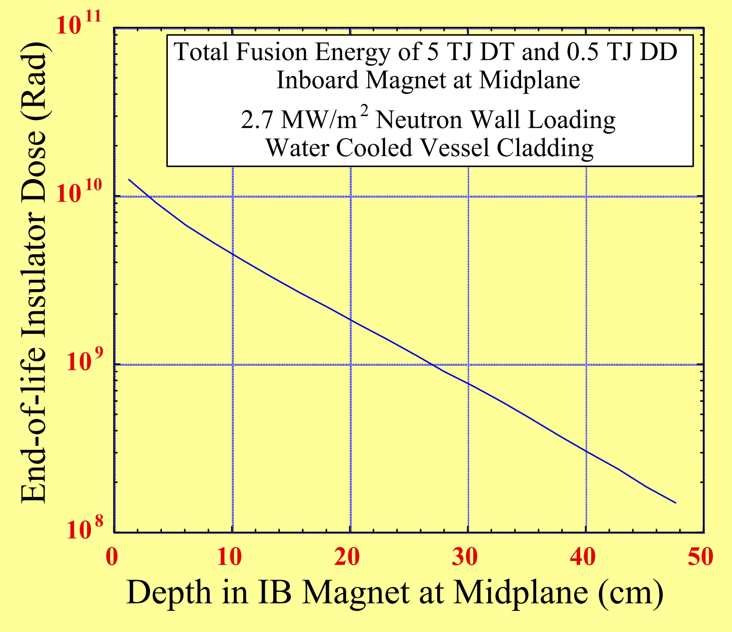
	Option 1	Option 2 (Baseline)
IB midplane	0.13	0.11
OB midplane	0.07	0.15
Divertor	0.016	0.016

- He Production in VV < 1 appm Allowing for Rewelding
- Contribution from DD shots very small (<0.15%)

Cumulative Peak Magnet Insulator Dose
(5 TJ DT Shots and 0.5 TJ DD Shots)

	Option 1	Option 2 (baseline)	% from DD Shots
IB midplane	1.47×10^{10}	1.26×10^{10}	13%
OB midplane	6.97×10^{6}	1.26×10^{7}	1.6%
Divertor	9.80×10^{8}	9.80×10^{8}	10%

- The insulator dose peaks in IB side at midplane and decreases as one moves poloidally to OB midplane due to increased shielding by VV
- Relative contribution from DD shots decreases as one moves poloidally from IB midplane to OB midplane
- Neutron contribution varies from 50% at front to 30% at back of magnet
- Peak cumulative insulator dose decreases by 14% in baseline design (option 2) compared to option 1



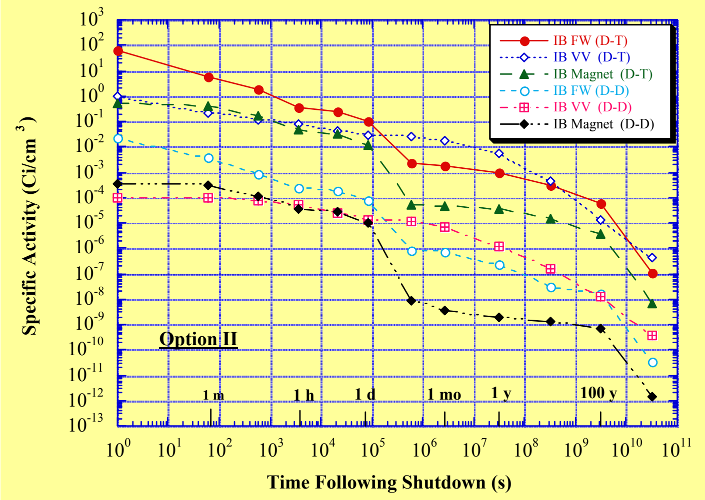
Insulator Lifetime Issues

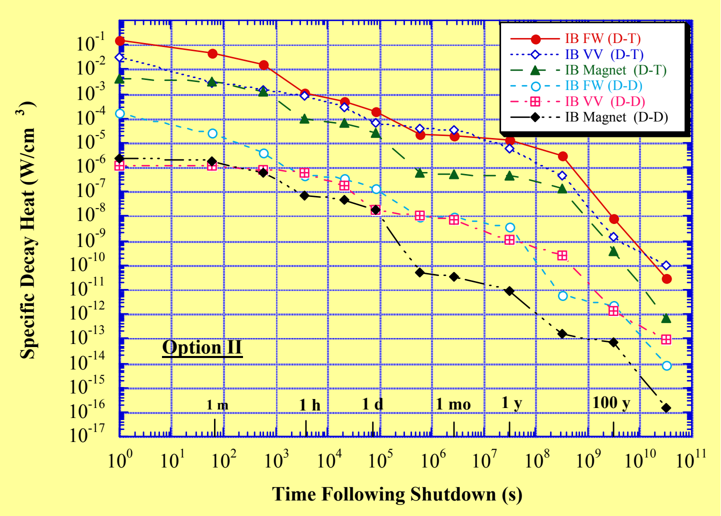
- The commonly accepted dose limit for epoxies is 10^9 Rads (ITER)
- Polyimides and bismaleimides are more radiation resistant with small degradation in shear strength at $>10^{10}$ Rads
- Hybrids of polyimides or bismaleimides and epoxies could provide radiation resistant insulators with more friendly processing requirements
- In FIRE design with wedged coils and added compression ring, the TF inner leg insulation does not have to have significant bond shear strength which is most sensitive to radiation
- In FIRE peak torsional shear stresses occur at top and bottom of IB leg behind divertor. End-of-life dose to insulator at this location reduced to $\sim10^9$ Rads
- Insulator dose decreases radially from front to back of coil. Dose decreases by an order of magnitude in ~22 cm of the IB magnet
- Based on analysis performed, magnet insulation materials with radiation tolerance to 1.5×10^{10} Rads under FIRE load conditions need to be developed. ***Otherwise***, the cumulative fusion energy (determined by fusion power, pulse width, and number of shots) should be decreased and/or radial build of FW/tiles/VV in IB side should be increased

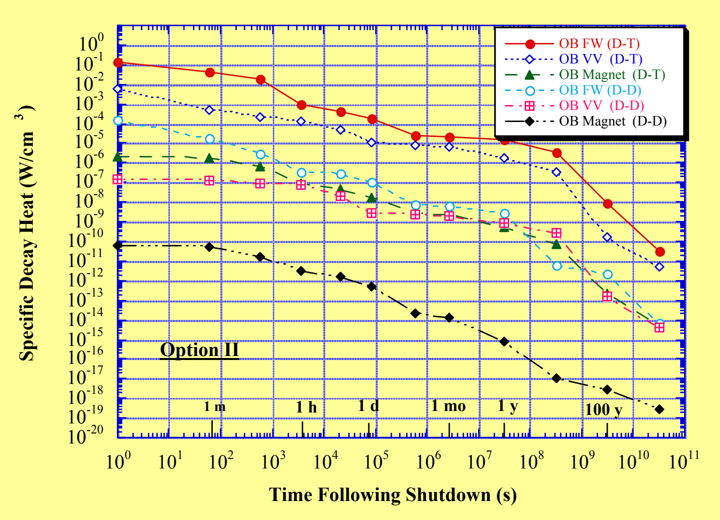
Activation Analysis

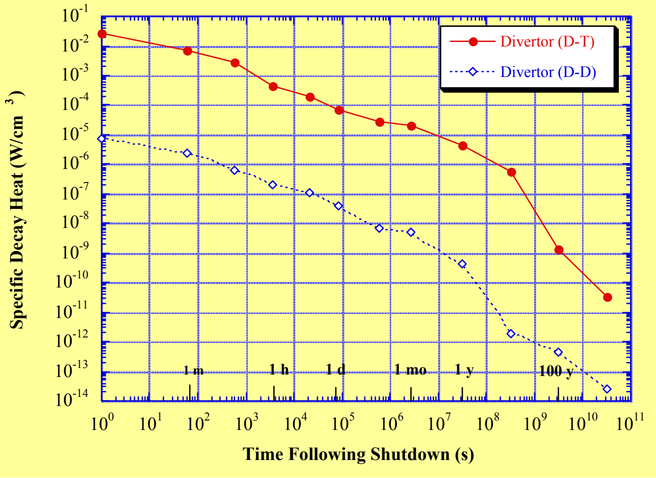
- Calculations performed for DT pulses with 200 MW of fusion power
- Four pulses per day with pulse width of 20 seconds and 3 hours between pulses
- Calculations also performed for DD pulses with 1 MW of fusion power
- Total fusion energy 5TJ DT and 0.5 TJ DD
- Specific activity and decay heat values calculated as a function of time following shutdown
- WDR for Class C waste calculated using 10CFR61 and Fetter waste disposal limits
- Biological dose rates calculated at different locations following shutdown to assess feasibility of hands-on maintenance

Activation and Decay Heat in FIRE Components





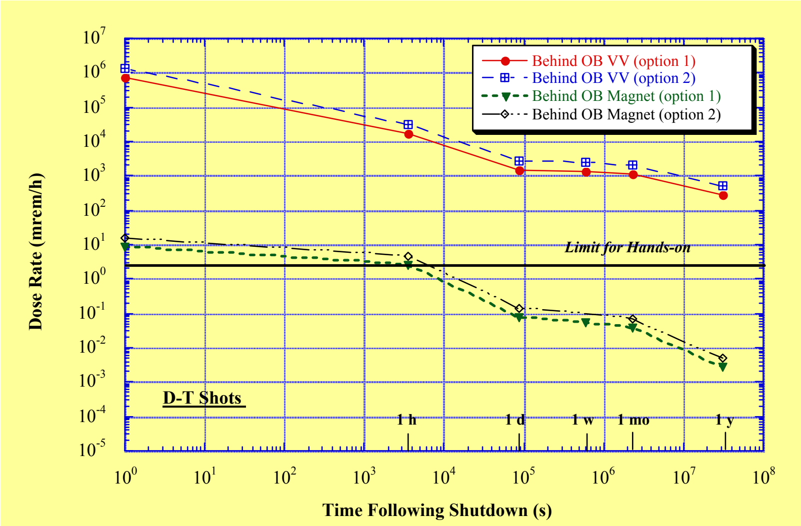


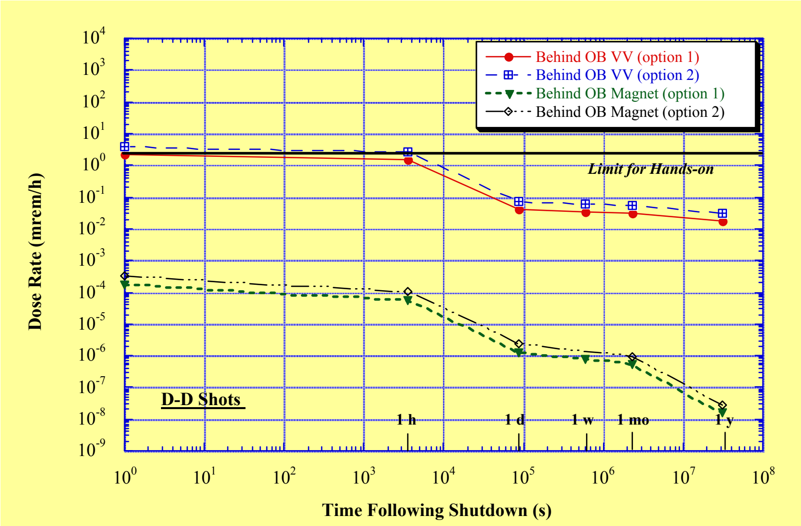


Activity and Decay Heat Values are Tolerable

- Low decay heat and activity at shutdown due to decay of short-lived radionuclides during the 3 hours between pulses
- Decay heat induced in FW/tiles, divertor, and Cu magnet at shutdown dominated by ^{62}Cu($T_{1/2} = 9.74$ min) and ^{66}Cu($T_{1/2} = 5.1$ min)
- VV decay heat at shutdown dominated by ^{52}V($T_{1/2} = 3.76$ min) and ^{56}Mn($T_{1/2} = 2.58$ hr)
- Activity and decay heat values at shutdown are almost fully dominated by activation during the last pulse
- Activity and decay heat generated following D-D shots are more than three orders of magnitude lower than the D-T shots

Biological Dose Rates at Midplane





- Biological dose rates behind VV are high for several years following DT shots
- Biological dose rates behind OB magnet are acceptable for the two FW/tiles options
- Biological dose rates behind VV and magnet are acceptable following DD shots
- Dose rates in baseline design (option 2) are twice the rates in option 1
- Dose rates behind magnet dominated by ^{62m}Co($T_{1/2}$ = 13.9 min) at shutdown and ^{60}Co($T_{1/2}$ = 5.27 yr) one week following shutdown
- Large midplane maintenance ports should be plugged to allow for hands-on maintenance

Feasibility of Hands-on Maintenance

- Following DT shots hands-on ex-vessel maintenance is possible with
  - The 110 cm long steel shield plug in midplane ports
  - The 20 cm shield at top of TF coil
- Following DD shots immediate access for maintenance is possible behind OB VV

All Components Qualify as Class C LLW

Zone	**Fetter**	**10CFR61**
IB FW	0.18 (^{108m}Ag)	1.98e-2 (^{63}Ni)
IB VV	5.67e-2 (^{94}Nb)	5.87e-2 (^{94}Nb, ^{63}Ni)
IB Magnet	2.35e-4 (^{108m}Ag)	1.15e-3 (^{63}Ni)
OB FW	0.14 (^{108m}Ag)	1.7e-2 (^{63}Ni)
OB VV	1.84e-3 (^{94}Nb)	2.44e-3 (^{94}Nb, ^{63}Ni)
OB Magnet	1.21e-6 (^{94}Nb)	1.37e-6 (^{94}Nb, ^{63}Ni)
Divertor	3.39e-2 (^{108m}Ag, ^{94}Nb)	1.33e-2 (^{94}Nb)

- According to Fetter limits, WDR values dominated by silver impurities in Cu alloys and niobium impurities in 316SS and 304SS
- According to 10CFR61 limits, WDR values for components made of Cu alloys are dominated by ^{63}Ni produced from Cu while WDR values of components made of SS are dominated by Nb impurities

Future Plans

- Three-dimensional calculations with special attention made to detailed geometrical configuration including gaps and large VV ports will be needed during conceptual design phase to determine
  - Neutron wall loading distribution in FIRE machine.
  - Nuclear performance parameters (nuclear heating, radiation damage, and insulator dose) in FW, VV, divertor, and magnet.
  - Magnet shielding requirements with impact of streaming.
  - Neutron and gamma fluxes and doses at critical diagnostics components.
  - Shielding and streaming at diagnostics interface.
  - Nuclear heating in the cryopumps located in the divertor port.
  - Amount of radioactivity and decay heat generated in different components.
  - Shielding requirements to allow for hands-on maintenance outside VV.
  - Shielding requirements during remote handling of in-vessel components.

Conclusions

- Modest values of nuclear heating occur in FW, divertor, VV, and magnet
- End-of-life He production values imply that VV will be reweldable
- Peak IB VV and magnet heating and damage decrease by ~15% for the baseline design with actively cooled vessel cladding behind the FW/tiles
- Insulators with radiation tolerance up to ~ 1.5×10^{10} Rads under FIRE load conditions should be used
- Activity and decay heat values after shutdown are low
- Following DT shots hands-on ex-vessel maintenance is possible with the 110 cm shield plug in midplane ports and the 20 cm shield at top of TF coil
- All components would qualify for disposal as class C LLW according to both 10CFR61 and Fetter limits

Models Used in Calculations

Radial Build of Outer Divertor Plate

Detailed radial build of outer divertor plate used in analysis:

- 5 mm W Brush (92% W)
- 1 mm region where W rods are joined to Cu heat sink
  (84% W, 14% Cu, 2% void)
- 19 mm heat sink made of Cu finger plates
  (78% CuCrZr, 20% water, 2% void)
- 30 mm mechanical attachment between Cu finger plates and backing plate
  (47% CuCrZr, 48% SS316, 5% void)
- 70 mm SS backing plate
  (84% SS316, 16% water)

Radial Build of VV

- 1.5 cm thick inner and outer 316SS facesheets
- Space between facesheets includes 60% 304SS and 40% water except in IB region where 11% 304SS and 89% water is used
- VV thickness:

IB midplane	5 cm
OB midplane	54 cm
Divertor	12 cm

- 1.5 cm layer of thermal insulation (10% Microtherm insulation) attached to back of coil-side VV facesheet

TF Coil Model

- Baseline design with 16 wedged TF coils analyzed
- BeCu used in inner legs and OFHC in outer legs
- 90% packing fraction used in coils
- 304SS coil case used in OB region with 4 cm front and 6 cm back thicknesses