M. Abdou

APEX Mechanical Design Considerations

presented by B. Nelson

APEX Meeting
UCLA

January 12, 1998

Presentation Outline

- Status of Activities for mechanical design and availability group
- General Design Requirements and Concept Information
- ITER First Wall and Limiter design (for comparison purposes)
- First Wall thickness considerations and recommendation
- Availability Considerations
- Vacuum Boundary Options
- Summary

Mechanical Design and Availability Group

Charter:

This group will be responsible for assisting all design conceptualization groups in developing mechanical design and integration. The group has responsibility for:

1. Vacuum boundary concept
   (separate vacuum vessel, resistive shield, or other approaches)
2. Mechanical configuration
3. Maintenance approach (innovative ideas to enhance maintainability)
4. Reliability (suggestions for reducing failure rates and for fault-tolerant designs)
5. Minimum wall thickness
6. Fabrication techniques

Members:

Chair: Brad Nelson, ORNL
Others from ORNL, including Paul Goranson, Paul Fogarty, John Haines, Dave Lousteau (ITER JCT)
Mark Tillack, UCSD
Siegfried Malang, FZK
M. Dagher, UCLA
Don Clemens, Rocketdyne
Igor
Alice

Status of Activities

Progress:

- Activities just getting underway (funding received in December)
- Reviewed charter for group and actions from previous meeting
- Developed list of design considerations and constraints
- Developed draft criteria for minimum first wall thickness
- Reviewed ITER limiter design
- Took first pass at vacuum boundary options and availability considerations

Plan:

- Begin to assist design advocates with specific designs
- Identify availability issues and possible improvements for specific designs

Goal and Scope

General Goal:

Develop attractive Fusion Power Technology system

Fusion Power Technology, FTP, is defined to include*:

- Vacuum environment
- Plasma exhaust
- Power extraction from plasma particles and radiation
- Power extraction from neutrons and secondary gammas
- Tritium breeding
- Tritium extraction and processing
- Radiation protection (shielding + confinement)

APEX is focused on power extraction, but other items must be considered

* ref. M. Abdou, APEX kick-off meeting, Oct. 15, 1997

General Design Requirements

Function	Requirement	Value/Goal
Power Extraction	Neutron Wall Load Surface Heat Flux	5 MW/m^2 avg* 7 MW/m^2 peak* 1.5 MW/m^2*
Tritium Breeding	Self Sufficient	TBR > 1
Shielding	Radiation exposure of coils (insulation) Nuclear heating of coils (sc cable) Reweldable confinement boundary	$< 1\times10^{9}$ Rad $< 1 kW/m^3$ < 1 appm He
Vacuum	Compatible with plasma - Base partial pressure, non-fuel - Base pressure, fuel (H,D,T)	 $< 1\times10^{-9}$ Torr $< 1\times10^{-7}$ Torr
Safety	containment boundaries confinement boundaries	1? 2?

* Values are minimum goals for steady state operation

Other Design Assumptions

Function	Requirement	Value/Goal
Plasma Exhaust	Divertor required?	TBD
Penetrations	Plasma Heating Power Density - NBI - ICH Diagnostics	 TBD MW/m^2 TBD MW/m^2 TBD
Operating Parameters	Pulse Length Number of pulses Disruptions	Steady State < 3,000 TBD
Availability	Maximize total availability	$A_{plant} > .75$ $A_{blanket/FW} > .98$

Concept Information needed by Mech Des. Group

- **Device type**
  - Point design device (tokamak, stellarator, RFP, etc.)
  - Limitations (will only work for _____)

- **Configuration**
  - General - 1 m^2 chunk of the FW/blanket
  - Integrated - schematic of system for point design device (eg, tokamak)

- **Size/total power:**
  - Point design - GW fusion power for developed concept
  - Limits, if any, on maximum/minimum size/power

- **Shielding:**
  - power deposition profile
  - thickness required for breeding
  - thickness required to limit coil heating/insulator damage

- **Coolant parameters:**
  - cooling media (lithium, flibe, helium, solid, combination)
  - flow rate per unit FW area or unit power
  - inlet and outlet temperatures
  - inlet and outlet pressure and pumping method

ITER First Wall design*

- Average surface heat flux of 0.25 MW/m^2, 0.5 MW/m^2 peak
- Average neutron wall load of ~1 ~~1.05~~ MW/m^2

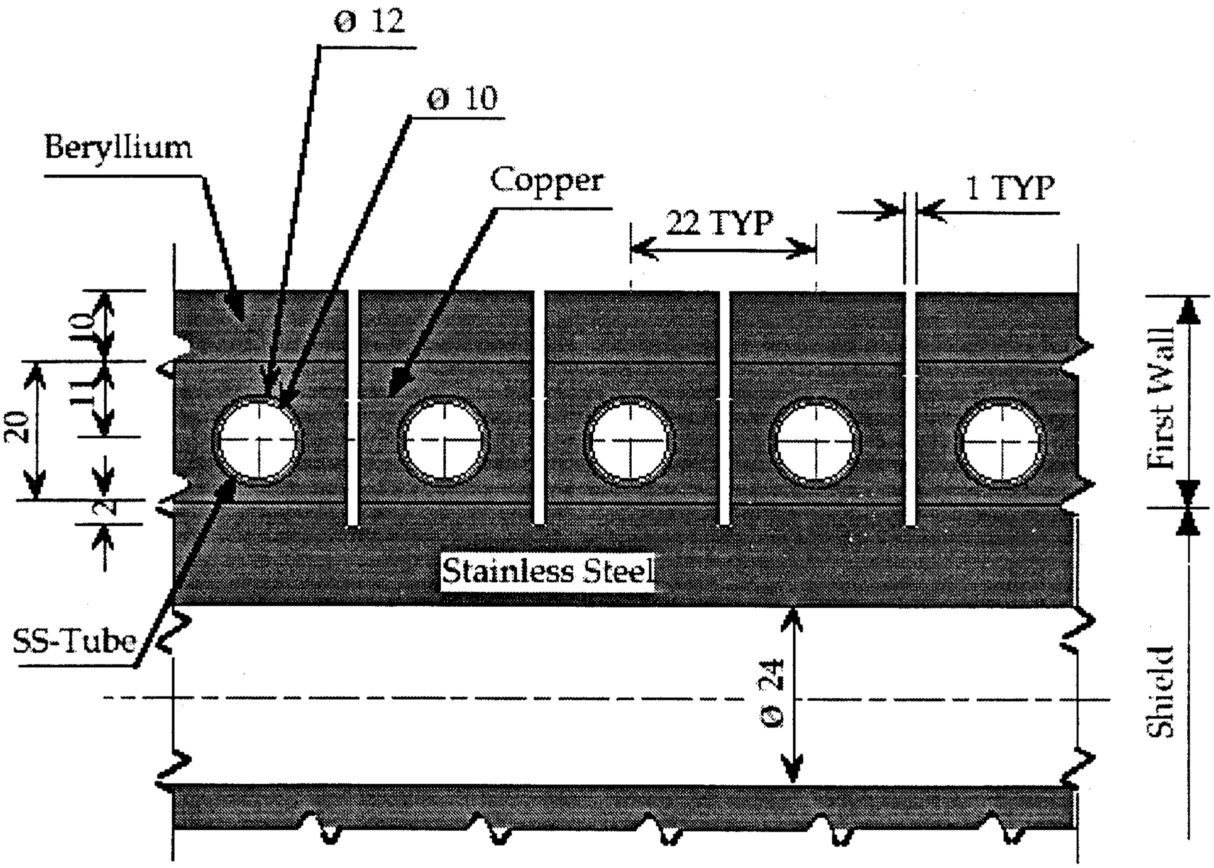


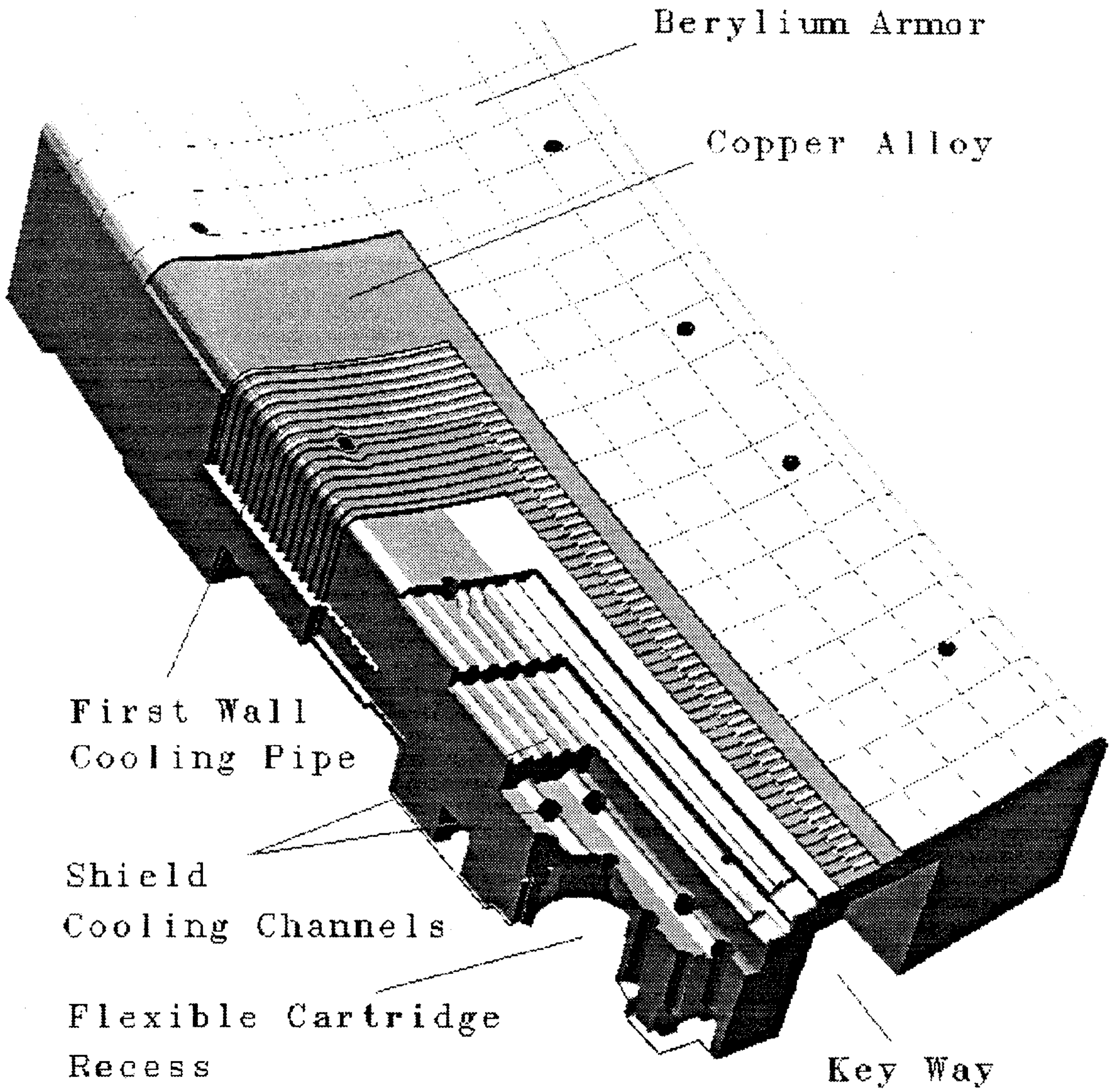
Fig. 2.1.2-19 Primary first wall cross-section

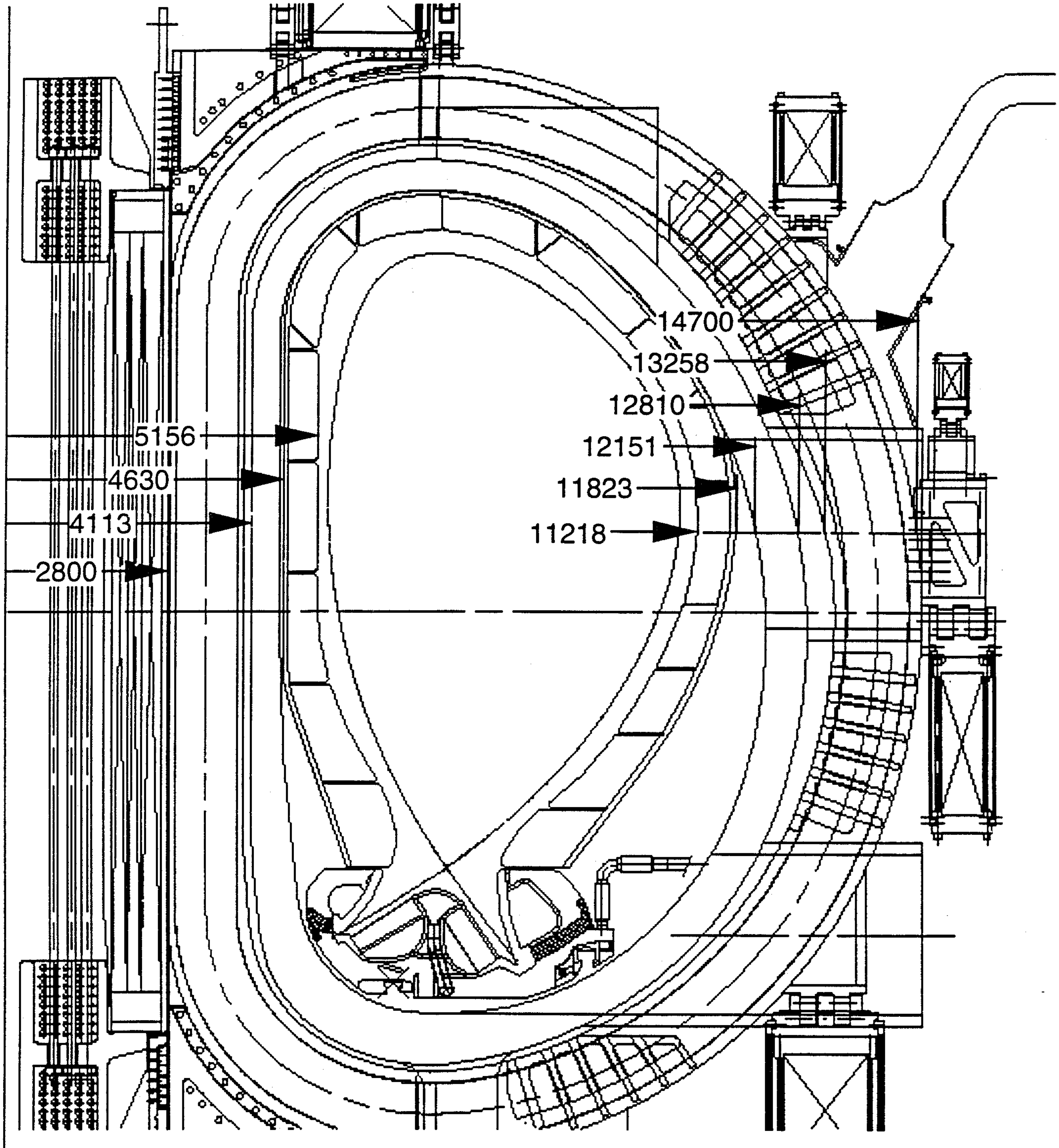
The first wall (FW) of the primary module comprises

- Beryllium armour
- A copper alloy heat sink
- Cooling tubes of 316 L(N)-IG stainless steel
- Coolant collectors located at the top and bottom of the shield block

* Ref. ITER DDD

ITER Blanket module design





ITER RADIAL BUILD (mm)

ITER First Wall Cooling Paramters *

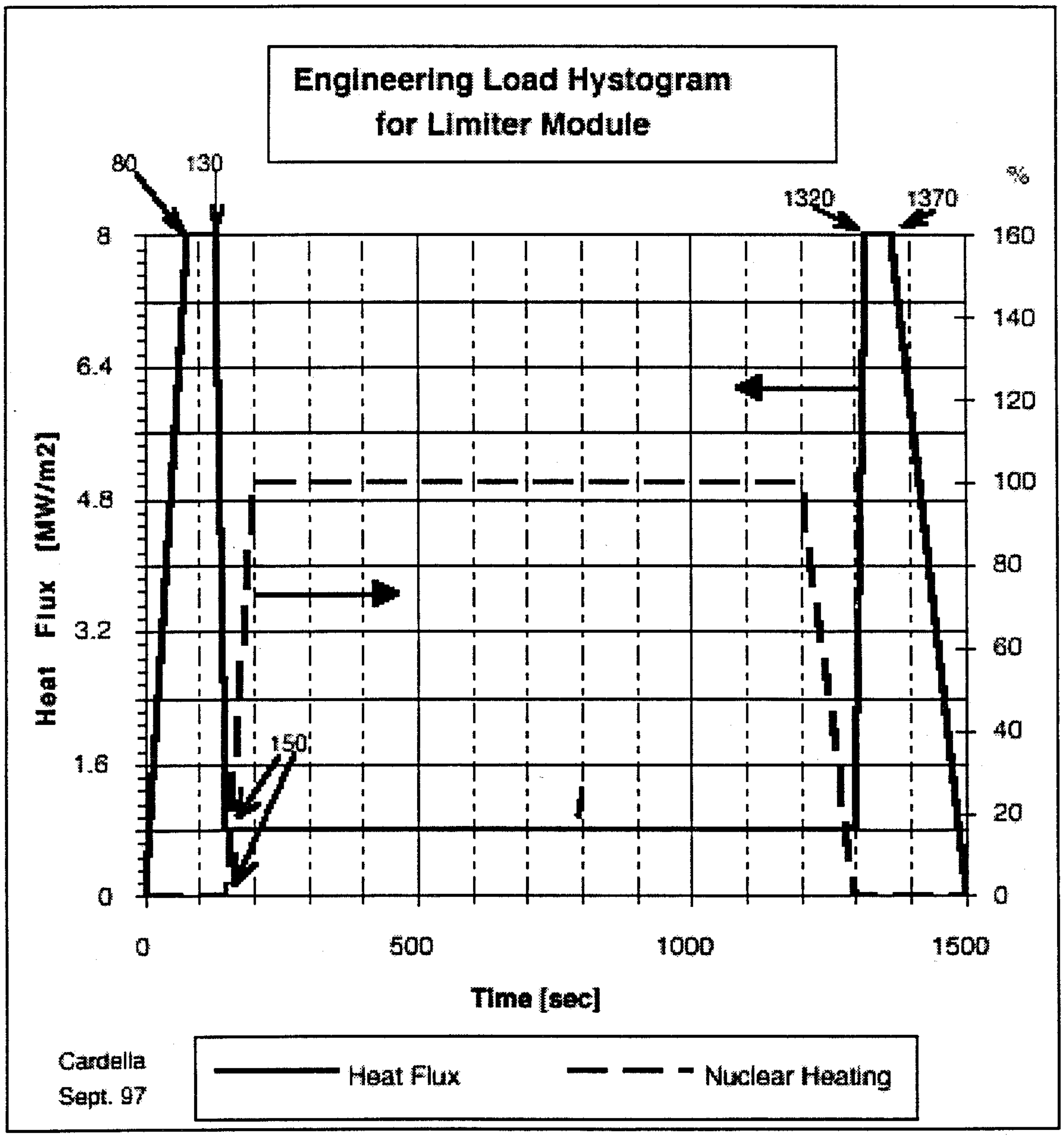
Table 2.1.8-1 Summary of Parameters of Cooling Systems

Access	Vertical Port	Equatorial Port
Modules Fed	No. 1-20	No. 21-26
Number of loops	10	4
Number of modules per loop	49 + in-port components*	60
Design Thermal Power (MW)**	~ 1460	~ 600
Nominal Inlet Temperature (°C)	140	140
Nominal Inlet Pressure (MPa)	3.8	3.8
Mass Flow Rate (kg/s)**		
Total	~ 6540	~ 2680
Per loop	~ 654	~ 670
Nominal Temperature Rise (°C)***	~ 51	~ 52
Pressure Drop (MPa)	~ 0.6	~ 0.6
Total Module Water Hold up (m^3) (assuming 15% water in 0.4 m thick modules)	~ 52	~ 19

* Ref. ITER DDD

ITER limiter design *

- Transient surface heat flux of 8 MW/m^2
- Average neutron wall load of 1.05 MW/m^2



* Ref. ITER DDD

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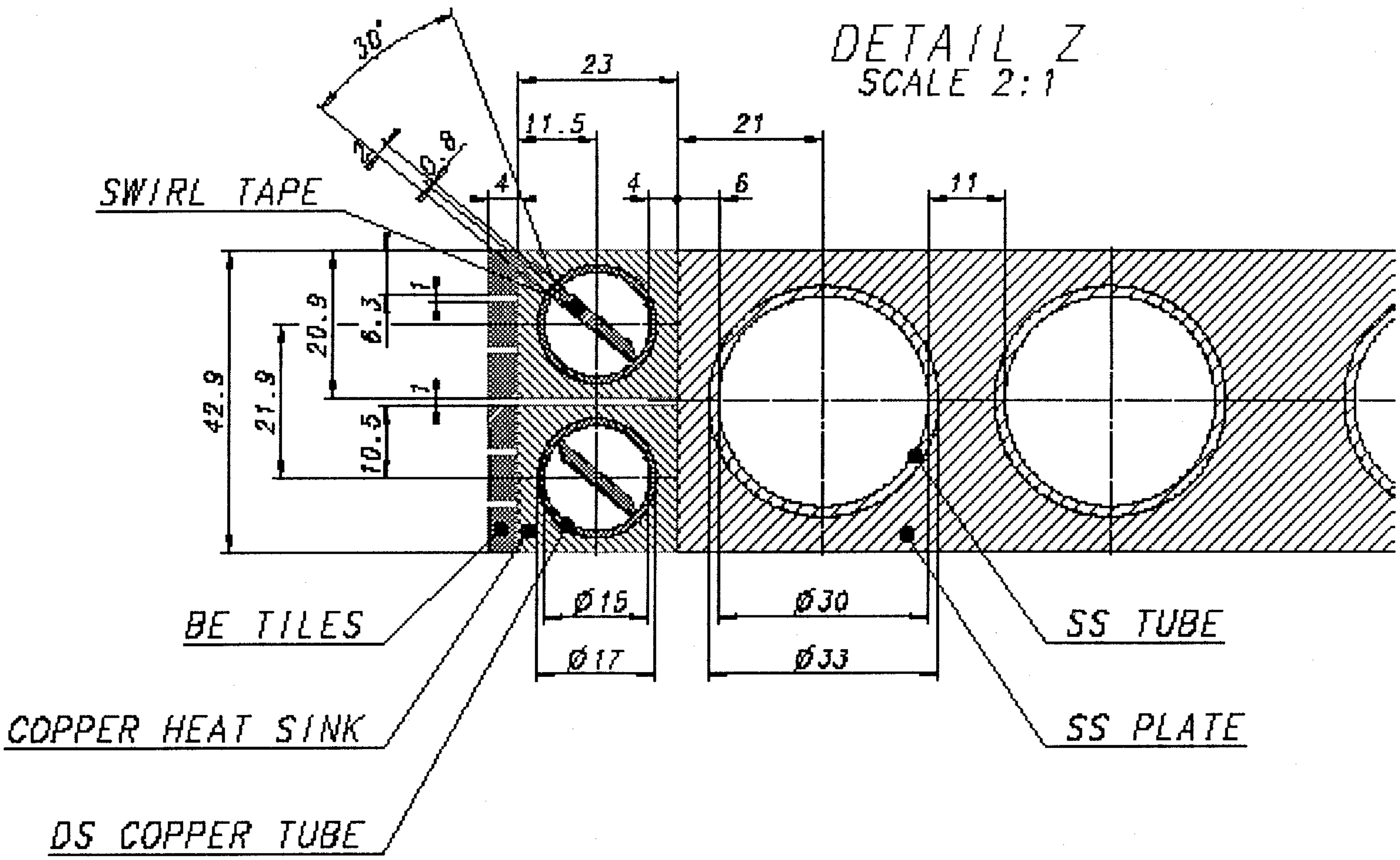

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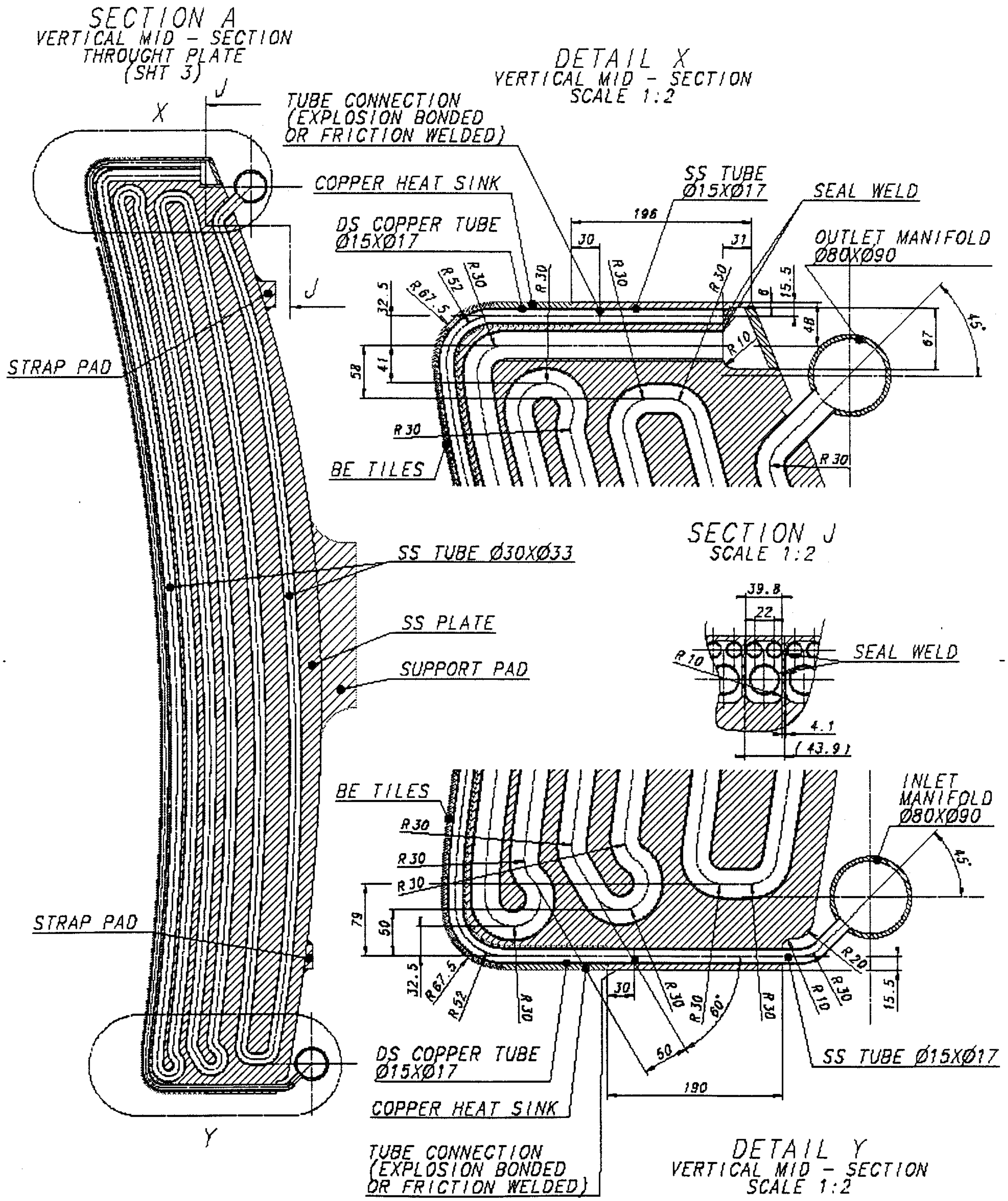

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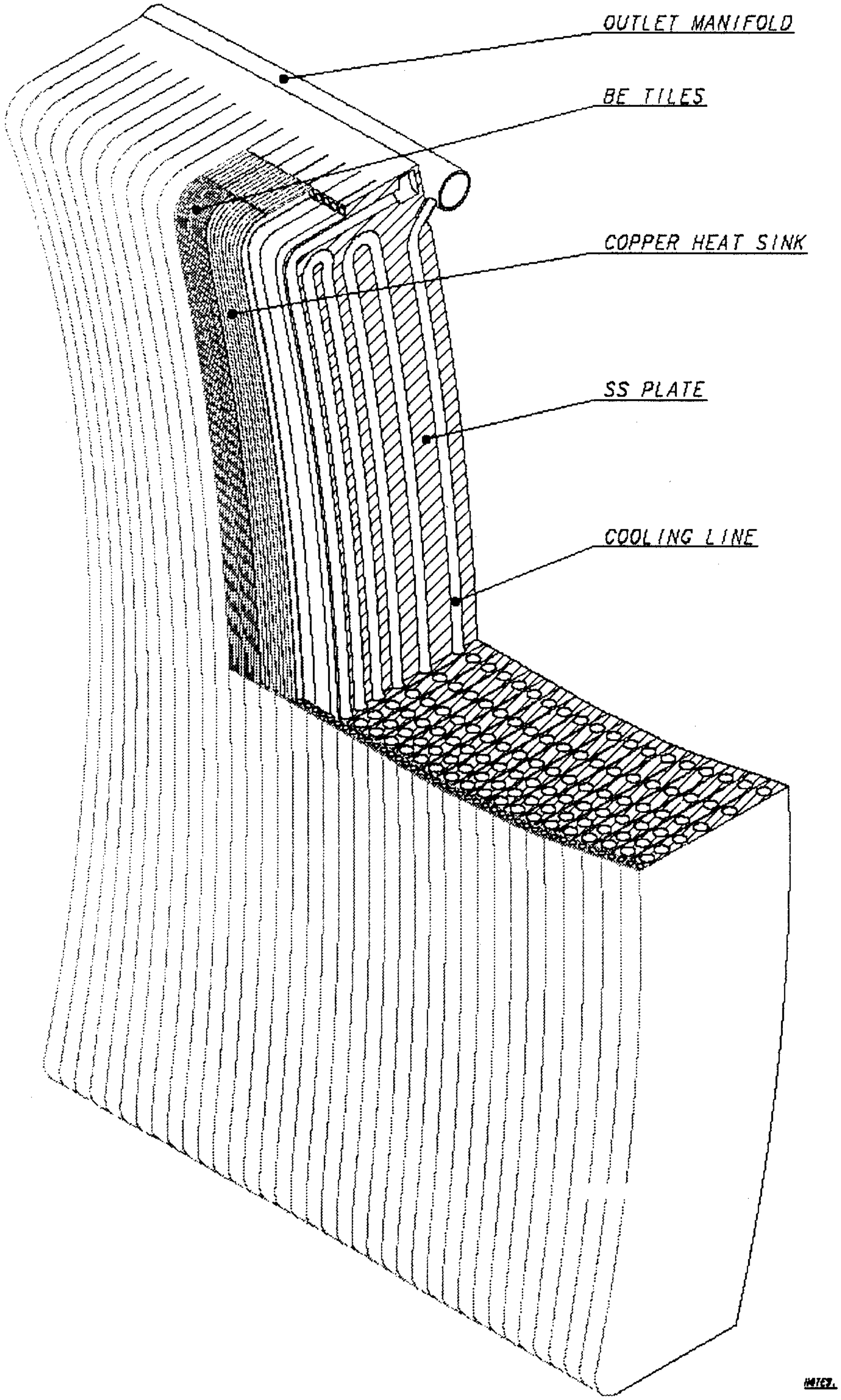
ITER limiter design *



* Ref. ITER DDD

ITER limiter cooling parameters *

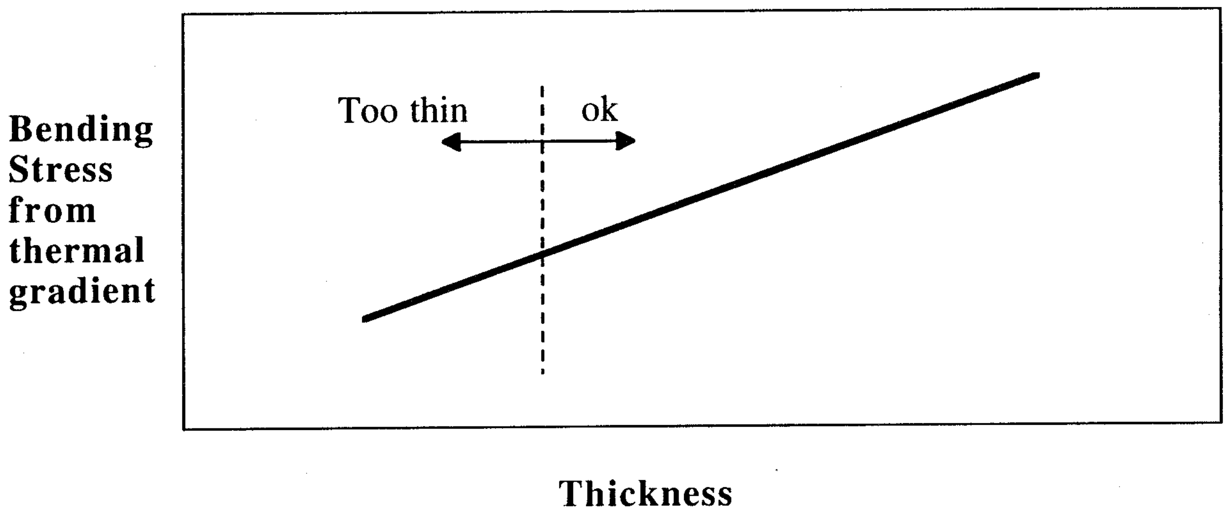
Access	Equatorial Port
Cooling System	Divertor PHTS
Number of Module per Coolant Loop	1
Nominal Thermal Power During Flat-Top Burn	~ 10 MW
Max. Plasma Heat Flux During Startup/Shutdown	~ 8 (-10) MW/m^2
Ave. Plasma Heat Flux During Startup/Shutdown	~ 3 - 3.8 MW/m^2
Inlet Temperature	140 °C
Inlet Pressure	4 MPa
First Wall	
Coolant tube diameter	15 mm
Coolant tube pitch	21 mm
Swirl twist ratio	2
Velocity	~8.2 m/s
Minimum CHF margin	~ 2
Mass Flow Rate per Module	~ 80 kg/s
Pressure Drop	~ 0.8 MPa
Temperature Rise During Startup/Shutdown	~ 43 °C
Temperature Rise During Flat-Top Burn	~ 12 °C
Total Module Water Hold up	~ 1 m^3

* Ref. ITER DDD

APEX FW thickness considerations / recommendations

Issue: **What is minimum practical thickness for first wall?**

- Thermal stresses main problem with high surface heat flux
- Thermal stresses can be reduced by using arbitrarily thin first wall
- Thermal stresses are not the only consideration for wall thickness



Approach: **List functions for first wall and their relation to wall thickness**

First Wall Functions

Intercept lost particles and radiated power

- small perturbations in the first wall surface geometry can result in local peaking
- power deposition much higher during disruptions

Withstand normal and off-normal mechanical loads

- normal operation: coolant pressure, gravity, installation, and maintenance loads
- off-normal: EM loads from plasma disruptions, seismic loads, accidental impact loads (eg dropping objects during maintenance), loads due to abnormal operation of connected components (eg distortion of mounting structure due to thermal excursion).

Provide coolant boundary

- in "conventional" designs, FW is the boundary between the plasma and the coolant
- assume coolant cannot contaminate the plasma vacuum space
- must consider corrosion, creep, blockages in coolant paths, coolant connection integrity, runaway electrons

Contribute to Plasma stability *(electrically conductive FW)*

First Wall Functions, (cont'd)

Minimize trapped gases

-- must not trap excessive amounts of fuel gases (such as tritium)

- compatible with vacuum pumping requirements.

Minimize "high Z" impurities in plasma

- "Low-Z" surface (eg carbon or beryllium)
- FW located very accurately with respect to plasma surface to prevent localheating / impurity evolution.

Accommodate loss of plasma conditions (survive impingement of pellets or direct NBI heating) .

Define boundary of plasma during startup/shutdown

- FW may need to provide a limiter function
- the heat load would be higher during transients such as startup and shutdown.

Provide for penetrations (heating, currnet drive, diagnostics, fueling, etc)

Maximize availability (FW must be reliable and maintainable, radiation damage must be considered)

FW thickness considerations and suggested criteria

Consideration	Relation to thickness	Criteria	Impacted Functions from failure
Maximum Temp (normal oper.)	T ∝ thickness	T < T matl.	Plasma contamination Coolant boundary
Maximum Temp (off-normal)	T ∝ thickness	Tcool side < Tcrit Need thermal inertia for high heat flux transients	Coolant boundary
Thermal Stress	Q ∝ thickness	Pm+Pb+Q < 3*Sm	Coolant boundary Surface contour
Pressure load*	Pm ∝ 1/thickness Pb ∝ 1/thickness^2	Pm < Sm Pm + Pb < 1.5 Sm	Coolant boundary Surface contour
Assembly loads	(same as pressure)	Support wt. of person (2*100 kg) standing on FW	Coolant boundary Surface contour
Impact load	(same as pressure)	20 (?) kg object dropped from height of plasma chamber	Coolant boundary Surface contour
Tritiium retention	Vol ∝ thickness Ret. ∝ temperature		
Corrosion	Margin ∝ thickness	1 mm allowance	Coolant boundary
Erosion	Margin ∝ thickness	1 mm allowance	Coolant boundary
Passive stability	Elec.cond. ∝ thickness	will not consider	Plasma stability
Runaway electrons	Penetration ∝ thickness	~~will not consider~~ consider part of Robbs' mess	Coolant boundary
Radiation effects	variable	material properties	Coolant boundary Mechanical integrity
Fabrication	variable	must be able to integrate first wall with structural and cooling connections	availability
Margin/tolerance	variable	thickness can vary locally by >20 % of total thickness or 2 mm, whichever is larger	availability

* Electromagnetic pressure may be inversely proportional to wall thickness if response is primarily resistive

Availability Considerations

- **Fusion Technology must be reliable <u>and</u> maintainable.**

$$\text{Availability} = \frac{\text{Mean Time Between Failures}}{\text{Mean Time Between Failures} + \text{Mean Time To Repair}}$$

- **General guidelines include:**

  - design is tolerant of a few failures
  - potential problems can be predicted and prevented,
  - any failures that do occur can be diagnosed and corrected quickly

Availability Considerations

- **Design features to consider (for fewer unscheduled failures, faster repair)**

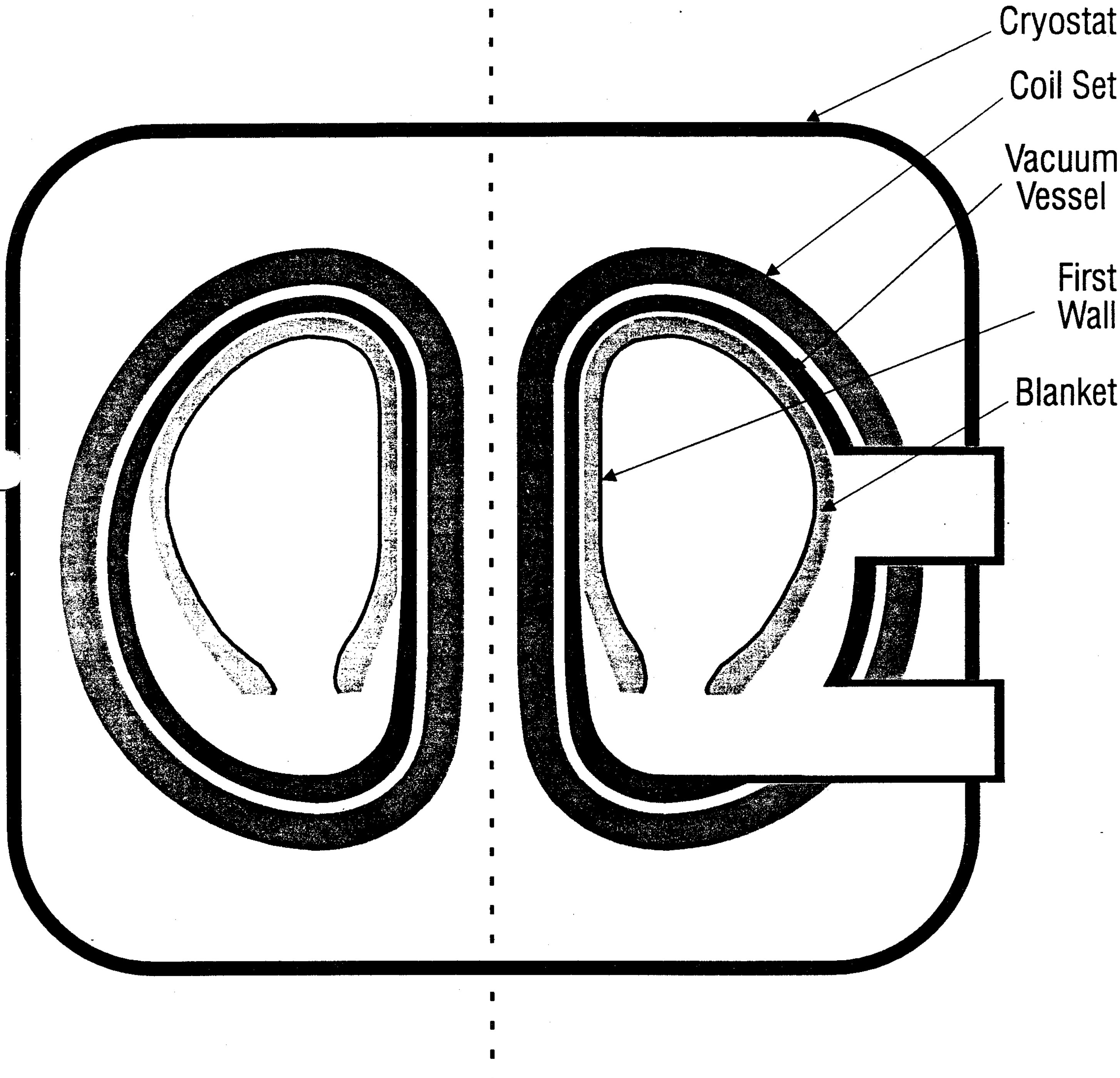
  - Keep designs as simple as possible (eg, minimize number of parts)
  - Standardization of features and components
  - Maximum margin (for transients, unforseen modes)
  - Use of proven designs where possible
  - Modular designs, pre-tested, minimizing series assembly operations
  - Redundancy where possible, continue operation until next scheduled repair
  - Minimize remote handling by providing sufficient shielding for hands-on access to high maintenance items (eg, pumps, valves, expansion joints, etc.)
  - In-situ inspection and repair to save down time (eg, replenish plasma facing surface by spray instead of removing and replacing)
  - Good access to coolant and structural connections (eg, from front, not back)
  - High failure rate items should be configured for quick maintainence

Availability Considerations

- **Design features to avoid (more unpredictable failures, slower repair)**

  - major discontinuities in structural stiffness (bellows should be last resort)
  - unshielded welds, bolts, insulators
  - electrical insulators near plasma vacuum
  - electrical insulators that have structural function
  - custom fit parts
  - multiple, non-standard plumbing connections
  - coolant and vacuum connections that cannot be isolated and leak checked
  - specialized ports, (eg, different adaptation of concept to accomodate each diagnostic and heating system)
  - interlocks with operator override (do not operate outside design envelope)

Conventional



CONVENTIONAL (P-FW-B-VV1-C-VV2)

Features:

- VV1 provides plasma vacuum, pressure (from coolant leaks), and radiation containment boundary
- FW has no VV function, therefore blanket exposed to plasma
- VV2 provides cryostat for SC coils and 2nd pressure/radiation (safety) boundary

Advantages:

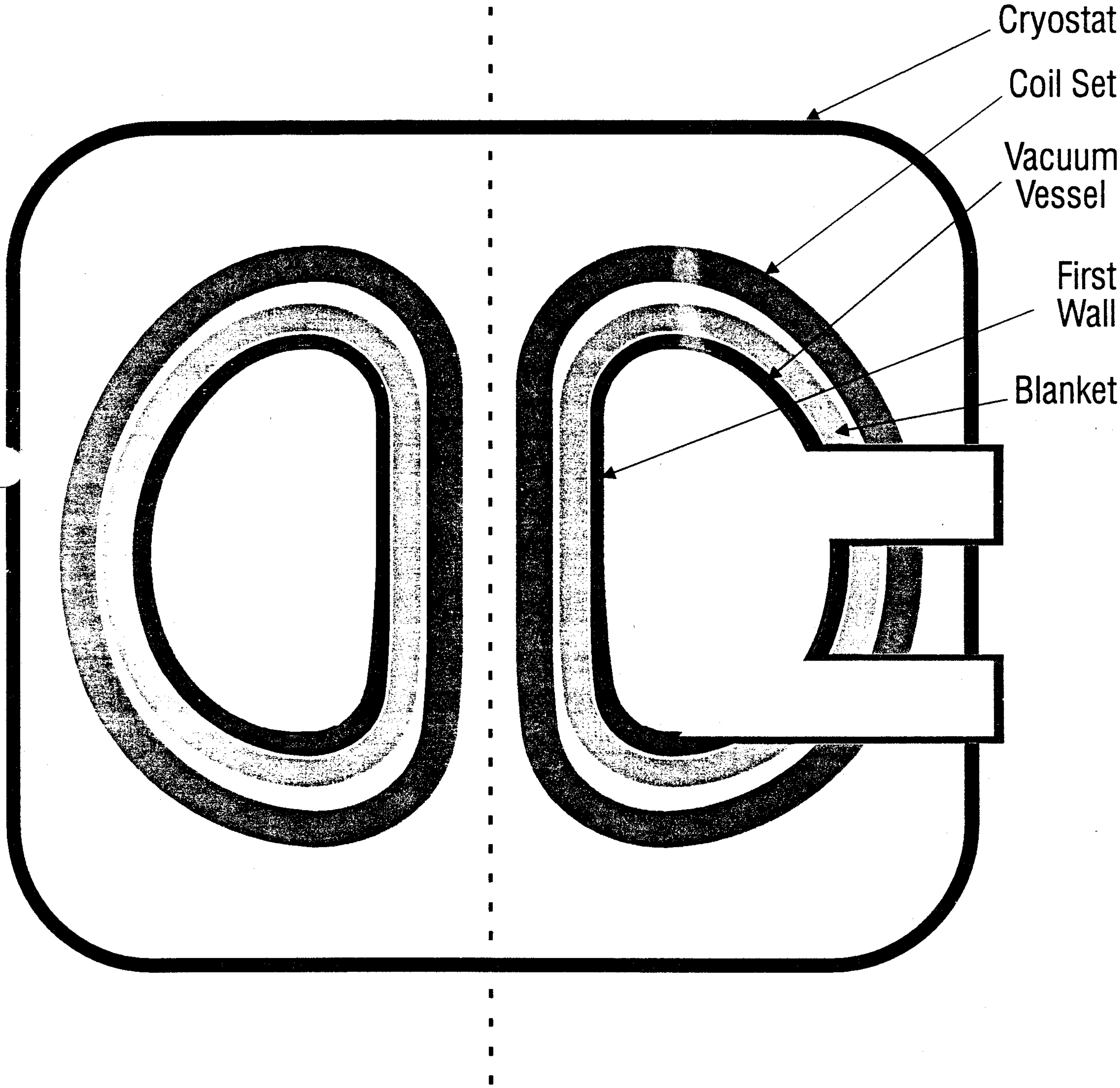
- Functions and requirements of each VV are distinct - design simplicity, minimum failure modes and effects of each component.
- Efficient use of space since plasma volume can be used for maintenance operations on the FW and blanket
- Simpler more flexible operation since each system is separated - for example, can raise pressure inside VV1 (as for maintenance) independently from that in VV2
- Simplest reactor containment scheme since all/only mobile contamination radioactive components are inside the minimum size safety boundary (the arrangement in which the reactor is connected to the balance-of-plant may minimize this advantage)
- FW and blanket provide shielding to VV1
  - Minimizes material property changes
  - Allows rewelding
- Can maintain (single) containment while performing maintenance of primary containment boundary

Disadvantages:

- FW and blanket are in the plasma volume - plasma exposed to coolants leaks
  - Limits design options of FW and blanket
  - Increase RAM requirements of FW and blanket
- Complex mechanical/electrical coupling between VV1 and VV2

Variation 1

Blanket Outside Vacuum Vessel



VARIATION 1 (P-FW-VV1-B-C-VV2)

Features:

- VV1 provides vacuum and containment boundary for plasma
- Blanket located between two vacuum and containment boundaries
- VV2 provides cryostat for SC coils and 2nd plasma containment boundary

Advantages:

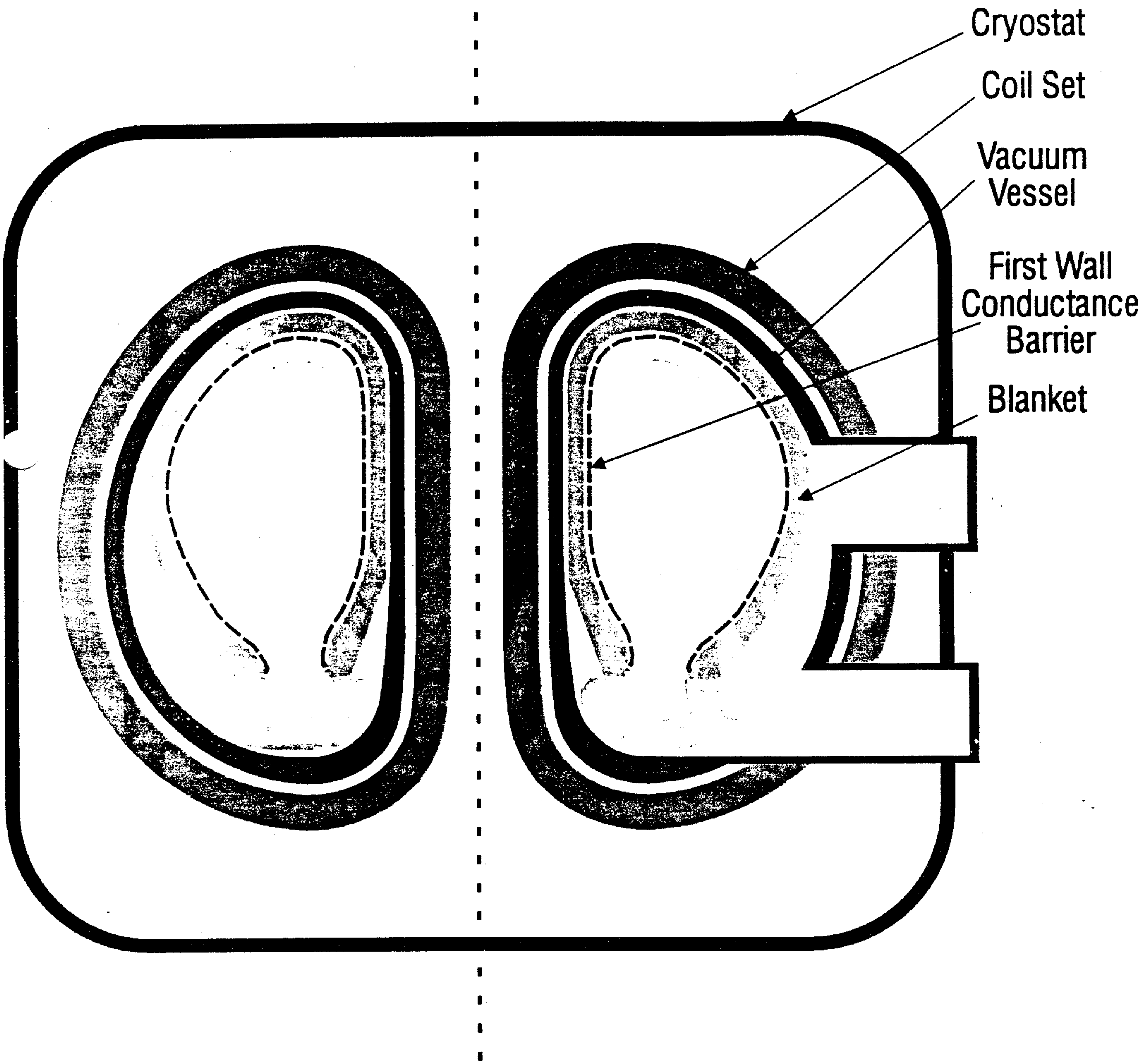
- Separate functions and requirements on each boundary
- Blanket is separated from plasma
  - Lower RAM requirements
  - More design options
- Separate plasma and cryostat volumes
- Can maintain single containment for blanket maintenance

Disadvantages:

- Coils must be thermally shielded from blanket (at higher temperature than VV)
- Large temperature differential between FW and VV1, or higher VV1 tempt, or lower FW tempt (more complex mechanical and electrical coupling between VV1 and VV2 if VV1 is at higher tempt).
- Maintainability of inboard blanket - increased radial build for maint. space?
- VV1 is shielded only by FW
- Increased power and electromagnetic loads on VV1 (which must be designed to higher criteria/code levels due to its containment function)

Variation 2

First Wall is Conductance Barrier



VARIATION 2 (P-FW/CB-B-VV1-C-VV2)

Features:

- Adds a conductance barrier between the blanket and FW
- Other features same as in the Conventional Arrangement

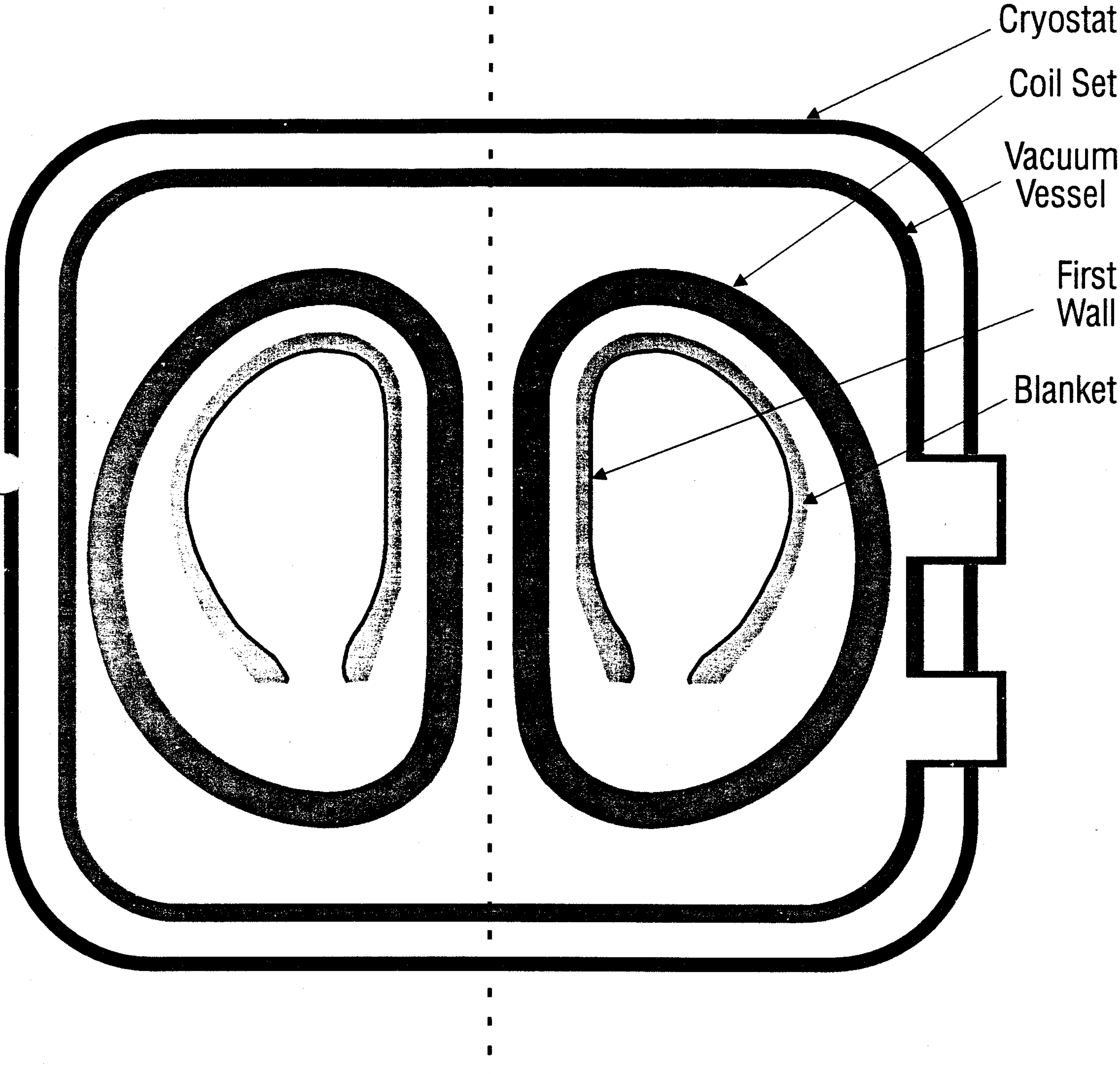
Advantages:

- All advantages of Conventional Arrangement
- Limits plasma exposure to blanket leaks
- More design options for blanket

Disadvantages:

- Separate FW or provided by conductance barrier
- Increased radial build
- More components
  - Cost
  - RAM impact
- Other disadvantages of Conventional Arrangement

Variation 3
Vacuum Vessel Outside Coils



VARIATION 3 (P-FW-B-C-VV2-VV2)

Features:

- Combined plasma and cryostat vacuum pressure/vacuum boundary
- Blanket exposed to both plasma and coils

Advantages:

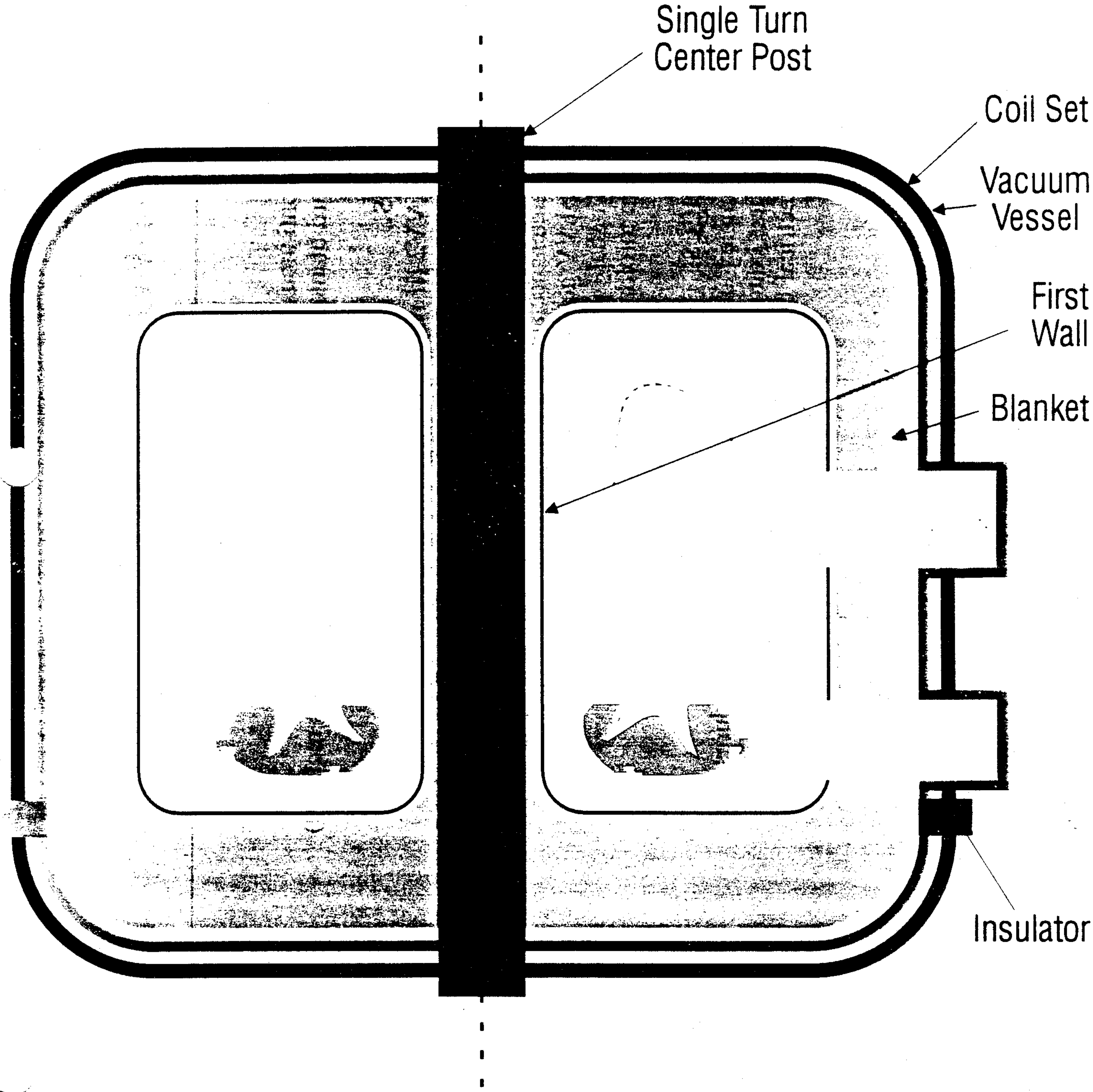
- Blanket shields SC coils
- Direct coupling of VV1 and VV2 - same temperature, same deflections from loads
- Good maintenance access to blanket, coils, VVs - possible to maintain double containment during maintenance
- Double containment for plasma, blanket, and coils
- Simplified VV design and construction - simple geometry, low power and em loads
- Reduced radial build - VV shielding thickness must be maintained but installation and thermal expansion gaps eliminated
- Coils (if SC) may provide cryopumping

Disadvantages:

- More complex and unconventional operational procedures
- Gas load on coils
- Larger first boundary

Variation 4

Vacuum Vessel Is TF Coil



VARIATION 4 (P-FW-B-VV1/C-VV2)

Features:
- Single/continuous return leg of TF coil used as VV1
- No inboard blanket - normal coils (demountable joints required)

Advantages:
- External VV2 (if required) for second containment
- Fewer components
- Outboard blanket shields coils
- Direct coupling of VV1 and VV2 if normal coils
- Good maintenance access
- Simplified VV geometry, low power and plasma em loads
- Reduced radial build
- Minimum toroidal ripple (port effects?)

Disadvantages:
- More complex and unconventional operational procedures
- Larger first boundary
- Large electrical break required in vacuum boundary

Summary

- **Mechanical Design Group Activities just starting**

- **Some Guidelines are proposed for Design Concept Evolution**
  - Basic Requirements for all concepts
  - Specific Concept Parameters must be defined (size, coolant, flow, etc)
  - FW thickness (design concept dependent)
  - Availability (must be included from onset of design, cannot be sprinkled on later)

- **ITER concepts for FW and limiter offered for comparison**

- **Alternate vacuum boundary config. may offer advantages for some concepts**