Achieving High Availability in Tokamak Power Plants

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Cost Of Electricity Is the Critical Measure Of Commercial Feasibility

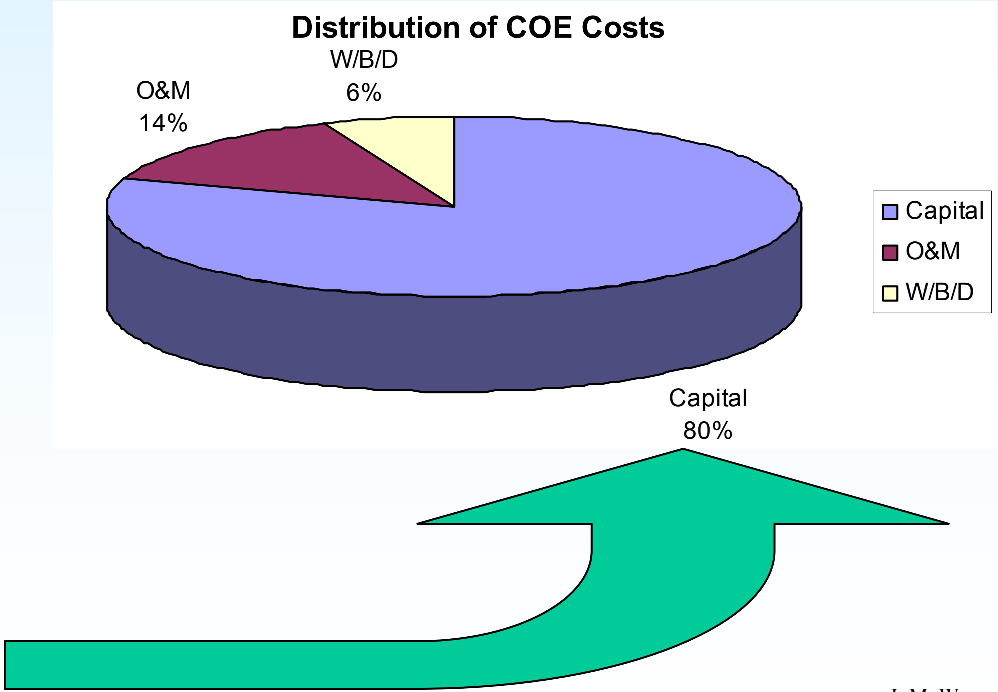
$$\frac{\text{Annualized Capital Cost + Yearly Operating Cost}}{(\text{Thermal Power x } \eta - \text{Recirculating Power}) \text{ x Plant Availability}}$$

- Plant Availability is one of the strongest factors that determine the Cost of Electricity
- Existing Fossil and Fission Plants are maximizing their availability to stay competitive (e.g., 85%, 90%, 95%)
- New plants must produce competitive COE values
- Capital intensive plants (high Capital Cost) must compensate with other factors

Cost Of Electricity Is the Critical Measure Of Commercial Feasibility

$$\frac{\text{Annualized Capital Cost + Yearly Operating Cost}}{(\text{Thermal Power x } \eta \text{ – Recirculating Power}) \text{ x Plant Availability}}$$

Capital Cost typically accounts for 80% of the annual cost to operate a fusion power plant



COE Factors That Fusion Can Influence

$$\frac{\text{Annualized Capital Cost + Yearly Operating Cost}}{(\text{Thermal Power x } \eta - \text{Recirculating Power}) \text{ x Plant Availability}}$$

Factor	Influence
Capital Cost	Fusion will probably higher capital costs than competitors
Operating Cost	Fuel very low cost; Maybe small operating staff; Power core maintenance may be high for wall, blanket, and divertor
Thermal Power	Thermal power level constrained by unit size, which is determined by utility size and transmission capability
Thermal Efficiency	Fusion will have to push the limit with Brayton gas cycle to stay competitive with efficiencies around 60% (>1100°C fluids)
Recirculating Power	Superconductors will help control recirculating power, but pumping liquid metals or helium increase recirculating power
Availability	Need long lived components (high MTBF) and short time to maintain (short MTTR) on all plant elements; need A > 90%??

What Establishes Plant Availability?

Availability is defined as the time the plant is available for power production compared to the total calendar time.

$$\text{Availability} = \frac{\text{Operating Time}}{\text{Operating Time} + \text{Sum of Outage Times}}$$

$$= \frac{1}{1 + \Sigma \frac{\text{Mean Times To Repair (MTTR)}}{\text{Mean Times Between Failures (MTBF)}} + \Sigma \frac{\text{Preventative Maintenance}}{\text{Time Between Maintenance Periods}}}$$

Availability can be improved by:

- Reducing time to repair and preventative maintenance actions
- Extending time between failures and maintenance periods

Mean Time Between Failure Depends on Component Reliability and Wearout

- Power core components must be highly reliable
  - Minimal unexpected failures are required to achieve maximum replacement during scheduled, concurrent, preventative maintenance periods
- Components must have long, predictable lifetimes
  - Divertors, first walls, and blankets must operate in excess of 4 full power years (or be super fast to replace)
  - All other components must be life of plant
    - Shield, vacuum vessel, cryovessel, and structural components
- System design must incorporate redundant features to minimize operational shutdowns

Mean Time To Repair (of Power Core) Is Established By Maintenance Philosophy

- **Both planned maintenance and unexpected failures must be quick, easy, accurate, and reliable**
- **Modular replacements must be available upon demand**
- **Repair and/or maintenance of modules done off-line to increase operational time and improve fidelity of repair**

The Remainder of the Talk Will Concentrate on the Maintenance Aspects of Fusion Power Plants and How It Can Be Improved

Operational Mean Time To Repair the Power Core Is Essential

- **Include both scheduled and unscheduled outages**
  - Availability = Total Time/(Total Time + Σ of Outages)
  - Outage figure of merit is MTTR/MTBF (repair or replace)
- **Plant must be designed for high maintainability**
  - Modular power core replacement
  - Simple coolant and mechanical connections
  - Highly automated maintenance operations
  - Power core building designed for efficient remote maintenance
- **Modules or sectors should be refurbished off-line**
  - Better inspection methods results in higher reliability

Criteria for Maintenance Approach

List does not imply priority

- Apply to scheduled and unscheduled maintenance
- Reduce operational maintenance time
- Improve reliability of replacement modules or sectors
- Increase reliability of maintenance operations
  - Failsafe approach
  - Accurate and repeatable maintenance operations
- Reduce cost (size) of building and maintenance equipment
- Reduce the cost of spares
- Reduce the volume of irradiated waste and contamination from dust and debris
- Keep it simple

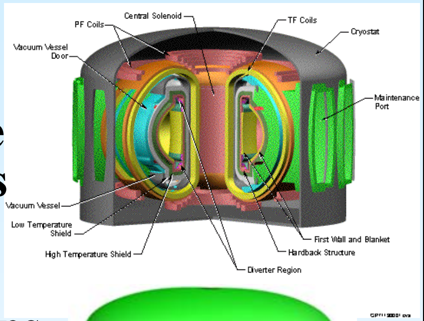
ARIES' Studies Show R&D Direction

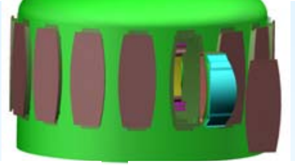
Starlite Demo

- Define demonstrations
  - Robotic maintenance
  - Reliability
  - Maintainability
  - Availability

ARIES-RS

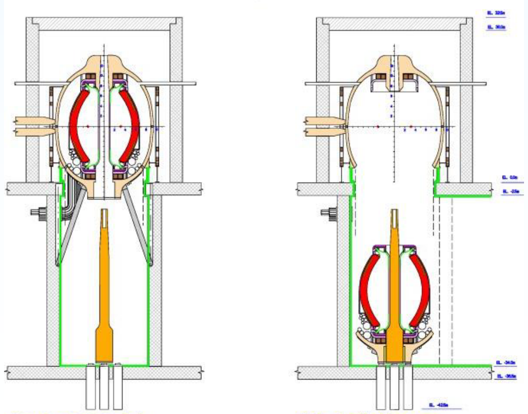
- Integrate maintenance into power core
  - Design power core with removable sectors
  - Design high-temperature, removable structure for life-limited components
  - Arrange all RF components in a single sector
  - Define and assess maintenance options
  - Define power core and maintenance facility





ARIES-ST

- Define vertical maintenance scheme
  - Remove centerpost only
  - Remove total power core
  - Use demountable TF coils
  - Split TF return shell



Elevation View of Showing FPC Maintenance Paths

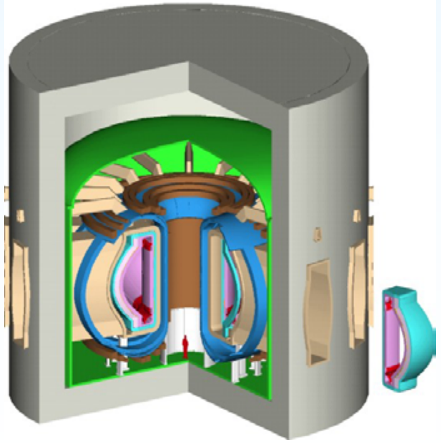
(a) Lower down the CP independantly

(b) Lower down the whole power core.

ARIES-AT

- Improve maintainability
  - Refine removable sector approach
  - Define contamination control during maintenance actions
  - Assess maintenance options
  - Define maintenance actions
  - Estimate scheduled maintenance times

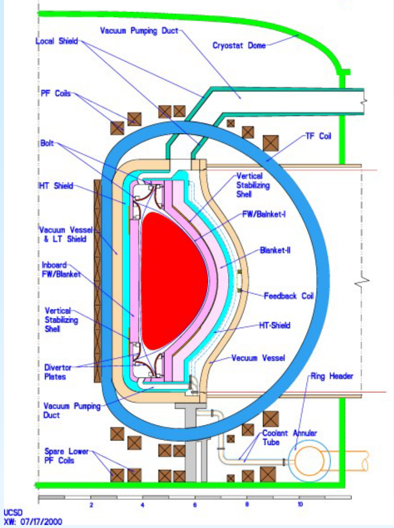
Cutout View Showing Maintenance Approach



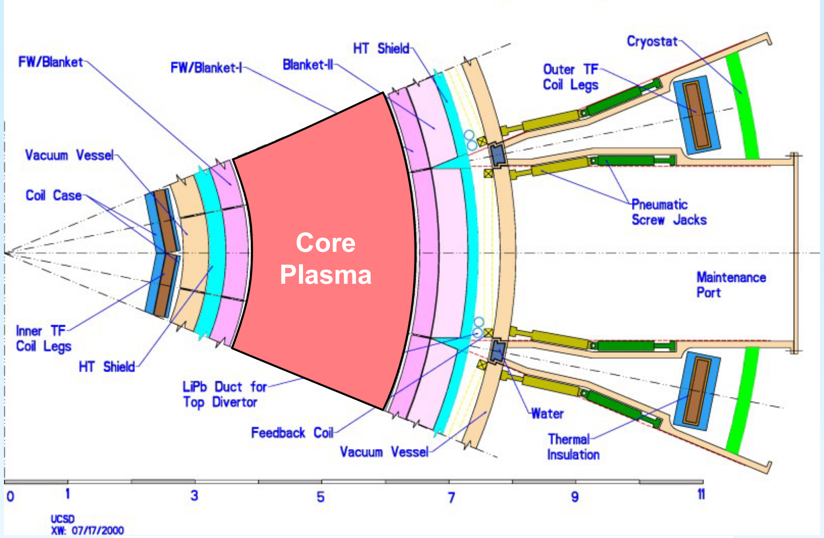
Example of AT Sector Replacement

Basic Operational Configuration

Cross Section of ARIES-AT Power Core Configuration

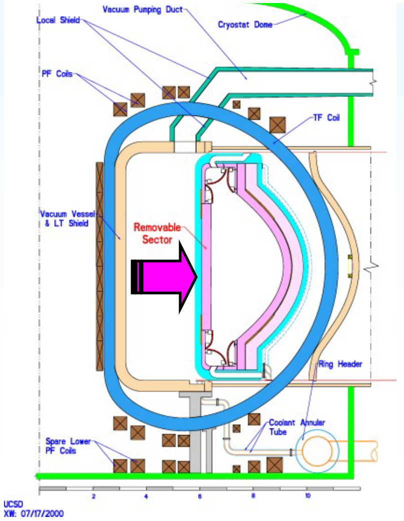


Plan View of ARIES-AT Power Core(1/16 Sector)

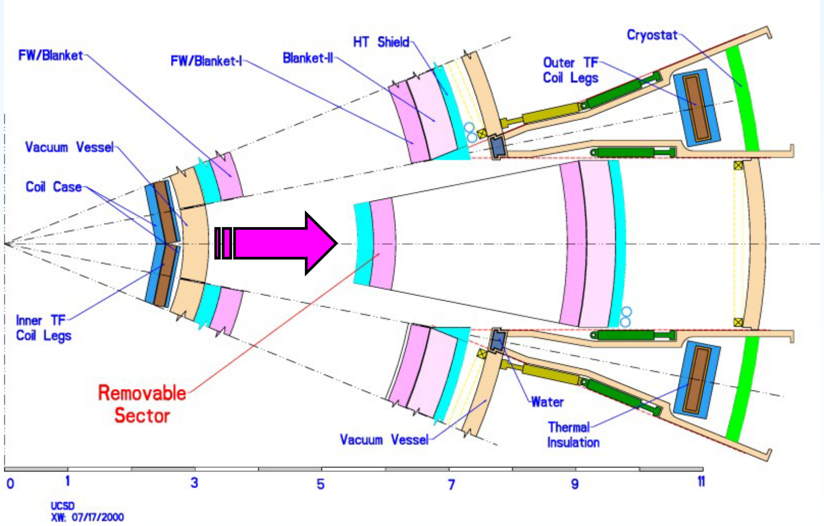


Withdrawal of Power Core Sector with Limited Life Components

Cross Section Showing Maintenance Approach

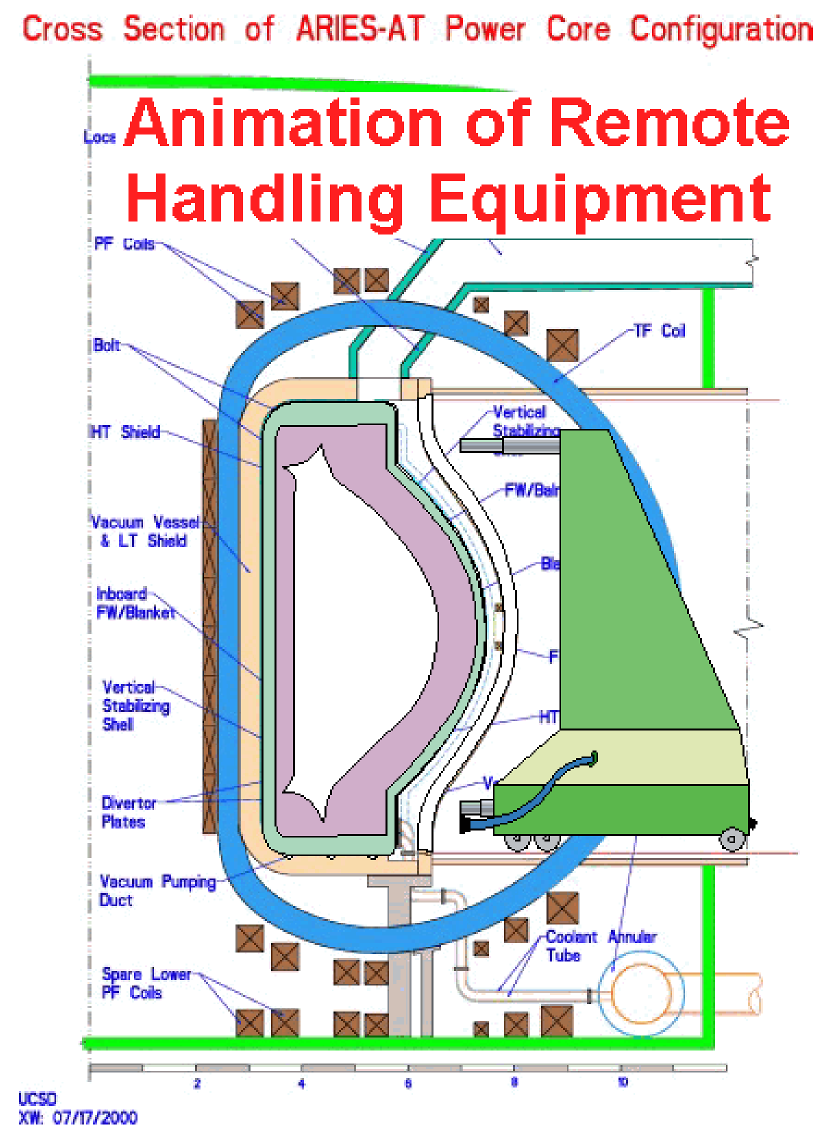


Plan View Showing the Removable Section Being Withdrawn



Sector Removal

Remote equipment is designed to remove shields and port doors, enter port enclosure, disconnect all coolant and mechanical connections, connect auxiliary cooling, and remove power core sector



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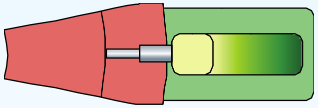
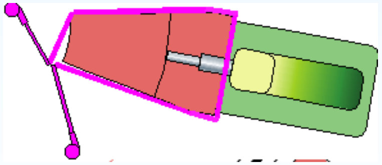
ARIES-AT
Maintenance Options Assessed

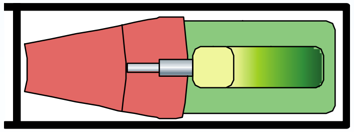
- In-situ maintenance
  - All maintenance conducted inside power core
- Replacement in corridor, hot structure returned
  - Life-limited components replaced in corridor, exo-core
- Replace with refurbished sector from hot cell
  - (A) Bare sector transport



  - (B) Wrapped sector transport



  - (C) Sector moved in transporter (ala ITER)



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Compare Coolant System Maintenance for Corridor and Hot Cell Approaches

Summary of Corridor Maintenance Connections

	Blanket to Shield	Sector to Header	Total
Simple Connection	4	-	4
Co-Axial Connection	4	5	9

Summary of Hot Cell Maintenance Connections

	Blanket to Shield	Sector to Header	Total
Simple Connection	(4 in hot cell)	-	-
Co-Axial Connection	(4 in hot cell)	5	5

Both approaches have same number of coolant plumbing connections, but the blanket to hot shield can be disconnected and reconnected off line for the hot cell approach. The hot cell approach would be faster and would assure a more reliable refurbished sector.

Comparison of Maintenance Approaches

In-Situ Advantages

- Smallest buildings
- Low maintenance and spares costs

Corridor Advantages

- Low spares costs
- Reduced irradiated waste

Hot Cell Advantages

- Faster online replacement
- Higher sector reliability
- Better contamination control
- Applicable to both scheduled and unscheduled maintenance

Scoring: 0 = Lowest, 4 = Highest

	Maintenance Approach		
Criteria (Importance)	**In-Situ Maintenance (Score)**	**Corridor Maintenance (Score)**	**Hot Cell Maintenance (Score)**
Maintenance Time 4	Slowest time as all operations have limited access. Arm or rail operations will be relatively slow and number of parallel operations will be limited. 1	Moderately slow time as not only must the sector be removed, but also access to remove/replace blanket modules is limited. Has the highest number of connections to be accomplished. 2	Fastest maintenance as number of on-line mechanical and coolant connections will be minimal and accessible. All refurbishment will be accomplished off-line. 4
Replacement Sector Reliability 4	Lowest reliability as all refurbishment and inspection must be in-situ with limited access. Limited time to complete. But it has lowest number of connections. 1	Moderately low reliability, as access is limited. High number of connections. Limited time to complete. 2	Highest reliability because of long time to complete and inspect refurbishment. High number of connections (same as Corridor Maintenance). 4
Building Cost 2	Probably the smallest building size, even considering the volume for arm and rails. 4	Might be the largest building size to provide space for refurbishment equipment in corridor. 2	Slightly less building size than Corridor Maintenance to just accommodate removal and transport sectors. 3
Maintenance Equipment Cost 1	Not clear, but this approach probably has the lowest maintenance cost even with maintenance arm or rail. One or two simpler transporters are needed. 4	Higher cost than Hot Cell approach as several portable refurbishment carts are needed to speed on-line maintenance. Also requires several transporters. 2	Moderate cost for 4-8 transporters, but transporters are moderate cost compared to mobile refurbishment carts. 3
Spare Equipment Cost 1	Lowest spare equipment cost as all high temperature shielding structure modules are used to the fullest. 4	Lowest spare equipment cost as all high temperature shielding structure modules are used to the fullest. 4	Highest spare equipment as high temperature shielding structure modules are extracted for refurbishment. Effect can be mitigated with fractional replacement. 2
Waste Volume 3	Lowest waste volume as all high temperature shielding structures are used to the fullest. 4	Lowest waste volume as all high temperature shielding structures are used to the fullest. 4	Highest waste volume as high temperature shielding structures are extracted for refurbishment. Effect can be mitigated with fractional replacement. 2
Contamination Control 2	Little contamination control as all cutting, disassembly, reconnecting, and reassembly is done within the torus. 0	Better because all cutting, disassembly, reconnecting, and reassembly are done outside the torus. However the corridor can be contaminated during disassembly and reassembly. 1	Minimal cutting and reassembly in torus or corridor. Contamination from segment probably controlled. 4
Applicability to Scheduled and Unscheduled Maintenance 3	Lots of disassembly to reach most distant modules. 1	Same approach on both. Some disassembly required to reach most distant modules. 2	Same approach on both. Random access to all modules. 4
Totals MAX. SCORE 80	39	46	69

Compare Transport Approaches

- Criteria stresses maintenance time and contamination control
- Minimal differences between approaches
- Selected cask enclosed as baseline approach based on safety considerations

	Sector Transport Approach		
Criteria (Importance)	**Bare Sector (Score)**	**Shrink-Wrapped Sector (Score)**	**Cask Enclosed Sector (Score)**
Time to Remove Cryoshield Door, Enclosure Port Door, and Vacuum Vessel Door Plus Transit to Hot Cell 4	Transporter removes cryoshield door, enclosure port door, and vacuum vessel door. Bare sector is a fast transit with transporter. All serial operations. 4	Removal of components and transit time should be as fast as bare sector. However time to accomplish shrink-wrap will increase the overall time. All serial operations. 3	Cask must make a trip for vacuum door and also sector. Transit time should be twice the time as bare sector. 2
Replacement Sector Reliability NA	0	0	0
Building Cost 2	Probably the smallest building size, with just enough corridor width to rotate transporter and sector. 4	Same as bare sector. 4	Slightly larger corridor width to accommodate cask length and Width. 3
Maintenance Equipment Cost 1	Transporter multi-purpose – removal of cryostat and vacuum vessel doors plus removal and transport of core sectors 4	Same transporter as bare approach. Requires shrink wrap equipment to seal opening and cover sector which is an added cost. 3	Requires transporter to remove sector. Requires mobile transporter cask to contain sector and transporter. 2
Spare Equipment Cost 1	Lowest spare equipment cost as only one type of maintenance equipment is required. 4	Transporter spares plus the shrink wrap equipment spares. 3	Transporter spares + cask spares. 2
Waste Volume (Lowered impact as the volume is minor compared to core volume) 1	Lowest waste volume, as all only one type of maintenance equipment is required. 4	Slightly higher waste than bare Approach. 3.5	Waste would include the transporter plus the cask. 2
Contamination Control (Importance increased) 4	Little to no contamination control as there is no containment barrier after the sector is removed. Likely debris contamination and gamma irradiation during transit. 0	Some control as there is a possible containment barrier after the sector is removed. Debris contamination should be controlled and gamma irradiation reduced during transit. 1	Best containment barrier to core. Best debris and gamma irradiation Protection. 4
Applicability to Scheduled and Unscheduled Maintenance NA	Lots of disassembly to reach most distant modules. 0	Same approach on both. Some disassembly required to reach most distant modules. 0	Same approach on both. Random access to all modules. 0
Totals MAXIMUM SCORE 52	36	33.5	✓ 36

Nearly Equal

Compare Frequency of Power Core Maintenance Actions

(Based on a power core lifetime of 4 FPY)

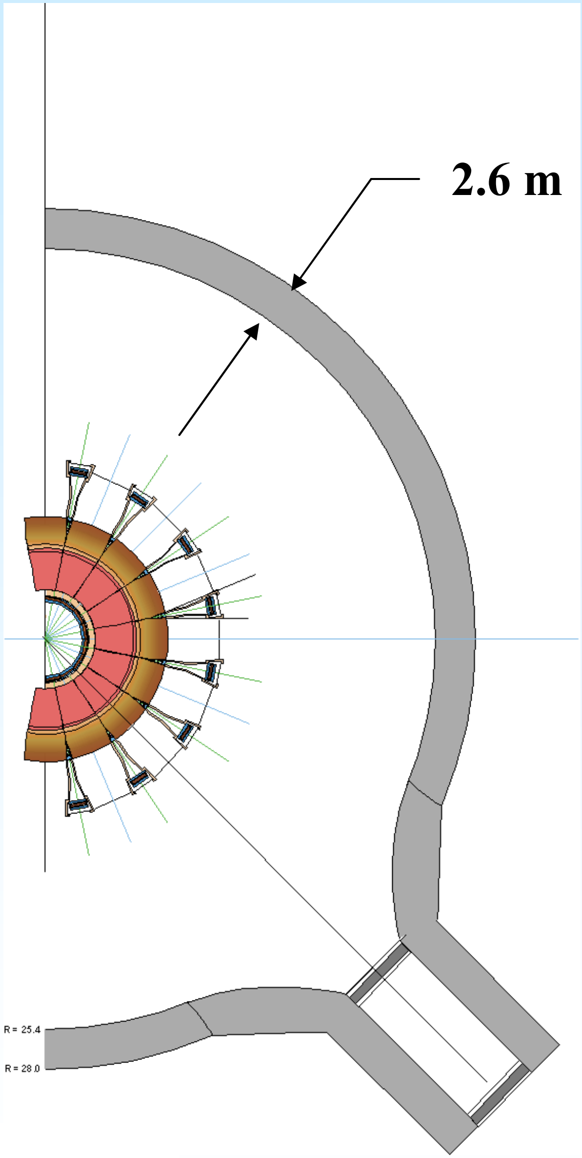
Fraction of Core Replaced	Frequency	Assessment	Recommendation
1/4 of core (4 sectors)	12 m/availability	Yearly maintenance is feasible. Cooldown and start up durations will be detrimental to availability goals. Requires minimal number of hot maintenance spares.	Too frequent.
1/3 of core (5 or 6 sectors)	16 m/availability	Very similar to annual. Fixed tasks continue to be a major factor of outage time. Requires small number of high temperature structure spares. Maintain BOP every other cycle.	#2 choice
1/2 of core (8 sectors)	24 m/availability	Probably will match up well with BOP major repair. Requires eight sets of spare hot structures.	#1 choice
Entire core (16 sectors)	48 m/availability	This four-year frequency also might be well matched with the BOP major repairs. Requires a large number of spare hot structures and maintenance equipment. Probably would yield highest availability.	#3 choice

Decisions for High Availability

- Sector Replacement Is Preferred Over In-situ Replacement of Components
- Refurbished Sectors in Hot Cell Is Better Than Corridor Maintenance
- Bare Transport Is Equal To Cask Enclosed Transport to Hot Cell, but Cask Transport Provides Better Contamination Control
- Replacement of Half of Power Core Sectors Every 24 months Is a Good Match With BOP Major Refurbishment Periods

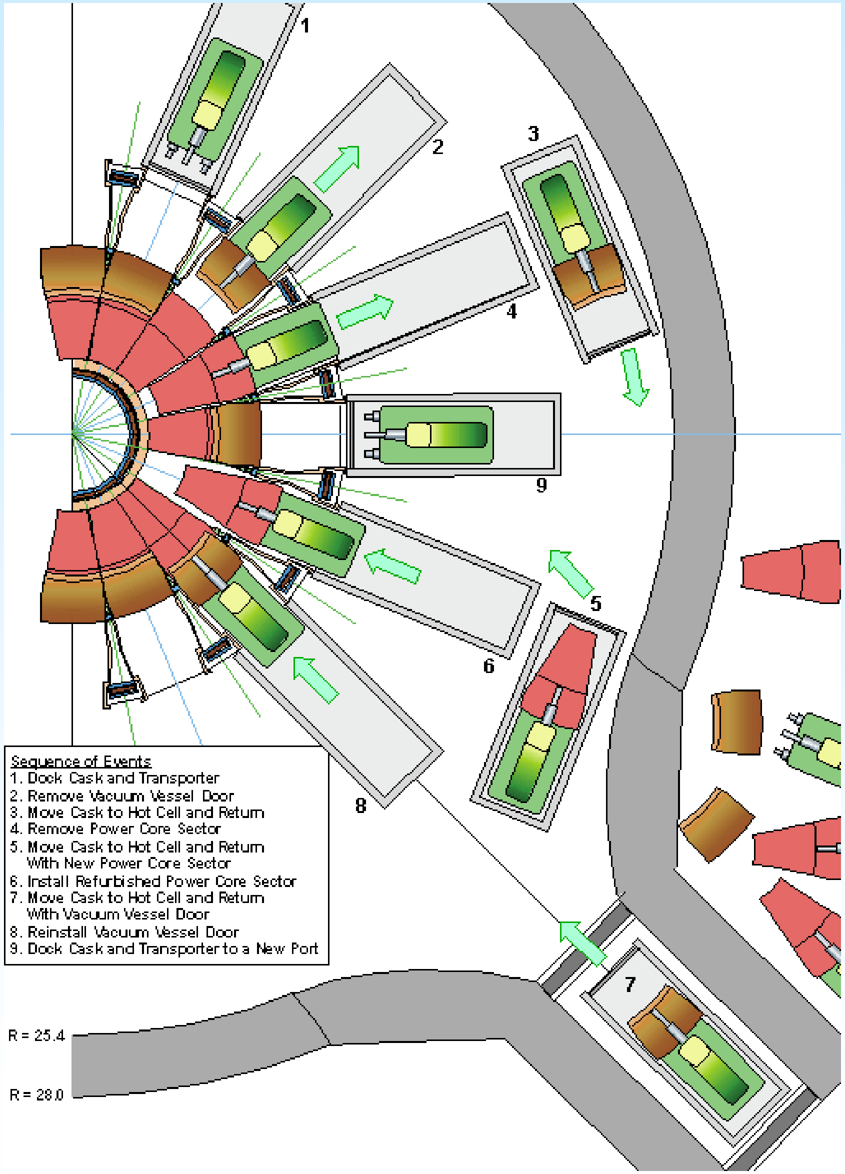
Impact of Power Core Maintenance on Building Configuration

- Bioshield (2.6-m-thick) is incorporated into building inner wall
- Building wall radius determined by transporter length + clear area access
- Extra space provided at airlock to assure that docked cask does not limit movement of other casks



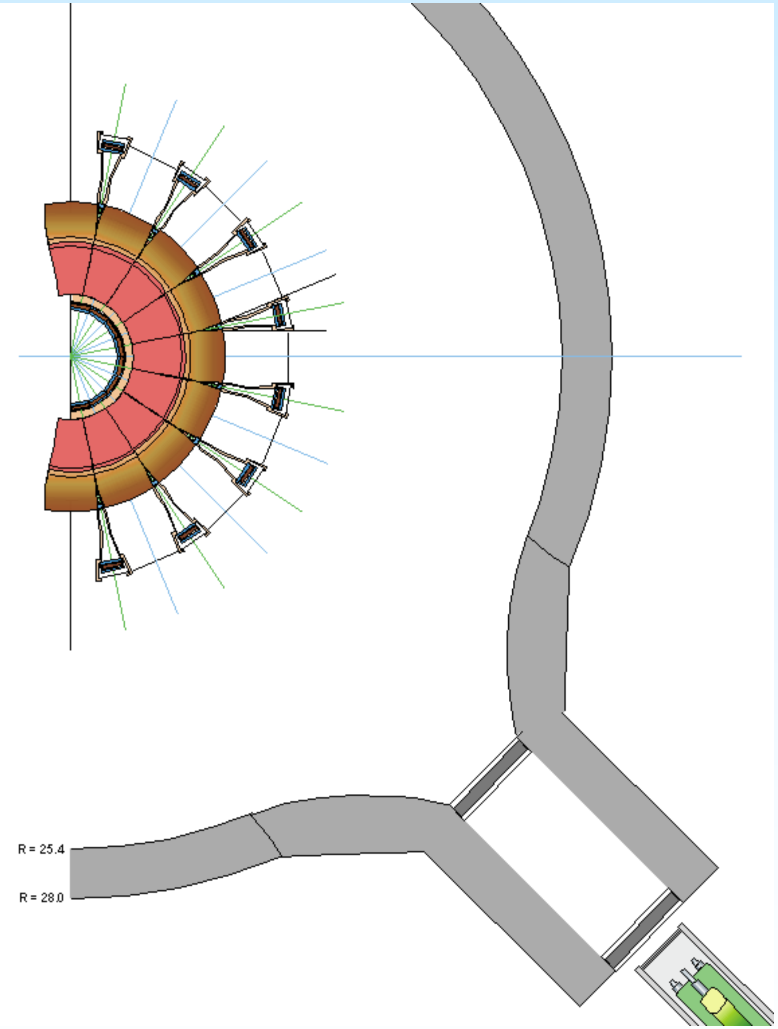
Power Core Removal Sequence

- Cask contains debris and dust
- Vacuum vessel door removed and transported to hot cell
- Core sector replaced with refurbished sector from hot cell
- Vacuum vessel door reinstalled
- Multiple casks and transporters can be used



Sequence of Events
1. Dock Cask and Transporter
2. Remove Vacuum Vessel Door
3. Move Cask to Hot Cell and Return
4. Remove Power Core Sector
5. Move Cask to Hot Cell and Return With New Power Core Sector
6. Install Refurbished Power Core Sector
7. Move Cask to Hot Cell and Return With Vacuum Vessel Door
8. Reinstall Vacuum Vessel Door
9. Dock Cask and Transporter to a New Port

Animation of Power Core Removal Sequence



(1) Remove Shield
(2) Move Shield to Storage Area
(3) Remove Port Enclosure Door
(4) Remove Vacuum Vessel Door
(5) Move VV Door to Storage Area
(6) Remove Core Sector
(7) Transport Sector in Corridor
(8) Exit Corridor Through Air Lock

Fixed Maintenance Times for Power Core

Shutdown Timeline

Maintenance Action	Duration of Serial Operations, h	Duration of Parallel Operations, h
Shutdown and preparation for maintenance		
Cooldown of systems, afterheat decay	24	
De-energize coils, keep cryogenic		2.0
Pressurize power core with inert gas		2.0
Drain coolants, fill with inert gas	6.0	
Subtotal for shutdown and preparation	30	

Dominated by cool-down of systems and core

Startup Timeline

Assumes streamlined processes for core evacuation, bake-out, and coolant fills

Maintenance Action	Duration of Serial Operations, h	Duration of Parallel Operations, h
Startup tasks		
Move transporters and casks to hot cell		0.8
Evacuate core interior	10.0	
Initiate trace or helium heating		10.0
Fill power core coolants	8.0	
Bake out (clean) power core chamber	12.0	
Checkout and power up systems	4.0	12.0
Subtotal for startup	34.0	

Repetitive Maintenance Times for Replacement of a Single Power Core Sector

- Assumes a single cask and transporter
- Defines major maintenance activities
- Assumes all removal and replacement activities are remote and automated
- Repetitive actions require less than 1.5 days

Maintenance Action	Duration of Serial Operations, h	Duration of Parallel Operations, h
Repetitive maintenance tasks		
Move cask to port and dock to port	1.0	
Open cask door and raise port isolation door	0.2	
Disengage vacuum vessel door	3.6	
Move transporter forward to engage vacuum door		0.2
Remove weld around vacuum door		2.0
Disconnect VS coil electrical and I&C connections		0.2
Disconnect vacuum door water coolant connections		1.0
Disengage door to prepare for removal		0.2
Remove vacuum vessel door into cask	1.0	
Lower isolation and transporter doors and undock cask	0.2	
Move to hot cell, unload vacuum door, return, and dock	2.5	
Open cask door and raise port isolation door	0.2	
Disengage power core sector	3.2	
Move transporter forward to engage power core sector		0.2
Disconnect I&C connections		0.2
Disconnect five coax LiPb coolant connections		2.0
Disengage mechanical supports		0.6
Disengage sector to prepare for removal		0.2
Remove power core sector into cask	1.0	
Lower isolation and transporter doors and undock cask	0.2	
Move to hot cell, unload sector, load new sector, return, and dock	3.0	
Open cask door and raise port isolation door	0.2	
Move power core sector from cask into near-final core position	1.0	
Install power core sector	7.7	
Align sector and finalize position		1.0
Engage mechanical supports		1.0
Connect five coax LiPb coolant connections		5.0
Connect I&C connections		0.5
Disengage transporter and move back inside cask		0.2
Lower isolation and transporter doors and undock cask	0.2	
Move to hot cell, load vacuum door, return, and dock	2.5	
Open cask door and raise port isolation door	0.2	
Move vacuum door from cask into near-final position	1.0	
Install vacuum door	5.7	
Align vacuum door and finalize position		1.0
Prep, weld, and inspect door perimeter		3.0
Connect door water coolant connections		1.0
Connect VS coil and I&C connections		0.5
Disengage transporter and move back inside cask		0.2
Lower isolation and transporter doors and undock cask	0.2	
Subtotal for repetitive tasks	34.8	

Maintenance Times for Replacing Different Number of Sectors

One cask and one transporter

Optimum Number Of Sectors

Number of Sectors Replaced	Shutdown and Startup Time, h	Time to Replace Sectors, h	Maintenance Action Duration, h	Maintenance Actions Over Four FPYs, h	Availability for Scheduled Core Outages	Equivalent Days/Year
4	64	139.2	203.2	812.8	0.9773	8.47
5	64	174	238	748.8	0.9791	7.80
6	64	208.8	272.8	Incl. in Above	-	-
8	**64**	**278.4**	**342.4**	**684.8**	**0.9808**	**7.13**
16	64	556.8	620.8	620.8	0.9826	6.47

30 h + 34 h

34.8 h x # Sectors

The equivalent maintenance days per operating year (FPY) will be used to determine if this maintenance scheme can achieve the necessary plant availability.

Multiple Sets of Casks and Transporters Can Improve Times

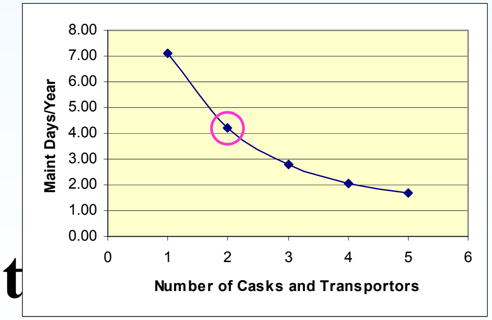
Equivalent Annual Maintenance Times for Multiple Sets

Optimum Number Of Sectors

No. of Sectors Replaced	Number of Maintenance Casks and Transporters				
	1	**2**	4	8	16
4	8.47	**5.57**	4.12	3.39	3.03
5 & 6	7.80	4.90	3.45	2.73	2.36
8	**7.13**	**4.23***	**2.78**	**2.06**	**1.70**
16	6.47	**3.57**	2.12	1.39	1.03

From prior slide

- **At least two sets should be used for redundancy (4.23 equivalent d/y)**
- **Availability improvements with more casks and transporters probably may not justify added cost (Retain as future option to enhance availability)**



Need to Establish Availability Goals Consistent with Energy Community

- All reasonably new electricity-generating plants are now operating in the 85-90% class
- In 25-40 years, state-of-the-art will be 90+%
- For Availability goals, separate power plant into three parts:
  - Balance of Plant (buildings, turbine-generators, electric plant, and miscellaneous equipment)
  - Reactor Plant Equipment (main heat transport, auxiliary cooling, radioactive waste, and I&C)
  - Power Core

Allocate Availability Goals

System Group	Avail Goal	Annual Days
– BOP (Balance of Plant)	0.975	9.37
– RPE (Reactor Plant Equip)	0.975	9.37
– Power Core	0.947	20.56
Total Power Plant	**0.900**	**~ 39.3**

The Annual Maintenance Days shown above represent both scheduled and unscheduled time. Assume equal times for both actions.

Thus, the Power Core must have ≤ 20.56 days of annual maintenance to achieve a plant availability goal of 0.90

Power Plant Maintenance Times

- **Allowable power core scheduled time is 10.28 d/FPY (1/2 of 20.56 d/FPY total power core goal)**
- **Two casks and two transporters can exchange 1/2 the core in 203.3 h (8.47 d) every other year**
- **Total power core replacement requires 16.93 d or 4.23 d/FPY (annual basis)**
- **This leaves an allowance of 10.28 d/FPY - 4.23 d/FPY and 6.05 d/FPY for other scheduled maintenance of other power core systems that are not maintained during the bi-annual replacement period.**

The ARIES-AT Power Plant Should Be Able To Achieve 90% Availability

System Group Maintenance	Maintenance Days/FPY	System Availability
Power Core, Major, Scheduled	4.23	0.989
Power Core, Minor, Scheduled	6.05	0.984
Power Core, Unscheduled	10.28	0.973
RPE, Scheduled and Unscheduled	9.37	0.975
BOP, Scheduled and Unscheduled	9.37	0.975
Total		0.900

Summary of Maintainability Approach and Availability Analysis

- Approach addresses the need to quickly accomplish remote maintenance in a safe and responsible manner
- Reasonable timelines are postulated for a highly automated maintenance system
- Power core availability goals should be attainable with a margin