Overview of ARIES Engineering Activities

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ARIES Peer Review

17 August 2000

Part 1. **Engineering figures of merit, concept improvement and innovation**

Part 2. **Highlights of lessons learned**

Part 3. **Impacts and interactions**

The ARIES Engineering Activity is a National Effort

UCSD	Power core engineering, CAD, H&CD systems, integration
UW	Neutronics, shielding, activation & waste, engineering design
ANL	Materials, blanket engineering, power conversion, tritium
MIT	Magnet systems
PPPL	TF magnets
Boeing	Manufacturing, RAMI, design integration
INEEL	Safety and environment

Part 1.

Engineering figures of merit,
concept improvement & innovation

"Progress toward an attractive and
credible fusion power plant"

Utility Requirements Translate into Specific Engineering Goals

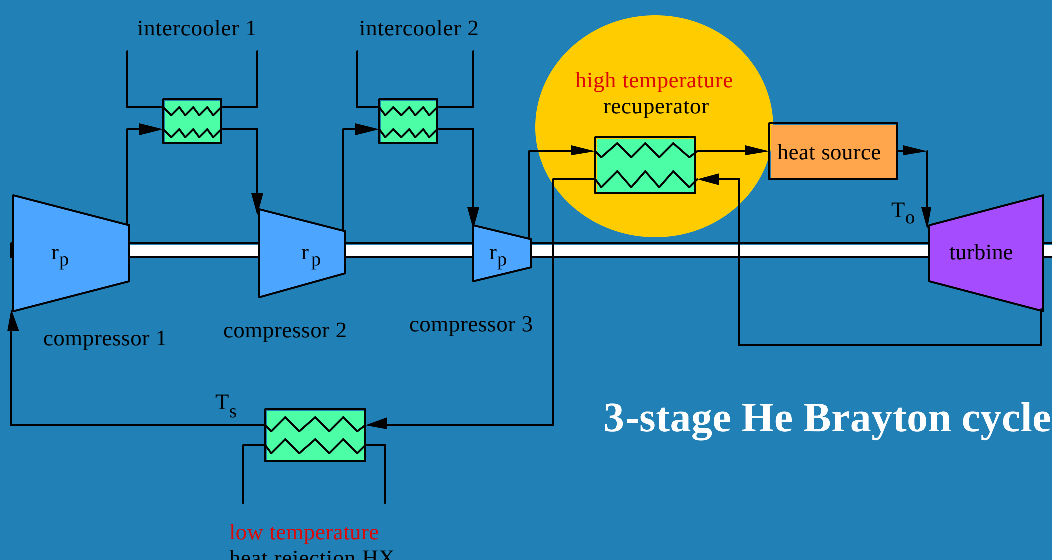
- Capital Cost
  - high conversion efficiency
  - low raw material and fabrication costs
  - low cost of expendable components
- Availability
  - power core design allowing rapid maintenance
  - design features enabling high reliability
- Safety and Waste

Higher efficiency has been sought to reduce the cost of the entire plant

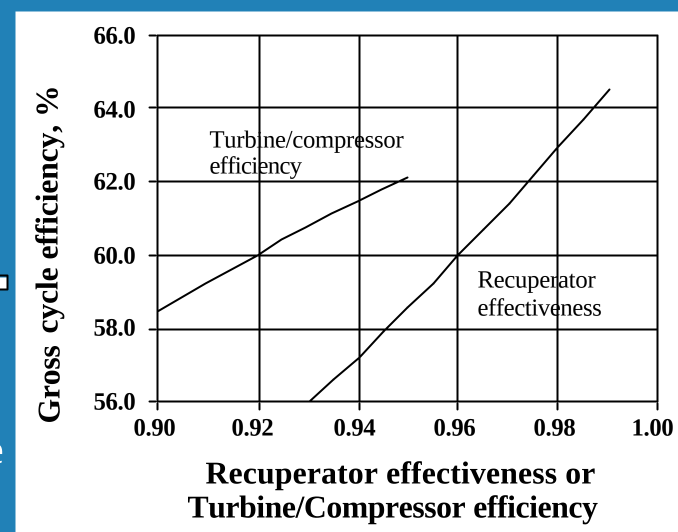
$$COE = \frac{\text{Annualized Capital Cost} + \text{Yearly Operating Cost}}{\text{Net Power x Plant Availability}}$$

- Conventional steam cycle 35% steel/water
- Supercritical Rankine 45% Li/V
- Low-temperature Brayton * >45% advanced FS/PbLi/He
- High-temperature Brayton * 60% SiC/He

*collaborated w/FZK,GA



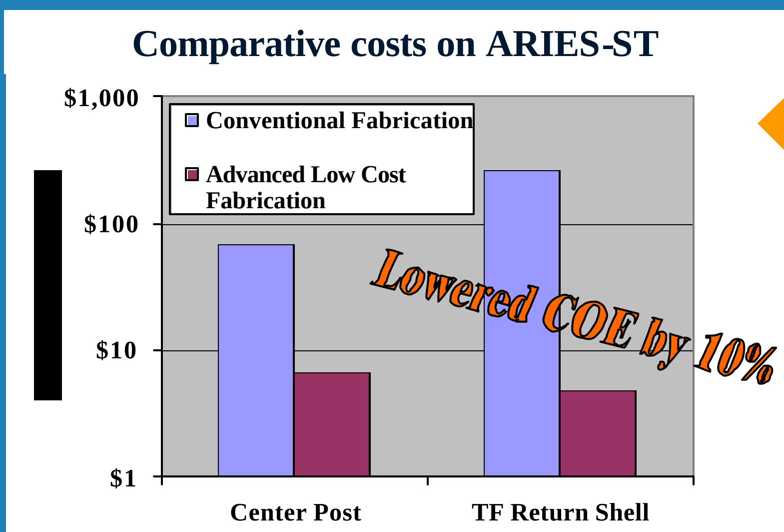
3-stage He Brayton cycle



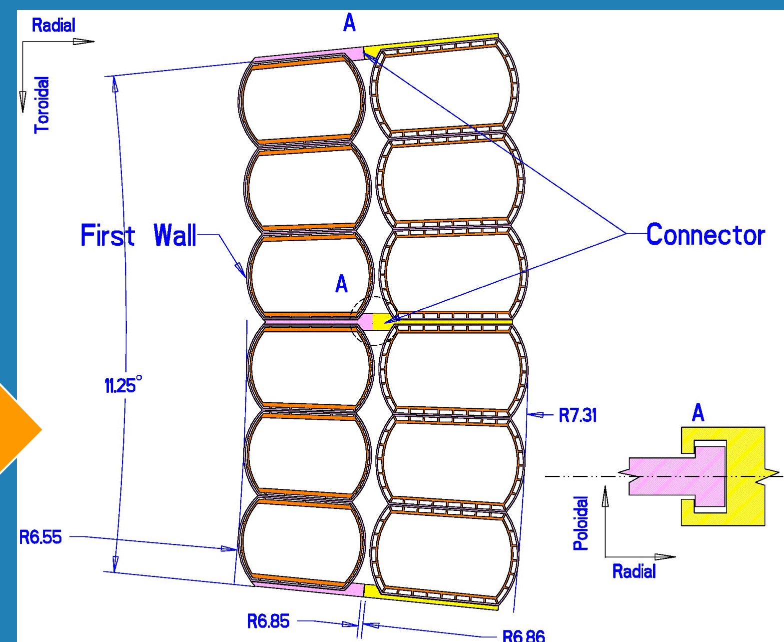
Importance of component efficiencies

A pathway to acceptable component costs has been established

- Low material unit cost — *e.g.*, shield filler ($400 → 200M in -RS)
- Reduced radial build — *e.g.*, optimized shield design
- Modern fabrication technology — *e.g.*, laser-forming of metals, HTSC

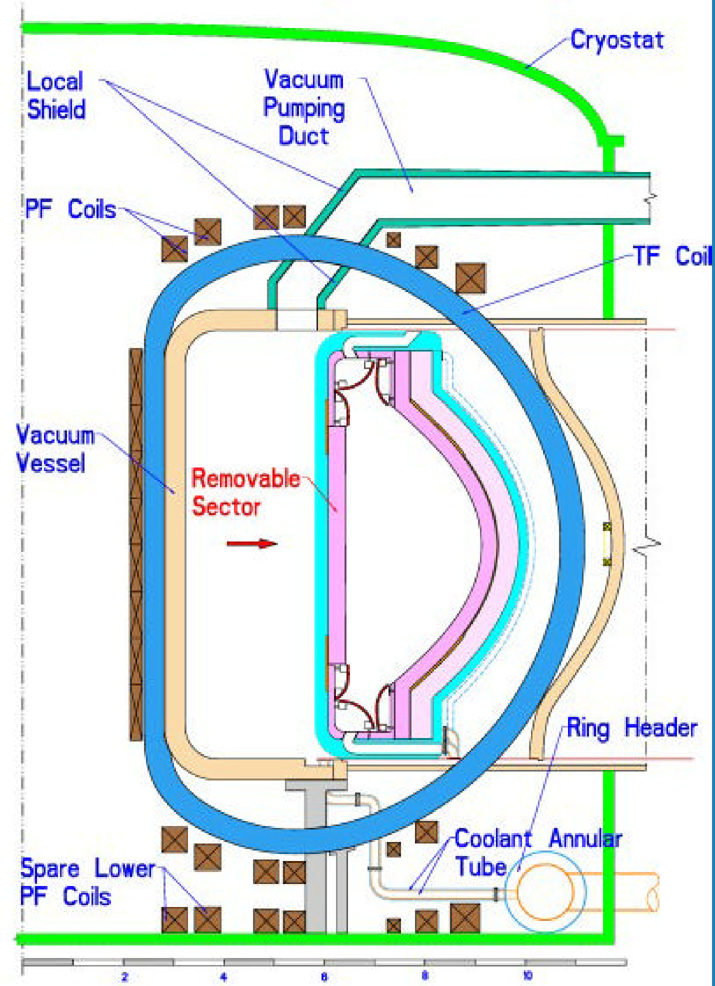


- Low FW/blanket replacement cost
  - radial segmentation
  - simplified fabrication
  - self-cooled designs w/ 10-20% structure



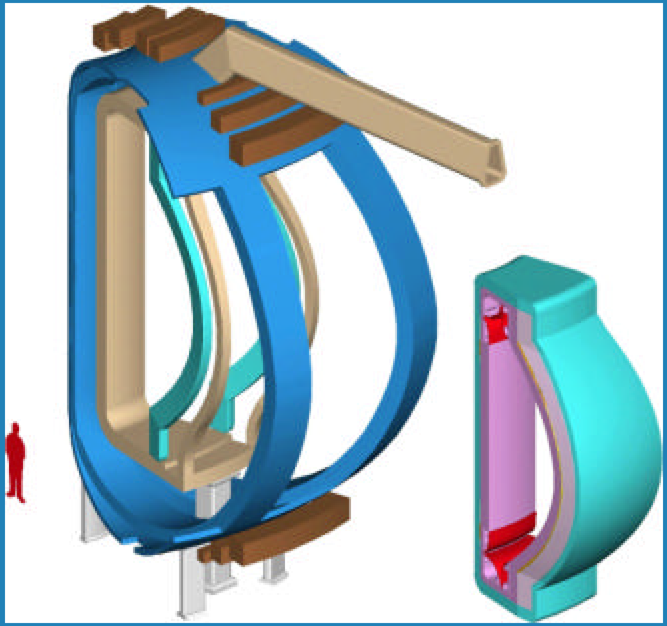
ARIES-AT blanket midplane cross section

Modular sector maintenance enables high availability



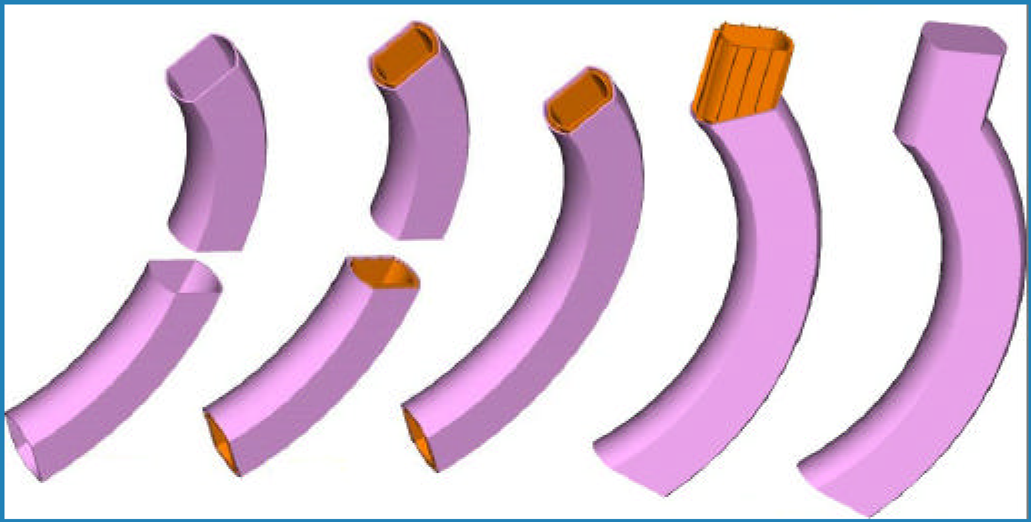
ARIES-AT elevation view

- Full sectors removed horizontally on rails
- Transport through maintenance corridors to hot cells
- Estimated maintenance time < 4 weeks



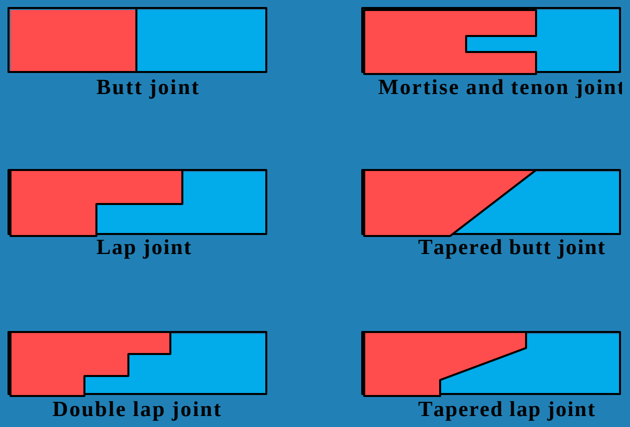
Reliability is achieved through sound design principles and testing

- Perception of poor availability is based on water-cooled steel, ceramic breeder blanket *(Bünde, Perkins, Abdou)*
  - 220 km of pipe
  - 37,000 butt welds
  - 5 km of longitudinal welds



ARIES-AT blanket construction is simple and robust

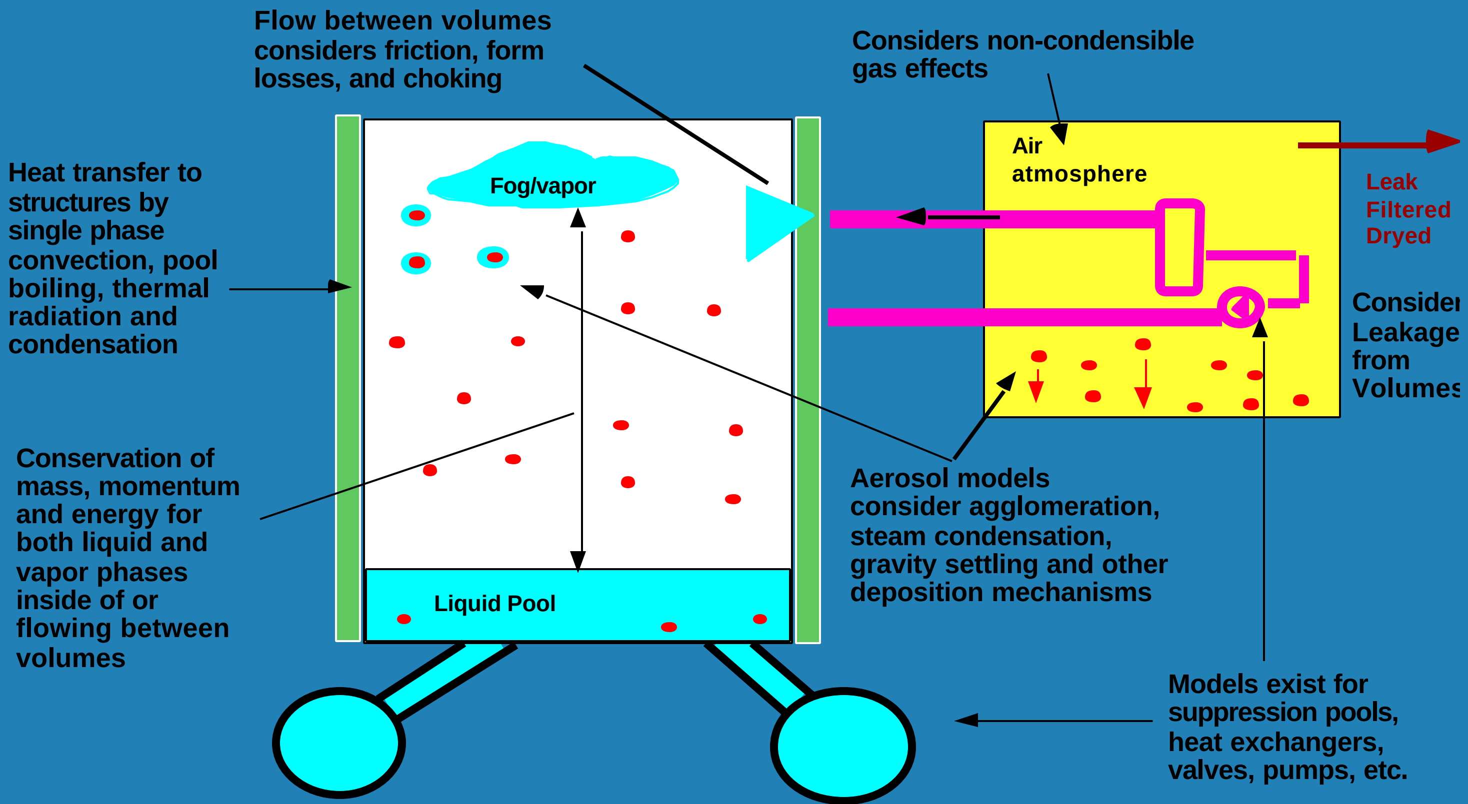
- Low failure rate is possible through:
  - Simple design and fabrication
  - Wide operating margins (T, p, σ)
  - Failure tolerance & redundancy
- ARIES-AT
  - 3680 m of pipe, 1440 braze joints
  - <1500 m braze length to headers (173 m exposed to plasma)



Safety and environmental requirements were developed & applied to all designs

REQUIREMENTS	IMPACTS
No public evacuation required in worst case accidents • 1 rem dose to most exposed individual • Broad range of accidents must be considered to cover entire risk spectrum	• Smart selection of materials (*e.g.,* no C, Be) • Broadened spectrum of accidents considered beyond traditional loss of coolant and loss of flow events • Considered bypass events, loss of vacuum and other scenarios that have been shown in ITER to have greater radiological impact
Waste generated from fusion power plants should not pose a burden to future generations • Consider recycle/reuse and clearing criteria in addition to low level waste criteria to characterize waste • Consider both volume and hazard	• Consideration given to minimizing both volume and hazard in designs • All waste can be disposed of as low level waste. Examining recycle/reuse potential of activated components. • Optimized radial build to minimize component volumes • Maintenance strategy to reduce volume

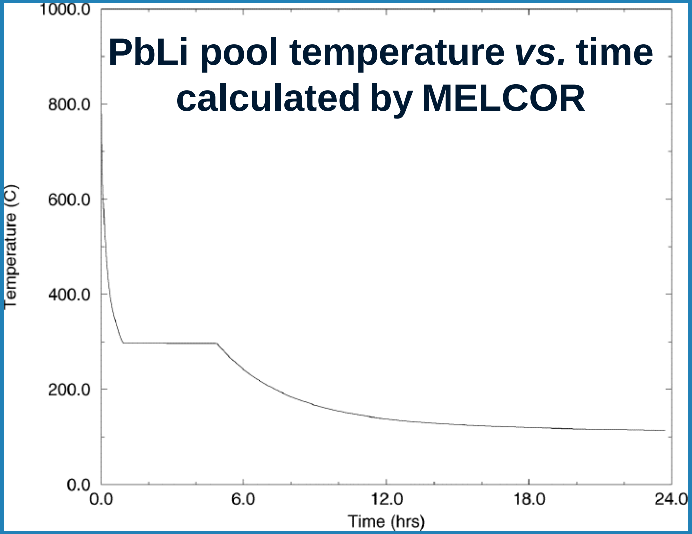
Safety is demonstrated through detailed analysis

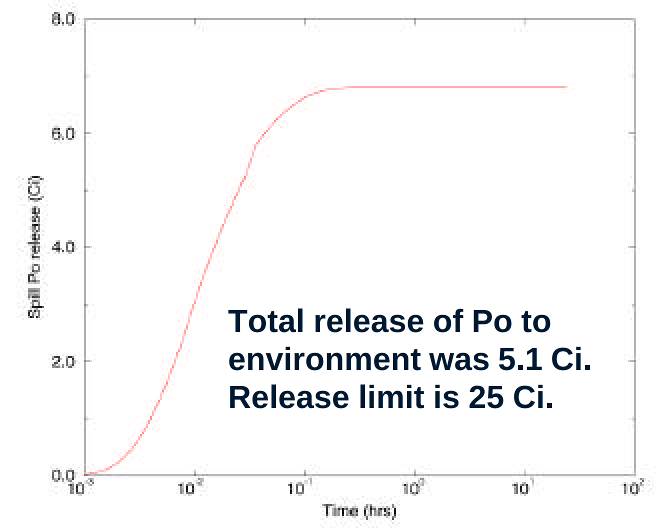


MELCOR is a fully integrated, engineering-level computer code that models the progression of accidents in light water reactor (LWR) nuclear power plants, including reactor cooling system and containment fluid flow, heat transfer, and aerosol transport. (Developed by SNLA)

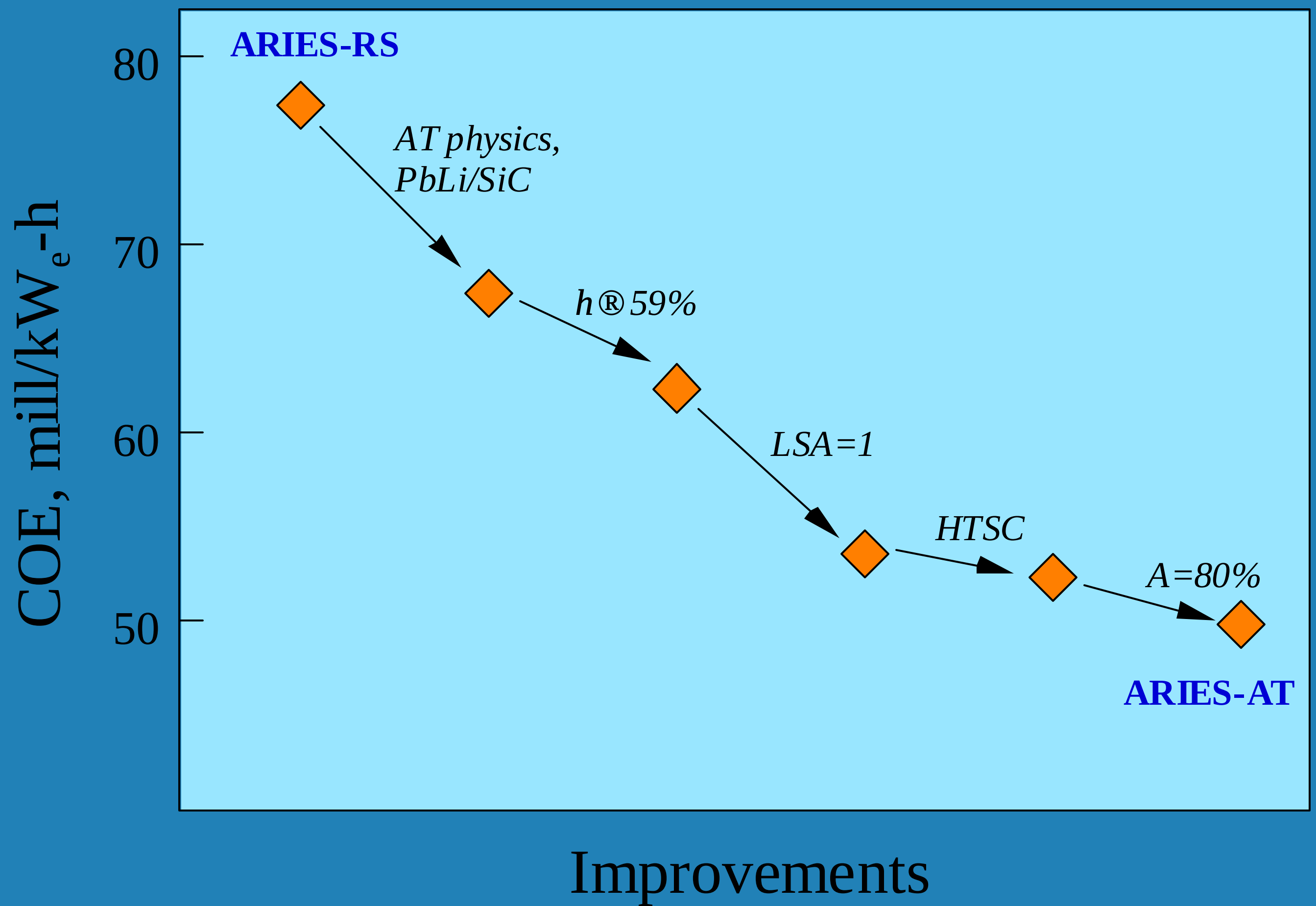
Results for ex-vessel LOCA into the area below the maintenance corridor

- The MELCOR model included all in-vessel fluid components plus the ring header and primary cooling system. MHD pressure drop was included.
- The total spill was about 110 m^3 of the total 150 m^3 in one of four loops.
- The initial Po concentration was 4 Ci/m^3. Total inventory in the loop is 600 Ci. Release of Po based on conservative extrapolation of data.
- The ventilation system provides 1 volume exchange per hour, which exhausts directly to the stack. The leak rate is one volume per day at 400 Pa overpressure.





Engineering advances play a major role in improving the attractiveness of fusion



Attacking individual challenges leads to real progress

Part 2.

Highlights of lessons learned

through design, analysis and assessment

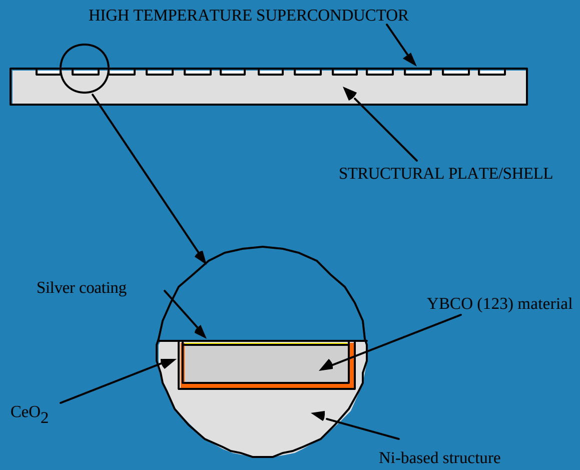
- Improvements to magnet performance and cost
- Power handling capabilities
- Inboard shield on a spherical torus

- Ability to operate Brayton cycle at moderate temperature
- Systemwide impacts of high coolant temperature
- Enhanced heat transfer in He using porous media
- Engineering of rf launchers for power plants
- "Ins and outs" of single-piece maintenance
- *etc.*, *etc.*, ...

Opportunities for improved magnet performance and cost

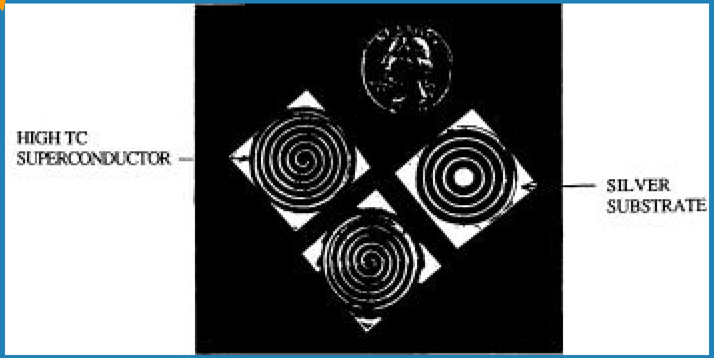
LTS: Improved Nb_3Sn, manufacturing

- Largest cost of LTS magnets is strands and manufacturing:
  - Innovations in **LTS** strands (performance, Cu laced, thin strands; 6x cost reduction possible) and manufacturing (react and wind with SS shell-like structure; 2x cost reduction possible) could decrease magnet costs by a factor of >4.



HTS: epitaxial YBCO

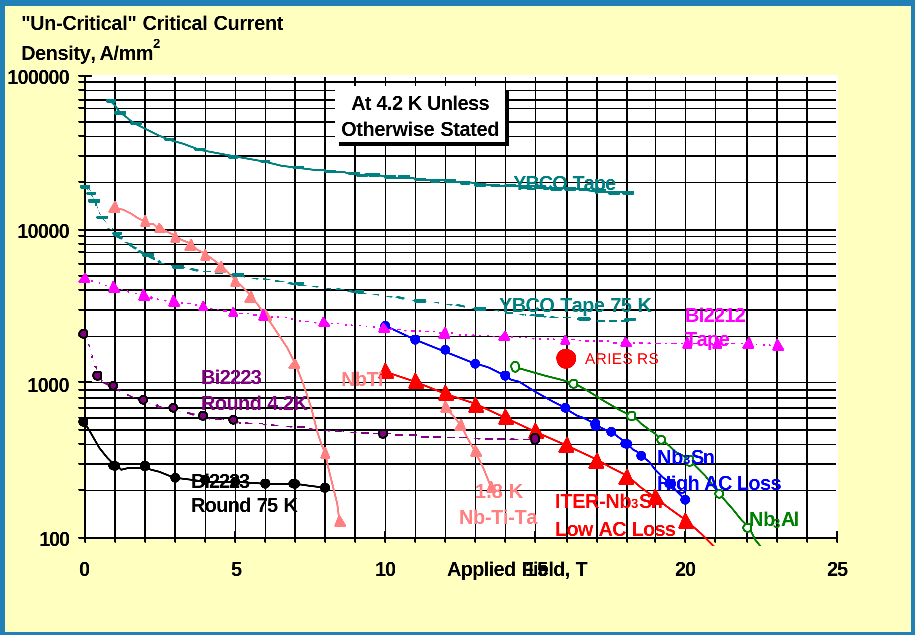
- Inexpensive manufacture would consist on layering **HTS** on structural shells with minimal winding!
  - If HTS at $1000/kg, and cost of structure is $40/kg, then cost of magnet could be ~$50/kg
  - Presently, cost of HTS is >10 x higher than LTS.

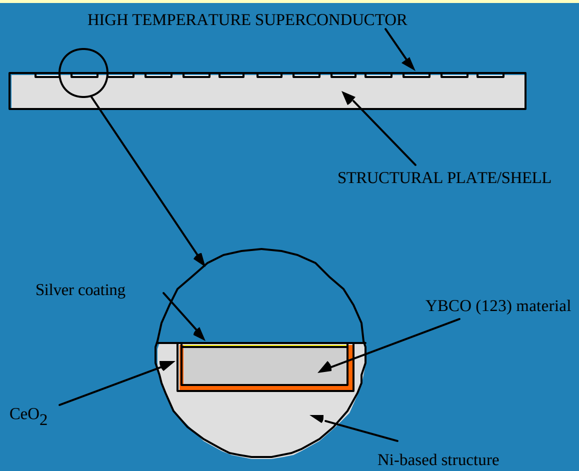


High temperature superconductors were reassessed in ARIES-AT

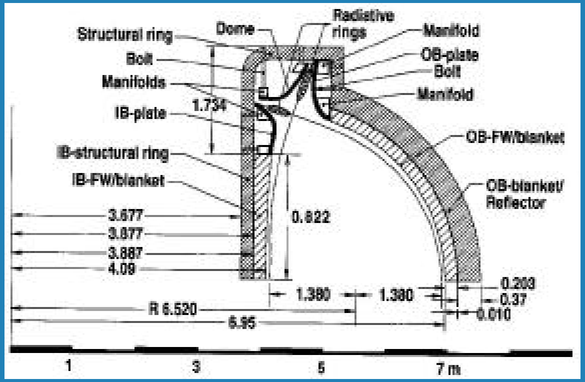
- HTS does not offer significant superconducting property advantages over low temperature superconductors due to the low field and low overall current density in ARIES-AT

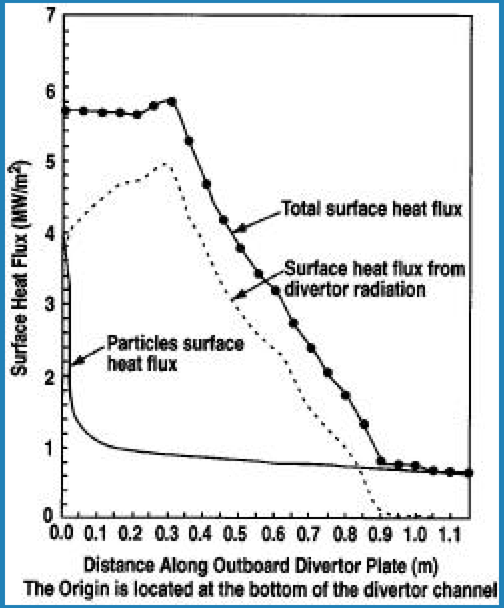
- HTS does offer **operational advantages**:
  - Higher temperature operation (even 77K), or dry magnets
  - Wide tapes deposited directly on the structure (less chance of energy dissipating events)
  - Reduced magnet protection concerns
- and **cost advantages**:
  - Cost of magnet could be significantly cheaper because of ease of fabrication using advanced manufacturing techniques



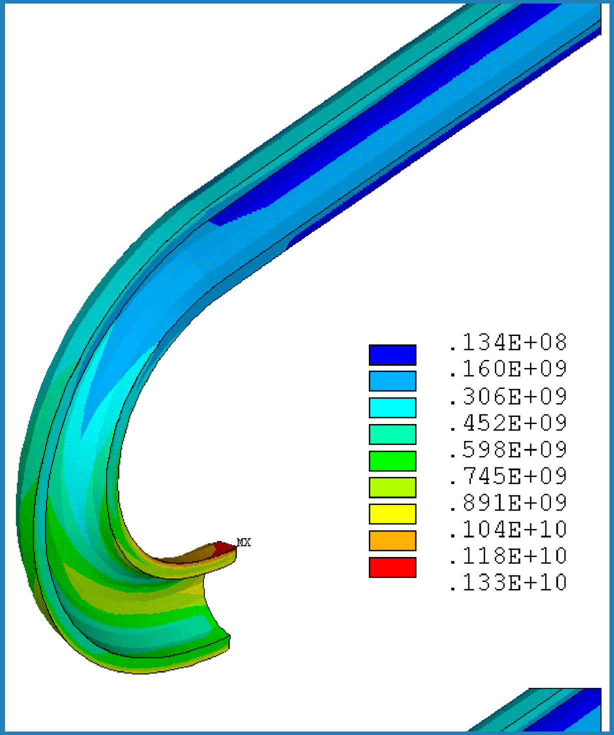


Power handling ability of in-vessel components was studied extensively





- Engineering limits of first wall, divertor, blanket
- Ferritic steel, vanadium alloy, SiC/SiC systems



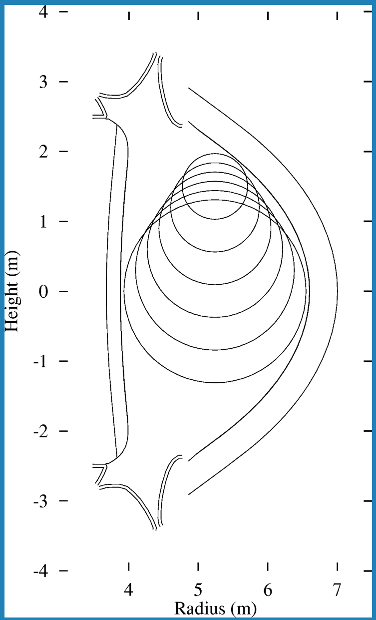
Heat flux along the ARIES-RS radiative divertor

Thermal + pressure stresses in the PMHX divertor

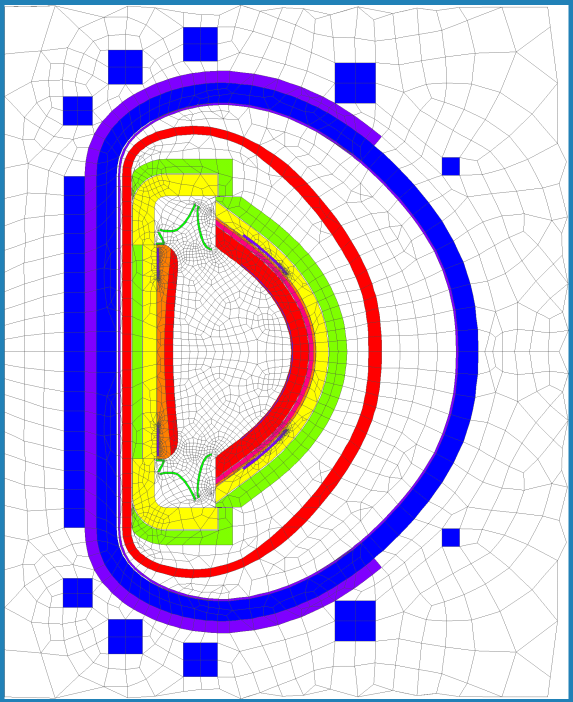
Disruptions are treated as rare but important events

- < 1 major disruption per year
- 90% β_{max} to mimimize frequency
- Thermal and E&M analysis are performed to establish survivability

- ARIES-I: 110 µm erosion of W *without vapor shielding*
- ARIES-RS: EM loads are manageable with proper design



Plasma displacement and quench model

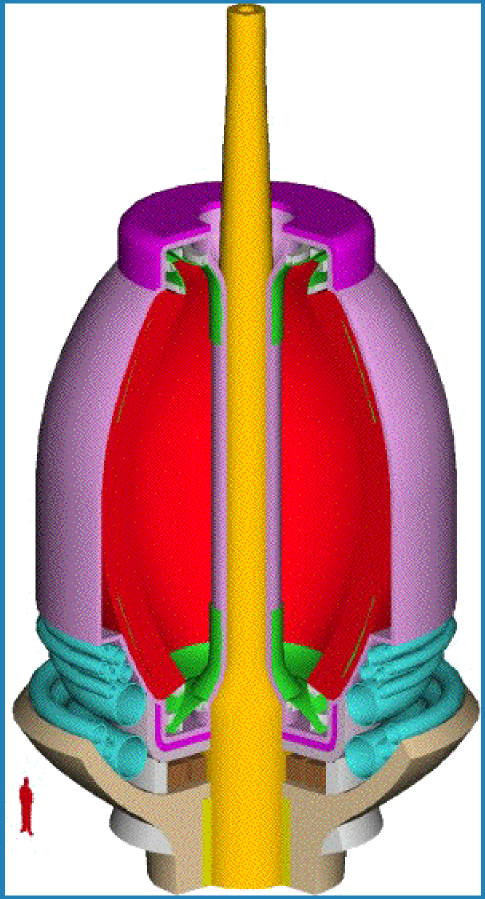


2D FEM model of currents

Maximum magnetic pressure and stress in ARIES-RS

Case	I_{peak} (MA)	P_{max} (MPa)	s_{max} (MPa)
10 ms quench	4.6@10 ms	0.66@10 ms	9.3@10 ms
100 ms quench w/drift	4.9@100 ms	0.66@100 ms	9.2@100 ms
2500 ms drift then 10 ms quench	3.6@2510 ms	0.74@10 ms	10@2510 ms

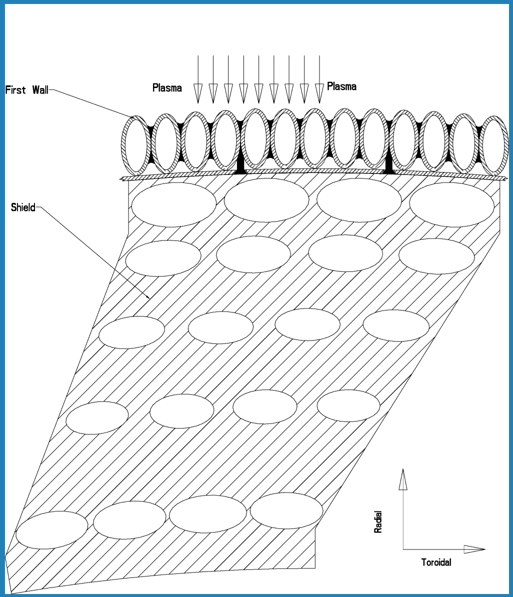
Inboard shield on a spherical torus



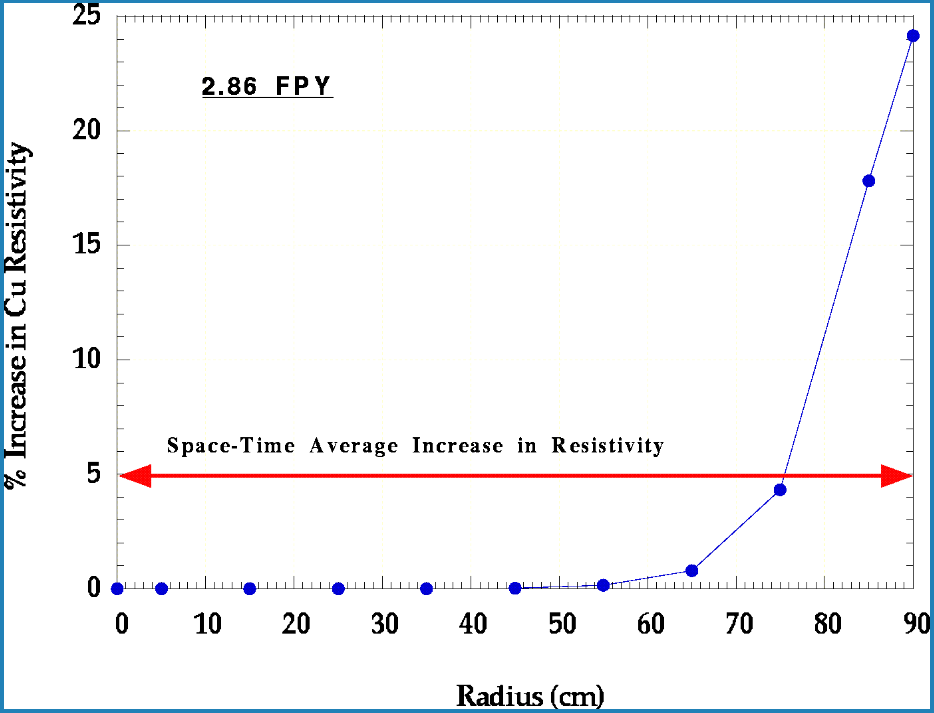
ARIES-ST power core replacement unit

- **Previous perception:** Any inboard (centerpost) shielding will lead to higher Joule losses and larger/more expensive ST power plants.
- **Conclusions of ARIES study:** A thin (20 cm) shield actually improves the system performance .
  - Reduces nuclear heating in the centerpost and allows for a higher conductor packing fraction
  - Reduces the increase in electrical resistivity due to neutron-induced transmutation
  - Improves the power balance by recovering high-grade heat from the shield
  - Allows the centerpost to meet the low-level waste disposal requirement with a lifetime similar to the first wall (more frequent replacement of the centerpost is not required).

The inboard shield protects the centerpost & minimizes waste heat



He-cooled ferritic steel inboard shield



Increase in Cu resistivity due to transmutations (20 cm shield)

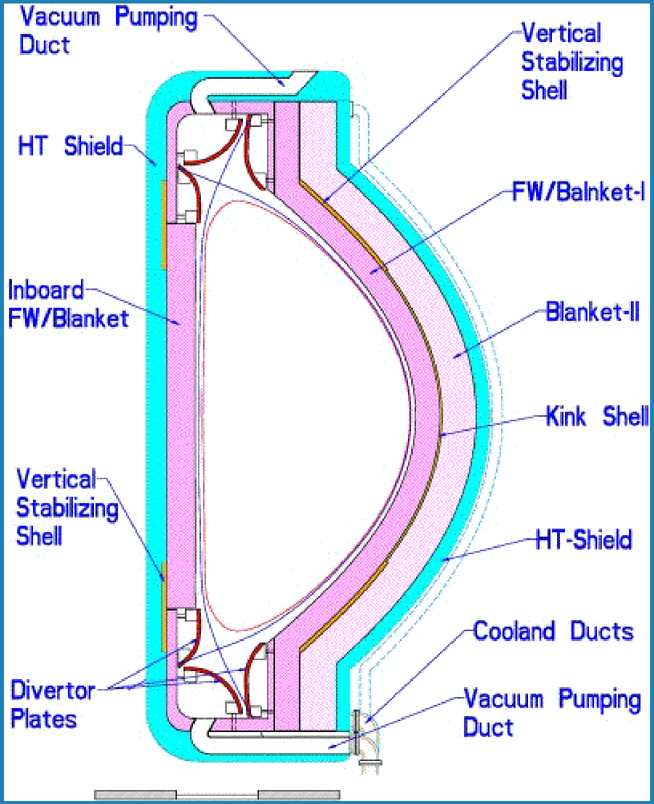
Surface heating	125 MW
Nuclear heating	285 MW
Structure/coolant	Steel/12 MPa He
He Inlet Temp.	300^{o}C
He Outlet Temp.	510^{o}C

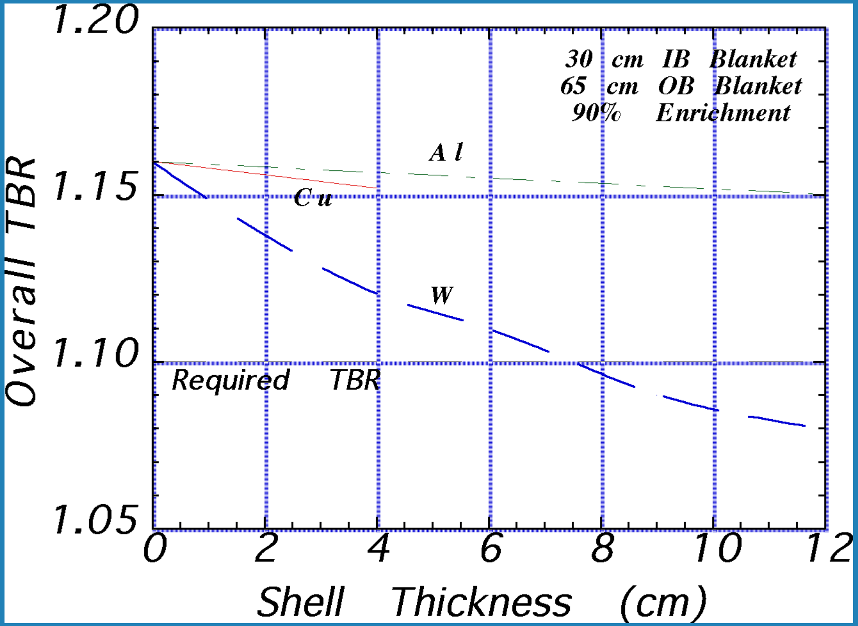
Part 3.

Impacts and Interactions

ARIES engineering has strong connections to national & international programs, both in and out of fusion

Integration of physics & engineering: *Vertical and kink stability*



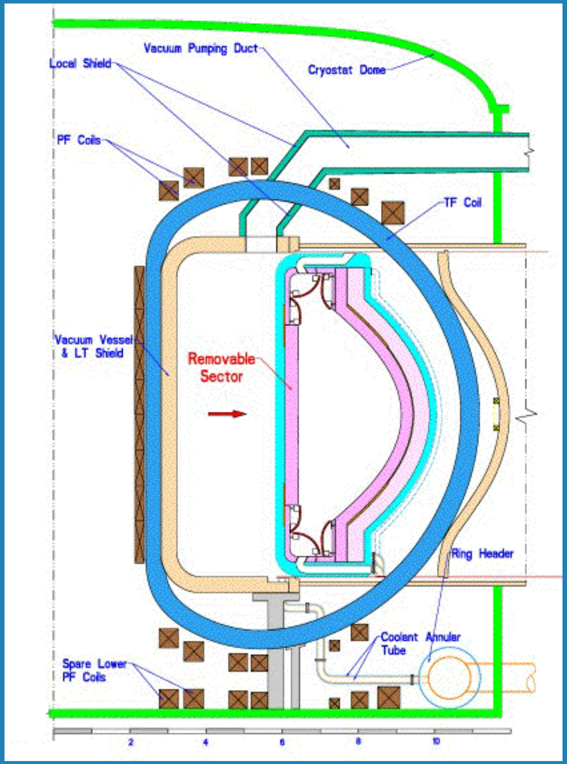


TBR is degraded by tungsten in the blanket

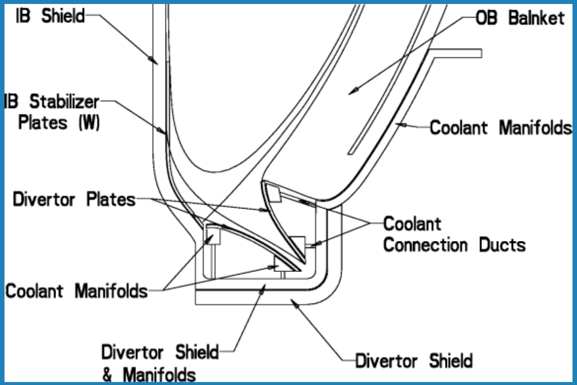
ARIES-AT vertical and kink shells are essential for high-beta operation, and required neutronic and thermomechanical integration as well as development of electrical joints.

Integration of physics & engineering: *Accomodation of high k and d*

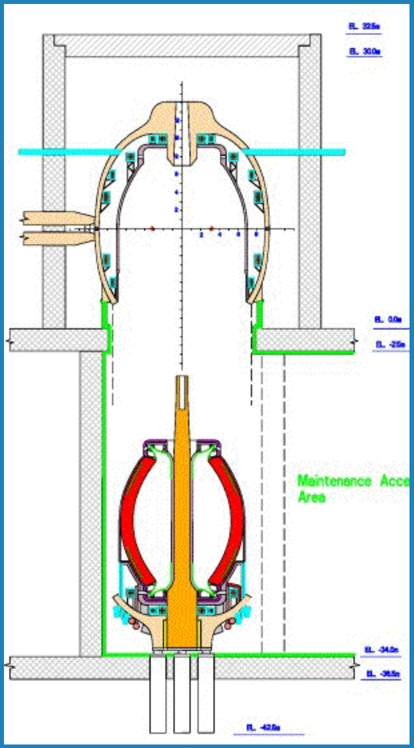
Impacts on configuration and maintenance, TF and PF coils, divertor geometry and power flows



ARIES-AT elevation view



ARIES-ST divertor



ARIES-ST maintenance

Interaction with the materials community has been especially strong

Feedback from design studies to materials program

(Minimum/goal performance based on integrated design & parametric studies)

- Activation guidance on alloy and impurity content (*e.g.*, Nb, Mo, Ag, *etc*.)
- TBR constraints on elements (*e.g.*, W).
- Neutron damage /transmutation rates (He, H).
- Reasonable heat flux and stress limits.
- Maximum and minimum temperature goals.
- Cost and lifetime goals.

Feedback from materials program to design studies

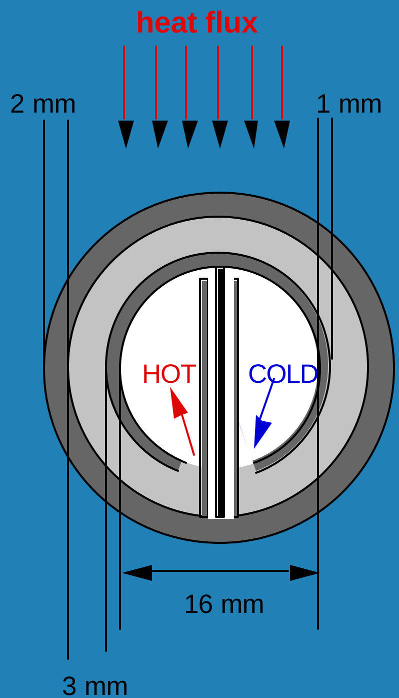
(Material performance characteristics)

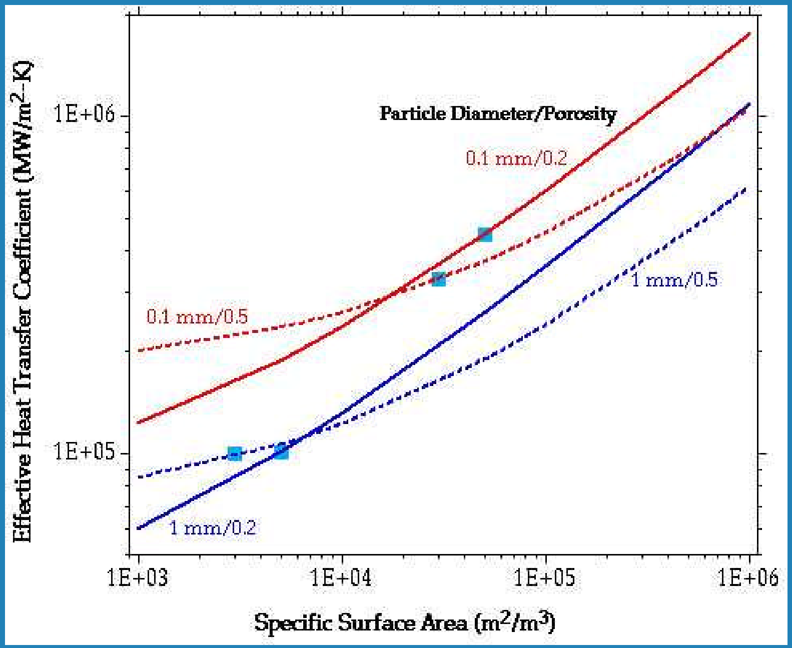
- Thermophysical and material properties input.
- Alloy constituents and impurity control:
  cost, practicality, effects on properties.
- Reweldability limits.
- Achievable T_{min}
  Ductility, fracture, influence of H/He,...,
- Achievable T_{max}
  Compatibility, strength, swelling,...,
- Guidance on reasonable extrapolations.

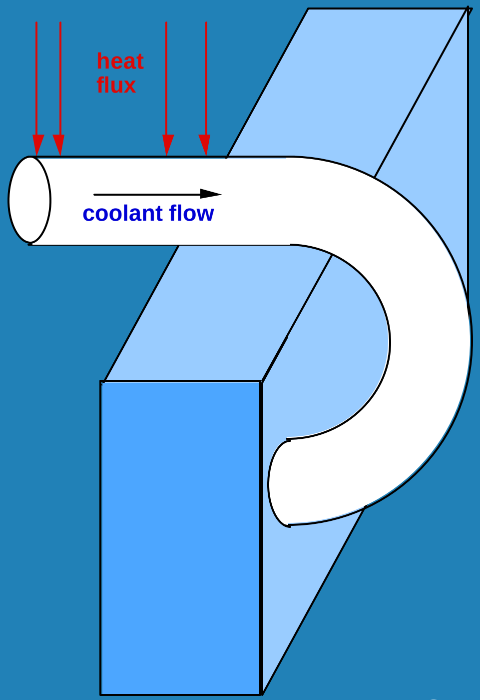
Community Interactions:
Starlite Materials Town Meeting, 10 May 1995, ANL.
ARIES Town Meeting on Design with Brittle Materials, 19 June 1997, UW.
Intl. Town Meeting on SiC/SiC, 18-19 Jan. 2000, ORNL.
Community liaison (M. Billone).

Work on high heat flux components is well coordinated with R&D

- Emphasis on tungsten plasma-interactive material
- High-temperature He coolant fully incorporated into power conversion
- Exploration of advanced heat removal with porous media
- Adoption of PbLi coolant with SiC channels (MHD issues)







Porous metal heat exchanger enables high heat transfer coefficient with He

The ARIES program has had a major impact on fusion technology research

Technology Result	Impact on the Program
• Introduced SiC composites as a high-performance fusion material.	⇒ Large world-wide research activity on SiC composite materials.
• Explored gas injection and impurity radiation to reduce heat load in the divertors.	⇒ Experiments in linear plasma machine and later in large tokamaks.
• Developed several high-performance innovative blanket concepts.	⇒ ARIES-ST dual coolant, ARIES-AT SiC/SiC blankets are candidates in EU study.
• Innovative superconducting magnet designs using plates and a structural cap (later used in ITER).	⇒ Current goals of magnet R&D program.

The ARIES program has had a major impact on fusion technology research

Technology Result	Impact on the Program
• Demonstrated benefits of RF systems for current drive, including launchers (*e.g.*, folded wave-guides).	⇒ Spurred interest in RF current drive expts (*e.g.*, fast-wave current drive in DIII-D).
• Introduction of advanced manufacturing techniques, reducing unit costs of components dramatically.	⇒ Application in next-generation experiments.
• Established the tradeoffs and advantages of inboard shielding on a ST power plant.	⇒ International consensus on the importance of inboard shielding.
• Emphasis on safety & environmental aspects of fusion.	⇒ Influence on DOE Safety standard, impacts on fusion materials and chamber research.