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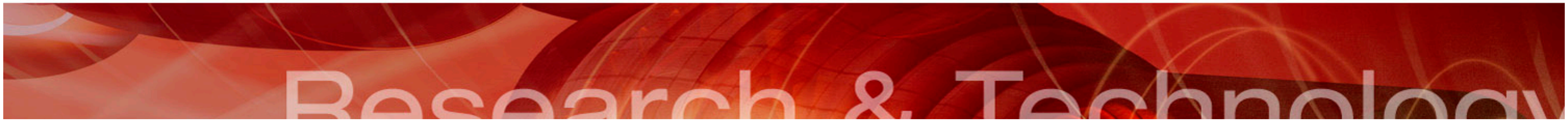

# Nuclear Fusion Power Plant Reliability Processes and Application to ARIES ACT He-cooled W-alloy Divertor Concept – Pt 2

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James B. Robinson: Reliability, Maintainability, and Testability; BCA
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# Divertor Reliability – M & P View



- Defining a Fusion RAMI Process
  - Aerospace RAMI Background
  - Adaptation to Fusion
- **Process Demonstration on a Reactor Divertor**
  - **Process for Divertor**
  - **Reliability Issues**
  - **Results**
- Conclusion

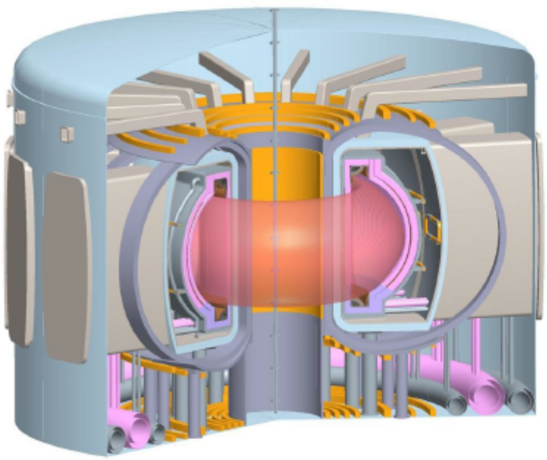
# Divertor Review Outline



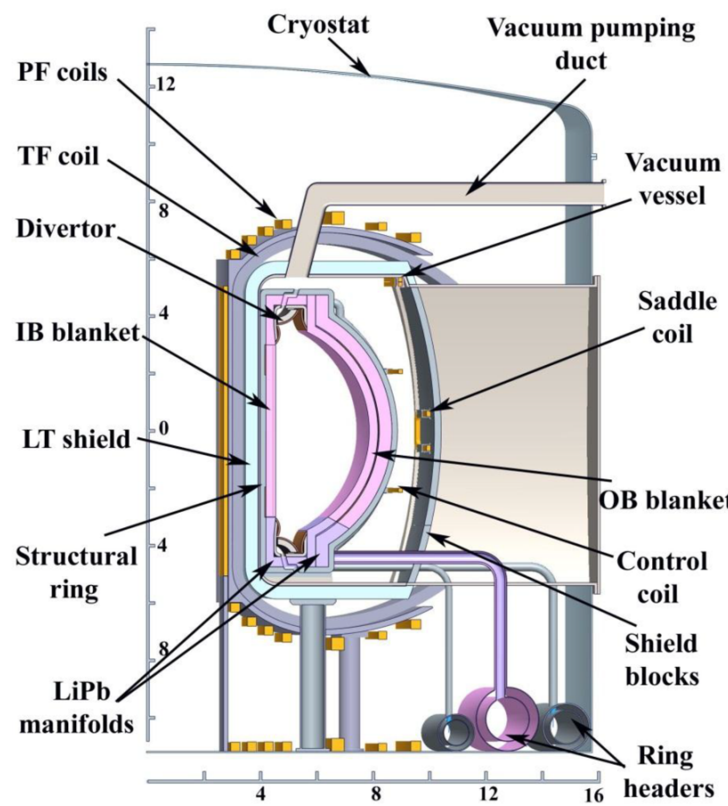
- **ARIES-ACT1 Power Plant Overview**
- **Material Environmental Durability Challenges**
- **ARIES-ACT1 He-Cooled W-Based Divertors**
- **Configurations and Typical Requirements**
- **Plate Divertor Concept**
- **Design Concept Review**
  - **Geometry**
  - **Materials**
  - **Fabrication and Processing**
- **Suitable NDE Methods and Capabilities and Considerations for the Divertors**
- **Preliminary Requirements and Candidate NDE Methods**
  - **Divertor Features Requiring NDE**
  - **Braze Joint Ultrasonic Inspection**
  - **Slot Tip Crack Inspection using an Eddy Current Technique**
- **NDE Technique Development and Advanced NDE Technologies**
- **Recommendations for the Current Concept**
  - **Design**
  - **Fabrication**
  - **NDE**
- **Outline of Boeing Concept Proposal**

# ARIES-ACT 1 Power Plant Overview





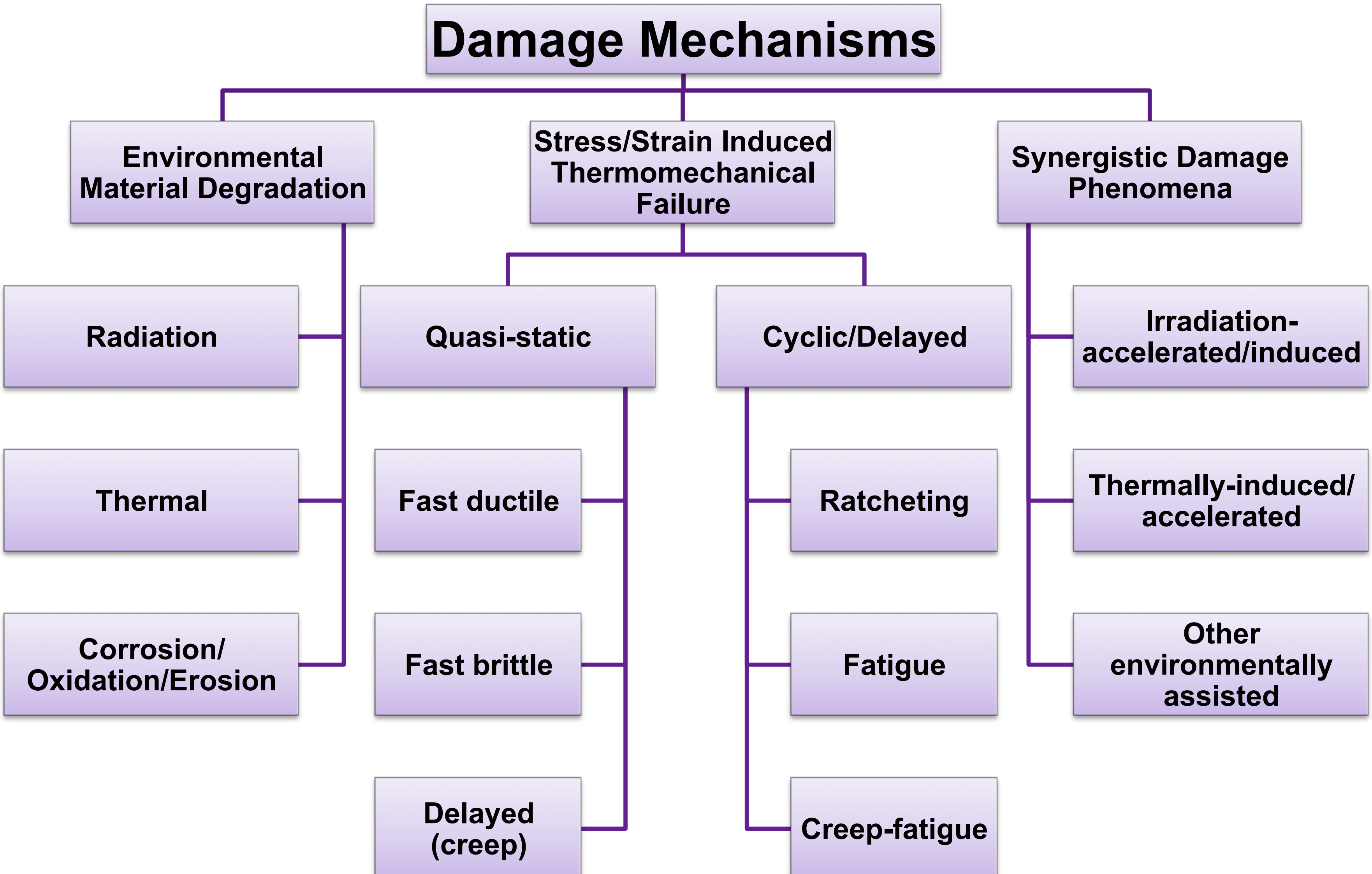
| Parameter | | Value |
|---|---|---|
| Major radius | R | 6.25 m |
| Aspect ratio | A | 4 |
| Elongation | k | 2.1 |
| Toroidal field on axis | $B_o$ | 6 T |
| Plasma Current | $I_p$ | 10.93 MA |
| Fusion power | $P_f$ | 1813 MW |
| Thermal power | $P_{th}$ | 2016 MW |
| Recirculating power | $P_{recirc}$ | 154 MW |
| Net electric power | $P_e$ | 1006 MW |
| Average wall load at FW | $P_n$ | 2.3 MW/m² |
| Maximum wall load at FW | | 3.6 MW/m² |
| Power conversion efficiency | $\eta_{th}$ | 57.9 % |




| | |
|---|---|
| FW/Blankets | LiPb cooled SiC/SiC structure $T_{Inlet}/T_{Outlet}$ = 740/1030°C |
| Structural ring or HT Shield | He-cooled ODS steel structure $T_{Inlet}/T_{Outlet}$ = 650/680°C |
| Upper/Lower Divertors | He-cooled W-based divertor and ODS steel cartridge $T_{Inlet}/T_{Outlet}$ = 700/800°C |
| Vacuum vessel | He-cooled Bainitic FS (3Cr-3WV) operating in ~400-500°C |
| LT shield | Water-cooled Bainitic FS and WC operating at the room temperature |

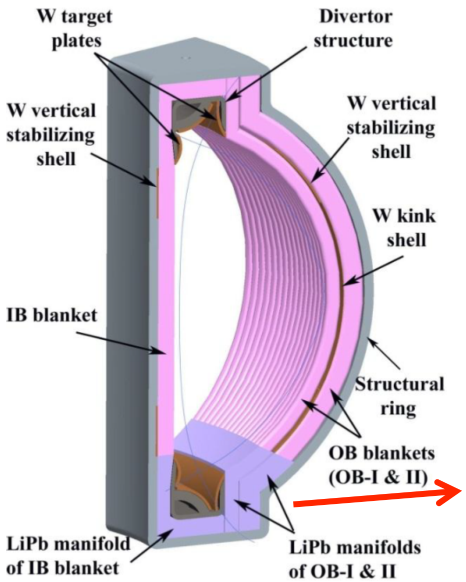
# Material Environmental Durability Challenges

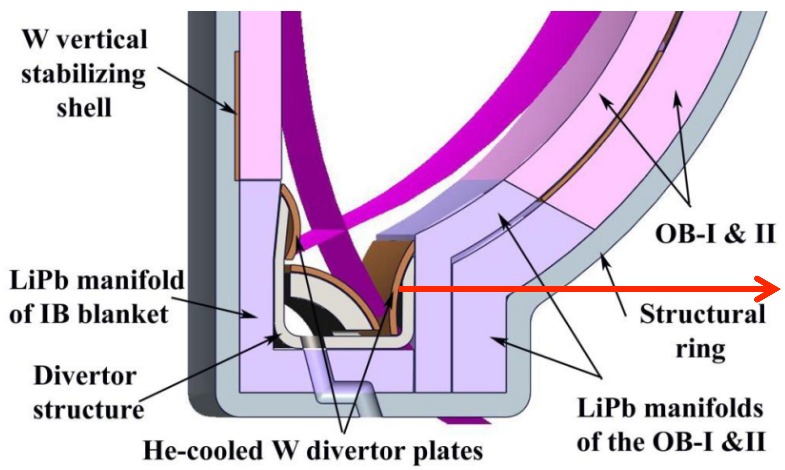




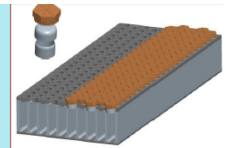
# ARIES-ACT1 He-Cooled W-Based Divertors



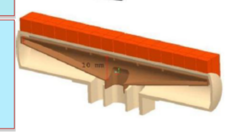


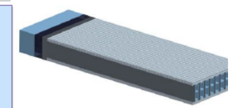

- Fingers arranged over the entire plate
- Imping-jet cooling, $T_{in}/T_{exit}$=700/800 °C
- **Allowable heat flux up to~14 MW/m²**
- Avoiding **joints** between W and ODS steel at the high heat flux region
- ~550,000 units for a power plant



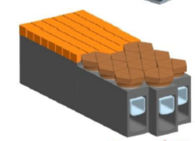
- T-Tube divertor: ~1.5 cm dia. X 10 cm long
- Impinging-jet cooling, $T_{in}/T_{exit}$=700/800 °C
- **Allowable heat flux up to~11 MW/m²**
- ~110,000 units for a power plant



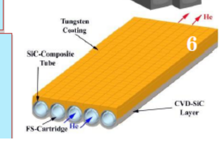
- Plate divertor: 20 cm x 100 cm
- Impinging-jet cooling, $T_{in}/T_{exit}$=700/800 °C
- **Allowable heat flux up to~9 MW/m²**
- ~750 units for a power plant



- Two zone divertor (any combination of the plate and finger and T-tube)
- Fingers for q>~8 MW/m², plate for q<~8 MW/m²
- Decreased number of finger units



- Tubular or T-Tube He-cooled SiC/SiC divertor
- Impinging-jet cooling, $T_{in}/T_{exit}$=600/700 °C
- **Allowable heat flux up to~5 MW/m²**



- **The current tokamak design for ARIES includes a plate divertor concept that employs tungsten as a structural material. The design features steel inserts in the channels, but all other materials are CP-W or a W alloy, in order to maximize the performance of the device.**
- **The high temperature capability of W permits a large allowable surface heat flux and makes the structure more tolerant to transients, such as those caused by ELMS, compared to other available alloy options.**

# Configurations and Typical Requirements



- **Comparison of different divertor concepts for a tokamak with an assumed divertor area of 150m²:**

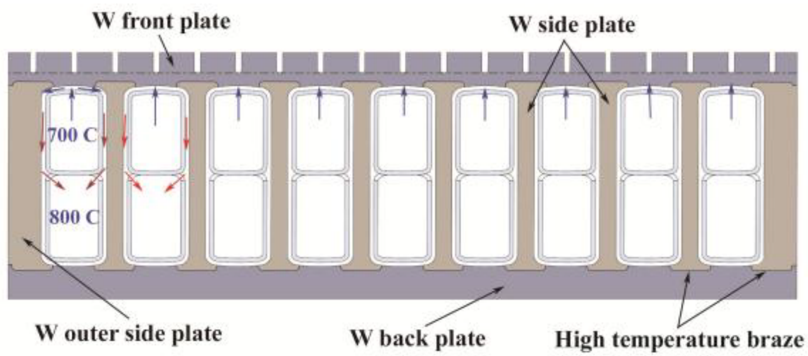
| Divertor concept | Unit characteristic dimensions | Number of units for a typical tokamak | Allowable incident heat flux (MW/m²) |
|---|---|---|---|
| Finger | 1.5 cm dia | ~535,000 | >12 |
| T-tube | 10 cm × 1.5 cm | ~110,000 | ~10–12 |
| Plate | 100 cm × 20 cm | ~750 | ~8–10 |

- **Design parameters and thermomechanical results for the plate-type divertor:**

| | |
|---|---|
| Surface heat flux | 10 MW/m² |
| Volumetric heat generation | 17.5 MW/m³ |
| Average neutron wall load | 3.2 MW/m² |
| He inlet temperature | 600 °C |
| He outlet temperature | 677 °C |
| He base pressure | 10 MPa |
| Pressure drop through the jet region | ~0.18 MPa |
| Ratio of pumping power to thermal power | <10% |
| Maximum W armor temperature | 1853 °C |
| Maximum W structural alloy temperature | 1295 °C |
| W re-crystallization temperature limit | 1300 °C |
| Maximum pressure stress | 110 MPa |
| $S_m$ limit at the corresponding temperature | 155 MPa |
| Maximum thermal stress | 310 MPa |
| Maximum thermal + primary stress | 359 MPa |
| $3S_m$ value at the corresponding temperature | 465 MPa |

http://dx.doi.org/10.1016/j.fusengdes.2010.08.015

- **Divertor type selection depends on the peak heat flux and heat flux profile.**
- **The plate-type divertor concept has been selected for the ARIES-ACT1 with peak-time average heat flux of 10.6 MW/m².**

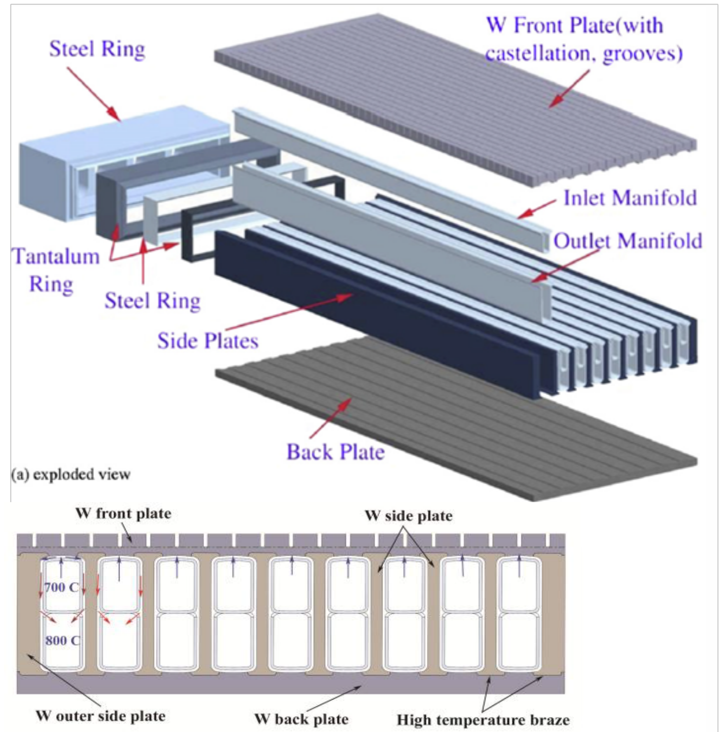


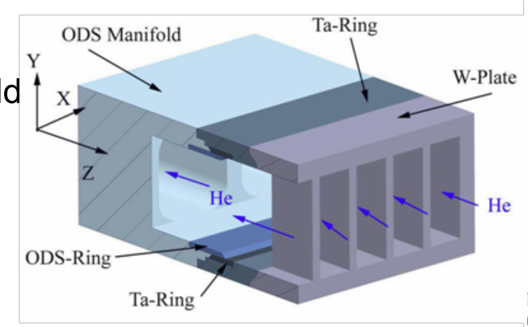

- **Thermal cycling imposed on the divertors will be of two types:**
  - High frequency (~3Hz)
    - Arising from ELMS
    - The resultant delta T is not defined.
  - Low frequency (10 -100 cycles total over lifetime)
    - Arising from warm shutdowns and subsequent reheating
    - The minimum W temperature will be controlled by external heating
    - Minimum temperature will be maintained above the DBTT

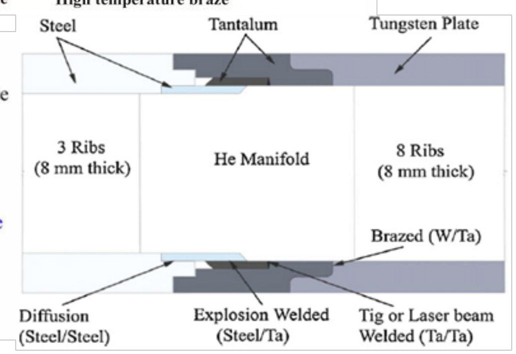
# Plate Divertor Concept



- **Baseline Materials**
  - Divertor assembly brazed with TBD alloy(s)
    - CP-W plasma-facing armor
    - TBD W alloy for other linear divertor core details
    - TBD ODS steel alloy manifolds (flow separators)
  - Transition section between core/header
    - Ta-2.5W tantalum alloy
  - Header
    - Machined from TBD steel alloy
    - Joined to He inlet/outlet ducts by TBD braze alloy(s) or welding
- **A Proposed Fabrication Sequence**
  - Machine 2 cm by 5 cm channels by EDM or ECM into a solid W plate.
  - Braze front plate, back plate and side-walls (each < 10mm) together with a high temperature braze alloy
  - Fabricate a W-ODS transition joint as follows:
    - explosion weld thin ODS ring to thin Ta ring,
    - seal weld thin ODS ring to ODS manifold,
    - diffusion weld thin ODS ring to the ODS manifold
    - braze thick Ta ring to the W-alloy plate,
    - TIG or laser weld thin Ta ring to larger Ta part



# Design Concept Review – Geometry and Materials



- **Geometry**
  - "Flat plate" divertor is actually curved (R ≈ 50-100 cm)
  - Curvature of brazed divertor core introduces many unaddressed challenges
    - Optimum braze joint thickness is ~0.02-0.03 mm.
    - Producibility & reliability decrease with increased braze joint thickness.
    - Proper fit-up of curved mating detail parts demands rigorous fabrication controls.
    - ODS steel manifolds must be inserted into curved core flow channels so as to create small precise flow passages.
- **W-Based Plasma Facing Materials**
  - Tungsten alloys are attractive candidates for fusion divertor applications because of their
    - very high melting point
    - good thermal conductivity
    - low sputtering yield
    - low activation characteristics
    - good thermal creep strength
  - These desirable properties are offset by poor ductility and fracture toughness below ~$0.3T_M$
  - Even at temperatures above the ductile-to-brittle transition temperature (DBTT), the fracture toughness of relatively pure W is low. This makes it difficult to fabricate W alloys into useful product forms at ambient temperatures
  - Its recrystallization temperature and DBTT bound the range of useful operation temperature.

# Design Concept Review – Materials I



- The selection of W alloys so far (mainly CP-W) has been based on existing experience and commercial availability (low risk).
- Chances of survival of components without cracking as a result of thermal cycles (low frequency – arising warm shutdowns and subsequent reheating, and more importantly transient ones arising from ELMs) are low. Thermal stresses on currently envisioned tungsten components and required dissimilar metal joints will likely exceed their capabilities. Laboratory experience with prototype W parts has underlined this threat.
- Relatively high risks of brittle fracture exist (during operation and fabrication) from very small defects at relatively low stress levels, especially at room and moderately elevated temperatures.

# Design Concept Review – Materials II



- **These issues have stimulated consideration of various higher performance W alloys (still relatively low risk and commercially available to some extent):**
  - Tungsten-rhenium alloys
    - Great choice, but Re leads to a lower thermal conductivity, relatively high activation by neutron irradiation, and cost escalation.
  - Dispersion strengthened tungsten with lanthanum-oxide (e.g. WL10 composed of W-1%$La_2O_3$)
    - Various improvements, but still has a rather limited temperature window
  - Vacuum-Metallized (VM) tungsten, doped with ppm amounts of Al and potassium silicate
    - Superior properties, but can be fabricated only as thin wires and sheets. Also suffers delamination when loaded in specific directions
- **A clear need exists for development of higher performance W alloys to address currently identified environmental structural durability shortcomings and fabrication challenges**

# Design Concept Review – Fabrication/Processing I

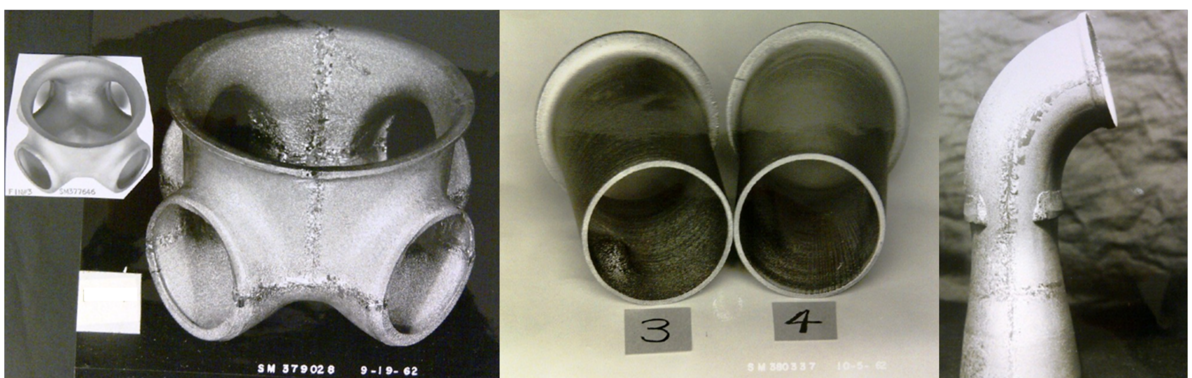


- **Baseline fabrication approaches**
  - Divertor assembly furnace brazed in vacuum with TBD braze alloy(s)
    - Thimbles deep drawn from sheet
    - Armor and other linear divertor core details machined from plate or bar
  - Transition section formed and/or machined from sheet or plate or bar and brazed to manifolds/core/header with TBD braze alloy(s)
  - Manifolds roll-formed from sheet to match divertor radius of curvature
  - Headers formed and/or machined from sheet or plate or bar
  - Assembly process for joining the core to the headers is not defined
- **Some proposed processes (machining and cutting) are fairly well developed ; others (forming and joining) will require process development**
- **General materials processing challenges include:**
  - Forming and machining  parts to attain proper braze joint gaps
  - Forming manifolds to
    - Attain proper flow channel gaps
    - Permit insertion into brazed tungsten channels
  - Dimensional control of brazed subassemblies/assemblies
  - Joining manifolds to header (preferably without brazing)
  - Nondestructive evaluation of brazed joints

# Design Concept Review – Fabrication/Processing II



- **Machining and Cutting**
  - **Satisfactory techniques have been developed and successfully employed for cutting, machining, blanking and shearing tungsten alloys.**
  - **Heating will probably be needed to minimize cracking.**
  - **Some parts may be machined with standard machine tools as part of the normal flow in a production shop with controlled processes.**
  - **Machining and other cutting processes applied to tantalum alloys and ODS steel are not expected to pose any serious problems.**
- **Forming**
  - **Aerospace parts have been hot-formed and welded from tungsten sheet.**




Manifold Tubes Elbow

  - **Deep drawing of the tungsten thimbles has reportedly been done successfully.**
  - **Forming process development will be required for ARIES parts.**

# Design Concept Review – Fabrication/Processing III



- **Joining**
  - Welding of tungsten is feasible if parts are heated above the DBTT, but the recrystallized structure of the welds and adjacent HAZs are extremely brittle.
  - Welding of ODS steel is also feasible, but creep strength & ductility will be reduced due to oxide particle agglomeration.
  - Explosive welding is feasible, but currently proposed geometry of ARIES parts do not lend themselves to this process.
  - ***At coupon level,*** brazing W to itself and other refractory metal alloys such as Ta-W, as well as braze joints with ODS steel is very feasible. A long list of commercially available and special purpose brazing filler alloys exists that covers a wide range of application temperatures, allowing the selection of an alloy that will provide the right combination of properties in service. The main challenge for filler alloys will be to meet the low-activation requirements.
  - ***At component level,*** brazing requirements as currently envisioned in ARIES will be very difficult to realistically achieve. Maintaining a uniform and thin braze joint thickness will require very precise fit-up of curved mating detail parts, demanding rigorous fabrication controls. Producibility and reliability decrease with joint thickness variations. Meeting sealing requirements, if any, will also be a very big challenge.

# Suitable NDE Methods and Capabilities



- **NDE Methods**
  - Probably Unsuitable for ARIES Divertors:
    - Infrared Thermography
    - Computed Tomography
    - Laser Shearography
    - X-ray, Gamma ray, Neutron radiography and Backscatter X-ray
    - Magnetic particle inspection
  - Suitable for ARIES Divertors:
    - Ultrasonic, Through Transmission, Pulse/Echo or Phased Array
    - Liquid penetrant inspection, also called dye penetrant inspection or penetrant testing
    - Eddy-current testing
- **NDE Method Capabilities**
  - NDE methods are assigned probability of detection (POD) values based upon demonstrated capabilities on known fatigue crack samples
  - POD values are based upon the utilization of commonly used industry NDE standards and specifications
  - NASA-STD-5009 (formerly MSFC-STD-1249) defines minimum detectable values for NDE methods on metallic components
  - Additional documents are available to assist with integrating the NDE and fracture control requirements
  - A POD study or demonstration may be required to validate NDE capability for some applications

# Considerations for the ARIES Divertor NDE



- **The primary divertor material is currently specified to be either tungsten or a tungsten alloy**
- **NDE will likely be required as follows:**
  - Wrought material stage to check for inherent flaws prior to machining operations
  - After each critical process (cutting, forming, machining, brazing) to check for surface and subsurface defects
- **NDE candidate methods must be defined based upon material properties, critical initial flaw sizes (CIF), NDE method detection capability and hardware accessibility**
- **Detectable CIF sizes may determine the suitability of various NDE techniques**
- **Assumption is that there will be no internal access to inlet or outlet manifolds**

# Preliminary Requirements and Candidate NDE Methods



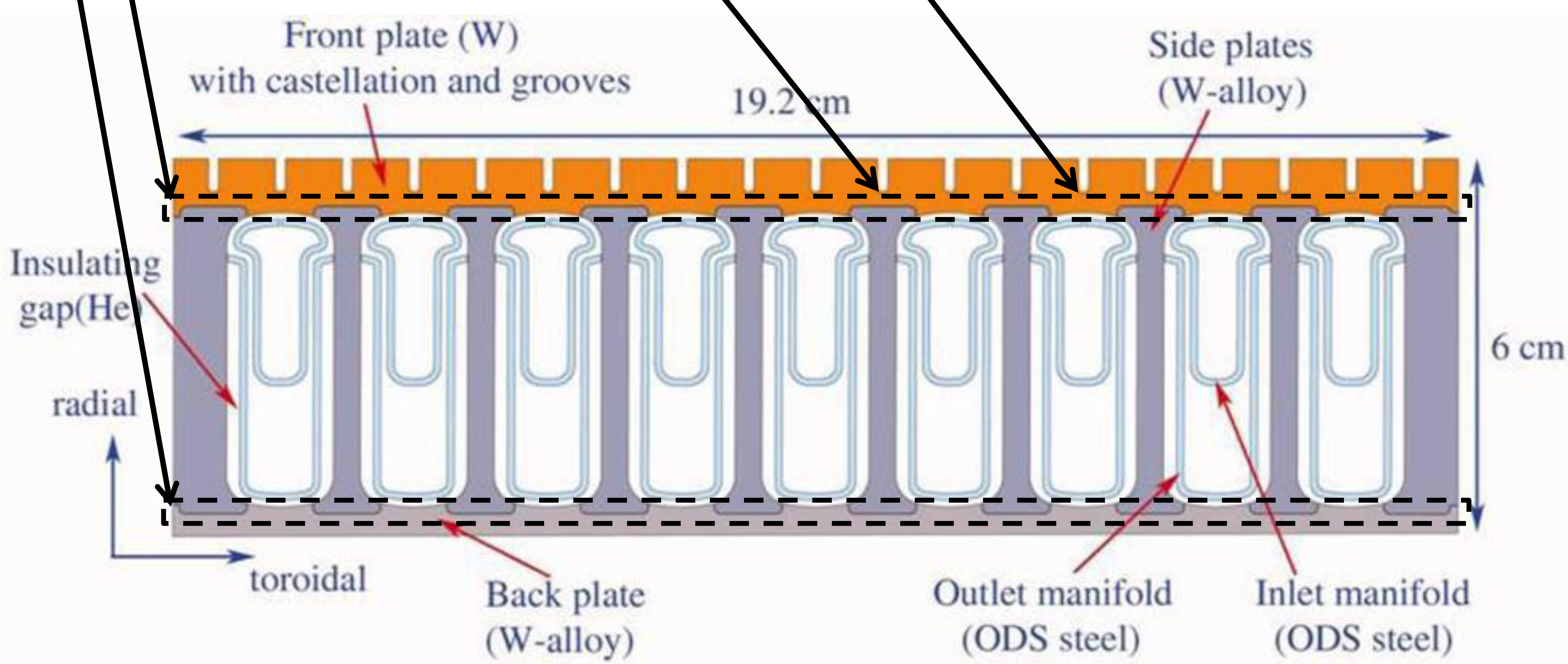
- **Wrought Materials (before machining)**
  - Ultrasonic inspection
- **Post Cutting, Forming and Machining**
  - Liquid penetrant or eddy current
- **Post Brazing**
  - Ultrasonic inspection using a combination or longitudinal, shear, or phased array techniques
- **In Service High Stress Slot Regions**
  - Eddy current or TBD method(s)

# Divertor Features Requiring NDE



Braze Inspection between:
1) Front Plate Armor & Side Plates
2) Back Plate and Side Plates

Potential Cracking at Tips of the Grooves

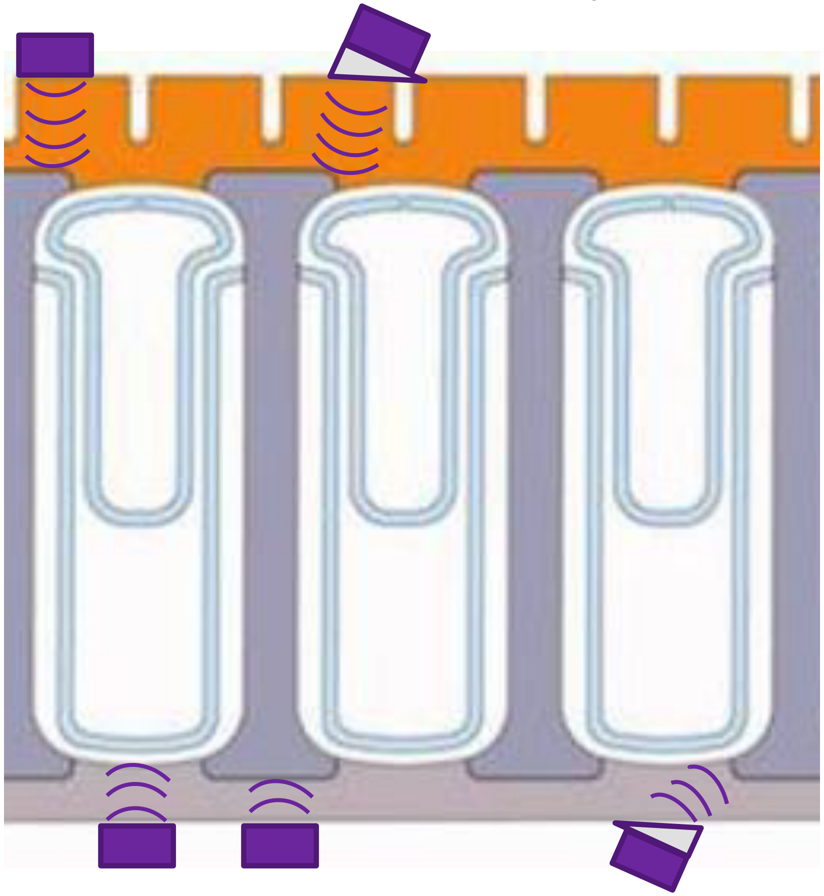


# Braze Joint Ultrasonic Inspection



- **Ultrasonic inspection technique to be developed**
- **Transducer to be located on front plate (armor) and back plate surfaces & sound pulsed to braze joint**
- **Combination of longitudinal wave and shear wave modes will likely be required to cover off-angle joint configuration**
- **Phased array ultrasonic technique to be evaluated as a potential option**
- **Reference standards will be required for feasibility tests & calibration**
- **Critical initial flaw (CIF) size is TBD**

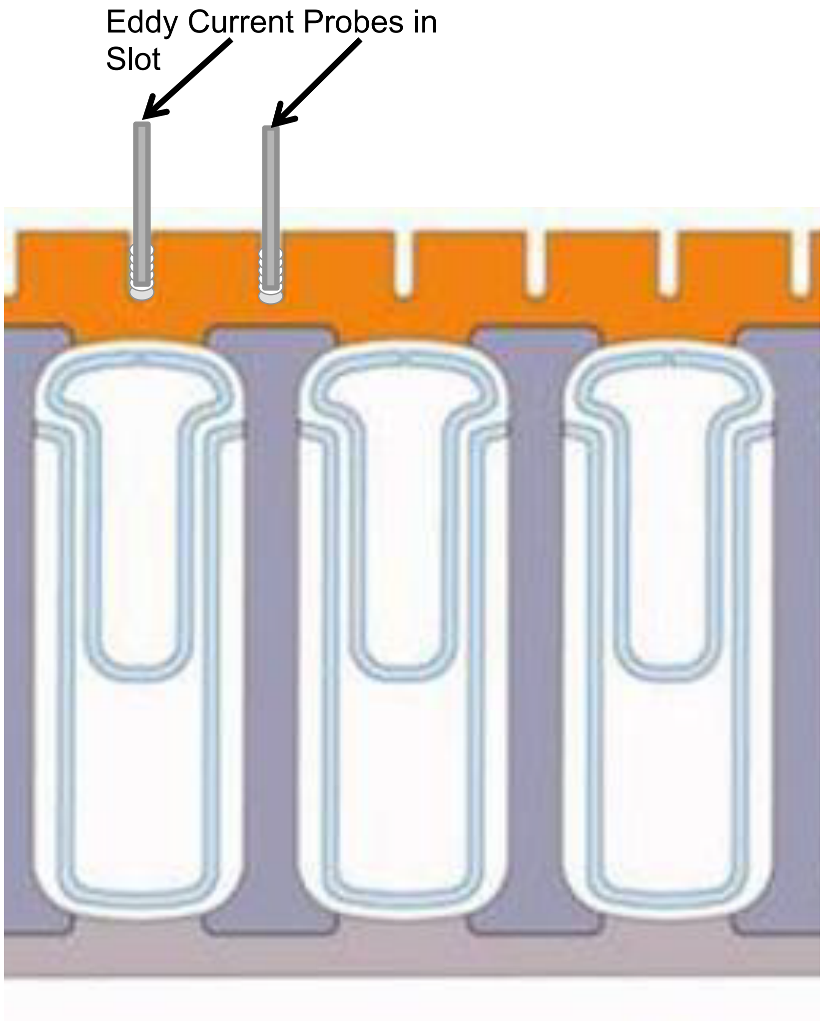
Ultrasonic transducers pulse sound to the braze joint



# Slot Tip Crack Inspection via Eddy Current Technique



- **Tungsten has a published electrical conductivity of ~31% IACS**
- **Small eddy current probe with a coil at the tip is positioned in slot**
- **Cracks at the tip of the slot disturb the eddy current field and are recorded**
- **Probes will travel the length of the slot using manual or automated/robotic fixtures**
- **Inspection within high radiation fields may require hardened equipment**
- **Reference standards with calibration notches required to validate feasibility and for system calibration**
- **Critical initial flaw (CIF) size is TBD**



# NDE Technique Development



- **Mechanical test samples will be required for development of design data and fabrication processes:**
  - Provide statistically valid design data (strength, modulus, ductility, fracture toughness, crack growth, creep, thermal expansion, radiation damage limits, etc.) at relevant elevated temperatures
  - Develop fabrication processes (forming, cutting, brazing, heat treatment, etc.)
- **The same samples may be evaluated before and after testing to aid in the development of NDE techniques:**
  - Develop/calibrate NDE methods
  - Validate the capability of the selected NDE methods
  - Aid in estimating probability of detection

# Advanced NDE Technologies: Automated Evaluation



- **Potential automation features can be developed and integrated into inspection systems to improve throughput, isolate radioactive items from human contact, and reduce time spent attending to the process by:**
  - Developing a motorized robotic crawler system
  - Integrating with developed positioning system to provide inspection location guidance
  - Providing situational awareness and positioning capability via on-board cameras
  - Utilizing automatic NDE sensor positioning and data collection to reduce inspection costs
  - Incorporating automated systems capability that scans and records data
  - Drawing on industrial experience developed within Boeing

# Advanced NDE Technologies: In Situ Evaluation



- **Develop and implement NDE sensor technology for in-situ detection and monitoring of difficult to access parts/ components**
- **Assess conditions in operational environment critical to monitoring infrastructure that provides more rapid data collection**
- **Reduce maintenance cycle time and disassembly required for access to perform inspections on critical components**
- **Provide a developmental framework, associated developmental tools and applicable techniques for predictive analytic models**

# Advanced NDE Technologies: Data Fusion



- **NDE Data Fusion is used to compare and verify indications acquired by one inspection method to data from another inspection method using the same reference coordinates for a more thorough evaluation of the information. It is a PC-based tool that uses AVS/Express visualization software to convert NDE measurements and part geometry data to display NDE data on CAD models.**
- **Advantages Include:**
  - Enables easy reference and comparison to the manufacturing baseline NDE data collected
  - Provides a tool that can be used as an off-line tool for data analysis (not for real-time in situ inspection analysis)
  - Provides assurance that parts are covered 100% by noting missing data (puzzle pieces)
  - Organizes data files into groups of parts to directly compare flown hardware over the entire part and not in portions
  - Tracks changes between maintenances monitoring against baseline NDE data
  - Incorporates a visualization capability to provide a better level of understanding of feature size/location for non-experts and management
  - Identifies trends indicating change in part material property in relation to location
  - Integrates finite element analysis and mechanical properties data (can be added to expand system capabilities)

# General Recommendations – I



- **While finalizing all current design concept details (geometry and materials) will remain a work in progress, it is very important to finalize a reasonable window that restricts changes to key material thermomechanical processing and fabrication parameters.**
- **It is well known that small changes in such parameters can significantly affect short and long term properties of low damage tolerance materials such as those currently envisioned (base and joint materials), especially in the extreme environments associated with fusion energy reactors. For example, changes in the level of cold work can significantly alter recrystallization temperatures.**
- **Necessary (statistically sound) structural design allowable and critical forming/joining parameter development efforts should be commenced once this window is established, otherwise high risks may be introduced late in the project.**

# General Recommendations – II



- **Special and nonstandard thermomechanical tests may need to be designed to carefully simulate environmental exposure effects where necessary. Due to complexities of such environmental fusion reactor simulations, focus should be on understanding requirements first and then testing accordingly to establish threshold properties, below which structural integrity is guaranteed. This is especially applicable to creep, fatigue, fracture toughness, and crack growth data.**
- **Structural lifetime analyses need to focus further on the various time dependant degradation phenomena anticipated at plasma facing surfaces and transition joints.**
- **Based on the selected design configurations, a preliminary list should be prepared to estimate the size of defects that have fairly high probabilities of detection in the proposed construction materials/joints, for selected state of the art NDT methods. This information would be used for design and reliability estimates, as well as to guide NDE development.**

# General Recommendations – III



- **Explore the relative producibility and cost of complex parts if made by the following alternative, nontraditional methods, as applicable to the shapes needed. Such a program could provide an entirely new design option for future reactor designers.**
  - Bulk additive manufacturing approaches
  - Powder metallurgy near-net shape manufacturing
  - Surface build up via deposition (e.g. CVD, PVD, Cold Spray, etc)
- **General Fabrication**
  - Fabrication of individual divertor parts are critical tasks that need to meet the requirements for high functionality, high reliability, and reasonable costs.
  - To control quality and properties, detailed processing specifications need to be created for shaping and joining processes, and specified on design drawings.
  - Standard repair procedures need to be developed and documented for frequent anticipated repairs.

# General Recommendations – IV



- **Fabrication Automation**
  - A plan should be developed to determine which operations will require or will benefit from automation.
  - Given enough funding and equipment, any degree of automation can be used, provided the manufacturing processes are fully developed, including tolerance limits for key dimensions and processing parameters.
  - Automation will be required for fabrication operations involving materials and assemblies that have become radioactive hazards.
  - Prime candidates for automation:
    - Armor machining
    - Thimble forming
    - Assembly of divertor cores and armor for brazing
    - Additive manufacturing
    - Cleaning processes
    - Dimensional inspection
    - Nondestructive inspection

# General Recommendations – V



- **Forming:**
  - Define candidate materials, processes and design configurations (including dimensions and tolerances) for forming (1) W divertor core faceplate (armor), backplate, exterior and interior bar walls, and (2) ODS steel manifolds
  - Determine material and process specification requirements for raw material formability and verify supplier acceptance of prospective requirements.
  - Verify supplier capability to produce the required formed parts.
- **Brazing:**
  - Define candidate component and braze alloy materials, processes and design configurations for brazing the following:
    - Tungsten divertor core (including armor and thimbles)
    - Design to shield armor/core brazed joints from extreme heating due to direct/indirect plasma attack
    - Ta alloy transition section to divertor core and ODS steel inlet/outlet header
    - Inlet/outlet header to manifolds
  - Determine material and process specification requirements for brazed assemblies and verify supplier acceptance of prospective requirements.
  - Verify supplier capability to produce the required brazed parts.
  - Prepare prototype brazed assemblies from selected materials and processes; compare predicted vs. actual dimensions and assess braze quality.

# General Recommendations – VI



- **NDE:**
  - Define which parts and assemblies need NDE evaluation
  - Develop a Destructive Inspection/Test Plan
  - Develop an NDE Plan that is integrated with the Fracture Control Plan
    - Identify and Validate NDE Methods
    - Dynamic subcomponent testing
    - Develop NDE reference standards
  - Prepare NDE specifications and technique sheets
  - Demonstrate on system unit simulated samples and mechanical property test samples
  - Establish an NDE database
  - Down-select validated methods
  - Implement and train personnel (production phase)

# Outline of Boeing Concept Proposal - I



- **Critical Issues:**
  - A review of the environmental durability requirements and structural integrity – lifetime assessments (analytic and experimental) made so far, indicate the clear need for tougher W alloys with improved ductility, lower DBTT, higher creep strength, higher recrystallization temperatures, superior corrosion, and neutron radiation damage resistance.
  - Fabricating divertor core detail parts that have the required tolerances on a production basis may be very challenging and uneconomical. Brazing may be very difficult to accomplish due to the curved divertor shape and dimensional tolerances required to achieve optimum braze joint gaps and fill them with minimal voids.
- **Objective:**
  - Address the two critical material and fabrication shortcomings to increase reliability and enable improved reactor performance by providing higher safety margins and design flexibility.
    - While developing a new material system may appear as a daunting task, it is important to note that key characterization efforts still outstanding for the current concept candidates, including addressing microstructural heterogeneities at joints and long term exposure effects will probably require the same level of resources and effort.

# Outline of Boeing Concept Proposal - II



- **Concept Proposal:**
  - Produce divertors in the current curved plate configuration in the form of a functionally graded composite structure, using a combination of additive manufacturing and severe plastic deformation fabrication approaches with very few or no braze joints.  Such manufacturing approaches are currently under development/investigation at Boeing for other alloys systems.
  - Use second-phase (HfC) particle-strengthened dilute W-Re alloys, such as W-3.6Re-0.26HfC (developed decades ago) that have been synthesized using novel ball milling and consolidation approaches currently under development/ investigation at Boeing for other alloys systems. The resultant ultrafinegrained structure with a high/uniform density of nanoscale second-phase particles will simultaneously provide ultra high temperature strength and neutron radiation damage resistance.
- **Advantages:**
  - A moderate addition of Re can appreciably improve the low-temperature ductility and high-temperature strength of W.  Additionally the presence of uniformly distributed fine particles of hafnium carbide (HfC) can dramatically increase the high-temperature strength of Re alloys.  Recrystallization temperatures are also much higher than those of CP-W.
  - The use of additive manufacturing approaches to fabricate integral inlet/outlet channels into one core piece will potentially eliminate joints in the core, reduce part count, and eliminate dissimilar junctions.  The process will also allow incorporation of compositional variations and blended/graded transitions.
  - Complex curvatures may be introduced as needed to optimize design

# Summary Conclusion



- **The ARIES ACT Divertor design is not sufficiently detailed to allow the determination of failure thresholds for insertion into the Reliability Model.**
- **The ARIES ACT Divertor design is sufficiently detailed to allow identification of the critical areas in which research efforts should be concentrated for the goal of achieving high divertor reliability, and for allowing suggestions as to how that research could be most effectively conducted.**