Safety, Activation, and Waste Disposal

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UCSD
I – Safety:
• Key features
• Accident identification
• Radioactive inventory and decay heat (SiC, V, FS)
• Design integration

II – Activation and radwaste classification:
• Strict requirement for low level waste only
• Constraints on material choices
• Need for impurity control
• Waste management: Dispose, recycle, or clear

III – Waste volume minimization:
• Improvements over past 10 years
• Innovative design solutions for waste minimization
ARIES-RS, -ST, -AT Designs Meet Safety Requirements

- No evacuation plan required even in worst case accident
  Dose at site boundary < 1 rem* for ARIES-RS,-ST,-AT designs
  Contributors to dose: Activation products
  T in breeder and structure
  W dust
  Po in LiPb
- Low activation materials for highly irradiated components
- Radioactive materials confined with multiple barriers: VV and cryostat
- No energy and pressurization threats to confinement barriers
  - Decay heat problem solved by design
    Segmented cooling system into 4 loops
    Decay heat removal system
    ⇒ Peak temp during accident < 800 °C
  - Chemical reactions avoided
    No water in Li system
    Separate LiPb and water cooled components
  - No combustible gas generated
    Avoid water in Li system
    No hydrides in shield
  - Chemical energy controlled by design
    Multiple barriers between components
    4 drain tanks for each Li or LiPb loop
    Avoid water, steam, or air interactions with hot materials
  - Overpressure protection system
  - Rapid plasma shutdown
    Highly reliable multiple systems needed
    High speed of action (< 1 s)
- Tritium inventory < 1 kg in FPC
- Low level waste (WDR < 1 for all components)
- Minimum volume of radwaste

* Early dose duration is usually 7 days exposure
Selective Accidents Assessed for Each Design*
With Most Scenarios Applied to ARIES-AT

**ARIES Designs**

- **Loss of coolant accident** (LOCA)  
  - No coolant in ALL loops  
  - Decay heat raises temperatures of solids  
  - High temperature mobilizes activation products

- **Loss of flow accident** (LOFA)  
  - Coolants stop flowing in all or some loops  
  - Decay heat raises temperatures of solids  
  - High temperature mobilizes activation products

- **Loss of vacuum accident** (LOVA)  
  - Failure in penetrations causes air ingress into VV  
  - Dust and T mobilized in VV  
  - Loops operate normally and cool down the system  
  - Buoyancy driven flow from VV to environment

- **By-pass events**  
  - In-vessel events (e.g., disruption-induced LOCA)  
  - Failure of penetration line  
  - Release path that by-passes confinement barriers  
  - Air ingress into VV  
  - Dust and T mobilized in VV  
  - Air exchanges between chamber and bypass room

- **Ex-vessel events that require plasma shutdown**  
  - Ex-vessel events not felt by plasma (e.g., pump seizure, LOCA, etc..)  
  - Blanket heat removal capability is reduced  
  - Plasma shutdown is required

- **Loss of power**  
  - Similar to LOFA

- **Transient overpower and plasma abnormalities**  
  - ELMS, MARFE, or over-fueling cause power excursion  
  - (FW/Blanket has margin to overcome this event)

- **External events**  
  - Seismic, airplane crash, tornado, etc…

- **Operator’s errors**

* Due to time and resources limitations, it was not possible to assess all accidents for each design. However, the most credible accidents were considered
Strong Safety-Design Integration Helped Meet Safety Requirements

• Safety requirements defined at beginning of study

• Safety constraints included in radial build definition, subsystem designs, and maintenance scheme

• Iteration with designers improved safety function implementation

• Confinement enhanced through:
  – Decay heat removal system
  – Chemical energy control
  – Safety grade plant shutdown

• Improved robustness of design response to off-normal events

• Detailed waste management assessment
## Activation and Waste: Requirements and Impacts

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Design Impacts</th>
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<tbody>
<tr>
<td><strong>Low level waste</strong></td>
<td>Use low activation materials (SiC, V, FS)</td>
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<tr>
<td></td>
<td>Control impurities</td>
</tr>
<tr>
<td></td>
<td>Limit components lifetime, if needed</td>
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<tr>
<td><strong>Reduce volume of waste</strong></td>
<td>Compact radial build</td>
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<tr>
<td></td>
<td>Optimize shield</td>
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<td></td>
<td>Segment blanket*</td>
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<td></td>
<td>Prolong components’ lifetimes</td>
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<tr>
<td></td>
<td>Recycle waste</td>
</tr>
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<td></td>
<td>Clear ex-vessel components</td>
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</tbody>
</table>

* to increase repository capacity  
* not applicable to toroidally helium-cooled options
Most Recent ARIES-AT Design is Safer and Simpler Compared to ARIES-RS and -ST

- SiC offers rapid decay of activity and decay heat at 1 min after shutdown, a major safety advantage
- ARIES-RS and ST require active means to remove decay heat
- ARIES-AT temperature during LOCA/LOFA events remained below allowable, requiring no active system for decay heat removal
  ⇒ Safer and simpler design
Three Options:

- Clear or “free release” of materials to industrial facilities if Clearance Index < 1
- Dispose near surface as Class A or Class C low level waste (LLW)
- Recycle waste and reuse in nuclear facilities

Clearance and disposal options addressed in details in ARIES studies

Waste could be recycled at unknown cost:

- INEEL 1994 study on V recycling
- Various studies on FS recycling
- No study available on SiC recycling
Because of Compactness, ARIES Components Cannot be Cleared

- All ARIES components have clearance index > 1 based on IAEA clearance limits
- NRC limits could be more restrictive than IAEA’s (dose ~1 mrem/y)

ARIES waste will be disposed of as LLW or could be recycled

* Defined as unrestricted release of items and materials from radiologically controlled areas
# Low Level Waste Achieved With Impurity Control

<table>
<thead>
<tr>
<th>Design</th>
<th>WDR*</th>
<th>LLW Classification</th>
<th>Impurity limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARIES-RS</td>
<td>&lt; 1</td>
<td>Class C</td>
<td>Nb ≤ 0.5 wppm for V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ir ≤ 0.02 wppm for Tenelon and MHT-9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ag ≤ 0.1 wppm for Tenelon and MHT-9</td>
</tr>
<tr>
<td>ARIES-ST</td>
<td>&lt; 1</td>
<td>Class C</td>
<td>Nb ≤ 0.5 wppm for ORNL-FS</td>
</tr>
<tr>
<td>ARIES-AT</td>
<td>&lt;&lt; 1</td>
<td>90% Class A</td>
<td>Nb ≤ 1 wppm for ORNL-FS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10% Class C</td>
<td>Mo ≤ 20 wppm for ORNL-FS</td>
</tr>
</tbody>
</table>

**Feedback to Fusion community:**

- Material developers should control Nb, Ag, and Ir impurities in low activation materials **below ppm level**. Higher level allowed for Mo.
- **NRC should develop Class A and Class C waste disposal limits** for materials of interest to fusion.
- **NRC should develop Clearance limits** for all radioactive isotopes.

* < 1 means low level waste
Recent ARIES Designs Generate Less Waste*

* Reported volumes are not compacted

<table>
<thead>
<tr>
<th>ARIES</th>
<th>Blanket/Shield/Vacuum Vessel/Magnet Volume ($10^3 \text{m}^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m)</td>
<td>I</td>
</tr>
<tr>
<td>SiC/Li$_2$ZrO$_3$</td>
<td>6.8</td>
</tr>
<tr>
<td>FS</td>
<td>V/Li</td>
</tr>
</tbody>
</table>

* Reported volumes are not compacted
Breakdown of ARIES-AT Waste

### Cumulative Compacted Waste Volume (m³)

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume (m³)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IB &amp; OB Blanket-I</td>
<td>287</td>
<td>22%</td>
</tr>
<tr>
<td>OB Blanket-II*</td>
<td>33</td>
<td>3%</td>
</tr>
<tr>
<td>Shield*</td>
<td>340</td>
<td>27%</td>
</tr>
<tr>
<td>V.V.</td>
<td>120</td>
<td>9%</td>
</tr>
<tr>
<td>Magnets</td>
<td>200</td>
<td>16%</td>
</tr>
<tr>
<td>Structure</td>
<td>150</td>
<td>12%</td>
</tr>
<tr>
<td>Cryostat</td>
<td>140</td>
<td>11%</td>
</tr>
</tbody>
</table>

* Successful effort made to lower blanket and shield contribution to 50% range by:
  - segmenting the blankets
  - optimizing the shield

* Assuming no spare components
ARIES-RS and –AT Blanket Segmented to Reduce Waste Volume

- Segmentation lowered cumulative blanket waste by factor of 2

- Back blanket segment could either be lifetime component or replaced less frequently than front segment

- Radiation damage determines service lifetime of individual components

<table>
<thead>
<tr>
<th>Design</th>
<th>Structure</th>
<th>limit</th>
<th>B-I Lifetime</th>
<th>B-II Lifetime</th>
<th>Shield Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARIES-RS</td>
<td>V</td>
<td>200 dpa</td>
<td>2.5</td>
<td>7.5</td>
<td>40</td>
</tr>
<tr>
<td>ARIES-ST</td>
<td>FS</td>
<td>200 dpa</td>
<td>3</td>
<td>---</td>
<td>40</td>
</tr>
<tr>
<td>ARIES-AT</td>
<td>SiC</td>
<td>3% burnup</td>
<td>4</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

- Massive shields are lifetime components. Radiation protection provided by blanket
Well Optimized Shield Helps Reduce Radial Standoff, Machine Size, and thus Waste Volume

- Machines made entirely out of V and SiC structures are large and expensive (COE > 100 mills/kWh)

- Better shielding materials (WC, B₄C, FS, H₂O) incorporated to reduce machine size

- Safety, economics, and breeding constraints limit the use of those materials, e.g.,
  - Li breeder ⇒ No water
  - Low COE ⇒ WC and B₄C for IB only
  - Limited breeding in ST ⇒ No WC and H₂O in IB shield

- Shielding design guidelines to reduce waste volume and cost:
  - Limit V and SiC structures to high temperature components
  - Use FS filler with SiC & V structures
  - Use less expensive FS structure for back low-temperature components
  - Employ highly efficient WC and B₄C fillers for IB side only (monitor WC decay heat)
  - Cool low-temperature components with water, if compatible with breeder
State-of-the-Art Codes and Latest Data Currently Used for Nuclear and Safety Analyses

- **Safety analysis:**
  - MELCOR code for accident progression
  - ANSYS finite element 1-, 2-, 3-D code for LOCA/LOFA

- **Activation analysis:**
  - ALARA 1-, 2-, 3-D code
    - Newly developed at UW
    - Can handle pulsed operation

- **Neutron and gamma transport analysis:**
  - DANTSYS discrete ordinate 1-, 2-, 3-D code system
  - MCNP 3-D Monte Carlo code

- **Nuclear data:**
  - FENDL-2 IAEA most recent cross section library