D-\(^3\)He Fueled Fusion Devices as Step Towards Total Fusion Safety

L. El-Guebaly and M. Zucchetti
Fusion Technology Institute
University of Wisconsin - Madison

Politecnico di Torino
Torino, Italy

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History & Background Info

- In late 1980s, fusion safety stimulated worldwide research for fuel cycles other than D-T.
- Advanced cycles (such as D-D, $\text{D}^{3}\text{He}$, $\text{p}^{11}\text{B}$, and $^{3}\text{He}^{3}\text{He}$) do not require breeding large amount of T (~56 kg/y for 1 GW of D-T fusion power).
- Some advanced cycles (e.g., D-$^{3}\text{He}$) are not completely aneutronic due to side D-D reactions.
- However, neutron wall loading can be kept low (by orders of magnitude) compared to D-T fueled plants with same output power.
- **Attractive features for D-$^{3}\text{He}$ fuel cycle include:**
  - No T breeding blanket.
  - All components are permanent, meaning no need to replace FW/shield during entire plant lifetime (~ 50 y).
  - Potential for direct energy conversion.
  - **Low activity, decay heat, and radwaste levels.**
  - Low releasable radioactive inventory from credible accidents.
- **Concerns for D-$^{3}\text{He}$ fuel cycle:**
  - $^{3}\text{He}$ availability.
  - Higher plasma ion temp (50-100 keV) compared to D-T (10-20 keV).
Objectives

• Apply most recent radwaste management schemes to D-\(^3\)He fueled devices: *ARIES-III* power plant and *Candor* experiment*.  

• Compare radiological aspect of D-\(^3\)He and D-T fuel cycles and highlight differences.

Handling Fusion Radwaste is Important to Future of Fusion Energy

• Majority of fusion power plants designed to date focused on disposal of active materials in repositories, adopting fission waste management approach preferred in 1970’s.

• New Strategy: Develop new framework for fusion:
  – Minimal amount should be disposed of in ground
  – Recycle and/or clear all active materials, if technically and economically feasible.

• Why?
  – Limited capacity of existing low-level waste repositories
  – Political difficulty of building new repositories
  – Tighter environmental controls
  – No long-lived radwaste burden for future generations.

• Impact: Promote fusion as nuclear source of energy with minimal environmental impact.
Fusion Designs Should Adopt MRCB Philosophy

M – Minimize volume of active materials by design or by employing advanced fuel cycle.

R – Recycle, if economically and technologically feasible.

C – Clear slightly-irradiated materials.

B – Burn active byproducts, if any, in fusion devices*. 

ARIES-III Power Plant Selected for Radwaste Assessment

ARIES Project Timeline

- ARIES-I
- ARIES-II
- ARIES-III
- ARIES-IV
- ARIES-RS
- SPPS

Calendar year
ARIES-III Power Plant

1000 MW\textsubscript{e} Output Power
7.5 m Major Radius
D-\textsuperscript{3}He Neutron Source:
\begin{itemize}
  \item 70\% 2.45 MeV n’s
  \item 30\% 14.1 MeV n’s
\end{itemize}
0.1 MW/m\textsuperscript{2} Average NWL
Ferritic Steel Structure
Organic Coolant with 44\% $\eta_{th}$
40 FPY Permanent Components
85\% Availability
ARIES-III LLW Classification for Geological Disposal

Temporary Storage

Class A Repository

Class C Repository

All ARIES-III Components

Least hazardous type of waste

<table>
<thead>
<tr>
<th>FW/Shield</th>
<th>√</th>
<th>no</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Vessel</td>
<td>√</td>
<td>no</td>
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<tr>
<td>Magnet:</td>
<td>√</td>
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</tr>
<tr>
<td>Nb₃Sn (6%)</td>
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<td>no</td>
</tr>
<tr>
<td>Incalloy (57%)</td>
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<td>no</td>
</tr>
<tr>
<td>Cu (29%)</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Insulator (4%)</td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Bioshield</td>
<td>√</td>
<td>√</td>
</tr>
</tbody>
</table>

> 8 m below ground surface + Thick Concrete Slab

≈ 8 m below ground surface

> 8 m below ground surface

Least hazardous type of waste
85% of ARIES-III Radwaste can be Cleared in < 10 y after Decommissioning

IAEA Clearance Index

FW/Shield
VV
Coil Case
WP
Bioshield

IAEA Limit

Time After Shutdown (s)

10^10
10^8
10^6
10^4
10^2
10^0

10^-2
10^-4
10^-6
10^-8
10^-10

Concrete Clearance Index

IAEA
US

Innermost Segment of Bioshield

Time After Shutdown (s)

1h
1d
1y
100y

Steel Clearance Index

IAEA
US

Limit

Innermost Segment of Bioshield

Time After Shutdown (s)

1h
1d
1y
100y
All ARIES-III Components can be Recycled in < 1 y Using Advanced and Conventional RH Equipment
Comparison of D-\(^3\)He and D-T Fueled Power Plants of Comparable Major Radii

ARIES-III radwaste inventory is \(~50\%\) of ARIES-CS’
Candor Experiment

2.5 m Major Radius
Cu Magnet
D-T Trigger to Reach Ignition
D-³He Neutron Source:
  - 74% 2.45 MeV n’s
  - 26% 14.1 MeV n’s
1.2 MW/m² Average NWL

Z (cm)
R (cm)
Candor Specific Activity

CANDOR Activation at 10 y, 30 y, 50 y after shutdown

Specific Activity (Bq/kg)

Back C-Clamp (AISI 316)
Mid C-Clamp (AISI 316)
Front C-Clamp (AISI 316)
Shaping and equilibrium coils
Central Post
External TFC (inboard)
Ext TFC (outboard) and Central Solenoid
Internal TFC

10 y
30 y
50 y
Hands-on Recycling of Candor Components is Feasible within 10-30 y
All Candor Components can be Cleared in 50-100 y
Conclusions

- Recycling and clearance of all components should be an essential goal of fusion studies to minimize radwaste stream.
- Advanced D-³He fuelled designs offer further step toward intrinsic safety and environmental goals.
- For D-³He fuelled ARIES-III power plant:
  - All in-vessel components qualify as Class A waste, the least hazardous type based on U.S. guidelines.
  - All components can be recycled using conventional and advanced remote handling equipment.
  - Bioshield contains traces of radioactivity and can be cleared from regulatory control after relatively short period of time (~10 y).
- D-³He fuelled Candor experiment reaches zero-waste option as all wastes can be cleared within 100 y.
- Low neutron production of D-³He fuel helps overcome some of engineering and material hurdles to fusion development.
- Advanced fuel cycle development should be carried out in parallel with current mainstream fusion pathway that primarily focuses on D-T tokamaks.