Assessment of Fusion Development Path: Initial Results of the ARIES “Pathways” Program

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Fusion Development Path: A Fascination with Facilities

Configuration Optimization

Concept Exploration/Proof of Principle

Theory, Simulation and Basic Plasma Science

MFE P&O

MFE PE(s)

MFE ITER (or FIRE)

Burning Plasma

Complete ITER Ops Phase 1

Complete IFMIF Ops 80 dpa

Prelim. IFMIF Ops 150 dpa

Materials Testing

Materials Science/Development

MFE IFMIF

Component Testing

Engineering Science/Technology Development

Internal Components Design

Demonstration

Design Studies

US Demo

MFE Program
<table>
<thead>
<tr>
<th>Issue</th>
<th>Approved devices</th>
<th>ITER</th>
<th>IFMIF</th>
<th>DEMO Phase 1</th>
<th>DEMO Phase 2</th>
<th>Power Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disruption avoidance</td>
<td>2</td>
<td>3</td>
<td></td>
<td>R</td>
<td>R</td>
<td>R</td>
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<tr>
<td>Steady-state operation</td>
<td>2</td>
<td>3</td>
<td></td>
<td>r</td>
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<tr>
<td>Divertor performance</td>
<td>1</td>
<td>3</td>
<td></td>
<td>R</td>
<td>R</td>
<td>R</td>
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<tr>
<td>Burning plasma (Q&gt;10)</td>
<td>3</td>
<td></td>
<td></td>
<td>R</td>
<td>R</td>
<td>R</td>
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<tr>
<td>Start up</td>
<td>1</td>
<td>3</td>
<td></td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Power plant plasma performance</td>
<td>1</td>
<td>3</td>
<td></td>
<td>r</td>
<td>R</td>
<td>R</td>
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<tr>
<td>Superconducting machine</td>
<td>2</td>
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<tr>
<td>Heating, current drive and fuelling</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>R</td>
<td>R</td>
<td>R</td>
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<tr>
<td>Power plant diagnostics &amp; control</td>
<td>1</td>
<td>2</td>
<td>r</td>
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<td></td>
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<tr>
<td>Tritium inventory control &amp; processing</td>
<td>1</td>
<td>3</td>
<td></td>
<td>R</td>
<td>R</td>
<td>R</td>
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<tr>
<td>Remote handling</td>
<td>1</td>
<td>2</td>
<td></td>
<td>R</td>
<td>R</td>
<td>R</td>
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<td>Materials characterisation</td>
<td></td>
<td>3</td>
<td></td>
<td>R</td>
<td>R</td>
<td></td>
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<td>Plasma-facing surface</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>R</td>
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<tr>
<td>FW/blanket/divertor materials</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FW/blanket/divertor components</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>R</td>
<td></td>
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<tr>
<td>T self sufficiency</td>
<td>1</td>
<td></td>
<td>3</td>
<td>R</td>
<td>R</td>
<td></td>
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<tr>
<td>Licensing for power plant</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>R</td>
</tr>
<tr>
<td>Electricity generation at high availability</td>
<td>1</td>
<td></td>
<td>3</td>
<td></td>
<td></td>
<td>R</td>
</tr>
</tbody>
</table>

Output: | Will help to resolve the issue | 1 |
|        | May resolve the issue           | 2 |
|        | Should resolve the issue        | 3 |
|        | Must resolve the issue          | 4 |

Input: | Solution is desirable | r |
|       | Solution is a requirement     | R |

UKAEA September 2007 (revised/improved version of original table in UKAEA FUS 521, 2005).
Fusion Development Focuses on Facilities Rather than the Path

- Current fusion development plans rely on large scale, expensive facilities. There is a difficult learning period between facilities (long lead times, $$$);
- It is argued that facilities provide a focal point to do the R&D. This is in contrast with the normal development path of any product in which the status of R&D necessitates a facility for experimentation;
- We need to focus on the “development path;”
- Use modern tools for “product development” to assess fusion development path.
- Use modern approaches for to “product development;” (e.g., science-based engineering development vs “cook and look”)
ARIES Pathways Program is developing “quantitative” measures to assess fusion development scenarios

- Identify what is important (metrics for prioritization of the R&D)  
  A new systems-based approach

- Develop metrics for the status of the field and the progress along the development path. Use these metrics to define:
  Technical Readiness Levels (TRLs)
  - What can and should be done in simulation facilities;
  - When we need and are ready to launch a new facility;
  - The mission and requirements of the new facilities;
  - Assess potential contributions of new facilities to move us along the fusion development path.
Technical Readiness Levels provides a basis for development path analysis

- TRLs are a set of 9 levels for assessing the maturity of a technology (level 1: “Basis principles observed” to level 9: “Total system used successfully in project operations”).
- Developed by NASA and are adopted by US DOD and DOE.
- Provides a framework for assessing a development strategy.

- Initial application of TRLs to fusion system clearly underlines the relative immaturity of fusion technologies compared to plasma physics.
- TRLs are very helpful in defining R&D steps and facilities.
We have adopted readiness levels as the basis for our evaluation methodology.

<table>
<thead>
<tr>
<th>TRL</th>
<th>Generic Description (defense acquisitions definitions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and formulated.</td>
</tr>
<tr>
<td>2</td>
<td>Technology concepts and/or applications formulated.</td>
</tr>
<tr>
<td>3</td>
<td>Analytical and experimental demonstration of critical function and/or proof of concept.</td>
</tr>
<tr>
<td>4</td>
<td>Component and/or bench-scale validation in a laboratory environment.</td>
</tr>
<tr>
<td>5</td>
<td>Component and/or breadboard validation in a relevant environment.</td>
</tr>
<tr>
<td>6</td>
<td>System/subsystem model or prototype demonstration in relevant environment.</td>
</tr>
<tr>
<td>7</td>
<td>System prototype demonstration in an operational environment.</td>
</tr>
<tr>
<td>8</td>
<td>Actual system completed and qualified through test and demonstration.</td>
</tr>
<tr>
<td>9</td>
<td>Actual system proven through successful mission operations.</td>
</tr>
</tbody>
</table>

TRL’s express increasing levels of integration and environmental relevance, terms which must be defined for each technology application.
### Example: TRLs for Plasma Facing Components.

<table>
<thead>
<tr>
<th>TRL</th>
<th>TRL Function</th>
<th>Generic Definition</th>
<th>Issue-Specific Definition</th>
<th>Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and formulated.</td>
<td>System studies to define tradeoffs and requirements on heat flux level, particle flux level, and effects on PFC's (temperature, mass transfer).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Technology concepts and/or applications formulated.</td>
<td>PFC concepts including armor and cooling configuration explored. Critical parameters characterized.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Analytical and experimental demonstration of critical function and/or proof of concept.</td>
<td>Data from coupon-scale heat flux and particle flux experiments; modeling of governing heat transfer and mass transfer processes as demonstration of function of PFC concept.</td>
<td>Small-scale facilities: e.g. e-beam and PISCES-like</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Component and/or bench-scale validation in a laboratory environment.</td>
<td>Bench-scale validation of PFC concept through submodule testing in lab environment simulating heat fluxes or particle fluxes at prototypical levels over long times.</td>
<td>Larger-scale facilities for submodule testing: Heat flux: e.g. larger-scale-beam Particle flux: e.g. larger-scale PISCES-like High-temperature + all expected range of conditions</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Component and/or breadboard validation in a relevant environment.</td>
<td>Integrated module testing of the PFC concept in an environment simulating the integration of heat fluxes and particle fluxes at prototypical levels over long times.</td>
<td>Integrated large facility: Prototypical plasma particle flux+heat flux e.g. an upgraded DIII-D/JET?</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>System/subsystem model or prototype demonstration in relevant environment.</td>
<td>Integrated testing of the PFC concept subsystem in an environment simulating the integration of heat fluxes and particle fluxes at prototypical levels over long times.</td>
<td>Integrated large facility: Prototypical plasma particle flux+heat flux</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>System prototype demonstration in an operational environment</td>
<td>Prototypic PFC system demonstration in a fusion machine.</td>
<td>Fusion machine ITER, CTF</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Actual system completed and qualified through test and demonstration</td>
<td>Actual PFC system demonstration qualification in a fusion machine over long operating times.</td>
<td>CTF</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Actual system proven through successful mission operations</td>
<td>Actual PFC system operation to end-of-life in fusion reactor with prototypical conditions and all interfacing subsystems.</td>
<td>DEMO</td>
<td></td>
</tr>
</tbody>
</table>

Power-plant relevant High-temperature gas–cooled PFCs

Low-temperature water–cooled PFCs
ARIES Pathways Program is developing “quantitative” measures to assess fusion development scenarios

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  - A new systems-based approach

- Develop metrics for the status of the field and the progress along the development path. Use these metrics to define:
  - What can and should be done in simulation facilities;
  - When we need and are ready to launch a new facility;
  - The mission and requirements of the new facilities;
  - Assess potential contributions of new facilities to move us along the fusion development path.
A new approach to System analysis to better understand the trade-offs

- Typical system analysis of fusion system seek an optimum set of parameters (minimum cost) based on a set of constraints.

- Our experience indicates that such “optimum” design points are usually driven by the constraints.
  - In some cases, a large design window is available when the constraint is “slightly” relaxed, allowing a more “robust” and credible design.

- Our new approach is to develop a large data base of candidate design points for a power plant and examine the available design space using modern visualization and data mining techniques.
We have examined a large portion of “parameter space” for power plants

Physics database was obtained by scanning the following parameters:

- $R$: 4.5 – 9.5 m,
- $B_0$: 5-10 T,
- $\beta_N$: 0.03 – 0.06
- $n/n_{GW}$: 0.4 – 1.1,
- $q_{cyl}$: 3.2 - 4.6,
- $Q$: 20 – 40
- $\kappa$: 1.8 – 2.2,
- $\delta$: 0.6 – 0.8,
- $f_{imp}$: 0.001 – 0.003

Over $10^6$ self-consistent physics data points were generated.

Systems model of a power plant was built around each data point and costed. ARIES-AT high-performance blanket is assumed.

The data base can then be scanned for different limits. For example, the results are shown for three different upper limits on heat flux on divertor exceeds limit: 8, 12, 16, and 20 MW/m$^2$ (using latest ITER rules, core radiation fraction typically $\sim$50%).
Parameter space for a fusion power plant can be identified by examining the generated data base.

- **flux limit boundary**

  - Red: Max. heat flux on divertor = 20 MW/m²
  - Yellow: Max. heat flux on divertor = 16 MW/m²
  - Green: Max. heat flux on divertor = 12 MW/m²
  - Blue: Max. heat flux on divertor = 8 MW/m²
Traditional system code analysis only identifies the boundaries of the parameter space.

\[ P_{\text{net electric}} = (1000 \pm 5) \text{MW} \]
Increasing power density allows access to more economical devices. But improvement saturates.

Max. heat flux on divertor = 8 MW/m²

Max. heat flux on divertor = 12 MW/m²

Max. heat flux on divertor = 16 MW/m²
Power density Parameter Space

Increasing power density allows access to more economical devices

- Max. heat flux on divertor = 8 MW/m²
- Max. heat flux on divertor = 12 MW/m²
- Max. heat flux on divertor = 16 MW/m²
- Max. heat flux on divertor = 20 MW/m²

But improvement saturates
Greenwald density fraction, however, appears not to be a critical parameter.
Summary

- Current fusion development plans relies on large scale, expensive facilities. There is a difficult learning period between facilities (long lead times, $$$).
- We need to focus on the “development path” and use modern tools for “product development” to assess fusion development path.
  - Technical Readiness Levels (TRLs)
  - Science-based engineering development with Final validation in an integrated, prototypical environment (as opposed to cook and look)
  - We should first focus on parameters that has the greatest impact on the final products. Our new approach to system analysis allows detailed examination of parameter space and cab utilized to optimize the development path (e.g., risk/benefit analysis).
Thank you!
Any Questions?