Fusion Development Path: A Roll-Back Approach Based on Conceptual Power Plant Studies

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We are transitioning from the Era of Fusion Science to the Era of Fusion Power

- Large-scale fusion facilities beyond ITER and NIF can only be justified in the context of their contribution to world energy supply. We will have
  - Different Customers (e.g., Power Producers)
  - Different criteria for success (e.g., Commercial viability)
  - Timing (e.g., Is there a market need?)
  - **Fusion is NOT the only game in town!**
- Is the currently envisioned fusion development path allows us the flexibility to respond to this changing circumstances?
  - Developing alternative plans and small changes in R&D today can have profound difference a decade from now.

ARIES Research Aims at a Balance Between Attractiveness & Feasibility

Top –Level Requirements for Commercial Fusion Power

- **Have an economically competitive life-cycle cost of electricity:**
  - Low recirculating power;
  - High power density;
  - High thermal conversion efficiency;
  - Less-expensive systems.
- **Gain Public acceptance by having excellent safety and environmental characteristics:**
  - Use low-activation and low toxicity materials and care in design.
- **Have operational reliability and high availability:**
  - Ease of maintenance, design margins, and extensive R&D.

- **Choice of Fusion Technologies Have a Dramatic Impact of Attractiveness of Fusion**

Power Plant Needs and State of Current Achievements

Technical Readiness Levels provides a basis for assessing the development strategy

Level	Generic Description
1	Basic principles observed and formulated.
2	Technology concepts and/or applications formulated.
3	Analytical and experimental demonstration of critical function and/or proof of concept.
4	Component and/or bench-scale validation in a laboratory environment.
5	Component and/or breadboard validation in a relevant environment.
6	System/subsystem model or prototype demonstration in relevant environment.
7	System prototype demonstration in an operational environment.
8	Actual system completed and qualified through test and demonstration.
9	Actual system proven through successful mission operations.

Increased integration

Increased Fidelity of environment

Basic & Applied Science Phase (Levels 1–6)

Validation Phase (Levels 7–8)

- Developed by NASA and are adopted by US DOD and DOE.
- TRLs are very helpful in defining R&D steps and facilities.

Example: TRLs for Plasma Facing Components

	Issue-Specific Description	Facilities
1	System studies to define tradeoffs and requirements on heat flux level, particle flux level, effects on PFC's (temperature, mass transfer).	Design studies, basic research
2	PFC concepts including armor and cooling configuration explored. Critical paramete	Code development, applied research
3	Data from coupon-scale heat and particle flux experiments; modeling of governing heat and mass transfer processes as demonstration of function of PFC concept.	Small-scale facilities: *e.g.*, e-beam and plasma simulators
4	Bench-scale validation of PFC concept through submodule testing in lab environment simulating heat fluxes or particle fluxes at prototypical levels over long times.	Larger-scale facilities for submodule testing, High-temperature + all expected range of conditions
5	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.	Integrated large facility: Prototypical plasma particle flux+heat flux (*e.g.* an upgraded DIII-D/JET?)
6	Integrated testing of the PFC concept subsystem in an environment simulatin levels ov	Integrated large facility: Prototypical plasma
7	Prototypic PFC system demonstration in a fusion machine.	Fusion machine ITER (w/ prototypic divertor), CTF
8	Actual PFC system demonstration qualification in a fusion machine over long operating times.	CTF
9	Actual PFC system operation to end-of-life in fusion reactor with prototypical conditions and all interfacing subsystems.	DEMO

Power-plant relevant high-temperature gas-cooled PFC

Low-temperature water-cooled PFC

Application to power plant systems highlights early stage of fusion engineering development

Example application of TRLs to power plant systems

	TRL								
	1	2	3	4	5	6	7	8	9
Power management									
Plasma power distribution	Completed	Completed	Completed	In Progress					
Heat and particle flux handling	Completed	Completed	In Progress						
High temperature and power conversion	Completed	Completed	In Progress						
Power core fabrication	Completed	Completed	In Progress						
Power core lifetime	Completed	Completed	In Progress						
Safety and environment									
Tritium control and confinement	Completed	Completed	Completed	In Progress					
Activation product control	Completed	Completed	Completed	Completed					
Radioactive waste management	Completed	Completed	In Progress						
Reliable/stable plant operations									
Plasma control	Completed	Completed	Completed	Completed					
Plant integrated control	Completed	Completed	In Progress						
Fuel cycle control	Completed	Completed	In Progress						
Maintenance	Completed								

(dark blue)	**Completed**
(light blue)	**In Progress**

For Details See ARIES Web site: http://aries.ucsd.edu (TRL Report)

ITER will provide substantial progress in some areas (plasma, safety)

	TRL								
	1	2	3	4	5	6	7	8	9
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Fuel cycle control									
Maintenance									

Absence of power-plant relevant technologies and limited capabilities severely limits ITER's contributions in many areas.

	Completed
	In Progress
	ITER

Substantial applied research is needed before integrated experiments to be contemplated

	Completed
	In Progress
	ITER

	TRL								
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Basic & Applied Science Phase

System demonstration and validation in operational environment

1st power plant

Some thoughts on Fusion Development

Currently envisioned development path has many shortcomings

Reference "Fast Track" Scenario:

10 years	+ 10 years	+ 10 years ≈ 30-35 years
build ITER	*exploit ITER*	*build DEMO*
+ *IFMIF*	+ *IFMIF*	*(Technology Validation)*

ITER construction delay, First DT plasma 2026? IFMIF?

TBM Experimental Program is not defined!
+10-20 years
~ 2026-2040

1) Large & expensive facility, Funding, EDA, construction ~ 20 years.
2) Requires > 10 years of operation
~ 2060-2070

2070:
Decision to field 1st commercial plant barring NO SETBACK

Bottle neck: Sequential Approach relying on expensive machines!

Fusion Energy Development Focuses on Facilities Rather than the Needed Science

- Current fusion development plans relies on large scale, expensive facilities:
  - Long lead times, $$$
  - Expensive operation time
  - Limited number of concepts that can be tested
  - Integrated tests either succeed or fail, this is an expensive and time-consuming approach to optimize concepts.

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 should Focus on Developing a Faster Fusion Energy Development Path!

- Use modern approaches for to “product development” (e.g., science-based engineering development vs “cook and look”)
  - Extensive “out-of-pile” testing to understand fundamental processes
  - Extensive use of simulation techniques to explore many of synergetic effects and define new experiments.
  - Careful planning of integrated experiments
  - Aiming for Validation in a fully integrated system
- Can we divide what needs to be done into separate “pieces”
  - R&D can be done in parallel (shorter development time)
  - Reduced requirements on the test stand (cheaper/faster
  - **Issues:** 1) Integration Risk, 2) Feasibility/cost?

A faster fusion development program requires decoupling of fusion engineering development from ITER

ITER construction delay, First DT plasma 2021? IFMIF?

ITER burning plasma experiments 2026-2035
Sat. tokamaks 2016-2035

IFMIF (…-2030)

Aggressive science-based R&D utilizing out-of-pile experiments
10 years (2020)
Funding Limited

Driven CTF (low Q)
6 years construction
10 years operation
(2020-2035)

1st of a kind Commercial power plant

2035:
Decision to field 1st commercial plant

Key is aggressive science-based engineering up-front

Thank you!

CTF should focus on validation and demonstration rather than experimentation

- Demo: Build and operated by industry (may be with government subsidy), Demo should demonstrate that fusion is a commercial reality (different than EU definition)
  - There should be NO open questions going from Demo to commercial (similar physics and technology, …)
- CTF: Integration of fusion nuclear technology with a fusion plasma (copious amount of fusion power but not necessarily a burning plasma). At the of its program, CTF should have demonstrated:
  - Complete fuel cycle with tritium accountability.
  - Power and particle management.
  - Necessary date for safety & licensing of a fusion facility.
  - Operability of a fusion energy facility, including plasma control, reliability of components, inspectability and maintainability of a power plant relevant device.
  - Large industrial involvement so that industry can attempt the Demo.

Can we develop fusion rapidly?

- Issues:
  - expertise (scientific workforce)
  - Test facilities (small and Medium scale)
  - Industrial involvement
  - Funding
- Considering the current state of Fusion Engineering, we need 5-10 years of program growth before the elements of a balanced program are in place and we are ready to field a CTF.
- Such a science-based engineering approach, will provide the data base and expertise needed to field a successful CTF in parallel to ITER ignition campaign and can lead to fielding a fusion Demo within 20-25 years.

Integration Risk Can Be Minimized

- Integration risk can be minimized if the device is divided along "Physical" boundaries as opposed to scientific/technical disciplines.
- MFE devices naturally divide along the in-vessel components:
  - **Plasma** only sees the first < 1mm of the in-vessel components and the EM field. (ITER results are applicable to power plant although no power producing blanket exists!)
  - **Power technologies** (all components between plasma and coils) see only neutron, heat, and EM loads (and the first <1mm also sees particle loads). It does not matter if the plasma is ignited or not!

- **Questions: Can we get "prototypical" neutron, heat particle, and EM loads in a smaller (i.e., "cheaper") device?**
  - <u>Developing power technologies is a "wider" mission than blanket or component testing.</u>