A Pilot Plant: The Fastest Path to Net Electricity from Fusion

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The MFE Program Needs to Move Faster

**Situation**

- Need to demonstrate the practicality of MFE soon.
- But: ITER’s earliest-case first plasma is in 2018.
  Earliest-case $Q = 10, 300 – 500$ seconds in 2028.

**Implications**

⇒ Building a Component Test Facility and *then* building Demo to produce net electricity may not be the fastest path.

⇒ Consider construction of a device to make *net electricity* as soon as a technically sound design can be developed.
  - $Q_{\text{eng}} > 1 \equiv \text{“Pilot Plant”},$ making net electricity.
  - Pilot Plant would also perform the component testing mission.
Three Key Science Needs for a Technically Sound MFE Pilot Plant Design

- Plasma Performance (Including ITER + Alternates)
- Integrated Plasma Material Interface
- Neutron Material Interactions

Themes from FESAC Priorities, Gaps and Opportunities Report (ReNeW Themes 1, 2 & 5 included in Plasma Performance)
What Science is Needed for a Technically Sound MFE Pilot Plant Design? (1)

Plasma Performance

• Scaling of confinement, operating limits and sustainment in non-inductive plasmas
• Confinement scaling to relevant $\rho^*$ and $\nu^*$
• Alpha heating physics
• Scaling information at low A
  • Power plant maintenance most credible at low A.
• Scaling information for stellarators
  • Stellarators most credible for disruption avoidance, sustainment with low recirculating power
• Are there faster/better/cheaper alternatives?
  • ICCs
Example: Confinement Scaling to ITER Long-Pulse “Hybrid” Mode Uncertain

Projection to CTF, Pilot Plant or Demo is not settled. Latest matched DIII-D + JET results look better on these axes, but still do not give needed favorable “Gyro-Bohm” scaling of B_τ.
What Science is Needed for a Technically Sound MFE Pilot Plant Design? (2)

Integrated Plasma-Materials Interface

- High heat and particle flux and fluence
  - What divertor designs work at needed power & duty factor?
  - What materials work at needed power & duty factor?
- Tritium retention
  - How to remove tritium in continuous operation?
  - All plasma-facing components (PFCs) must operate very hot.
- Dust production
  - How to remove dust in continuous operation?
- Practical experience with high-pressure He-cooled PFCs
- Practical experience with liquid metal PFCs
- Effects of ELMs and high-energy disruptions
  - Major issue for blanket / first wall survival in tokamaks & STs.

Significant synergy with many IFE concepts.
Pilot Plant PMI Challenges Similar to PMI Challenges Projected for CTF

• Heat flux, pulse length, duty factor for Pilot Plant (PP) ~ CTF
  - CTF: 2x ITER’s heat flux  Demo: 4x ITER’s heat flux
  - CTF: 2 week pulses  Demo: Few month pulses
  - CTF: 30% duty factor  Demo: up to ~70% duty factor

• Real-time dust removal, tritium inventory control and component lifetime issues are challenging due to CTF, PP & Demo missions
  - Must remove dust and tritium in real time: CTF, PP, Demo
  - Need to demonstrate PFC solution that allows long periods of high power operation between change-outs, including off-normal events: CTF, PP, Demo
  - ITER with few % duty factor, plans to change out divertors after ~ 0.08 full-power years – at much lower power density.

• Many solutions used on ITER are not CTF, PP or Demo relevant.
  - Beryllium first wall
  - Stainless-steel vacuum vessel
  - Water cooled ~200C PFCs
  - Intermittent dust collection and tritium clean-up

CTF, PP or Demo: All Would Need New PMI Solutions.
What Science is Needed for a Technically Sound MFE Pilot Plant Design? (3)

• A strong blanket technology program is required for CTF, PP or Demo.
• Design of CTF, PP or Demo would be informed by a powerful point neutron source such as IFMIF (or MTS?). For example:
  • Vacuum vessel design depends on properties of hot main blankets: electrical conduction paths, structural integrity, size, services (coolant, T purge fluid).
  • Hot main blanket design depends on material properties w/14 MeV neutrons.
  • Same logic holds for many other components, e.g., divertors, antennas.
  • Point neutron source needed to develop materials for test blankets.
• Tritium breeding uncertainties can be mitigated by Li isotopic mix.
  • Tritium cycle can be confirmed in Pilot Plant.
• ReNeW on this topic:
  A later possibility might be to include a provision for materials irradiation capabilities as part of a large-scale nuclear facility such as the proposed Fusion Nuclear Science Facility. However, it must be emphasized that bulk material property data from a fusion relevant neutron source would inform the design, construction and licensing of such facilities.

A point neutron source has high synergy with many IFE concepts.
Facilities to Contribute to a Technically Sound MFE Pilot Plant Design

Plasma Performance
Existing Tokamaks, Asian S/C Tokamaks, ITER, NSTX, MAST, LHD, W7-X, (NCSX?)

Integrated PMI
Existing Tokamaks, Asian S/C Tokamaks, ITER, NSTX, MAST, Test Stands, Integrated PMI Facility
(Significant synergy with IFE)

Neutron-Materials
Fission Reactors, Ion Beams, Blanket Test Stands, IFMIF (or MTS?)
(Strong synergy with IFE)
Roles of Major Facilities

- **Plasma Performance**
  - ITER for $\rho^*$ scaling, $\alpha$–particle heating
  - Existing tokamaks, Asian S/C tokamaks for AT pilot plant option
  - LHD, W7-X, (NCSX?) at relevant $\beta$ and $\nu*$ for stellarator pilot plant option
  - NSTX, MAST at relevant $\beta$ and $\nu*$ for low aspect ratio pilot plant option

- **Integrated Plasma-Material Interface**
  - Existing tokamaks, Asian S/C tokamaks, NSTX-U, MAST, test stands, for initial tests of new PFC geometries and materials.
  - ITER for effects of high-energy ELMs and disruptions.
  - Long-pulse, hot walls, high-heat-flux DD confinement facility for integrated power and particle handling studies. Develops solutions for divertor lifetime, tritium retention, dust clean-up, long-pulse disruption avoidance.

- **Neutron Material Interactions**
  - Fission reactors, ion beams to sieve candidate materials.
  - Blanket test stands to develop required technologies.
  - IFMIF (or MTS?) with correct He/dpa to investigate materials physics at high fluence; qualify materials to be used in PP design, then test blankets.
Is a Pilot Plant Smaller than a Demo?

- Assume conservatively that recirculating power, $P_{\text{rec}}$, is constant from Pilot Plant (PP) to Demo
- Assume recirculating fraction in Demo is 20%; $Q_{\text{eng}} = 5$
- Assume Pilot Plant $Q_{\text{eng}} = 1.2$
- $P_{e,\text{gross,Demo}} = 5 P_{\text{rec}}$; $P_{e,\text{gross,PP}} = 1.2 P_{\text{rec}}$
- $P_{e,\text{gross,PP}} = 0.24 P_{e,\text{gross,Demo}}$
- Assume Demo-level $B$ & $\beta \Rightarrow R^3 \propto P_{\text{fus}} \propto P_{e,\text{gross}}$
  
  Assume adequate confinement
- $P_{\text{fus,PP}} = 0.24 P_{\text{fus,Demo}}$; $R_{\text{PP}} = 0.62 R_{\text{Demo}}$
- Neutron wall loading in Pilot Plant $= 0.62$ Demo neutron wall loading

Obviously there are other factors (e.g., neutron m.f.p.). On the other hand $P_{\text{rec}} = \text{constant}$ is conservative. Initial looks at Tokamak, ST, Stellarator support $R_{\text{PP}} \sim 0.6 R_{\text{Demo}}$
Spreadsheet Pilot Plants Assuming High Confinement are Encouraging

• **Tokamak**
  - \( R/a = 4.0m/1.0m, B_0 = 6T, I_p = 8MA \)
  - \( H = 1.5, P_{fus} = 520MW, Q_p = 10, Q_{eng} \approx 1 \)

• **ST**
  - \( R/a = 1.5m/0.9m, B_0 = 2.2T, I_p = 15 MA \)
  - \( H = 1.7, P_{fus} = 500MW, Q_p = 25, Q_{eng} \approx 1 \)

• **Stellarator**
  - \( R/<a> = 4.5m/1.0m, B_0 = 5.7T \)
  - \( H_{ISS04} = 2, P_{fus} = 470MW, Q_p = 40, Q_{eng} \approx 4 \)

These spreadsheet analyses are only very first looks. Engineering scaled simply from ARIES studies.
Much More Analysis is Required

• **What would an MFE Pilot Plant look like?**
  – Advanced Tokamak (Superconducting for $Q_{\text{eng}} > 1$)
  – Spherical Torus (Most readily maintained configuration)
  – Stellarator (Lowest recirculating power, no disruptions)

  *Any design should prototype Demo maintenance approach.*

• **What near-term program of Modeling, Test Stand R&D, New Facilities is necessary to support a Pilot Plant?**
  – Plasma performance
  – Integrated plasma material interface
  – Neutron interactive materials
A Pilot Plant is an Exciting Goal

• We can explain it to our sponsors and the public
  – We have a plan to make net electricity soon.
  – This will put fusion “on the map” as an energy option.

• It would culminate the key FESAC Themes
  – Creating Predictable High-Performance Steady-State Plasmas
  – Taming the Plasma-Material Interface
  – Harnessing Fusion Power

• ARIES + Fusion Community Pilot Plant Study?
  – What would a tokamak, ST or stellarator Pilot Plant look like?
  – What supporting program is needed for a technically sound design?
  – A similar IFE Pilot Plant study should be carried out in parallel.