The Fusion Nuclear Regime, Our Next Step
What Does it Need to Do?

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SOFE Town Hall on Fusion Energy, June 4, 2019
The Compact Pilot Plant (CPP)

The Compact Pilot Plant is identified in the National Academy Study report

2\textsuperscript{nd} Major Recommendation: the US should start a national program of interconnected science and technology research extending beyond what will be accomplished with ITER and leading to construction of a compact fusion pilot plant at the lowest possible capital cost

In first phase, pilot plant should be capable of demonstrating fusion electricity for periods lasting minutes.....

In the second phase, the pilot plant should be capable of uninterrupted operation for many days allowing fusion materials and component testing consistent with a commercial power plant......

What is compact? Size, cost, power....... Lowest possible cost, and leading to low COE?
Lower unit electric power plants as the end product?
Presumably fusion electricity is net electricity
Are two phases actually required? Do the two phases require different fusion cores?
Why is it called a Pilot Plant? Will this be a problem for the Office of Science?
What is the difference between a CPP and an FNSF?
What does a Compact Pilot Plant / Fusion Nuclear Science Facility Need to do?

**Strongly advance fusion neutron exposure** of all fusion core, near-core and ex-core components towards power plant levels

**Utilize and advance fusion power plant relevant materials** addressing radiation resistance, activation, operating temperatures, chemical compatibility, and plasma material damage

**Operate in fusion power plant relevant environmental conditions**; temperatures, pressures/stresses, flow rates, hydrogen, B-field, neutrons, and gradients

**Produce tritium in quantities that closely approaches or exceeds consumption** from fusion reactions, plant losses and decay

**Extract, process, inject, and exhaust significant quantities of tritium** in a manner that meets all safety criteria, requiring a high level of inventory prediction, control and accountancy
What does a Compact Pilot Plant / Fusion Nuclear Science Facility Need to do?

**Routinely operate plasmas for long durations**...generally considered to be days to weeks, and ultimately \( \sim 1 \text{ year} \) for a power plant

**Advance and demonstration enabling technologies that support the very long duration plasma operations** with sufficient performance and reliability to project to DEMO and power plants

**Demonstrate safe and environmentally friendly plant operations**, in particular with respect to tritium leakage, hot cell operations, onsite radioactive material processing and storage, no evacuation plan and meet or exceed all regulatory aspects

**Develop power plant relevant subsystems for robust and high efficiency operation**, including net electricity production, heating and current drive, pumping, heat exchanger, cryo-plant, etc.

**Advance toward high availability**, including gains in subsystem and component reliability, progress in capabilities and efficiency of remote maintenance operations, accumulation of reliability and failure rate data that can be used to project and design future systems
### What is the Fusion Nuclear Regime?

<table>
<thead>
<tr>
<th></th>
<th>ITER</th>
<th>CPP/FNSF</th>
<th>Power Plant (ACT1&amp;2)</th>
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</thead>
<tbody>
<tr>
<td>Fusion power, MW</td>
<td>500</td>
<td>518</td>
<td>1800-2600</td>
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<tr>
<td>Major radius, m</td>
<td>6.2</td>
<td>4.8</td>
<td>6.2-9.8</td>
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<tr>
<td>Ave neutron wall load, MW/m²</td>
<td>0.57 (0.76 peak)</td>
<td>1.2 (1.75 peak)</td>
<td>1.5-2.5 (2.3-3.8 peak)</td>
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<tr>
<td>Plasma pulse length, s</td>
<td>500-3000</td>
<td>10⁵ - 10⁶</td>
<td>3x10⁷</td>
</tr>
<tr>
<td>DT operation, years</td>
<td>20 (~ 1 FPY)</td>
<td>25 (7.8 FPY)</td>
<td>40 FPY</td>
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<tr>
<td>Peak material damage, dpa</td>
<td>3</td>
<td>7, 20, 30, 40, 40-80</td>
<td>150-200</td>
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<td>TBR</td>
<td>1.07</td>
<td>1.05</td>
<td></td>
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<tr>
<td>Materials</td>
<td>SS, CuCrZr, H₂O, W</td>
<td>RAFM, W, SiC-c, He, PbLi, Li₂TiO₃</td>
<td>RAFM, W, SiC-c, He, PbLi, Li₂TiO₃</td>
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<tr>
<td>Operating temperatures</td>
<td>150-285 C</td>
<td>300-600 C</td>
<td>300-600 C</td>
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<tr>
<td>Maintenance</td>
<td>Port based, small piece</td>
<td>Radial, Full sector</td>
<td>Radial, Full sector</td>
</tr>
</tbody>
</table>

- **Fusion power growing**
- **Devices getting larger?**
- **Increasing rate of damage, He prod**
- **Ultra-long plasma durations**
- **High neutron exposure**
- **High damage, He and H production**
- **Tritium self-sufficiency**
- **Transition to fusion nuclear relevant materials**
- **Power plant operating environment**
- **High availability**
Fusion nuclear materials development

Plasma facing materials and components

Blanket and fuel cycle development

Enabling Technologies (magnets, H/CD, fueling, diagnostics, etc.)

Worldwide short and long pulse plasma facilities
JET, ASDEX-U, WEST, JT-60SA, KSTAR, EAST

DIII-D NSTX-U

Plasma Optimization

Notional timeline to establish
Pre-CPP/FNSF R&D
CPP/FNSF Design & Construct
CPP/FNSF Operation

Utilize int’l collaborations where they are better positioned to do R&D
Any Next Step Should be Fusion Nuclear, and Will Involve a Critical Materials-Component Exploration → Optimization

Establish the actual fusion in-service material and scientific/engineering database on all components in the fusion core and near core

- How do materials behave
- How do components behave

Subject to high temperatures,
- high stresses,
- high neutron damage,
- high He and H production,
- hydrogen in material matrix (H, D, T)
- multi-material interfaces
- gradients in all these parameters

The CPP/FNSF needs to push to high nuclear exposures in a systematic way

We must prepare for the CPP/FNSF with 1) fusion prototypic neutron source material exposures, and 2) highly integrated non-nuclear component testing
Tritium, Making it, Retrieving it, Accounting for it, Controlling it

A CPP/FNSF will have to generate its own tritium, although it will have to start with an inventory produced somewhere else (fission plant?)

A CPP/FNSF will be the first complete tritium self-sufficient system

CPP/FNSF producing $P_{\text{fusion}} = 518$ MW

Tritium consumption = 28.8 kg /FPY (ITER lifetime consumption)

DT operation phases, plasma on-time (making neutrons):
- Phase 3 – 274 days....21.6 kg Tritium consumed
- 4 – 460 days....36.3 kg
- 5 – 639 days....50.4 kg
- 6 – 894 days....70.5 kg
- 7 – 894 days....70.5 kg $\rightarrow$ 250 kg T consumed

Single plasma pulse is $\sim 10$ days long, requires 0.79 kg of T

$9.14 \times 10^{-7}$ kg/s of T is consumed (1.82x10$^{20}$ tritons/s)

Tritium breeding ratio = 1.07

Including all penetrations for H/CD, TBM, MTM, diagnostics

Tritium migration modeling, tracking movement and losses

A power plant would consume $\sim 4000-5000$ kg T in its life
A CPP/FNSF Will Have Major Plasma Challenges

The plasma pulse length must grow by ~300 times for a CPP/FNSF and ~10^4 times for a power plant, beyond ITER

With plasma on-times per year advancing from 3x10^-4 for present devices, to 0.05 for ITER, to 0.35 for CPP/FNSF, and 0.85 for power plants

Such long plasma durations raise many questions about the plasma operating point, and require major improvements for plasma support systems

Plasma facing components are metal, we think
What beta to assume? Above the no wall limit?
How high an energy confinement is credible?
100% non-inductive plasma current
Strong plasma shaping, internal feedback coils
Mitigated disruptions? No runaway electrons
ELMs
Density relative to Greenwald density
Radiative divertor solutions, DN or SN?

How Can We Take Full Advantage of a DD Phase on the CPP/FNSF?
Plasma and Engineering Enabling Technologies, the Stuff That Makes it Work

Transitioning to new materials
Transitioning to high temperatures
Long pulse plasma loading
Continuous operation
Nuclear damage and gamma rays
Limited access and resolution

Diagnostics
Plasma Control

TF coil, case and super-structure
Improved LTSC
Magnets
HTSC Tape

Pellet Fueling and Continuous Cryo-pumping
Remote Maintenance

Heating and Current Drive
EC
LH
ICRF
How Compact Can a CPP/FNSF Be?

Inboard build determines the device size for a tokamak

Magnet radiation limits dominate requirements for shielding

Breeding zone thickness determined by TBR requirement

Aspect ratio can drive need for inboard breeding

Material choices for shielding, breeding, structure
He vs H₂O, WC vs Borated-Fe, Cu vs SC

Actual TF/CS magnet builds (winding pack and structural), B and <j>

Burning out components or protecting for plant life

Assumptions for $q_{\text{div, peak}}$, $\beta_N$, $H_{98}$, B
The FNSF Can Actually Provide Both Missions Described in the NAS report for the Pilot Plant

The FNSF design reference operating point for the plasma, was constructed to reflect the power plant regime, but many operating points are available to the device.

<table>
<thead>
<tr>
<th></th>
<th>FNSF-ref</th>
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</thead>
<tbody>
<tr>
<td>Plasma gain ($P_{fus}/P_{aux}$)</td>
<td>Q</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
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<tr>
<td>Engr gain ($P_{elec}/P_{rec}$)</td>
<td>$Q_{engr}$</td>
<td>0.77</td>
<td>0.98</td>
<td>1.12</td>
<td>1.26</td>
<td>1.40</td>
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<tr>
<td>Beta</td>
<td>$\beta_N$</td>
<td>2.5</td>
<td>2.5 - 3.3</td>
<td>2.5 - 3.3</td>
<td>2.8 - 3.3</td>
<td>2.8 - 3.3</td>
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<tr>
<td>Energy confinement</td>
<td>$H_{98}$</td>
<td>1.0</td>
<td>1.2 - 1.6</td>
<td>1.3 - 1.6</td>
<td>1.4 - 1.6</td>
<td>1.4 - 1.6</td>
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<tr>
<td>Density/density limit</td>
<td>$n/n_{Gr}$</td>
<td>0.9</td>
<td>0.45 - 0.9</td>
<td>0.6 - 0.9</td>
<td>0.7 - 0.9</td>
<td>0.7 - 0.9</td>
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<tr>
<td>Net electric power</td>
<td>$P_{net,elec}$</td>
<td>-80</td>
<td>-10 - 17</td>
<td>14 - 27</td>
<td>45 - 60</td>
<td>54 - 95</td>
</tr>
</tbody>
</table>

A facility like the FNSF can produce net electricity by being somewhat more aggressive on plasma physics.
Any Compact Pilot Plant will be very similar to the FNSF

Net electricity can be produced with somewhat more aggressive plasma physics than assumed for the reference operating point in the FNSF, in the same device with the same fusion core.

The NEXT step in the US fusion development path **MUST be Nuclear**, but is not a power plant......whatever you want to call it, a CPP, a FNSF

- Establishing the strongly fusion nuclear & plasma in-service environment for the first time, and optimizing the fusion core material-components
- Establishing the first tritium self-sufficient facility
- Establishing the first sustained ultra-long pulse plasmas and the multiple enabling technologies that support these
- Provide the first integrated operation of a strongly fusion nuclear plant with all relevant subsystems
Backup Slides
A nearer term facility like the FNSF requires a number of technical philosophies/approaches to be defined/explored.

**Pre-FNSF R&D** – how do we see the R&D evolution to prepare us for the FNSF, design and operation

**Facility missions and metrics** – what progress does the facility make on the pathway to a power plant

**Physics strategy** – how do we choose plasma parameters, what’s their impact

**Long term power plant relevance and engineering strategy** – design choices are made to keep the scientific/technology development on track, avoid diversions that do not contribute to the power plant vision

Minimal, Moderate, and Maximal FNSF

**Qualification requirements to install a component/material in the FNSF** – fusion neutron exposure to the dpa level, highly integrated non-nuclear testing.....plasma-vacuum systems are not consistent with “cook and look” approach to FNS, remote-maintenance

**FNSF program plan** – phases, material/temperature/dpa evolution, operation and maintenance

**Blanket (divertor/launchers) choices and testing strategy** – provide the process by which we test and advance fusion core components, and backups

**Hot Cell** – how do we access and process the information from the FNSF operation
Pre-FNSF: Fusion Core Components, Evolution to Integrated Component Testing (Blanket, Divertor, RF Launcher)

- **Breeding blanket**
  - DCLL RA FM 350-550 C (including MTM, TBM, Diag, RF penetrations)
  - DCLL CNA/RA FM 400-600 C (including MTM, TBM, Diag, RF penetrations)
  - DCLL CNA and/or ODS 450-650 C (including MTM, TBM, Diag, RF penetrations)

- **Vacuum Vessel Bainitic Steel**
  - Integrated blanket test

- **Divertor**
  - Tungsten-1 Divertor
  - Tungsten-2 Divertor
  - RAFM/Cu coated RF
  - RAFM/W coated RF

- **RF launchers**
  - RF test stand

- **Linear plasma**
  - Tokamak
  - HHF

- **Tritium Liquid Metal**
  - Integrated blanket test
  - FW →
  - Linear plasma
  - Tokamak
  - HHF

- **US DEMO**
  - Tritium Liquid Metal
  - Integrated blanket test
  - FW →
  - Linear plasma
  - Tokamak
  - HHF
<table>
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<tr>
<th>Phase</th>
<th>1</th>
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<th>5</th>
<th>6</th>
<th>7</th>
<th>PP</th>
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<tr>
<td>He/H DD DT DT DT DT DT PP</td>
<td>1-2</td>
<td>2-3</td>
<td>2.75</td>
<td>4.5</td>
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<td>6.5</td>
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<td>$N_w^{peak}$, MW/m²</td>
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<td>1.75</td>
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<td>Plasma on-</td>
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<td>25</td>
<td>35</td>
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<td>time, %/year</td>
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<td></td>
<td></td>
<td>55 d</td>
<td>91 d</td>
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<td>Plasma duty</td>
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<td>67</td>
<td>91</td>
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<td>cycle, %</td>
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<td></td>
<td>(1d/2d)</td>
<td>(2d/1d)</td>
<td>(5d/.5d)</td>
<td>(10d/.5d)</td>
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<td>Total</td>
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<td>1131 d</td>
<td>1120 d</td>
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<td>maintenance</td>
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<td>200 d/yr</td>
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<td>224 d/yr</td>
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<td>Peak dpa</td>
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<td>7.2</td>
<td>19.7</td>
<td>30.6</td>
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<td>&lt; 550</td>
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<td>RAFM Gen1</td>
<td>RAFM-CNA</td>
<td>RAFM- CNA &amp; ODS</td>
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25.3 years DT, 7.8 years neutrons, 650 plasma pulses
Components in fusion core would be evolved and tested in the FNSF.

We concentrate on the blankets, but there are others that may have a testing sequence.....materials, temperatures, design, etc.
Blanket Layout and Testing

There are several DIFFERENT blanket geometries due to multiple functions in the FNSF

**DCLL 550/400C RAFM** (some are taken for autopsy)

- DCLL 550/400C RAFM/ LH: 1
- DCLL 550/400C RAFM/ EC: 0
- DCLL 550/400C RAFM/ NB: 2
- DCLL 550/400C RAFM/ IC: 1
- DCLL 600/450C RAFM CNA (next phase T and RAFM): 2
- DCLL 550/400C RAFM/ MTM: 1
- DCLL 550/400C RAFM/ TBM-HCLL: 1
- DCLL 550/400C RAFM/ TBM-HCCB(PB): 1
- DCLL 550/400C RAFM/ Diagnostic: 3

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Nuclear analysis of different sectors

Step 9: 1 LH added, 1
Step 10: 3 Diagnostics added, 3
Step 11: 4 TBM added, 4
Step 12: 1 IC added, 1
Step 13: 1 LH added, 1
Step 14: 1 EC added, 1

A. Davis, UW

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Top view
Divertor Testing, must fit into the allocated envelope

What will be the preferred W or other divertor material?
- W or W-alloy
- W/X composites
- W/Wm composites
- ???

Will there be variants like RAFM?
Structure & armor design

Magnetic geometries

Structure Temperature ranges
- Taken from Snead, 2016

W/RAF laminate (Garrison)
W/RAF laminate (Garrison)
FZJ
FZJ
WC in Fe matrix (Álvarez et al., 2015)

X-divertor, KDEMO Covelle, Univ Texas

Flat plat fully detach
\( F_{\text{div,rad}} \approx 100\% \)

ITER-like tilted plate
\( F_{\text{div,rad}} \approx 75\% \)
What do we do with the Sectors: Blankets, Divertors, Launchers in the Hot Cells?

Inspect
Decontaminate (clean off)
Inspect
Dismantle
Inspect
Examine untreated surfaces
Examine mounts/connectors
Cut samples
  FW
  Side wall
  Grid plates
  Mounting hardware
  SR
  Div armor
  Div structure
  FCI
  W stabilizer
  ...... 
Material examinations (PIE, mech prop tests, He bubbles, etc.)
Also examine the test specimens in the material test module & surveillance samples
Hot Cell

We are anticipating a hot cell sequence from large intact sectors progressively down to small material samples, requiring a transfer from hot cell 1 to hot cell 2, etc…. we want information quickly

Robotic and computer controlled systems would dominate the processing 10,000 Sv/hr dose at FW vs 6 mSv/year background

Issues include 1) high dose and hardened equipment, 2) complex processing (tritium, surface materials), 3) decay heat, and 4) need for rapid turnaround
Full Sector Maintenance is Pursued to Provide Fast, Flexible and Reliable Approach

Possible Test Blanket Module (TBM, RF) maintenance

Inspection
Minor Maintenance
Major Maintenance

How much time does it take?