A Vision for Attaining and Exploring a Burning Plasma for Attractive Fusion Power

3. Achieve Q>30 as soon as possible

by Dale Meade summarizing discussions on burning plasma strategy with many colleagues.

3.1. Description of Strategic Approach

Attaining and exploring a burning plasma core suitable for an Attractive Fusion Power Plant is a critical milestone on the path to attractive magnetic fusion energy. Fusion power plant studies [1, 2, 3] have shown that Q > 30 is required for economical fusion energy. This is a highly non-linear regime, where alpha heating and subsequent transport, define the pressure profile. In addition, a self-consistent high-bootstrap current fraction is required for steady-state operation of a tokamak fusion power plant, presenting additional non-linear coupling within the plasma. External control of this self-organized high-gain burning plasma state becomes less practical as the fusion gain is increased. The existence of a stable Attractive Fusion Core (AFC) state is a major scientific issue for the practicality of an attractive magnetic fusion power plant. The broader scientific community has understood for years that the high gain (Q > 30) milestone must be accomplished in the path to attractive fusion energy. For example, John Holdren, President's Science Advisor (2010-2015) has stated that "until we can understand and master the physics of a **burning plasma—a plasma that is generating enough fusion energy to sustain its temperature and density**—we will not know whether fusion can ever be managed as a practical energy source" [4].

There are several strategic possibilities to accomplish the Attractive Fusion Core Mission:

1. An early achievement at the smallest size, lowest cost and program risk that focuses on the exploration of the Q > 30 non-linear burning plasma regime and employs existing technologies to the extent possible, and only employing extensions of existing technologies (e.g. PMI/Divertor) where required to access the non-linear burning plasma regime.

2. A mid-term achievement of very long pulse sustainment of Q > 30 at larger size to accommodate the shielding required to protect high temperature superconducting coils (HTS) from sustained thermal loads and neutron damage, but without a tritium breeding blanket. This approach would allow sustained high performance at Q > 30 and would employ nuclear technologies only to meet the Q > 30 Mission thereby avoiding the even larger size and complexity that a breeding blanket would require. This mission would constrained by the tritium site inventory and associated safety regulations that would limit the pulse duration, repetition rate and total neutron fluence. This facility would require a PFC/divertor with fusion relevant PFC materials capable of handling DEMO scale power densities, but would not require neutron resistant structural materials.

3. A longer term achievement Q > 30 on a demonstration power plant (DEMO) scale facility based on high- field high temperature superconducting (HTS) coils. This would be the largest size, highest cost facility and carrying with it the increased risk of trying to control non-linear Q > 30 plasmas with reactor scale plasma energies for the first time. This is not the recommended strategy for developing a new technology.

This White Paper will focus on the fastest path with lowest risk and cost to an Attractive Fusion Core Experiment (AFCX) capable of attaining and exploring a $Q > 30$ plasma by choosing the high-density high-field approach, and making a slight modification to the FIRE-2004 Design that was vetted at Snowmass 2002 and carried through to a successful Physics Validation Review by DOE in 2004. Increasing the linear dimensions for FIRE-2004 by 10% (isomorphic transformation) maintains the same magnetic stresses in the magnetic coils. As an example, the projected H-Mode performance with fixed profiles increases to $Q > 30$ using ITER98(y, 2) scaling with $H98 \leq 1$, $n/n_{GW} \approx 0.7$ and $\beta_N \approx 1.7$. This AFCX approach is not a replacement for ITER, it is a separate complementary mission of attaining $Q > 30$ that is unattainable by ITER using the same design criteria and the existing ITER engineering limits. AFCX would be of the same physical scale as prior DT experiments, TFTR and JET, that were constructed in ~ 8 years. This approach was technically ready in 1989, and would take advantage of prior design activities, CIT (1986-1989), BPX (1990-1991) and FIRE (1998-2005). During the intervening 13 years there have been advances in physics, engineering and manufacturing can be used to further optimize performance and reduce construction costs.

Table 1. Parameters of DT Tokamaks	TFTR	AFCX	JET	ITER	ARIES
Major radius (m)	2.5	2.35	2.8	6.2	5.2
Plasma Volume (m^3)	30	41	80	840	350
B (T)	5.6	10	4	5.3	6
Q = Fusion Power/Ext Heating Power	0.3	>30	0.7	10	45
Fusion Power (MW)	11	~200	16	500	1760
Fusion Power density (MWm^{-3})	0.37	~5	0.18	0.61	5.0
Tritium Site Inventory (gmT)	5	30	90	~2,000	~3,000
Start of DT ops	1993	~2037	1997	~2037	TBD
Construction Cost	$0.7B	~$2B	$0.8B	~$50B*	TBD

* Based on official cost estimates of US (9.1%) [11] and EU (45.3%) [12] shares in ITER.

The AFCX design would:

- Incorporate advanced tokamak features (e.g.. shaping, Hi-B CD, etc) into the basic design
- Incorporate advanced divertor and PFCs to deal with reactor relevant power densities
- Exploit benefits of high plasma density: stabilize TAEs, enhance radiation of exhaust plasma energy, mitigation of disruption runaway avalanche, etc
- Exploit innovations in design, construction, manufacturing, and materials to reduce cost and improve performance.

3.2 Benefits – This strategic element would allow the U. S. magnetic fusion program to retire the critical $Q > 30$ milestone risk as early as possible at the lowest cost, and would provide the justification for proceeding with the construction of integrated fusion nuclear projects (FNSF, DEMO, Pilot Plant, and commercial power plants). This activity would re-establish the US as a world leader in magnetic fusion research, and would provide a driving focus for strengthening and sustaining the U.S. scientific, engineering and industrial fusion infrastructure for decades. This approach would allow the large integrated nuclear technology facilities built after ITER to be designed with confidence to reach Q values required for an attractive fusion power plant, instead of having the additional requirement of being designed to be an advanced burning plasma experiment. The risk of cost increases and schedule delays is reduced since comparable scale copper coil DT facilities with comparable tritium site inventories have already been constructed (TFTR, JET). This approach is consistent with the technical assessment at Snowmass 2002 -- "*A FIRE-based development plan reduces initial facility investment costs and allows optimization of experiments for separable missions. It is a lower risk option, as it requires "smaller" extrapolation in physics and technology basis. Assuming a successful outcome, a FIRE-based development path provides further optimization before integration steps, allowing a more advanced and/or less costly integration step to follow.*" [5]

Previously this high-density high-field approach was considered at a dead-end after the high-gain burn demonstration due to lack of a high field superconductor to carry the design forward to a power plant. **However, advances over the past decade in high-field high-temperature superconductors now make the high-density high-field path feasible all the way to an attractive Fusion Power Plant**. [6]

3.3 Strategic Elements

A successful Q > 30 technical achievement would provide research advancing the following strategic elements discussed during the U. S. Fusion Community process. The evaluation of contributions based on the AFCX approach is illustrated in Table 2 with 10 being required for a power plant.

Table 2: Contributions for Q > 30: AFCX	1	2	3	4	5	6	7	8	9	10
1. Burning Plasmas	▨	▨	▨	▨	▨	▨	▨	▨	▨	
2. HTS Magnet Development	▨	▨	▨							
3. Configuration Research	▨	▨	▨							
4. Stellarators	▨	▨	▨							
5. Theory/Computation	▨	▨	▨	▨	▨					
6. Plasma-materials and divertor	▨	▨	▨	▨	▨	▨	▨			
7. Fusion nuclear materials	▨	▨								
8. Tritium fuel cycle	▨	▨								
9. Sustained High Performance Tokamaks	▨	▨	▨	▨	▨	▨				

Burning Plasmas – Previous burning plasma experiments on TFTR (1993-1997) and JET have produced over 10 MW of fusion power and explored the physics of the weakly burning regime (Q ~ 1). Important results included: isotope effect on energy confinement, confirmation of expectations for: alpha particle confinement, alpha heating of electrons, collisional transfer of alpha energy to the electrons, excitation of alpha-driven TAE modes and alpha ash transport. The achievement of Q > 30 would essentially retire all the tokamak burning plasma technical risk, particularly the risk associated with attaining and controlling a tokamak fusion power plant burning plasma. There would be some risk remaining regarding the long time sustainment of a Q > 30 plasma in a tokamak that would remain as a major objective for DEMO.

HTS Development – This achievement does not require HTS coils, but would have the impact of stimulating the urgent development of high field HTS coils for implementation on large integrated fusion facilities of the DEMO scale that would follow.

Stellarators – While stellarators do not require a bootstrap current for plasma sustainment, the dynamics of a burning plasma modifying the plasma pressure profile in accordance with local plasma energy transport thereby creating bootstrap currents is of great importance to address the issue of $Q > 30$ performance in a stellarator.

Configuration Research – Many of the systems under study in Configuration Research depend on a large degree of self-organization, and therefore must also address the issue of whether a stable high Q state is possible.

Theory/Computation – A significant theory/computation effort should be initiated to model the performance of self-organized high fusion gain plasmas. This capability would be essential in analyzing high-gain experiments and in refining the high-gain experimental program.

Plasma-materials and divertor – The most attractive approach to high gain involves a high density plasma operating with fusion power plant scale divertor and exhaust power densities for moderate pulse lengths and low duty cycle. This is a significant challenge for plasma facing components and the divertor. This is a high priority area no matter what future path is chosen for magnetic fusion. A significant focused effort should be immediately launched in this area. The $Q > 30$ initiative would provide a very convincing test of PMI/divertor capabilities on a fusion plasma with the exception of long time scale material migration and neutron damage effects on the properties of plasma facing and divertor materials.

Fusion nuclear materials – The $Q > 30$ initiative would not require neutron resistant structural materials. However, the damage to coil insulation would provide a limit to the production of fusion energy, which in FIRE was 6.5 TJ of fusion energy resulting in a total of 30,000 pulses including ≈ 3000 full power full pulse length pulses. This area needs to be revisited for recent advances in materials and for the increased fusion power and longer pulses in AFCX.

Tritium fuel cycle – The tritium site inventory requirements for a compact high field $Q > 30$ initiative are ≤ 30 gmT similar to TFTR (≤ 5 gmT) and JET (≤ 90 gmT) and much less than the ≈2,000 gmT site inventory for ITER. No significant development beyond TFTR/JET is required.

Sustained high performance tokamak – The strategy would be to do the $Q > 30$ achievement at modest pulse length first and then use that information as input for the design of a Sustained High Performance ($Q > 30$) tokamak, such as a compact high-field (HTS) DEMO Class facility.

3.4 Impact of ITER – The ITER project was initiated in 2006 with the goal of producing $Q \approx 10$ at fusion power levels of 500 MW. Important physics goals include: determination of plasma energy confinement at large scale and exploring alpha particle physics when the alpha heating power is ~ twice the external heating power. At these conditions, the plasma pressure profile is not modified significantly by the self-heating and 33% of the plasma heating power is available to control the plasma behavior. Under the most optimistic conditions, it is expected that ITER could begin DT operation in 2036. [10]

The Q > 30 initiative is envisioned as an effort in parallel to ITER with a complementary mission that is aimed at a different operating regime – high-field, high-density with strong non-linear self-organization. There would be a commonality of needs for some DT compatible systems such as: auxiliary heating, PFC/divertor, diagnostics and plasma control actuators.

3.5 International Context – The major international programs will extend previous weakly burning DT plasma experiments with Q ~ 1 in JET (2019) to determine plasma performance projections for ITER-like plasma facing components (Be first wall and W divertor targets). Beginning in 2020, sustained Advanced Tokamak non-burning DD plasmas will be explored at large size (R = 3m, B = 2.25T) in JT60-SA, and at smaller size in EAST and KSTAR for longer plasma durations. This would be followed, beginning in early 2037, by DT experiments with Q ≈ 10 and fusion powers of 500 MW at near reactor size (R = 6.2m, B=5.3T) in ITER. There is currently no facility in international fusion program plans capable of exploring Q > 30 burning plasma physics prior to the construction of DEMO.

3.6 Decision Points: The AFCX Q > 30 achievement is put forward as part of a **technical issues driven** Multi-Machine Development Plan [5]. The major elements are:

1. Non-Burning Plasma Confinement - existing Tokamaks + JT60SA (2020)
   Theory and Modeling of high-gain non-linear burning plasmas (new initiative)
2. Non-Burning PMI/Divertor - existing tokamak upgrades, linear, and focused DTT
3. Burning Plasmas- JET(Q~1, 2020), ITER (Q ≈ 10, 2038) and AFCX(Q ≥ 30, 2038)
4. Materials Development - fission and spallation neutron sources, IFMIF (2028)
5. Integrated Nuclear Test Facilities – Fusion Nuclear Science Facility (FNSF) for Closing the Fuel Cycle and Neutron Testing of components in a fusion environment.
6. Fusion Demonstration Scale Nuclear Facilities – DEMO, Pilot Plant, Net-Electric Demo

Input Links: For AFCX, the present confinement physics (similar to ITER) is sufficient for initial design. Results from JT60-SA, EAST, KSTAR on AT modes will be used to refine design for current drive systems during facility construction. There is a major link to PMI/Divertor research that is needed to update the prior FIRE divertor design, and to decide on the appropriate material for the first wall. The present Be first wall (like ITER) is not suitable for a DEMO- should this be changed to a DEMO-relevant material? Theory and computer models will be used to predict behavior and develop operating regimes for high-gain non-linear plasmas.
Output Links: The most critical output is data on attaining Q≥ 30 and controlling the non-linear high-gain burning plasma state. In addition, the data on the performance of the PMI/divertor at high power densities will be critical for the design of a DEMO leading to attractive fusion power. Note: an FNSF would be needed in parallel with the Q> 30 initiative to support a U. S. style DEMO design.

3.7 Rough timeline:

1. Immediate actions
   - Update/assess projections of plasma performance and engineering design of AFCX.
   - Update and assess possible revisions to FIRE PFC/Divertor Design
   - Initiate a more focused Divertor Test Program with fusion relevant materials ASAP on existing facilities. Utilize international facilities with fusion relevant PFC materials

   Complete CD-1 in 2 years

2. Complete design, begin staged construction (similar to ITER)**. Complete CD-2 in 4 years**
3. Complete Stage 1 Construction and begin initial non-DT operations **Complete in 7 years**
4. Complete Stage 2 Construction, System and plasma commissioning and ready to begin DT **Complete CD-4** in **5 years**

3.8 Concluding Remarks

The key technical issue for magnetic fusion energy is whether a high gain Q >30 burning plasma confined by a magnetic field can be attained and controlled. This is part of an issues driven strategic approach based on the traditional strategy for developing high technology products, **namely resolving key fusion power plant technical issues before building large expensive nuclear integration facilities of the DEMO Class** (DEMO, Pilot Plant, Net-Electric Demo). This is similar to the approach recommended by the National Academy review of Inertial Fusion Energy (2013).

This approach would have the lowest overall risk, the shortest time scale and lowest overall cost.

3.10 References

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