Fusion Science Review Board
Considerations for Oversight by a Fusion Energy Consortium

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The “fusion” devil is in the details!! Nobel Peace laureate Andre Sakharov has been quoted by his Russian colleagues, some whom I know personally, as saying “with one (appropriate) false assumption, you can prove any theory.” In fusion, changing one or several really big “ifs” into (an assumed) certainty allows one to project putting electrical power on the grid quickly. And in fusion, it is often quite difficult to sort out real achievements, i.e., facts, from religious-like beliefs. An independent expert panel as unbiased as possible and free from funding dependency, i.e., something equivalent to a fusion “supreme court,” must be formed to sort through the facts and beliefs and make a technical judgment that can provide guidance to investors. Such a panel can readily be formed in the present time because of the large number of fusion experts who have retired over the last decade or two and who are now free from the “don’t bite the hand that feeds you” restrictions previously placed on them.

Approaches to fusion can be categorized as either (1) steady state, or (2) pulsed.

STEADY-STATE FUSION

Steady state is exemplified by magnetic confinement fusion (MCF). The burning plasma, once formed, continues to burn ad infinitum. In a reactor, energy must be released continuously. Because the plasma must be contained, the combined pressure of the plasma and magnetic field is limited by the strength of materials of the vessel used to confine the plasma. This typically leads to a plasma pressure of around 1 atm, so since the plasma temperature must be on the order of 8 keV, the plasma density is limited to about 1^{14}/cubic-cm although some approaches try to raise this value by about an order or magnitude or so.

When the plasma runs continuously, the initial startup energy is negligible and the figure of merit is

> Q=rate of fusion energy production (units: Watt)/rate of heating required to sustain the plasma (units: Watt).

Examples of private companies trying to produce what would ultimately be steady-state burning plasma are:

Tri-Alpha
Tokamak Energy
Lockheed Martin

These differ by the type of plasma configuration used and the type of fusion fuel used.

Generic steady-state questions:

- What density, temperature, lifetime and size have been attained in a single experiment? With what fusion fuel? What Q has been attained and for how long? What are the challenges of extending all of the system components to steady-state operation?
- How do present experimentally demonstrated results compare with projections made when the experiment was first conceived?
- What density, temperature and size are required for a reactor?
- What is the next step? Will the present technique for plasma start-up work or will a new, untried approach need to be developed? What are the criteria for success or failure of the next step? What if the criteria for success are not met?
- What is the basis for believing the next step will be successful? If computer modeling, how complete is the simulation and how well has the simulation predicted past and present experiments with no modification? If scaling laws, how well has the scaling law predicted past and present experiments with no modification?
- How will the reactor plasma be sustained and refueled? Will fluctuations in the sustainment method or refueling have a negative impact on sustaining the plasma and possibly lead to quenching of the plasma?
- How are reactor components (coils, etc.) shielded from fusion product damage?
- How will heat be extracted from a reactor?

PULSED FUSION

Pulsed fusion is exemplified by inertial confinement fusion (ICF), magnetized target fusion (MTF), and others. Fusion temperatures are obtained by compressing the fusion fuel. The pressure of the burning plasma is much higher than the strength of any material (e.g., 1^{12} atm in ICF), but the burning plasma quickly expands to a low pressure after it has burned and released its energy. The fusion energy is released in very small fractions of a second, from nanoseconds to milliseconds, depending upon the approach. Production of fusion energy in a “continuous” manner then requires multiple pulses per second. Pulsed reactors have the potential of advantage of readily adapting to load demand simply by adjusting the pulse rate.

The figure of merit is gain:

G=fusion energy released (units: Joule)/energy required to get the plasma to burn (units: Joule).

Gain can have multiple definitions depending upon the denominator, energy required. Sometimes, this is simply the thermal energy in the plasma at burn time. For ICF and MTF, this is often the kinetic energy of the pusher used to compress the plasma. Of course, the only definition relevant to energy production is the total energy from the wall plug required to produce the burning plasma: this includes, e.g., the energy to charge the capacitor bank that drives the laser flash lamps in laser-driven ICF.

Examples of private companies that are pursuing pulsed approaches are:

Helion
General Fusion
MIFTI
LPP-Focus Fusion

Based on information publicly available, it appears that the first three use a high (relative to the initial fusion fuel) density liner or pusher to compress the plasma. They differ in the type of liner, how the liner is propelled, and the plasma configuration within the liner. The first two require a magnetic field in the plasma fuel to reduce thermal conduction losses. The third apparently does not use a strongly magnetized plasma fuel so it is not obvious how losses are overcome with the low implosion velocity reported in publications.

LPP uses a plasma focus electrical discharge to directly heat and compress the fusion fuel directly by a magnetic field without the intermediary liner or pusher.

Generic pulsed fusion questions (implosion questions not relevant to LLP):

- What density, temperature, lifetime, and size have been attained in a single plasma formation experiment? How do present experimentally demonstrated plasma formation results compare with projections made when the experiment was first conceived?
- Does the method for combining the formation and implosion systems potentially disrupt the implosion symmetry?
- What is the energy, velocity, and symmetry (convergence) attained in a complete implosion experiment without plasma inside the pusher/liner? How do present experimentally demonstrated implosions results compare with projections made when the experiment was first conceived?
- Has a combined, integrated plasma formation/implosion experiment been conducted? If not, when? What gain and other significant parameters (convergence, density, temperature) have been attained in a (or is expected to be attained in your first) single integrated implosion experiment with plasma (and how is gain defined)?
- What initial density, temperature and size and implosion system energy and velocity are required for a reactor? What would be the pulse rate?
- What is the next step? What are the criteria for success or failure for the next step? What if the criteria for success are not met?
- What is the basis for believing the next step will be successful? If computer modeling, how complete is the simulation and how well has the simulation predicted past and present experiments with no modification? If scaling laws, how well has the scaling law predicted past and present experiments with no modification?
- How are reactor components (coils, etc.) shielded from fusion product damage?
- How will heat be extracted from a reactor?

ADDITIONAL COMMENTS

Although the fusion triple-product (density* confinement time*temperature) is often used as a figure of merit, the qualifier that the temperature must be of the order of 8-10 keV is not always stated (certainly, if the temperature is below about 4 keV, the plasma cannot produce net energy). Furthermore, this really applies to a pulsed system, but at the present state of research, all fusion experiments are pulsed. Reaching a triple-product of approximately 1^{24} sec*eV/cubic-meter is certainly a necessary, but not sufficient, condition for energy production, whether steady-state or pulsed. For steady-state, this product must be infinite, since the time in the product must be infinite. For pulsed, this value must be exceeded by perhaps a factor of 10 or more for useful energy production. It is worth noting that the fluorescent bulb has essentially an infinite triple product but, of course, it operates a very low temperature.

This parameter is derived under the assumption that all plasma loss mechanisms are exactly balanced by some external heating source. Use of this parameter ignores the fact that there is, in general, for each density and temperature, a minimum size plasma that must be formed. For example, the size of burning plasma in tokamaks must be on the order of meters, whereas in ICF the minimum size is on the order of 10^{-2} cm.

An index of all known private fusion energy development companies with contact information and website links is provided at: http://science.fusion4freedom.us/private-fusion-research/

Additional information on many of these companies and projects including scientific papers and news articles is provided at:
http://science.fusion4freedom.us/innovative-confinement-concepts/