Topical Area **MFE** Title: **Burning Plasma Science**

• **Description** Fusion energy is released by burning light elements using nuclear reactions which consume mass and release large amounts of energy in the form of extremely energetic charged particles or neutrons. The most reactive fusion fuel is a 50/50 mix of deuterium (D) and tritium (T) which requires fuel temperatures of ~200 million °C and the product of the fuel density n and energy confinement τ_E such that the Lawson product $n\tau_E > 2 \times 10^{20}$ m^{-3} s. The energetic charged particles (3.5 MeV alphas for the D-T reaction) are confined by the magnetic field and deposit their energy in the plasma. Other reactions are possible but higher temperatures and better confinement is required. In magnetic fusion, plasmas are heated to reaction conditions using external auxiliary power (Paux) and produce fusion power (Pfusion). The most fundamental metric is the fusion gain, Q = Pfusion/Paux. Magnetic fusion reactors will require Q ≥ 25 to be economically attractive. With Lawson product only ~20% higher, "ignition" is obtained, where the plasma is self-sustained purely by its alpha particle heating. The science of burning plasmas consists of: (1) the physics of magnetic confinement in the "dimensionlessly large" reactor regime (transport, MHD stability and edge plasma parameters), (2) the behavior of the plasma in the presence of energetic alpha particles (alpha confinement, induced instabilities, and energy transfer to the bulk plasma), (3) dynamic control of the self heated plasma and (4) power and particle exhaust, especially, removal of helium ash.

• **Status** Burning plasma science has been studied initially with deuterium plasmas which have served to provide understanding of plasma behavior near burning conditions and have allowed the first studies of energetic particle behavior at near burning plasma conditions. A series of experiments using 50/50 D-T fuel has been carried out on TFTR and JET which have produced fusion powers of 11 to 16 MW and Q values of 0.3 to 0.6 for durations of about one second. These experiments have confirmed many of the physics models for burning plasmas, but experiments are needed to study the science of a strongly burning plasma (Q ≥ 10) for longer time durations.

Current Research and Development

• R&D Goals and Challenges
- Obtain and explore controlled fusion burning plasmas
- Investigate plasma confinement phenomena in the reactor regime of a large size relative to gyro radius, in an experiment that integrates confinement and stability in the core and edge plasma.
- Explore and understand the phenomena associated with reactor-levels of fusion alpha-particles in a magnetically confined plasma especially the instabilities that may be excited by their presence.
- Establish the practical feasibility of controlled burn in a self-heated burning plasma through passive and active influences on the overall power balance.
- Explore the compatibility of self-heating with the pressure and current profiles required for optimal stability, transport, and steady-state (long pulse high duty cycle) sustainment.
- Establish the practical feasibility of power and particle (esp., helium) exhaust.

These goals draw together the progress that has been achieved in many topical areas during the past. However no existing facility possesses sufficient confinement to take this next step to a burning plasma experiment that addresses these goals.

• **Related R&D Activities**
- inertial fusion burning plasma studies such as those proposed for NIF
- stellar dynamics (e.g., the marginal stability model for the sun)
- much of the fusion program research and technology is in support of obtaining a burning plasma.

• **Recent Successes**
- theory, modeling and experiments on energetic particle induced instabilities
- theory, modeling and experiments on transport and MHD (e.g., disruptions)
- development of comprehensive diagnostics (J, Er, alphas, ...) for burning plasma experiments
- confirmation of the physics of a weakly burning D-T plasma and production of significant fusion power

• **Budget**
The next step to an experimental burning plasma requires a capital construction project at least of the magnitude of one of the major fusion facilities (TFTR, JET, JT-60) built in the 1970s. However the US fusion budget at its current level is insufficient to support such a project domestically. Refer to the Burning Plasma Options paper for more details.

Anticipated Contributions Relative to Metrics

Science

(1) Enter and diagnose the regime where alpha heating dominates the power balance and defines the plasma pressure profile $Q \geq 10$ and preferably $Q \rightarrow \infty$.
(2) Determine the transport properties, MHD stability, and edge-plasma characteristics of a reactor-size plasma.
(3) Demonstrate quantitative predictive understanding of alpha particle dynamics, both single-particle and collective effects, in the strongly burning plasma regime.
(4) Demonstrate global thermal stability at high Q.
(5) Demonstrate high bootstrap-fraction burning plasma operation.
(6) Demonstrate power exhaust and alpha ash removal for at least 10 energy confinement times.

Energy

Demonstrate scientific feasibility of high-Q DT controlled fusion reactions using magnetic confinement.

Technology

Integrate safe handling of tritium into a burning plasma environment. Demonstrate fueling and heating technologies for a reactor-scale plasma. Establish plasma-facing component technologies for reactors. Demonstrate remote handling technologies.

• **Near Term $\leq$ 5 years**
- Possibly further ($Q \sim 1$) experiments on JET briefly in 2003.
- No alpha-dominated experiments are possible using the existing MFE facilities.
- Carry out design activities and related experimental investigations on prototypical facilities to establish optimal configurations and expectations for a next step burning plasma experiment.
- Develop the engineering basis for a next step burning plasma experiment.
- Develop a scientific consensus worldwide in support of the burning plasma physics mission.

Mid Term ~ 5 to 20 years (2004 to 2019)
- Explore burning plasma physics on an alpha-heated magnetically confined plasma.
- Demonstrate efficient alpha energy transfer to bulk plasma with alphas providing at least 65% of heating power ($Q > 10$).
- Demonstrate sustained burn for at least 5 energy confinement times.
- Respond appropriately to a decision in ~2000 by the international participants on the construction of ITER

Long Term > 20 years
- Demonstrate steady state burning plasma at $Q > 25$ providing the burning plasma science basis for a MFE reactor.

Critics Say

Present MFE concepts, especially the tokamak, don't project to reactor systems with economics competitive with natural gas, fossil fuels and fission. High Q plasmas based on today's most advanced magnetic configuration can't be controlled at advanced performance and the plasma may constantly disrupt resulting in a reactor concept with low reliability. The science of the final MFE reactor may be quite different from the concepts investigated over the last 50 years and the burning plasma science developed in today's magnetic concepts may not be generic.

Proponents Say

The leading MFE configurations (tokamak, stellarators and spherical torus) project a power plant COE within a factor of two of existing fission power plants if a high Q plasma can be sustained with high reliability. Tokamaks are sufficiently advanced that burning plasma physics can be accessed with a modest extension of existing science and facilities. Thus far, there appear to be no technical show stoppers, therefore the burning plasma physics step can be taken with reasonable assurance. Burning plasma physics should first be demonstrated to establish scientific feasibility and to understand the scientific issues of a strongly burning plasma, many of which are generic to all MFE reactor concepts. Subsequently the magnetic configuration can be optimized to develop an attractive MFE reactor with favorable economics and high reliability.