Answers to 5 Workshop Questions
Boundary Science

The purpose of this Workshop is to discuss scientific issues associated with burning plasmas. A second follow-on Workshop will target technology issues. For historical reasons, particularly within the US fusion community, boundary physics problems are frequently characterized as technological in nature. Consequently, we should exercise some care in deciding the topics addressed at the Workshop and considered in this document.

The Webster's Collegiate Dictionary defines science as "knowledge covering general truths or the operation of general laws esp. as obtained and tested through scientific method" and techology as "a technical method for achieving a practical purpose." One might then differentiate a scientific issue from a technological one by asking a question such as

> Will a physicist be developing and testing a model to address this issue and then be applying that model to design future experiments: or devices?

We will take a broader view of the needs of the fusion program as a way of determining the answers to the Workshop's five questions. By asking "what are the crucial boundary physics issues that must be addressed before we can build an operating fusion power plant?" we obtain not only a list of issues addressable by a burning plasma experiment, but also some perspective on the long-term needs in boundary physics.

The requirements for study of each of the power plant issues can be quantified along three axes:

1. Tritium fraction (more precisely, D-T fraction),
2. Pulse length and duty factor,
3. Core plasma stored energy.

In general, a burning plasma experiment will necessarily score highly along the first axis, the D-T fraction. The score on the other two axes will depend on the details of the design. For instance, an ITER-FDR-like device would score well on all three counts.

A shortcoming of the current state of boundary physics is that two of these three axes are characterized by dimensional quantities. This results from the rather primitive treatment of material surfaces in experimental operations, modeling, and theory. In fact, one potential conclusion from this Workshop is that the state of materials science research, as it relates to fusion, needs to mature substantially before it can be considered on a par with more traditional plasma science areas such as MHD and transport.

(1) What are the compelling scientific issues which could be addressed by a burning plasma experimental facility?

Issues that could be addressed by any burning plasma experiment would be:

1. Consistency of the plasma boundary with a burning core.
2. Disruption damage effects.
3. Tritium retention.
4. Helium ash pumping.
5. Heating of plasma-facing components by fast-alpha particles.

A particular burning plasma experiment will also operate at sufficiently high specific energy (plasma thermal energy divided by wall area) levels as to make disruption damage effects qualitatively more severe than in current devices. In particular, the "vapor shielding" effect expected from simulations does not occur in current devices, but would in a burning plasma experiment.

The most aggressive burning plasma experiments contemplated, i.e., those of the ITER class, would involve long pulse lengths and / or high duty factors. Such devices would permit study of erosion and plasma-facing component lifetime issues, as well as those of dust generation. Tritium retention would be a significant concern.

(2) Identify those burning plasma scientific issues which are inaccessible for study in existing or near-term non-burning plasma experiments.

Of these issues, helium ash pumping and PFC heating by fast-alphas have already been studied. Further experiments could be carried out on existing and near-term non-burning devices via helium injection in the first case and via simulation of fast alphas with RF heating.

Tritium retention was and still is being analyzed in JET and TFTR. More could be learned by isotope exchange experiments on existing and near-term devices.

Such experiments would be the only viable approach for testing tritium removal techniques.

Conceivably, the consistency of core and boundary plasmas could be examined in a non-burning plasma by rapid feedback on neutral beam or RF power on some divertor parameter, e.g., H_α emission near the target. However, designing such an experiment so as to everyone's satisfaction would be difficult.

The JT-60SC and Tore Supra - Ceil projects may permit study of erosion / PFC lifetime issues. However, to be truly productive the state of the materials and the nature and magnitude of fluxes to the walls will have to be vastly more well diagnosed than they have in the past.

Disruption damage effects could also be studied in existing and near-term devices. The real need, however, is for disruption mitigation studies. Because the consequences of a disruption in an ITER-class device are potentially so severe, thoroughly understanding them at a smaller scale is advisable.

(3) What is the present physics basis and confidence level in achieving burning plasma conditions? In particular, how have recent developments in theory and experiment affected our confidence in achieving burning plasma conditions?

Recent developments in theory and experiment have led to a relatively high level of confidence in the ability to simultaneously maintain good core confinement and satisfactory power and particle control in the edge plasma (e.g., via detached operation). Stability has not been addressed. However, if the core plasma must be operated in an advanced tokamak mode with low edge density, the confidence level would be much lower since that may lead to an incompatibility with high density divertor operation. Furthermore, a low edge density may invalidate fluid models of the scrape-off layer plasma. The lack of correspondingly effective kinetic models would make predicting operation in such cases much more difficult.

Existing experiments have demonstrated high confinement operation at densities near and above the Greenwald density limit. To the extent that these operating modes rely upon technologies such as central pellet fuelling and divertor pumping that can be applied to a burning plasma with equal efficacy, reaching similarly high densities would seem plausible. However, in the absence of a complete and well-tested theory for the density limit, some degree of uncertainty must persist in this claim.

Experiments and simulations of helium ash transport do not point toward problems in the burning plasma regime. Confidence in these expectations is relatively high.

Measurements of fast α losses on TFTR and JET indicated good agreement with classical (orbit loss) models. The mechanisms considered included prompt, collisional scattering, and ripple-induced losses. Collective effects are not expected to alter the behavior of these losses. MHD and TAE and related losses would be larger, but estimates for ITER are in the few percent range. Confidence in these predictions is high.

Disruption models point toward very different behavior in a burning plasma experiment. Insofar as a near-term burning plasma experiment will not have access to fully effective disruption-avoidance techniques and will likely be pushing stability limits, disruptions are inevitable. Confidence in achieving burning plasma conditions can be obtained by designing the machine to facilitate quick and cost-effective replacement of the divertor hardware. Confidence in the model predictions is not exceedingly high, but testing of them in a modest-scale burning plasma experiment would appear to be a prudent intermediate step on the way to the design of a larger scale device.

The remaining issues: tritium retention, erosion / PFC lifetime, and dust generation, do not directly affect the ability to *achieve* burning plasma conditions. However, depending on the integrated run time of the device and the plasma stored energy, they could control the duration of experimental operations. Safety concerns associated with in-vessel tritium inventory and dust accumulation or excessive erosion of PFC's may force remediation efforts. Due to the primitive understanding of these issues and even lack of appropriate diagnostics, confidence in predicting their severity is poor. The situation is exacerbated by the fact that graphite, the most widely tested and robust material in existing experiments, will give rise to the highest levels of tritium retention.

(4) How comprehensively can these burning plasma science issues be addressed establishing a firm basis for extrapolation in scale and magnetic configuration?

Establishing a firm basis for extrapolation requires a deep understanding of the underlying physics. In boundary science, only the edge plasma and neutral transport models are on a path toward this level of understanding. Additional progress is required in turbulent transport theories, both in the core plasma and the scrape-off layer before extrapolation can be done with confidence. However, the boundary conditions at the materials surfaces are currently based on relatively unsophisticated models that cannot be extrapolated. Radiative scenarios, such as the RI mode, need to be more thoroughly studied before they can be applied to future devices.

The effects of disruptions will be qualitatively worse at the higher energy levels and currents of a burning plasma experiment. Even though existing models of these phenomena exist, they can only be verified in a tokamak device operating under such conditions.

Likewise, other materials-related issues can only be understood fully by doing long-pulse experiments with good diagnostic coverage. Meeting that objective would involve new experimental efforts. Corresponding new theoretical models would have to follow along.

One virtue of boundary science issues is that they are in many ways applicable to all magnetic configurations. This is particularly true of plasma-materials interaction concerns. To some extent, knowledge in this area can even be applied to inertial fusion energy devices.

(5) Are there compelling scientific issues outside of fusion energy which can be addressed by a burning plasma experimental facility?

Materials science problems are pervasive in everyday technology. If the materials science of fusion devices were to be developed, non-fusion applications would likely be found.