Plasma Boundary Science

a report on the discussions held at the Snowmass Fusion meeting

12 July through 23 July, 1999

1. Executive Summary (G D Porter)

The boundary plasma discussions held at the 1999 Snowmass meeting focused on issues related to MFE concepts, particularly on issues relevant to tokamaks, with some input from the IFE community. This is not to say there are not important boundary plasma issues for all concepts, but reflects priorities for the first of these Snowmass meetings.

1.1 Description

The boundary of a hot thermonuclear plasma is the region in which the external world interacts with the fusing core plasma. Plasma boundary physics is a key issue for the development of fusion power because of both the effect of exhaust power and particles on material walls, and the effect of recycling neutrals, impurities, and edge turbulence on the core plasma. In MFE configurations, this region has equilibrium profiles which require at least a 2-D description (and 3-D in some configurations such as the stellarator) and spans radially from the "edge" of the confined plasma to limiting walls. For example the region between the 96% flux surface and the limiting surface of a diverted tokamak is usually analyzed with boundary codes, and includes the H-mode pedestal region. Power and particles which are exhausted from the confined plasma are transported across the magnetic field into the boundary region where they flow rapidly to the walls once on open magnetic field lines. The plasma interaction with the walls can produce intense local heating which, unless controlled, causes rapid erosion or even melting of the wall material. In addition, the interaction releases both fuel and impurity ions from the walls. A small fraction (typically a few percent) of the fuel particles are transported to the confined plasma, and affect the characteristics of the pedestal region, and hence the core confinement. Similarly a small fraction of the impurity ions are transported to the confined plasma where they act to dilute the fuel plasmas, and to radiate, thus affecting the character of the pedestal region and core plasma. Impurity ions created from plasma interaction with the walls are transported to different regions of the walls, creating areas of material removal, and other areas of material deposition. Both the erosion and deposition regions form technological problems for the development of a fusion reactor based on any MFE concept. The boundary region must also provide sufficient helium pumping to control the accumulation of ash.

The boundary plasma region is especially rich in the number of interesting components: plasma, neutral gas, photons, and material surfaces. The characteristics of the boundary are determined by the detailed physics of transport across and along the magnetic field. Parallel transport processes appear to be classical, while cross field transport is caused by plasma turbulence. Other physics elements relevant to the study of the boundary region include: Atomic physics of fuel and impurity species; neutral and impurity evolution and transport from material walls under photon and plasma irradiation; the structure of electric fields in the boundary region, and their effect on plasma flows. The grand challenge of boundary plasma science is to integrate the physics understanding from all of these physics disciplines into a self-consistent model.

1.2 Status

Understanding of the physics of the boundary plasma has progressed rapidly for diverted tokamaks over the past 5 years. Operating modes which greatly reduce the power loading on material walls have been demonstrated. These reductions have been achieved by injection of hydrogen and/or impurity gas which enhances the radiated power from the intrinsic impurities (carbon) or the injected impurity. Low temperature (~1 eV), recombining divertor plasmas have been obtained in this way. Codes which successfully integrate the physical processes for a particular plasma condition relevant to standard tokamaks have been developed and validated against well-diagnosed tokamak plasmas. Successful development of these codes has been achieved by the integration of many physics packages into the code; rapid progress in the ability to diagnose the plasma in the SOL and divertor regions; and sufficient experimental time to provide the requisite data. The existence of well diagnosed plasmas has permitted thorough testing of the models against experiment. The codes have been successfully used to aid design of divertor modifications of existing devices, and divertor designs of future devices. Extrapolation of the boundary plasma parameters to future MFE devices, both advanced tokamaks and alternate concepts, indicate the power loads will be more intense than seen in standard tokamaks. This may push the boundary plasma into different operating regimes for which the physics models have not been adequately tested. Hence the physics models contained in these codes must be expanded to permit application to a broader range of operating conditions. Continued development of the integration codes will require further development in diagnostics capability and experimental time to permit adequate tests of the physics models.

1.3 R&D Goals and Challenges for future development

The needs for future development can be grouped into four broad areas, which comprise R&D goals.

1.3.1 Improve understanding of transport physics

Determination of the turbulence induced cross field transport rates for a variety of MFE configurations is one of the major issues which must be solved to successfully design a fusion reactor based on magnetic confinement. The rates for thermal transport of electrons and ions must be known as well as those for fuel and impurity ions. Significant progress has been achieved in 3D simulations of the edge turbulence and the resulting transport from first principles, but more work remains. Physics based models of transport rates across magnetic field lines is required to develop a truly predictive model of the boundary plasma. Existing 3-D edge turbulence codes can be used to develop simplified scaling laws for the transport rates. These laws must be validated by detailed comparison with the large database of edge plasma parameters which has been accumulated as part of the ITER design process. The simplified laws can then be implemented into the comprehensive codes to permit predictive simulations.

Advanced tokamak modes and alternate magnetic configurations such as the ST may operate with less collisional SOLs than the standard tokamak, so the treatment of kinetic effects may need improvement in the plasma models and data interpretation. In the extreme limit of collisionless edges it might be more appropriate to use collisionless theories developed in the mirror program. The treatment of kinetic effects may include the effect of non-Maxwellian electron distributions on atomic physics rates.

The treatment of plasma drifts must be incorporated into codes which simulate the plasma flows in the edge.

The models for neutral transport in the edge must be improved to cover both fluid and kinetic effects in a computationally efficient way. In addition, diagnostics which determine the neutral density throughout the edge region must be developed to better validate the models.

SOL plasmas in some devices today are optically opaque to some lines, and future devices may be even more opaque, so radiation transport treatment may be required in the boundary models.

1.3.2 Develop active boundary control schemes for new plasma regimes

Present techniques for controlling the edge plasma, which relies on the detached plasma regime, may not be applicable for future, more compact, less collisional devices. Alternate control techniques, such as a radiating mantle, must be developed.

1.3.3 Expand capability of integration codes

Boundary modeling has focused in the past on plasma and neutral transport in the boundary region only, dealing with the core and materials interfaces as boundary conditions. Since the recycling neutrals and impurities affect the core, and the plasma material interaction affects the material surfaces, there is a need to couple the physics of the SOL, core, and materials more realistically. The capability of the comprehensive edge codes must be expanded to self-consistently treat the effect of the edge plasma on the core plasma. A coupled core/edge code will permit predictive simulation of effects such as the L- to H-mode transition, and ELMs. The treatment of plasma material interactions must be expanded in the comprehensive codes to permit better description of the interaction with a broad variety of materials, such as liquid walls. An important aspect of improved SOL/materials coupling is the ability to determine the level of tritium retention, especially in devices with carbon walls. Diagnostics must be enhanced and/or developed which permit thorough validation of the plasma material interaction models to identify the source of core impurities. This validation will require dedicated experiments on existing facilities.

1.3.4 Expand geometric capability of integration codes

The geometric capability of the comprehensive codes must be expanded from 2 to 3-D to permit predictive simulation of devices such as the stellarator.

1.4 Anticipated metrics for R&D goals

- **Near term (< 5 years)**
    - Compare simulation of edge turbulence in standard tokamaks with detailed experimental results.
    - Compare a self consistent core/edge simulation with experimental results of time dependent phenomena such as plasma startup, L– to H– mode transition, and ELMs.
    - Compare experimentally determined wall erosion and redeposition profiles with simulations with realistic plasma material interaction models.
    - Compare simulated and measured core neutral densities and determine their effect on core confinement.
- **Intermediate term (5 to 10 years)**
    - Compare SOL scaling laws with experiment for a variety of operating modes and devices.
    - Compare simulation of SOL plasmas with experimental results in a regime in which kinetic effects are important.
    - Compare simulation of plasma flows, including drift effects, with 2D experimental measurements.
- **Far term (> 10 years)**
    - Compare simulation of 3D SOL parameters with experiment.

2 Introduction

The study of the plasma characteristics in the periphery of a fusion device is important for the development of current experiments, as well as the development of a power system. The boundary plasma discussions held at the 1999 Snowmass meeting focused on issues related to MFE concepts, with some input from the IFE community. This is not to say there are not important boundary plasma issues for the IFE concepts, but reflects priorities for the first of these meetings. The discussion of the boundary plasma issues in this report is therefore predominately relevant to the edge of MFE devices. There is some discussion of atomic physics issues important for IFE.

Boundary plasma physics is aimed at controlling power and particle flows in the periphery of hot confined plasmas. The power and particles which are exhausted from the fusing plasma flow along and across field lines to points which intersect walls surrounding the plasma. The plasma characteristics in this region must be controlled to prevent damage to these walls. This means not only preventing excessive heat loads which would melt the walls, but also preventing intense sputtering of the walls in order to obtain sufficient wall lifetimes to permit acceptable maintenance periods. Techniques which can be used to control the exhaust are constrained, however, by the need to control the flow of both fuel and impurity ions back to the hot core plasma. Adequate control of these plasma flows require integration of multiple physics disciplines; atomic physics, neutral/plasma interactions, turbulence and transport, and plasma material interactions. The integration is typically done by developing comprehensive codes which model all aspects of the plasma from the edge of the core (typically the 95% poloidal flux surface of a tokamak) to a limiting surface on the open field lines. The viability of these codes is determined by detailed quantitative comparison with experimental results from operating devices. This comparison is made possible by the development of innovative diagnostics which determine the plasma characteristics throughout the 2-D boundary region. Some devices require 3-D analysis. The rapid progress in boundary plasma science which has been achieved over the last decade has come about because of a strong interaction among theory, modeling, and experiment.

This report is divided into sections which reflect the physics disciplines which must be integrated into the modeling codes. The physics and issues associated with plasma neutral interactions are described in Section 3. Issues associated with atomic physics, both for diagnostic purposes, and for control of radiated power, are described in Section 3. The physics of plasma material interactions are described in Section 5. Finally, the physics of boundary turbulence and transport is described in Section 6

3 Plasma Neutral interactions (M A Mahdavi and P Mioduczewski)

3.1 Introduction

Neutrals can reduce the divertor target heat load and enhance impurity and helium ash exhaust through several independent mechanisms in the Scrape-Off-Layer (SOL) and divertor plasmas. There is evidence of deterioration of core plasma confinement at high neutral influx to the core. A high concentration of neutrals at the divertor or other limiting surfaces is not only unavoidable but might be necessary for control of heat loads in high-powered devices. Thus the two regions of very high and very low neutral density must co-exist. Much effort in recent years has been devoted to developing techniques that enhance the desirable aspects of neutrals and minimize their deleterious effects. We describe the sources and sinks of neutrals in Section 3.2, the role of neutrals in the SOL and divertor plasmas in Section 3.3, the role of neutrals in the core plasma in Section 3.4, and finally we discuss the status of modeling and diagnostics relevant to neutrals in Section 3.5.

3.2 Neutral Sources and Sinks

The main sources of neutrals in MFE devices are recycling of the plasma on the plasma facing surfaces (with prompt or delayed release of gas); volume recombination in the divertor plasma; external gases; pellet injection; and Neutral Beam Injection (NBI). Neutral hydrogen in the plasma edge can also be created by dissociation of hydrocarbons or reactive fueling with hydrogen-containing molecules. Gas desorption at plasma start-up can be a significant source of neutrals early in the discharge. Normally the dominant source of fuel neutrals is from recycling. Volume recombination approaches the recycling source in detached plasmas. The recycling flux in a reactor is expected to be four orders of magnitude greater than the fuel burn rate and far greater than external particle sources intended for core fueling or to establish flows in the SOL (see the following discussion). The recycling flux is far greater than levels tolerable by the core plasma. However the divertor plasma is an effective neutral shield and the great majority of the recycling neutrals are re-ionized in the divertor or SOL plasmas. Neutral attenuation factors of the order of 100 are not difficult to achieve in semi open divertor configurations.

It is important to note that uncontrolled release of particles absorbed by the wall has been a difficult problem for many of the existing short pulse devices and much effort is being devoted to controlling this source of neutrals which can drastically increase the plasma particles.

For a systematic study of the effect of neutrals on plasma performance, one should be able to vary the neutral sources through gas puffing as well as through the introduction of additional recycling sources or recycling reduction by wall conditioning and/or divertor pumping. Recycling mechanisms and hence the type and state of the resulting neutral species can be affected by the wall state. The surface of the wall can be made of low-, medium-, or high-Z material, it can be depleted or saturated with hydrogen, it can be covered with hydrocarbons or other impurities, it can be at room temperature or elevated temperatures, etc. Depending on these specific surface conditions, a number of surface processes can be effective. The mechanisms are:

1. Kinetic reflection: 20-30% of the particles are directly reflected as neutral atoms with energies up to the incident energy.
2. Thermal desorption: desorption of molecularly adsorbed species.
3. Langmuir-Hinshelwood reaction: implanted atoms diffuse to the surface where they recombine with another atom and the recombination provides the necessary desorption energy.

4. Eley-Rideal reaction: prompt desorption following the reaction of species from the plasma phase with surface adsorbed species. This process can produce fast molecules in highly vibrational states.
5. Particle-induced desorption: desorption of surface atoms by incident plasma particles or neutrals as well as by electrons and photons.

It is easy to imagine that recycling species with a variety of properties can emerge, including thermal or fast particles, atoms or molecules, particles in the ground state or in various states of excitation. Furthermore, various molecular combinations of hydrogen and carbon molecules, i.e. hydrocarbons and their radicals in various states can emerge.

A variety of techniques for recycling control have been devised. These fall into three categories; discharge cleaning, wall coating, and active pumping. Discharge cleaning techniques, mostly using hydrogenic isotopes, have been successfully employed for removing impurities adsorbed by the vessel walls. With the advent of graphite targets, which can absorb and release large quantities of hydrogen, helium glow discharge cleaning was introduced to moderate the level of wall released particles. In addition to discharge conditioning, wall coating techniques such a boronization are extensively used in many devices to further reduce oxygen and carbon levels in the plasma. Recently active divertor and limiter pumping were introduced in several tokamaks for long pulse particle and impurity exhaust. Divertor pumping has proved to be a powerful tool for several particle control applications. It is currently the only effective tool for density control in H-mode plasmas and for inducing large SOL flows. Pumped limiters have been effective for long pulse density control in limited plasmas.

Neutrals also play an important role in impurity production. Charge-exchange processes can produce neutrals with energies up to the kV range. These charge exchange fluxes are relatively low on the first wall of the main chamber, but the large area can account for a significant total flux of neutrals incident on the wall. Most of the charge-exchange flux occurs in and around the divertor .The fluxes in the divertor region can get high, but the particle energies are low. For materials like carbon, the sputtering rates can still be high. This might be the area with the highest impurity source rate, but systematic studies are necessary. Reducing the divertor neutral density with pumping could have a profound effect on the impurity production as well. To understand these correlations, systematic studies of correlations between neutrals and impurities need to be undertaken.

3.3 Role of Neutrals on the Divertor Plasma Behavior

It has been shown that Coronal Equilibrium (CE) radiation cannot reduce the divertor heat load by more than roughly a factor of 2 in a high powered device without volume recombination or a mechanism for the parallel momentum loss. This limitation is due to the plasma ionization potential that is dumped onto the divertor targets. This heat reduction limit could be relaxed significantly by neutral-ion collisions that remove a significant fraction of the parallel momentum, and by enhancing impurity radiation relative to the CE. Although neutral-ion collisions are considered to be a key factor for divertor detachment in tokamaks, more systematic modeling studies and better diagnostics are needed to understand the exact role of the neutrals in present devices and to make projections for future machines.

Volume recombination can greatly reduce the ionization potential heat load on the target plates. Observations in tokamaks such as DIII-D and C-MOD show direct evidence of significant levels of volume recombination in detached plasmas. Modeling calculations support these observations and show that volume recombination indeed contributes significantly to reducing the divertor heat load.

In addition to a small external particle source needed to replenish the D/T fuel in burning plasmas, particle injection rates of the order of 10 percent of the recycling source in conjunction with divertor pumping might be desirable to establish a plasma flow along magnetic field lines towards the divertor. In DIII and DIII-D, such forced flows have been shown to be effective in increasing the divertor concentration of impurities relative to the core plasma which increases the divertor radiation and for a given concentration of impurities in the core plasma. Parallel flows in the SOL are also found to be important for access to densities above the Greenwald limit in H-mode plasmas.

3.4 Effect of neutrals on the main plasma

There are numerous reports on observations of deleterious effects of neutrals on the confined plasma. It is commonly observed that confinement can be improved with wall conditioning. To what extent this is due to neutrals and/or impurities, is not clear because of inadequate diagnostic tools and insufficient theoretical work. Experimentally a correlation between the core plasma performance and external parameters such as the gas injection rate, neutral pressure at the wall, or wall preparation techniques is observed on a variety of MFE devices. Various ideas put forward to explain these observations include damping of the ExB rotation in the Edge Transport Barrier (ETB), enhanced heat loss by charge exchange neutrals and enhanced impurity radiation causing impurity neutral charge exchange collisions. In the divertor plasmas, all the neutral effects are considered desirable. There has been more quantitative work on the neutral effects on the divertor plasma than on the core plasmas since the existing diagnostics and codes permit more accurate determinations of the neutral density in the divertor plasma. Nevertheless, even in the divertor and SOL plasma diagnostics for measurements of neutrals and their velocity distribution are needed.

Divertor pumping is a very effective means to reduce the neutrals pressure in the divertor. This has been used to control the plasma density in DIII-D and other tokamaks. The effect on confinement, however, is unclear. In C-MOD, it appears the main plasma is very little influenced by the divertor pressure. Recent experiments with divertor flaps, connecting divertor and main chamber, have changed divertor pressures, but had essentially no impact on the main plasma.

In order to understand the effects of wall conditions on plasma performance, it would be important to study and understand the correlations between wall state, emerging neutrals, and effects on plasma performance. Experiments with divertor pumping and divertor flaps seem to indicate that it is not necessarily the neutral pressure that affects confinement, instead, it might be the state of the neutrals and the details of the fueling process.

Changes in wall conditions and configuration can cause significant changes in the power threshold for L-H transitions. However, there is very little quantitative information on how wall conditions affect the transition. An obvious potential mechanism is the coupling of the dynamics of the neutrals to the transition mechanism. In the case of the DIII-D tokamak, it has been shown that the neutral density at the edge is large enough to lead to momentum loss by charge-exchange comparable to that induced by an alternative candidate, ion orbit loss.

Neutrals may play multiple roles in relation to the transition. They clearly affect the particle and energy fluxes, which are the effective local transition parameters. They also change the ion momentum loss through charge exchange friction. Because of the poloidal localization of the charge exchange damping near the x-point (remembering that the strike-points dominate recycling) neutrals may modify the topology as well as the magnitude of the ExB flow shear.

In DIII-D, a significant correlation has been found between the neutral density in the edge plasma and the power threshold for L to H transitions. The power threshold correlates well with the charge-exchange damping rate or the neutral penetration inside the separatrix. A possible mechanism responsible for the effect of neutrals on the transition threshold is a change in the damping of the poloidal component of the ExB shear flow.

Initial analysis provide strong indications of the effect of neutrals on the L-H transition and, possibly, on the quality of improved confinement regimes. However, the required neutrals information has been obtained from computer models and needs to be verified with experimental measurement of the important parameters. Furthermore, flows of ions and neutrals have not been included in the analysis. Finally, impurity effects, which could be very significant, have not been treated in the analysis to date. The goal for future work is to further develop the existing models and include the above effects (and possibly others) as well as to develop controlled experiments to actively explore the properties and effects of neutral particles.

3.5 Diagnostics and Modeling

Monte Carlo codes such as DEGAS and EIRENE, coupled with plasma codes are capable of tracking the neutrals very well. The core plasma, as well as the wall are simply treated as boundary conditions for the sophisticated edge codes. The very complicated recycling processes are input as a single, constant number for the recycling coefficient. The challenge in the modeling area is to integrate the whole dynamic system consisting of wall, plasma boundary, and a simplified core plasma, sophisticated enough to respond to the wall and boundary changes. In absence of direct measurements, these codes are extensively used to calculate the neutral density in the divertor and core plasmas. The code results are very sensitive to the plasma parameters in the SOL. Point measurements of neutral density to benchmark the code results are badly needed. Another uncertainty in the code results is the variability of neutral wall interactions in the present short pulse devices, which is difficult to take into consideration.

Neutrals play an important role in fueling, impurity production, confinement, overall plasma performance. But they are the least diagnosed species in any device. If we want to better understand the important plasma-neutrals interactions, the diagnostics efforts need to be strengthened considerably. Neutral density measurements, using pressure or penning gauges and residual gas analyzers are extensively used in many devices, and much valuable information has been deduced from these diagnostics. These diagnostics measure the neutral density in appendages of the vacuum vessel where neutrals have equilibrated with the wall or measure neutral flux inside the vacuum vessel. Line emission spectroscopy is used in many devices to obtain neutral density and temperature in the plasma volume. However, none of these diagnostics provide a sufficiently accurate or spatially localized measure of the neutral density or its velocity distribution. Laser fluorescence spectroscopy, which can provide high spatial resolution measurements of neutral density and velocity distribution is a mature diagnostic technique, however due to limitations of laser technology, in most devices the techniques has not been applied to ground-state transitions of hydrogenic species (It has been done in TEXTOR with Lyman-alpha, frequency tripling).

4 Atomic Physics (S Krashinennikov and J Albritton)

We have identified RADIATIVE/SPECTRAL DIAGNOSTICS as a science issue which is important for both MFE and IFE concepts. The atomic physics issues relevant for diagnostics doesn't impinge directly on the concepts, but is important for the continued advancement of both concepts.

4.1 Atomic physics issues from the ICF perspective

In indirect-drive icf, the laser heats the wall of the hohlraum, a high-Z material, to make x-rays which are then absorbed by the target capsule, a low-Z material, and drive it's implosion. The initial radiation conversion process, its energy efficiency, the details of the resulting spectrum, and then the radiative properties of the hohlraum and capsule determine the successive partitioning of the x-ray energy and thereby govern the energetics of the system and also the details of the implosion itself. Here we have in mind ~ 1 keV photons. The implosion drive in indirect-drive icf involves non-LTE (nonlocal thermal dynamic equilibrium) ionization and excitation kinetics and radiation transport which is integral to target performance. Non-LTE electron heat conduction and coupled radiation/hydrodynamics also enters. The key physics issues can be divided into several key specialities.

4.1.1 Atomic data

This broad category includes data for the atomic structure/energy levels of materials in the holhraum/pellet combination; transition rates for radiative collisional transitions; and widths of spectral lines due to the motion of radiators and electric fields of plasma particles acting on the radiators. Understanding of these physics processes is adequate for existing experiments, certainly for the qualitative and semi-quantitative state of just about everything. Quantitative improvements are limited by computational resources, both numerical methods and machines. Experimental data is similarly in reasonably good shape and agreement. State-of-the-art accuracy is taxing, but not necessarily required to support the next generation concepts. The issue here then turns on the precision required for diagnostic applications.

4.1.2 Atomic kinetics

This physics issues is basically one of determining the probability distribution of ionization and excitation states, and self-consistently coupling kinetics, radiation, free electrons and hydrodynamics in the non-LTE regime. Existing capabilities in this area are not as satisfactory as for atomic data, because the large number of ionization and excitation states readily fills current computational capacity and leaves the distribution only approximately determined. On the other hand, the concepts seem to be reasonably well supported by efficient low order moment treatments of the distribution and which are now becoming complete with respect to the inclusion of all the transition processes. This is an area where if the gains made to date can be consolidated, then probably we're OK for the next generation concepts. Again the issue of diagnostic applications can call for substantial resources and advances.

Further work may be required to adequately support the next generation concepts for self-consistent coupling. Here we have mostly semi-empirical understanding without much integration of the underlying physics treatments. Much experimentation is devoted to extending and exploring the scaling curves into and around the regime of the next generation concepts. A few cliffs, not near the main parameter space, have been identified. The challenge of synthesizing the results of experiments and theory and modeling remains unmet. The experience of the program is that the semi-empirical support of at least the next generation concepts appears to be reasonably good.

4.1.3 Transport

Understanding of radiation transport in IFE seems adequate. A nagging problem concerns the overlapping of spectral lines whose centers and widths are not perfectly known, but this poses such a difficult problem that it recommends itself for awaiting the outcome of next generation experiments. The situation is perhaps not good-enough for non-thermal electrons. Finite mean-free-path electron transport treatments remain insufficient to support the concepts. The physics models are adequate, but the methodological and computational resources are inadequate. Both research and development are needed. Existing engineering treatments appear sufficient to support the next generation concepts reasonably well, but going on to very high performance systems will almost certainly require advances.

4.2 Atomic physics and radiation for MFE

In standard operational regimes of magnetic confinement devices we have impurity radiation and neutral hydrogen radiation due to plasma neutralization on material surfaces and volumetric recombination. Neither impurity nor hydrogen are in LTE. The plasma background can have significant non-Maxwellian distribution function features. Hydrogenic species include both atomic and molecular neutrals and ions. Atomic physics and radiation effects relevant to disruptions are similar to those found in ICF regimes

4.2.1 Atomic physics and radiation

Impurity radiation (both low- and high-Z) in standard regimes is transparent, implying that only atomic kinetics plays an important role. Atomic kinetic data for atomized impurities are in a reasonably good shape, although the data contains only Maxwell-averaged rate constants. The existing data is not as good for molecular impurities (like CH_n).

Hydrogen Lyman lines can be trapped in the plasmas encountered in existing MFE devices, so both atomic/molecular kinetics and radiation transport are important. Atomic/molecular kinetics for existing MFE device conditions is in a reasonable shape. Radiation transport requires rather accurate models for the line shapes including collisional, motional, Stark, and Zeeman effects. Coupling of atomic/molecular kinetics to radiation transport and neutral transport must be done.

5 Plasma Material interactions (M Ulrickson)

5.1 Introduction

Improved control of edge density and impurity influx have been largely responsible for the improvement in tokamak performance in the last fifteen years. Improved control has been achieved through better understanding of the complex interactions between plasma physics, surface science and solid state physics that occur at the plasma to material interface. Our understanding has been achieved through a combination of laboratory experiments, experiments and measurements on tokamaks and modeling of the observed phenomena.

5.2 Gas trapping and release

Plasma particle fluxes to the surface of plasma facing materials are very large. The fraction of particles that are trapped in the surface or bulk material has a strong influence on the density of the edge plasma since recycled particles fuel the plasma. Some of the incident particles are simply reflected back to the plasma while others stop in the material. The particles that are deposited in the material can diffuse through the material to the coolant where they may become a safety issue. Alternatively, trapped particles can diffuse back to the surface where they can be re-emitted as atoms or molecules.

The release of atoms and molecules from a surface depends strongly on the surface morphology, surface cleanliness and the presence of the plasma particle and photon flux (UV and soft x-ray). Extensive surface science experiments are being conducted to understand the mechanisms controlling the release of particles from surfaces. Techniques for cleaning surfaces and coatings that can reduce gas release are being investigated.

Trapped particles can diffuse along grain boundaries, through grains and along the surface of pores in some materials. In some cases, there are chemical reactions between the plasma particles and the material (e.g., hydride formation). A combination of chemistry and solid state physics is needed to understand the transport of plasma particles in plasma facing materials.

Particles can be trapped at radiation damage sites due to neutron or energetic particle bombardment. The strength of the traps is a function of the energy of the bombarding particle, the operating temperature and the nature of the material. Healing of the trapping sites may occur if the operating temperature is high enough, but some materials are damaged more rapidly at elevated temperatures. The binding of plasma particles in the trap sites depends on the nature of the sites.

5.3 Erosion

There are several erosion mechanisms that take place in an operating fusion device. They include: sputtering, evaporation chemical erosion. Such erosion will gradually thin the plasma facing material and require replacement of the component. The eroded particles may cause contamination of the edge and/or core plasma. Several techniques have been developed for controlling either the amount of erosion or the transport of the eroded particles back to the main plasma.

Bombardment of a surface with energetic particles will cause the surface to be eroded through knock-on type interactions (the incident may give enough energy to a near surface atom to cause it to be ejected). Extensive laboratory measurements of the energy and angle dependence of sputtering process have lead to fundamental understanding of the process and physical models of the phenomena. Further studies of liquid surfaces are needed.

At elevated temperatures the vapor pressure of any material can become very large. If the evaporated flux is too large severe plasma contamination will result. Bombardment of the surface can reduce the surface binding energy and increase the evaporation rate at a given temperature. Laboratory measurements of such effects have led to a partial physical model of the temperature, energy and flux dependence of this effect. Further measurements are needed.

In some cases (e.g., hydrogen and carbon), the plasma particles may chemically interact with the plasma facing material to form a volatile species that is easily removed from the surface. Laboratory measurements of such phenomena have led to a partial understanding of the dependence on temperature, flux and material.

5.4 Material transport and deposition

Eroded material may be transported trough the edge plasma to the core plasma and cause a reduction of reactivity. There has been some success at limiting this effect through the use of poloidal divertors in tokamaks. Eroded material that is not transported far enough away from the surface will be redeposited on nearby surfaces. The structure of the redeposited material is likely to be very different from the parent material. If the deposition is thick enough, there may be spallation of the surface or excessive temperatures may be experienced. These effects are detrimental to good plasma operation.

The eroded material is interacting with a hot plasma. Electron or ion impact ionization of the eroded atoms will cause the atoms to follow field lines to a nearby surface. The mean free path for ionization depends on the plasma temperature and density. Ionization extracts energy from the plasma. A combination of plasma physics and atomic physics is needed to understand these effects. There have been extensive laboratory and fusion device studies of these phenomena. In some cases, there is a lack of fundamental atomic physics data in the relevant temperature and density range.

A molecule leaving a plasma-facing surface can have a very complex interaction with the edge plasma. It may be ionized, broken into smaller pieces, rotational and vibrational states may be excited and various of the pieces may be redeposited. Molecular physics must be added to understand the penetration of molecules. Some models have been developed to follow the transport of selected molecules.

Since both plasma ions and redepositing material may strike the same point, there can be codepostion of both species. The morphology of the coating created depends on the materials present, the temperature and the fluxes of particles. Some combinations of materials have been studied to determine the structure of the layers and the binding energy of the trapped plasma particles.

5.5 Edge plasma effects

The edge plasma is strongly influenced by the material emitted from the plasma facing material. In some early tokamaks, the plasma performance was totally dominated by plasma wall interactions. Existing devices are still influenced by plasma materials interactions and see improvement in performance when surface effects are better controlled.

Ionization and line radiation from eroded material can cool the edge plasma. This effect has been exploited to reduce the heat flux on the plasma facing material by increasing radiated power while reducing conducted power. It has been found that the region of radiation must be kept well separated from the main plasma to avoid contamination. Modeling of this effect requires a combination of fluid transport, plasma physics, gas transport and atomic physics. These models are still in the development stage.

The plasma naturally forms an electric potential with respect to the wall due to the greater mobility of electrons compared to ions. If the operating temperature of the wall becomes too high the surface may emit electrons and reduce the plasma potential. This fundamentally alters the interaction of the plasma with the wall. Eroded material being ionized near the surface has a similar effect. Plasma edge models must include this effect.

Deuterium-tritium fusion generates helium. The helium ash must be removed from the plasma to prevent reduction of the reaction rate. It has been found that pumping of particles at the plasma edge helps control the plasma density and may help control the density profile. Trapping of plasma particles in redeposited layers is a pumping mechanism, but unless the trapped material can be removed later there are inventory issues (safety issue). The use of flowing liquid surfaces may offer an alternative to conventional vacuum pumping of particles (experiments are needed).

5.6 Modeling

As can be seen from the above discussion, there are many models to describe individual phenomena. In some cases, those models are well developed and can be use for predictions. Several are not yet matured and fully confirmed by experiments. There is one glaring need for modeling. We need to combine all the models together to be able to follow a particle all the way from the surface to the main plasma and back. Such an integrated material surface, plasma edge and plasma core model should be developed. It will require science input from many disciplines. Such a model will also require super computer type hardware for reasonable execution times.

6 Plasma turbulence and transport (R Cohen)

6.1 Description

The boundary plasma -- both on open field lines and closed flux surfaces -- is observed, in tokamaks and at least one stellarator, to be characterized by large-amplitude fluctuations of density, temperature and electrostatic potential. The resulting transport is comparable to Bohm diffusion levels, and is believed to be the primary mechanism supporting the width of the scrapeoff layer (in competition with rapid loss along field lines of heat which crosses the separatrix). In this regard turbulence in the scrapeoff layer is beneficial, in contrast to the situation in core plasmas and the closed flux-surface portion of the boundary plasma, as it increases the area on bounding surfaces over which the escaping charged-particle energy is deposited (except, if it is increased to the point that energy is deposited in undesirable places).

The boundary plasma has a number of unique attributes which can significantly affect turbulence. These include: sizeable populations of neutral particle species, wall boundary conditions, the presence of both open field lines and closed flux surfaces, and the existence of an x-point on the separatrix dividing these regions. In addition, equilibrium radial scale lengths are of the same order as observed and simulated radial correlation lengths, guaranteeing at least some non-locality of the transport. Finally, strong, complex 2-D (and possibly 3-D) convective flows driven by the above effects may also be important.

6.2 Status

Turbulence in the closed-flux-surface "edge" region of tokamaks has been the subject of significant experimental and theoretical effort (e.g. through the auspices of the Transport Task Force), resulting in characterization of edge turbulence and its connection to the L-H transition through suppression mechanisms connected to steep gradients of equilibrium quantities and/or zonal flows. H-mode confinement is typically interrupted by recurring ELMs that dump particles and energy into the SOL. These modes are believed to be caused by MHD modes driven by the steepening pressure gradient in the edge during the H-mode.

The effort in the open-field-line region of a tokamak has been much smaller, with only a hand full of experimental, computational, and theoretical investigators in the U.S. (and perhaps two hand fulls world-wide). Nevertheless, work in recent years has resulted in a growing experimental database, largely from probe and far-infrared data, showing universally large fluctuation levels and correlations of these with macroscopic fluxes as well as macroscopic profiles that affect these fluxes. Theoretical and computational work has established a set of plausible modes and the importance of geometrical effects (e.g. x points) and wall boundary conditions, and simulations have indicated saturation levels comparable to those observed experimentally. There has been little analytical work on nonlinear effects.

There has been relatively little on boundary plasma turbulence of alternate configurations; some exceptions are the turbulence characterization studies on the WVII stellerator and some work on suppression of turbulence in reversed-field pinches with biasing.

6.3 Current Research and Development:

- **R&D Goals and challenges:**

There are a variety of outstanding issues. These are addressed below.

- **Related R&D Activities:**

Core turbulence; all activities which determine the boundary-plasma equilibrium

- **Recent successes:**

Various theoretical, computational and experimental studies suggesting connection of boundary turbulence to the L-H transition (several mechanisms have been suggested; those involving flow generation and turbulence suppression by sheared flows have received the most attention in the U.S., but others involving diamagnetic suppression, electromagnetic skin effect, etc. are also plausible)

Theoretical/computational identification of resistive x-point instabilities as a potentially dominant mode in L-mode boundary plasmas (closed and open flux surfaces); demonstration that this mode saturates at levels and spectra comparable to observations; demonstration that this mode is subject to rotational shear stabilization/turbulence suppression and so can be an important player in L-H transitions.

Development of 3-D boundary plasma turbulence codes that can accommodate realistic geometry and boundary conditions; verification that these codes produce realistic fluctuation levels and reproduce important phenomenology (e.g. as in previous bullets).

6.4 Anticipated contributions relative to Metrics:

This was only briefly discussed at Snowmass.

Possible goals/metrics:

1. Goal: Believable simulations of boundary turbulence for any of the major MFE configurations.
   Metric: comparison of simulated and experimentally measured quantities for simulation of a particular configuration.

2. Goal: Development of reduced descriptions for turbulent fluxes that can be used in a boundary-plasma transport code that can predict self-consistent edge behavior in future devices. Here "reduced" means something simpler than a 3-D turbulence code.
   Metric: the degree to which a working example works (reproduces results of a full 3-D simulation and/or experiment).

3. Goal: development of good macroscopic description of boundary plasmas including turbulence effects.
   Metric: determination of the adequacy of diffusive treatments of boundary turbulence

Metric: Consistency of formulation of alternatives to transport codes with model diffusion coefficients

6.5 Summary of discussions

The boundary turbulence sub-group met by iteself for two hours, followed by a 1/2 hour joint discussion with the core turbulence group. The bulk of the discussion centered on identification of key outstanding issues and methods of attack. These are:

- Parametric dependence of turbulence and the self-consistent SOL equilibrium quantities. Included among the parameters are geometric effects (e.g. what is the role of the x points?). To attack:
  - dedicated experiments
  - 3-D turbulence codes (benchmarked against one another and experiment)
  - dimensional (scaling) analysis
- Non-local transport: clearly an issue since, for example, correlation lengths are comparable to radial scale lengths. How important is it? How does it manifest itself?
  - Develop specific criteria for what an experiment needs to look for
  - Imaging diagnostics would be helpful
  - Simulation/modeling
- Cross-coupling of SOL with edge and edge + SOL with core
  - Measure same parameters in core and edge and SOL
  - Codes and/or code combinations that span these regions

There was considerable discussion on the subjects of kinetic effects and the role of the x point. Both of these may be regarded as sub-sets of the above key issues.

With regard to kinetic effects, it was noted that these may be considerably more important for a spherical tokamak than a conventional tokamak, because of its shorter parallel connection length and larger mirror ratio. A review of old mirror literature could be helpful. Also, a gyrokinetic code would be a good tool for studying such effects.

With regard to x-point effects, there was interest in both the boundary-plasma and (core) turbulence groups in determing how important they are. It was pointed out that x points and walls play a similar role, introducing resistive effects. Hence one might expect somewhat similar turbulence in diverted and limited tokamaks. But identification of the differences in turbulence between these two configurations could be very helpful in elucidating the role of x points. A more basic question might then be, how important is the dissipation from either effect (walls or x points), compared to a situation with only closed flux surfaces? The two primary code groups (LLNL and Maryland) appear to be drawing opposite conclusions (significant and negligible effect, respectively), underscoring the need for intercode comparisons.