Summary of Transport/Confinement Breakout Session

Question 1: What major BP-related developments (in theory, modeling, experiment and technology) have occurred in this area since the Snowmass 2002 study?

- Growing maturity of gyro-kinetic codes
  - Full torus simulations (real geometry)
  - "Full physics" such as kinetic electrons, EM effects, etc.
- Emerging understanding of zonal flows
  - More complete theory developed
  - Several direct measurements of zonal flows and GAM's
- Improved core transport simulation of experiments
  - Simultaneous modeling of density, temperature, and rotation
  - Modeling of ITB formation
- Initial efforts at pedestal modeling that integrate multiple effects
- Intermittent fluctuation structures partly responsible for SOL transport
- L-H threshold linked to flow boundary conditions imposed by SOL
- Experimental observations of self-generated core rotation
  - Similar results from several different tokamaks
  - SOL sets boundary condition
- Correlation observed between energy and momentum transport
  - Momentum convection seen in torque-free plasmas
- Expanded fluctuation measurements
  - Initial measurement of fluctuations at small wavelengths
  - Development of magnetic fluctuation diagnostic
- Density peaking in H-mode plasmas in absence of Ware pinch
- Developed ITB mechanisms more suitable to BP experiments
  - Feedback control to increase ITB duration
  - Triggering by off-axis RF heating
  - Triggering by NCS and Shafranov shift, especially at rational q crossing, correlated with turbulence amplitude decrease
- Demonstration of H_H~1 at n/n_{GW}~1 with high triangularity
- Confirmation of gyro-Bohm-like transport scaling in H-mode plasmas
  - Both heat and particle transport, including trace tritium
  - Turbulence correlation lengths, decorrelation times, and amplitude profiles scale with gyroradius as predicted
- Improved understanding of β and ν^* scalings of transport
  - Dedicated experiments found no β scaling of transport
  - Experiments validated strong (unfavorable) ν^* scaling of transport (evidence for zonal flows?)
  - Progress in understanding differences between scaling relations derived from multi-machine confinement databases and dedicated dimensionless parameter studies

Question 2: What issues remain to be resolved for a successful BP experiment in ITER?

Electron Thermal Transport:

- Need to understand cause of electron anomaly, especially since electron loss channel is important to burning plasmas and burn control
  - ITG mode and TEM likely contribute; ETG mode a strong possibility
  - Not known if magnetic turbulence plays a role
  - Non-fluctuation transport mechanisms, and the effect of MHD on electron transport, need to be tested against experiment
- Need aggressive scientific approach with experiment and theory comparison
  - High k turbulence diagnostic comparison with simulation; identification of electron streamers; nature and role of multiscale couplings
  - Role of zonal flow in TEM needs further study and clarification
  - Role of magnetic shear in electron ITB needs to be clarified
- Need simulation refinement to give convergence of ETG mode at large scales
  - Also need to include kinetic ions in simulations

Ion Thermal Transport:

- Theory of ion thermal transport is the most developed, but
  - Need to resolve disagreements between different codes (Cyclone controversies)
  - Predictive capability for burning plasmas should be advanced by extending the transport models to the plasma boundary
- Amount of transport stiffness needs to be resolved
  - Including more precise shaping effects in theory-based models, and comparing with experimental shape scans, should help to determine the transport stiffness
- Need to improve synthetic diagnostics in transport simulations, especially for fluctuation measurements
- Development of predictive capability needs scientific closure wherein understanding and hypotheses developed thus far are thoroughly and convincingly tested

Particle and Impurity Transport:

- Study linkage between impurity and main ion density profiles
  - Need to understand H-mode density peaking and anomalous particle pinch
  - Control of helium ash (*i.e.*, τ_p^*/τ_E) and other impurities is an important research task since this has high leverage on fusion performance
- Gyrokinetic simulations of turbulent particle transport need to include kinetic particles
  - Qualitative issues remain about effect of zonal flows on particle transport
  - Need to test predictions that anomalous particle pinch depends on ∇T_e and ∇q, and sort out relative importance
- Need to extend particle pinch theory beyond quasilinear theory
- Need to develop credible model for pellet fueling
- Study of operational density limit should be extended to (more) collisionless plasmas

Momentum Transport and Rotation:

- Question of whether a diffusive/convective model is useful or not for momentum transport should be resolved
  - What are the important "off-diagonal" terms in the transport matrix?
  - Gyrokinetic simulation codes should begin addressing momentum transport
  - Need to incorporate effects of non-axisymmetric magnetic fields on rotation studies, especially at high beta
- What is the origin of self-generated flows, and how do they scale to ITER?
  - Is there a physics basis for the empirical $V_\phi \propto W/I_p$ scaling?
  - What are the dimensionless parameters that govern self-generated flows?
- Need to understand poloidal rotation measurements (which affects E×B shear)
  - Collisional damping of poloidal flows is an open question

H-mode Threshold and Pedestal Transport:

- Need comprehensive, integrated model of H mode pedestal and L-H transition:
  - Develop understanding of different processes affecting pedestal (flow shear, magnetic shear, incident transport fluxes, neutrals, MHD fluctuations, etc.)
  - Requires efforts integrated over several topical areas
  - Scaling of H-mode pedestal width and height (especially with ρ^*)
  - L-H threshold scaling (small margin of error for ITER)
  - Need dynamic modeling of pedestal and ELM
  - Improved diagnosis of pedestal profiles, including during ELM cycle
  - Should study pedestal in vicinity of L-H threshold
- Need to expand pedestal diagnostic capabilities, and develop new codes and new collaborations
  - SOL poloidal flows appear to be important
  - Need to reconcile pedestal temperatures on JET and JT-60U
  - Test emerging multiple-effect models

Improved H-Mode Transport:

- Continue development of reduced theory-based transport models which are critical to AT scenario modeling (for both the current ramp up and flat top phases)
- Demonstrate that improved confinement modes extrapolate to the burning plasma regime
  - Study AT modes in low rotation plasmas with $T_i \sim T_e$
  - Need to understand the source of improved confinement in hybrid plasmas; are the confinement trends the same as for standard H-mode plasmas?
  - Reconcile improved energy confinement with need for impurity control
  - Does the higher q_{95} in AT modes limit pedestal height, and thus limit Q?
- Existing transport control tools do not readily extrapolate to ITER — we must develop new tools such as
  - Torque-free or RF-driven rotation
  - RF flow drive (ion cyclotron wave looks promising)
  - Preferential ITB formation at rational q location
  - Shafranov-shift stabilization of turbulence

Question 3: What are the consequences of resolving these issues, or not, in the next ~10 years?

Improving our understanding of energy, particle, and momentum transport should be an important part of the risk management plan for a burning plasma experiment such as ITER. If the energy confinement is too poor, or if the impurity confinement is too good, then it is possible that ITER will not achieve its fusion performance goals. This risk can be mitigated by, among other possibilities, (1) developing transport control tools, (2) affecting the H-mode pedestal height, (3) utilizing ITB and other improved confinement scenarios. In addition, our ability to develop reliable AT scenarios for ITER and beyond is closely tied to our understanding of the transport physics, given the highly non-linear nature of a burning plasma.

Question 4: What issues should be resolved by a successful BP experiment?

ITER will provide a comprehensive benchmark of transport understanding and predictive capability for burning plasmas. This will test the soundness of our transport understanding in regimes of low rotation, T_i~T_e, and small ρ^*. The ITER benchmark test is especially important for AT scenarios that have high confinement factors in present day experiments but which exploit hot ion mode and strong toroidal rotation. As part of a risk management plan, the ITER diagnostic capabilities should be maximized to provide researchers will enough information to overcome any unforeseen obstacles.

Research on ITER will also have to resolve transport control issues and related control requirements in a highly non-linear burning plasma environment. Owing to the large amount of centrally deposited alpha heating power, local transport control is the only possibility for controlling the pressure and bootstrap current profiles in self-sustained plasmas configurations (see 1999 Snowmass report). It is presently an open question as to whether ITER will have the tools required for transport control.

Question 5: What contributions can/should the U.S. fusion program make to resolving these issues?

The U.S. is a world leader in all areas of transport/confinement research, with the most flexible, best diagnosed facilities; superior theory, modeling and simulation capabilities; and unmatched turbulence diagnostics. There exists a great opportunity for the U.S. to lead ITER research in this area, but this requires focus and commitment on our part. The field of transport/confinement physics provides a good mix of short and long term research possibilities, and would engage all segments of the U.S. transport community (*i.e.*, theory/simulation, modeling, turbulence and transport measurements).

While a burning plasma experiment such as ITER will extend the explored range of plasma parameters, it is not an ideal vehicle for transport studies. This is because ITER will have fewer fluctuation and transport diagnostics than existing devices, and ITER likely will have inferior measurement capabilities (*e.g.*, profile resolution). In addition. many next step questions will not be addressable owing to ITER's design realities. Answering burning plasma transport questions prior to and during ITER operation will require a solid base program with viable experiments. The U.S. will need ancillary facilities to ITER for transport studies and to serve as idea test beds for ITER. This will require some expansion of diagnostic capabilities in existing devices.

Question 6: How should the BPO be structured to best help the community make these contributions?

Members of the transport/confinement group expressed the opinion that a useful function of the BPO will be to provide physics support for the ITPA. In that regard, the BPO can serve as a base for building up expertise that the ITPA can then draw from. However, the BPO should also allow the U.S. some independence to pursue our own goals. The BPO should not focus only on ITER, for example. While the activities of the BPO transport group and the TTF should be kept distinct, these two groups should work together to ensure that optimum progress is being made in the transport area. Another useful purpose of the BPO will be to identify and recommend areas of research, and sign up advocates to make credible scientific proposals for research on U.S. (and international) facilities. The BPO will allow the community to vet burning plasma issues, which adds weigh to getting the important issues funded and implemented. Of course, our institutions will need to support the vetted BPO agenda. While the BPO should have some near term deliverables, it will also serve as an organization to educate the community on critical burning plasma issues that need to be resolved.

Our group felt that the BPO should have a strong “bottom up” component. The topical groups should be the prime movers because they are the most democratic part of the organization. The topical groups can spawn task groups for specific problems that have well defined deliverables. Having effective leadership of the topical groups will be a key element to a successful BPO.

An important issue for the transport/confinement group was how to best involve university researchers in the BPO. It was remarked that the funding agencies should make it easier for universities to spend their grant money on BPO activities. Also, to reach a wide audience, the BPO should make use of remote participation tools. Finally, people felt that is was important to integrate students into the BPO activities.