Summary of US-Korea Workshop

Opportunities for Expanded Fusion Science and Technology Collaborations with the KSTAR Project

May 19-20, 2004
General Atomics, San Diego, California, USA

A two-day Workshop attended by selected US and Korea National Fusion Program representatives was held at General Atomics on 19-20 May 2004. The purpose of the Workshop was to discuss opportunities and draft conceptual plans for expansion of US fusion science and technology collaborations intended to support timely completion and initial operation of the Korean KSTAR (Korea Superconducting Tokamak Advanced Research) Project. The Workshop Agenda detailing presentations, speakers and discussion sessions can be found at the conclusion of this summary. Electronic copies of the presentations themselves and of this Summary are available for downloading at http://web.gat.com/kstar/ or by request to John Wesley (wesley@fusion.gat.com) or Hyeon Park (hpark@pppl.gov). Many technical details and graphics not addressed in this *Summary* will be found in the downloadable files. Short summaries of the Korean and all of the US-authored presentations follow the introductory and background material presented immediately below.

Based upon discussions among US and Korean representatives that took place during and after the Workshop, a provisional first-year plan for an expanded US-KSTAR collaboration has been prepared by the Workshop organizers. This first-draft plan reflects KSTAR priorities for US –> KSTAR collaboration and comprises approximately \$1.6 M of US funding for FY05. The plan supports a selection of physics design tasks, heating and current drive system and fueling system technology development, preparations for bring KSTAR into the US Fusion Grid Collaboratory and initial design studies for various conventional and advanced-capability plasma diagnostics. If this draft plan is implemented as proposed in FY05, it will constitute a three-fold increase in US-KSTAR collaboration funding.

1. Background: The KSTAR Project and Korean Participation in ITER

The KSTAR Project is the centerpiece of the Korean National Fusion Program, which includes fusion science and technology R&D at several Korean national laboratories, universities and industries. Korea's goal in establishing this National Program and in constructing the all-superconducting KSTAR tokamak (Figure 1 below: R = 1.8 m, a = 0.5 m, b/a = 1.8, DN and SN divertor, B 3.5 T, I = 2 MA, DD plasma capability, eventually (in ~2013) with up to 300-s pulse duration) has been to make a major impact on world fusion research and to provide both plasma science and magnet and plasma technology support for the forthcoming construction and eventual operation of ITER (International Thermonuclear Experimental Reactor).

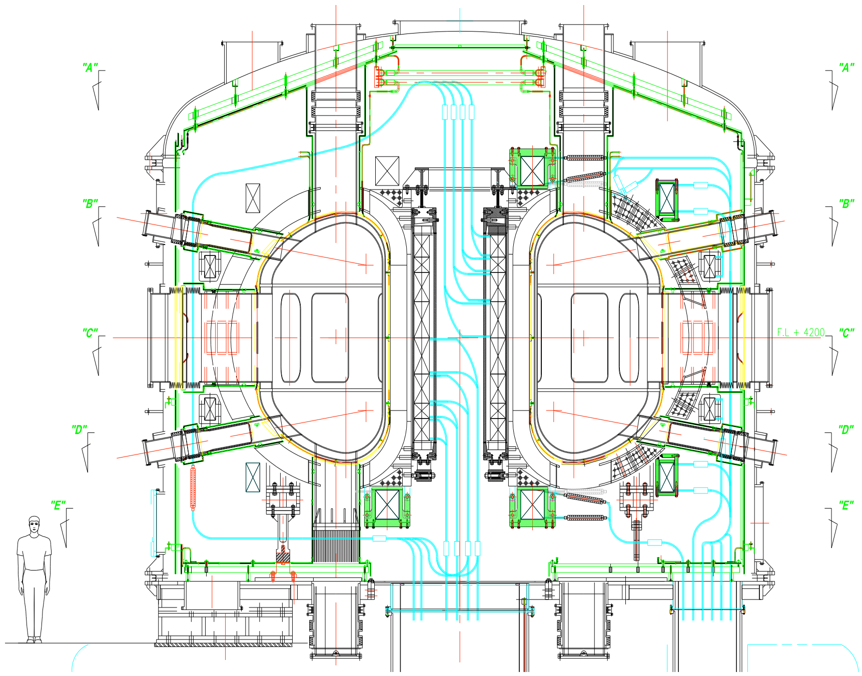

Fig.1. Elevation cross-section of the KSTAR tokamak. The superconducting toroidal and poloidal-field coils are enclosed in a large cryostat vacuum vessel. In-vessel plasma-facing-component and plasma control and stabilization systems (not shown here) will allow steady-state operation with high-elongation, high-triangularity, double-null and single-null divertor plasmas

Ground was broken on the new KSTAR facility in the fall of 1997. In 2004, all major aspects of the facility construction are complete and initial tokamak systems assembly work and winding of the large-diameter NbTi outboard poloidal field coils within the KSTAR facility are under way.

Fig. 2. The KSTAR facility in Daejon, Korea

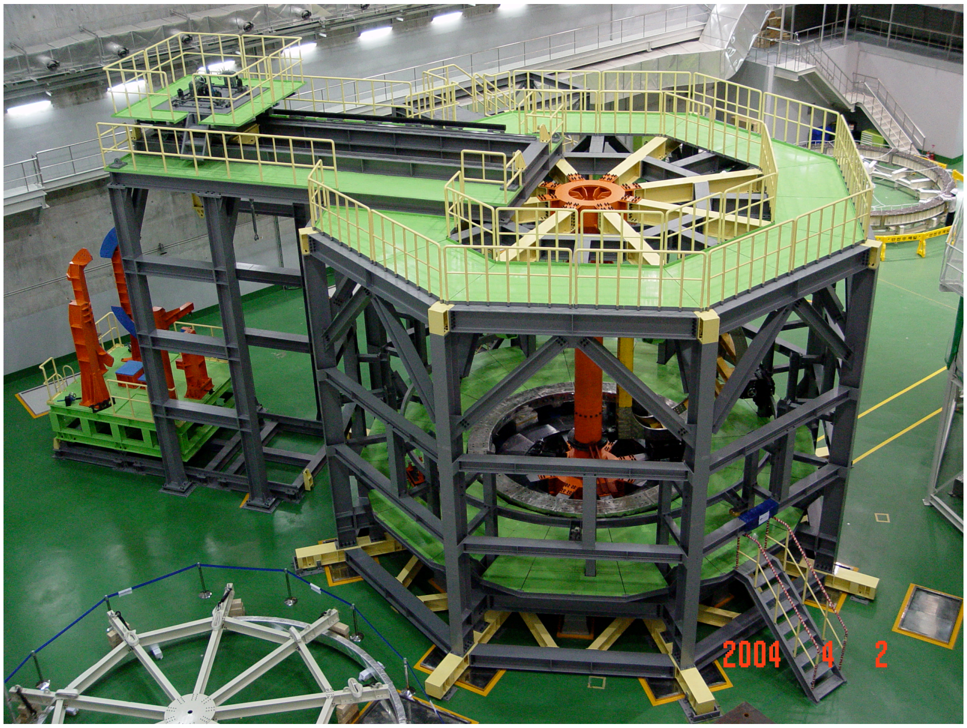

Fig. 3. KSTAR tokamak systems assembly tooling

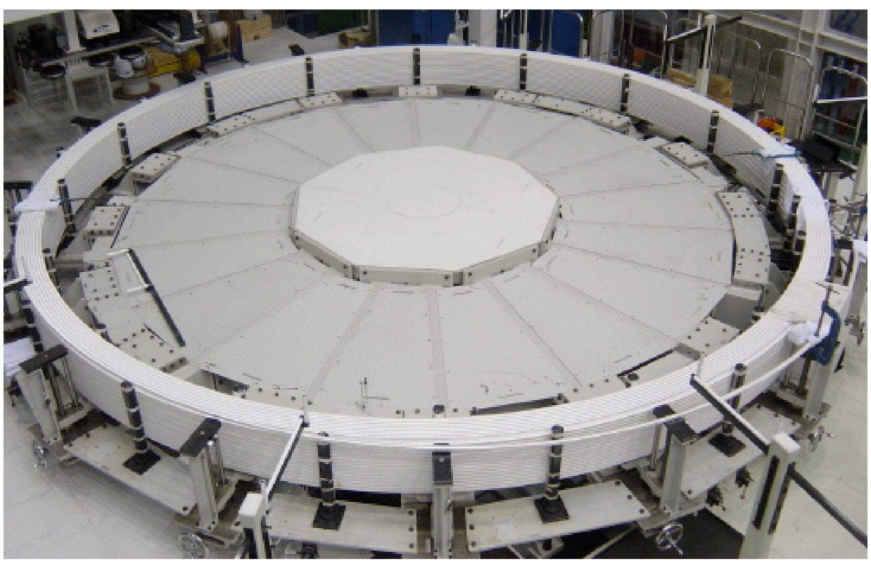

Fig. 4. On-site winding of the KSTAR PF6U NbTi superconducting coil

In 2003, Korea became a full (*sans* site offer) ITER Party. In May 2004, KSTAR site preparation and tokamak system construction and initial assembly are well underway, approximately half of the superconducting toroidal and poloidal field coils have been wound and impregnated, and fabrication of the vacuum vessel sections, the first NB injector vacuum vessel and many ICRF components is complete. A recent Korean government/industry review of the ‘baseline’ (Korean-resources-only) construction and assembly schedule now projects KSTAR ‘first plasma’ at the end of 2007 and initial 'baseline plasma’ experiments (1.5 MA divertor H-mode plasma with long-pulse NBI heating) beginning by the end of 2009.

Full ‘baseline plasma’ capabilities: 2 MA, 14 MW NBI, 6 MW ICRH/FWCD, 1.5 MW LHCD and 1 MW ECH/ECCD, a full set of ‘conventional’ diagnostics and up to 20-s DD pulse duration are now projected by mid-2012. Upgrades commencing in mid-2013 to the EC system (to 3 MW), to the pulse-duration capabilities of the already-installed auxiliary H/CD systems and the pulse-duration capabilities of the plasma-facing-component systems and installation of ‘advanced’ diagnostics are now projected to allow the start of KSTAR integrated ‘advanced tokamak’ long-pulse high-performance DD experiments in 2016. Given present expectations that ITER first-plasma operation (HH) can occur in 2015 and that DT experiments will start in 2018, with this ‘baseline’ schedule, KSTAR will be well-positioned to provide timely plasma science and technology experience inputs for ITER tokamak systems commissioning and for initial ITER HH, DD and DT plasma experiments.

The ‘baseline’ schedule detailed herein is predicated on ‘Korea-only’ funding of the KSTAR Project. Korean presentations during the Workshop also identified the possibility of using ex-Korea staff and hardware resources (now envisioned by the KSTAR Project as coming from expanded collaborations with the US, European Union and Japan national fusion programs) to accelerate the pace of certain time-critical aspects of KSTAR H/CD and diagnostic system development, installation and commissioning for plasma operation. Under this ‘accelerated’ approach, as outlined by the KSTAR team during the Workshop, the duration of the baseline operation program would be shortened by one year, the long-pulse/full-performance upgrade would begin in mid 2012 and long-pulse/high-performance/fully integrated AT experiments could begin by mid 2015 (*cf* 2016 in the ‘baseline’ plan). This acceleration would, as the KSTAR delegation and others at the Workshop noted, provide more ‘lead-time’ and opportunities for KSTAR inputs to ITER operation planning before ITER HH, DD and DT plasma experiments commence.

Figure 5 below, prepared by John Wesley, juxtaposes simplified versions of the ITER 2001 Final Design Report construction and plasma operation schedules (adjusted for a beginning-of-CY2005 start date) and the baseline and accelerated KSTAR schedules. The intent of this Figure is to show, for information, the approximate time relationship of the various construction and operation phases of the two projects. Full details of the KSTAR ‘baseline’ and ‘accelerated’ schedules can be found in the KSTAR presentation files available on-line at the Workshop website http://web.gat.com/kstar/ or from John Wesley (wesley@fusion.gat.com) or Hyeon Park (hpark@pppl.gov).

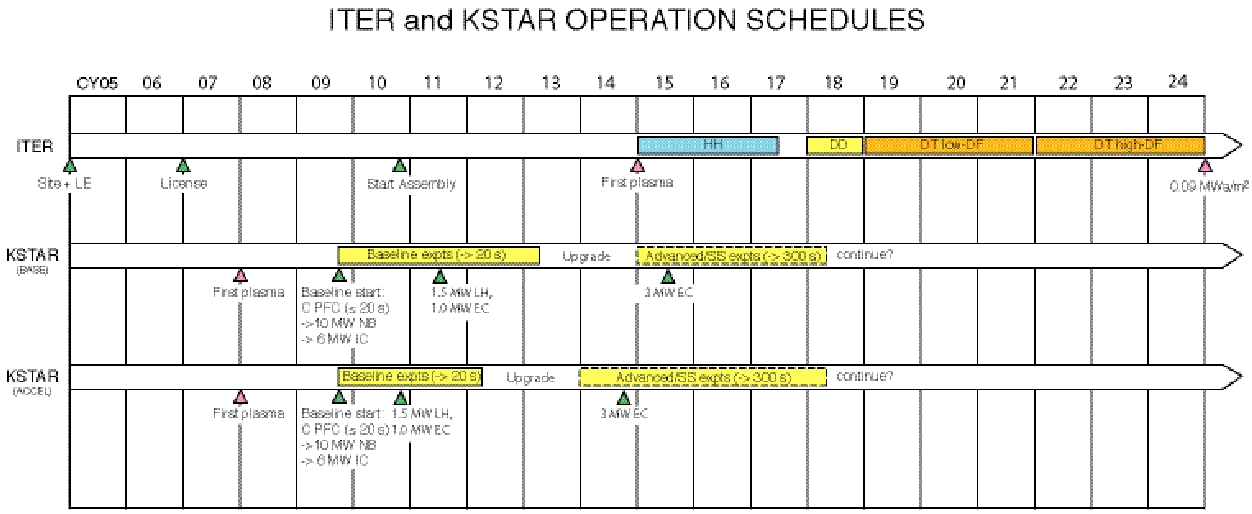

Fig. 5. ITER and KSTAR schedules

2. Workshop Announcement and Prospectus

A 2-day Workshop to review the status of the Korean KSTAR (Korea Superconducting Tokamak Advanced Research) Project and to discuss future (2005 and thereafter) opportunities for expanded US collaboration with KSTAR will be held at General Atomics on 19-20 May 2004. The Workshop will conclude with an executive session on May 20 to prepare a Workshop Report. Hyeon Park (hpark@pppl.gov) and John Wesley (wesley@fusion.gat.com) are the local organizers. The Workshop focus will be on presentation of ways in which US fusion science and technology institutions and staff can collaborate with the KSTAR Project to support timely attainment of KSTAR goals to achieve 'baseline' plasma operation and science study capabilities by 2008. Four topics identified by the KSTAR team of being of high interest have been selected for discussion: 1) near-term application of the Grid-Computing based Collaboratory for KSTAR physics design and pre-operation plasma simulation; 2) physics and technology collaboration in ancillary systems (IC, LH and EC) intended to support eventual steady-state operation; 3) physics design collaboration on plasma operation and control and MHD stability (eg., axisymmetric and RWM control in AT/SS regimes) and 4) collaboration on conventional and innovative diagnostics and turbulence-visualization means that will address both near-term and advanced-tokamak/steady-state goals of the KSTAR Program. An Agenda comprising a series of short invited presentations on these topics has been established. The organizers expect that these presentations will focus on primarily on schedule and resource requirement aspects of the proposed collaborations and will serve as input to the preparation of a coherent US plan for future US-Korea collaborations on KSTAR.

Additional Background and Suggestions for Contributors

A program of reciprocal information exchange and US physics and engineering design support for selected KSTAR tokamak systems has been in place since 1995, and significant recent progress has been made in joint design and analysis of key systems including the electron cyclotron current drive system, diagnostic port cassette designs and the plasma control system architecture and software. Korea has officially joined the ITER negotiations and is currently planning to contribute to necessary ITER R&D through enhanced international collaboration on the KSTAR facility. Given these new developments, it is timely and appropriate for us to hold a US–Korea Workshop aimed at exploring and strengthening bilateral ties between our two programs.

Owing to time and travel cost limitations, this Workshop will focus on Korean presentations of KSTAR status and needs for future ex-Korea collaboration, and on presentations by potential US collaborating institutions and staff on what they see as promising opportunities for US-to-Korea collaboration with KSTAR. Presenters are asked to limit their oral presentation to 15 minutes (plus 5 minutes of discussion), to focus primarily on resource and schedule aspects (additional scientific and technical details can be incorporated into the electronically distributed version).

Content of the electronically-submitted presentations can go beyond what can be presented at the Workshop, but should as a minimum include:

a) A brief summary of what is proposed, what will be furnished to KSTAR and why the proposed contribution will lead to long-term benefit to the US in fusion science and/or technology.

b) Discussion of what can realistically be done by the US with a modest investment sufficient to provide consulting services to the KSTAR program to share existing design studies and analysis. How does the proposed program relate to on-going base program activities or other on-going or proposed international collaboration activities?

c) Discussion of what more could be done by the US with increased funds sufficient for design, prototype development, fabrication and/or testing of key technology in collaboration with the KSTAR team. How do hardware-related activities and project timeline fit with the planned KSTAR schedule?

d) Presentation should include a table showing approximate scope, fiscal magnitude and time-line of their proposed activity. For continuing KSTAR-related US programs, these data can include the proposed incremental in FY 05 and new proposals can start from FY 06. These inputs will be incorporated into an 'expanded collaboration' White Paper [this *Workshop Summary*] that will be drawn up afterwards. Cost and planning can be divided into engineering consulting, full system engineering design, prototype system fabrication if needed, and full system fabrication.

3. Summary of Korean Presentations

Extensive details of the KSTAR Project status and schedule for expected completion and initial and ultimate operation of KSTAR were presented. Selected highlights of both the present status and future schedule and plans have already been summarized above in Section 1, *Background*. Many additional details of the status of the superconducting coil fabrication and testing, vacuum vessel and cryostat vessel fabrication and test and plans for tokamak system assembly will be found in the presentation files available on-line. Details of diagnostic and rf system plans, fabrication and testing were also presented and are similarly available on-line.

The consensus of the US participants attending the *Workshop* and Wesley's summary of the Korean status presentations is that very good progress is being made by the KSTAR Project in bring the KSTAR facility into full operation and in fabrication and initial assembly of all major KSTAR tokamak systems, The Project seems (on the basis of what was presented during the *Workshop*) to now be on a credible track to achieve first plasma as scheduled by the end of 2007. Furthermore, the KSTAR Project has recognized the importance of bringing in ex-Korea expertise and human and hardware resources — in the form of expanded bilateral collaborations — for selected heating/current-drive, diagnostic and plasma control systems, so as to facilitate timely (relative to ITER) attainment of KSTAR 'baseline' and 'advanced/steady-state' plasma operation capabilities. The KSTAR team is presently negotiating with the European Union and Japan national fusion programs for elements of this type of expanded collaboration. This *Workshop* represents the start of planning for a similar expansion of US-KSTAR collaboration.

The Korean presentations concluded with an account by Director-General G. S. Lee of the intention of Korea to make KSTAR an international facility for fusion research and for pre-operation and during-operation support for ITER. Realization of the various bilateral collaborations to bring KSTAR into timely full-performance capability will be a key element of this plan. Other elements will include establishing a broad, internationally-based structure and protocols for managing and effecting the KSTAR operation plan and for using state-of-the-art electronic resources (eg., access-grid computing for data analysis and remote operation of KSTAR) to establish KSTAR as a first-of-kind facility for international collaboration on fusion science and technology development. Such a facility could be a fertile and highly-relevant training ground for the teams and staff who will be responsible for ITER operation.

4. Summary of US Presentations

Summaries prepared by Park and Wesley of the various US-authored presentations follow below. Per the guidance given to the *Workshop* participants, these summaries focus primarily on resource requirements (labor, procurements and fabrication, at the pre-conceptual planning level). No attempt was made or intended during the *Workshop* to assess or compare proposed plans with regard to scientific or technical content or with regard to accuracy or realism of resource, fiscal and schedule data.

The summaries are organized according to the four broad categories of KSTAR interest identified in the *Workshop Announcement*. In what follows, there are actually five categories: diagnostics are split into 'conventional' and 'advanced' categories.

Category 1: Steady-State Technologies

Long-pulse-capable current drive systems for both the plasma core and edge will be an essential part of the steady-state operation of KSTAR, and KSTAR proposes to have a mix of long-pulse-capable positive-NBI, ICRF, LH and EC systems to support exploration and optimization of fully-stationary integrated steady-state 'advanced-tokamak' operation. Neutral beam injection (NBI) and ICRF technology development that will ultimately be consistent with up to 300-s duration pulses is in progress with Korean funding. For LH and EC heating and current drive, KSTAR proposes to employ source frequencies that will be the same as those to be used for ITER; LHCD system at 5 GHz and ECCD at 170 GHz system. As has been stated above, KSTAR is negotiating with the EU and Japan to acquire 170 GHz EC sources being developed for ITER. At the same time, the KSTAR Project has requested a US commitment for EC launchers and antenna system, plus US assistance with development and fabrication of a KSTAR-specialized 5-GHz LH launcher.

Wesley notes here as an aside that present 'reference' plans for the initial installation of ITER H/CD systems provide for a mix of negative-ion NBI, ICRF and EC systems and put LH forward as a 'leading candidate' for a future (after initial operation commences) 20-MW LH upgrade. There are a number of advocates for as-early-as-possible addition of LH capabilities to ITER, and timely (relative to ITER's schedule) successful 5-GHz LH physics results and system operating experience from KSTAR could (in Wesley's opinion) contribute to making an early positive decision on the ITER LH upgrade.

KSTAR will also require steady-state-capable (actively-cooled) plasma-facing-component (PFC) systems for the high-heat-flux divertor targets, NBI in-vessel protective armor and first-wall tiles, and for at-risk plasma-facing-surfaces of the rf launchers. Present KSTAR plans focus on using carbon tiles and/or conventional refractory-metal surfaces for the 20-s pulse versions of these thermal exhaust and protection systems. US representatives submitted a proposal that KSTAR should consider use — perhaps for 300-s operations — of the actively-cooled 'tungsten brush' high-heat-flux designs developed in the US as an ITER divertor candidate.

Wesley notes here, as an aside, that tritium retention in ITER in co-deposited C layers is a critical DT operation issue, and that a number of 'strawman' proposals are in circulation within the ITER/ITPA community to consider switching the ITER divertor PFC design to an all-metal (likely tungsten) concept. Long-pulse operation of a KSTAR all-tungsten divertor system would provide potentially valuable insight to ITER as to the pros and cons of such a choice.

Finally, KSTAR will, like any tokamak aspiring to steady-state operation, require particle fueling and exhaust technologies compatible with continuous plasma fueling and exhaust. A US collaboration presentation addressed development of a steady-state-qualified repetitive pellet injector and a KSTAR-compatible pellet guide tube system to allow high-field-side injection.

Steady-State Technology Presentations

1) LHCD launcher and associated technologies: This proposal, presented by Joel Hosea (PPPL), comprises developing a 5-GHz lower-hybrid antenna (grill launcher) design that is capable producing a wide and controllable (variable) k-parallel spectrum. Some preliminary design and component concept development for this type of system has already been done at PPPL under the existing (FY04 and before) US-KSTAR collaboration task. Such a variable-spectrum antenna design would be different from the fixed-spectrum design being developed by the EU for ITER. We (US and PPPL) believe that a variable-spectrum design is optimal for the KSTAR, where physics of current drive can be fully tested with the wide k-parallel spectra and wave launch

direction change. Positive physics and launcher engineering outcomes from KSTAR could impact the design of the ITER LH antenna system. However, there are number of launcher technology implementation issues (steady-state cooling, handling of reflected power) that must be resolved to make this system applicable to a long-pulse, steady-state device.

R&D for design and prototype	$400K/year, for two years
Fabrication	$5M
Total	$5.8M

2) ECCD proposal: Rich Callis (GA) presented a comprehensive R&D plan for the proposed KSTAR 3-MW, 170-GHz EC system. This would be versatile system that could be used for core current drive and current profile optimization or as a radially-localized heating or current source for MHD control, eg., to stabilize neoclassical tearing mode instabilities or modify sawtooth periods. These capabilities will be an essential element for the study of the MHD stability limit of KSTAR operation. If the KSTAR system is 170 GHz, R&D for the launcher and waveguide system and operating experience with all of the system components (including the gryotrons) will be directly relevant to the ITER project.

Transmission line	
Design	$237K
Fabrication	$3.5M
Installation and commission	$125K
Total	$3.9M

Antenna (launcher)	
Design	$678K
Fabrication	$2.2M
Installation and commission	$200K
Total	$3.1M

3) Tungsten 'brush' PFCs: Mike Ulrickson (Sandia) presented a proposal for the US to provide actively-cooled 'tungsten-brush' plasma-facing-component systems for the KSTAR divertor targets. In the tungsten-brush concept, a closely-packed array of tungsten cylinders ('bristles') is diffusion bonded in a perpendicular fashion to a copper-tube heat removal structure. The resulting tessellated surface relieves thermal stresses and limits propagation of melt damage to the cylinder tips. Electron beam thermal testing of prototypes shows that the design can withstand sustained (continuous) heat loads of up to 25 MW/m^2 for thousands of pulses.

Steady-state designs of this type have been proposed for the ITER divertor targets, and are being advocated by some in the ITER/ITPA PFC community as being a promising lower-tritium-retention replacement for the present ITER carbon PFC targets. But there has, so far, not been a plasma exposure test of a tungsten brush system in a tokamak, high-performance or otherwise. A full-system test in KSTAR would provide key technology validating data for ITER and would also elucidate boundary and disruption science and operation issues such as tungsten impurity release and in-vessel migration during normal and 'off-normal' operation (ELMs and disruptions) and long-term accumulation of tungsten in the core of AT plasmas.

A complete system for KSTAR would cost about $15M to fabricate and install. Design and prototype testing would, together, cost $300K. The total program cost breakdown is:

Design	$150K
Prototype test	$150K
Fabricate full system	$15M
Total	$15.3M

Wesley notes here that there are significant KSTAR and ITER schedule and ‘option-selection’ issues associated with a KSTAR test of tungsten-brush (or other tungsten concept) PFCs. As inspection of Figure 5 shows, if ITER were to identify tungsten targets as their first-plasma (HH phase) option, then with-plasma testing of candidate W designs during the 20-s KSTAR baseline phase is likely required to provide adequate time for procurement of the ITER first-plasma PFCs. On the other hand, if the ITER were to start with C targets for the HH phase and then switch (if C-target tritium retention proves to be a problem) to W for the DT phase, then KSTAR testing of steady-state tungsten concepts during the ‘steady-state/AT’ phase might be able to provide timely technology and plasma science input to the ITER DT-phase PFC choice and validation.

There was no intent or opportunity during the *Workshop* to discuss these types of ex-KSTAR scheduling and science and technology data flow issues.

4) Repetitive Pellet Injector System: Efficient plasma fueling that can be implemented in KSTAR on a continuous basis (ultimately for up to 300-s pulses) will essential for long-pulse and/or steady-state operation of KSTAR (and ITER). High-field-side (HFS) pellet injection [in which pellets are launched into the plasma from the high-toroidal-field (small-R) side of the plasma] is presently seen as the most promising candidate means for achieving this type of steady-state fueling. Dave Rasmussen (ORNL) presented how a repetitive high-field-side pellet injector system can be implemented on KSTAR. The design of the repetitive injector itself follows from designs already tested on DIII-D and JET. The principal system design realization issues for KSTAR center around the routing and bend radii of the guide tube that will be needed to route pellets to the HFS plasma surface. Finalizing the design of the guide tube (or tubes) is a relatively urgent R&D project for KSTAR, since the route of the piping must be determined prior the installation of other in-vessel components and closing of the cryostat.

Design + R&D for Repetitive Pellet Injector and Guide Tube	$80K/year (x 3 years)
Fab and install two injectors	$300K
Total	$540K

Category 2: Control, Stability and AT Modes

The ultimate mission for KSTAR is to demonstrate, in an integrated manner, the science and technology bases for high-performance, non-inductively-sustained ‘advanced tokamak’ operation. Demonstration and science exploration of such operation in KSTAR could, for example, provide timely operational planning and possibly even 'upgrade hardware' decision information for such steady-state AT scenarios in ITER. Wesley notes, for example, that a 300-s duration AT demonstration in KSTAR would correspond, in terms of simple current-profile-relaxation-time scalings, to about a 10,000-s duration pulse in ITER.

Long-pulse and/or steady-state AT operation in KSTAR will require active stabilization of resistive wall modes (RWMs), and may, depending on the scenario selected, also require active stabilization or control of other MHD instabilities including neoclassical tearing modes (NTMs) and edge localized modes (ELMs). US presentations at the Workshop focused on three classes of control and scenario issues: 1) RWM stabilization via external feedback; 2) 'advanced' control system development and implementation, and 3) scenario scoping and simulation studies:

1) IC Coil and Passive Stabilizer Physics Design Validation: The KSTAR tokamak design incorporates a system of in-vessel passive stabilizing plates and in-vessel control coils that are intended to provide both axisymmetric (vertical and radial position) instability and non-axisymmetic instabilities (non-axisymmetric static error field and RWM). Assessments made to date by the KSTAR Project of the system performance confirm the general adequacy of the proposed concept for n = 0 and static error-field correction (see eg., the on-line presentation by M. Kwon). There remain, however, open questions about system performance for RWM stabilization.

Steve Sabbagh (Columbia University) made a presentation about US capabilities (the VALEN code) for assessment of RWM stability in tokamaks and how these codes can be applied to assess the effectiveness of KSTAR's proposed system for active RWM control. Steve's presentation emphasized the importance of the optimizing the coupling of the KSTAR internal control (IC) coils to the plasma in order to increase the achievable stability (beta) limit in the presence of an RWM. However, the immediate question on the table for KSTAR is how well the as-proposed system will work, and the first priority for the KSTAR Project is to obtain a validation of the design of the plates and IC coils before the Project has to commit to manufacturing and final installation details for these components. If the findings of the VALEN analysis identify limitations, then the Project is willing to accept changes to the current design.

The VALEN code analysis \to be employed for evaluating the RWM stability limit and feedback power supply requirements (power/gain and bandwidth) for KSTAR will be highly relevant to the design of the ITER system.

Validation of the current KSTAR system	$150K
Feedback study and first plasma stability	$200K
Stability of advanced operation modes	$200K
Total (3 years)	$550K

2) Advanced Control System Development: General Atomics (GA) and the DIII-D Plasma Control Group are already working with the KSTAR Project to develop the basic digital plasma control system (PCS) software to be used by KSTAR for control of 'Day-1' plasmas. The 'Day-1' KSTAR PCS (KPCS) software is based on the PCS software being used for DIII-D plasma control and will be configured to operate within the overall network-based KSTAR tokamak and

facility control systems that will be provided by the KSTAR Project. The 'Day-1' version of the KPCS software, now planned to be delivered to KSTAR by 2006, will support radial and vertical position control and elementary shape and divertor configuration and plasma density control for 'first-plasma' and initial 'baseline' plasma operation. More advanced control functions, including MIMO (multiple input, multiple output) 'advanced' shape control, kinetic/performance control and MHD instability control (eg, RWM feedback control) can be added to the system software as KSTAR needs evolve and the necessary 'actuators' become available. The advanced-control task will necessarily include development of off-line simulation models (KSIM plant, control system and plasma models) for the 'advanced control' functions to be addressed.

Dave Humphreys (GA) presented the plan for joint KSTAR-GA development of the advanced control system. The plan addresses magnetics, kinetics and advanced scenario control needs. The GA portion of the work would be performed on an approximately-constant 0.5 FTE level-of-effort basis, with focus evolving in successive years to follow the evolution of KSTAR needs and the emerging system ('actuator') capabilities.

Advanced PCS and KSIM development	\$150K/year (x 5 years)
Total	\$750K

A 5-year US effort costing a total of \$750K plus continuation of the present level of Korea-US matching funds (from KSTAR) will be needed to complete development of the full 'advanced performance' version of the KPCS software and associated KSIM development models.

3) Simulation of AT Modes and Operation Scenarios: A predictive modeling capability to support KSTAR plasma performance assessment and control system design will be needed for both 'conventional' and advanced 'AT/steady-state' operating modes. Chuck Kessel (PPPL) presented his plan for the AT operation modes using TSC and other available predictive codes. Scoping studies with parametric 0-D models would be used a basis to define candidate 'reference' scenarios that could then be modeled in more detail (1.5-D) with TSC.

Scoping and Simulation of AT Scenarios	\$60K/year (x 3 years)
Total	\$180K

Total cost of the initial scoping and scenario modeling effort with existing TSC models will be \$180K. This effort will employ basic parametric transport and MHD stability modeling bases sufficient to yield a set of self-consistent reference scenarios (eg., as have already been developed for ITER and FIRE). Incorporation of more-advanced theoretical or experiment derived local transport and MHD stability models will require more effort, plus validating data from on-going AT experiments. Wesley notes that first-principles-based predictive AT modeling is still very much a subject of intense R&D within the world magnetic fusion community.

Category 3: Conventional Diagnostics

As a modern research-capable tokamak, KSTAR will require a comprehensive and highly-reliable set of 'conventional' plasma diagnostics capable of providing key plasma profile information [eg., n_e, n_i, T_e, T_i and $q(r)$] on a continuous, high-time-resolution basis. The KSTAR team has identified conceptual designs and a 'staged' implementation plan (see Kwon's presentation) that will make this set of diagnostics available on a timely basis during the 'baseline' plasma operation development phase. The KSTAR team has also identified needs for ex-Korea collaboration in some of the more-sophisticated profile systems, this to assume reliable operation and timely availability of the required hardware systems and data analysis capabilities.

US initiatives in three systems —Thomson Scattering, Motional Stark Effect and Charge Exchange Recombination have been identified as candidates for US collaboration. In addition to these three KSTAR-solicited initiatives, US representatives also proposed development and installation of an Intense Diagnostic Neutral Beam (IDNB) system for KSTAR, with the intent of the KSTAR system being a prototype for a similar IDNB system for ITER (KSTAR positive-ion heating/current-drive neutral beam systems are adequate to support KSTAR neutral-injection-based diagnostic needs; ITER will require a separate 'high-intensity' diagnostic neutral beam to obtain adequate neutral-injection-based diagnostic system performance).

Fiscal details of the four US initiatives are summarized below. Estimates for the total system design, fabrication and installation costs are given. It is assumed that there will be US-Korea cost-sharing of the overall cost, since utilization of KSTAR engineering and design staff to complete the diagnostic work will be required. Costs for the engineering/design work from KSTAR is estimated based on US standard costing bases. The expected US:Korea funding ratio (US:KO) is indicated for the three Korea-solicited initiatives.

1) Thomson Scattering system: The presentation was given by Dave Johnson (PPPL) and provided a detail cost estimate and plan for the KSTAR system:

TS System	(US:KO = 5:2)
Design	$700K ($129K for cassette and $200K for collection optics)
Fabrication	$1.5M
Installation and commission	$300K
Total	$2.5M

2) Motional Stark Effect (MSE) system: Fred Levinton (Nova Photonics) presented the detail plan and budget for the KSTAR system:

MSE System	(US:KO = 6:1)
Design	$400K ($79K for cassette and $250K for collection optics)
Fabrication	$1.2M
Installation and commission	$300K
Total	$1.9M

3) Charge Exchange Recombination Spectroscopy (CHERS): Don Hillis (ORNL) presented the detail plan and budget for the KSTAR system:

CHERS system	(US:KO = 4:1)
Design	\$500K (\$129K for cassette and \$133K for collection optics (background system is not included)
Fabrication	\$1.0M
Installation and commission	\$600K
Total	\$2.1M

4) Intense Diagnostic Neutral Beam: Jaeyoung Park from LANL made a presentation on development of an ITER-prototype Intense Diagnostic Neutral Beam system that could be tested in KSTAR. The KSTAR and ITER systems would employ a magnetically-insulated-diode (MID) intense positive-ion beam source (~50 A/cm^2). This MID source would be capable of repetitive pulse operation and would provide short neutral beam pulses (1-2 μs) with high repetition rate (~30 Hz) to improve signal-to-noise ratio. The beam energy of 125 keV/amu is optimized to support CHERS and MSE. Low beam divergence (1˚ divergence) will be obtained with modified electrodes and additional electric quadruple beam shaping.

Development of a prototype system suitable for installation on KSTAR would require a 4-year effort that encompasses both MID source optimization and IDNB fabrication and test:

Task 1: Characterize and optimize MID source	2 years, \$1.2M/yr
Task 2: Development of DNB system (for KSTAR)	2 years, \$1.2M/yr
Total (4 years)	\$4.8M

Category 4: 'Advanced' Turbulence and Fluctuation Visualization Diagnostics

Experience with conventional 0-D and 1-D turbulence-viewing diagnostics in present tokamaks has resulted in a rapid evolution in the associated plasma diagnostic technologies and opportunities to construct systems that can provide 2-dimensional visualization of plasma turbulence and fluctuations. The large plasma viewing ports available in KSTAR are well suited to the installation of such visualization diagnostics. For complex phenomena such as turbulence and fluctuations, visualization measurements and comparison of these data with numerical simulations developed for a corresponding 'synthetic diagnostic' may the best way to learn the physics of the underlying complex system. In any case, turbulence visualization tools are expected to be a standard by the time KSTAR is fully operational. Visualization diagnostics will certainly attract international interest for physics research.

1) Beam Emission Spectroscopy: The presentation was given by George McKee (University of Wisconsin). BES has been applied in several present tokamaks for visualization of the physics of L/H transition and zonal flows at the edge of the plasmas. All of the neutral-beam-based diagnostics in KSTAR, including BES system, will be located in Bay M. The current design of the front-end optics of the BES system may have to be reviewed in order to accommodate the 64-channel viewing array that is being proposed for the 'advanced' KSTAR system.

Design	$300K ($50K for cassette and $250K for collection optics)
Fabrication	$800K
Installation and commission	$200K
Total	$1.3M

2) <u>Microwave Imaging Systems</u>: Neville Luhmann (UCD) summarized recent progress and results from microwave imaging systems which provide 1-D and 2-D imaging of temperature fluctuations of internal MHD activity and poloidal rotation of density turbulence. Electron Cyclotron Emission Imaging and Microwave Imaging Reflectometry systems respectively yield data on temperature and density fluctuation. The combined use of these methods for 2-D imaging in KSTAR is feasible and is expected to yield important physics data for transport and MHD studies. Fiscal details for a three-year plan and budget are:

Design	$500K ($200K for cassette and $300K for optics and arrays)
Fabrication	$800K
Installation and commission	$200K
Total	$1.5M

Category 5: Grid-based Collaboratory

The KSTAR team has identified implementation of a grid-computing-based collaboration capability (*aka* Grid-Based Collaboratory) to be an essential element of their proposed future use of the KSTAR facility as a shared international research device. For KSTAR application, the Collaboratory approach could address many shared-use issues, including 1) remote control for KSTAR experiments and communication among on-site and off-site participants, 2) world-wide transfer of data and maintenance of relevant security, and 3) international collaboration on KSTAR physics experiment design and subsequent data analysis. These KSTAR issues parallel the similar issues now being addressed by the development of the US *National Fusion Collaboratory* (FusionGrid), which is intended to provide capabilities for domestic and international fusion experiment implementation and data analysis. Leaders of the FusionGrid development team (Dave Schissel [GA], Martin Greenwald [MIT] and Doug McCune [PPPL]) presented their vision for a consolidated plan for the KSTAR Collaboratory and gave a demonstration of the present (still-developing) US domestic capabilities. The presenters and Korean and US participants in the *Workshop* noted that a successful development of Collaboratory software and the corresponding communication and human-interface networks for the KSTAR Project would have favorable implications for the similar software and network developments needed for ITER.

Explicit incorporation of KSTAR into the FusionGrid development and utilization effort and eventual extension of the Collaboratory software to address real-time data handling and access during extended-duration KSTAR pulses is estimated by the presenters to require a $250K/year level-of-effort over the course of a 5-year program. Total cost will be $1.25M. This modest (less than 1 FTE per annum) level of effort is (will be) possible only if implemented within the much-larger and independently-funded US National Fusion Collaboratory program.

Workshop Summary, Discussion and Draft Plan for the FY2005 US Effort

Specific details for the proposed FY05 collaborations are as follows. In all cases, the work plans and fiscal allocations cited are provisional and subject to the usual US fusion program budget planning and funding allocation process for FY05.

Steady-State Technology ($370K): LHCD and ECCD systems are essential for the steady-state operation of KSTAR and US expertise in both LHCD antenna and ECCD launcher system design and fabrication can make a significant contribution on these areas. At this point, it will be beneficial for the US team to explore the essential parts of antenna/launcher system design for KSTAR, anticipating future hardware procurement and installation. Funding of $150K is suggested for LHCD physics design and component development (PPPL), $150K for ECCD physics and launcher/transmission system design (GA) and $70K for repetitive pellet injector and HFS guide-tube design studies (ORNL). The guide-tube design studies are particularly urgent with regard to finalization of the KSTAR in-vessel systems design.

Control, Stability and AT Modes ($350K): These are critical items for the KSTAR design validation, component construction and initial operation. Validation of the current design of IC coils and passive plate with the VALEN code is urgently required before the manufacturing of the components and procurement of the control power supplies begin. Continuation of the basic and advanced KPCS software development is extremely important to support the first-plasma and advanced operation. Self-consistent TSC-based scenario modeling will provide ‘reference-case’ plasma scenarios and profiles needed for both conventional and AT stability and control system design and validation. The corresponding FY05 allocations are respectively $150K for Columbia University, $150K for GA and $50K for PPPL

Conventional Diagnostics ($520K): A reliable set of ‘conventional’ profile diagnostics are essential for the meaningful physics studies in KSTAR. $150K for Thomson scattering (PPPL), $150K for CHERS (ORNL) and $150K for MSE (Photonics) are required to meet the goal of meaningful initial plasma operation. These allocations are primarily for time-critical in-vessel and in-port system design activities.

Advanced/Visualization Diagnostics ($200K): Beam-Emission-Spectroscopy (BES) and microwave-based reflectometry and emission imaging systems (MIR/ECEI) are identified as major tools for physics study on KSTAR. $50K (University of Wisconsin) will support initial ‘front-end-optics’ design work for BES system; $150K (to UC Davis) will support in-port design work for the combined MIR/ECEI system.

Grid-Based Collaboratory ($250K): $250K is suggested to initiate developing a cost effective grid based collaboratory concept for KSTAR. The work will encompass both near-term implementation of protocols and software to bring the KSTAR Project into on-going US national and international grid-collaboration activities (Fusion Grid) and to examine requirements for adapting grid collaboration capabilities for eventual KSTAR remote operation, data sharing and collaborative data analysis.

Table 1 summarizes the total-cost fiscal parameters of the US presentations. Presentation of total cost here is only to show the nature and approximate fiscal magnitude of possible US collaborations. The Table also details KSTAR priorities for the proposed collaborations as they were voiced by the Korean delegation. There are two priority categories: 1) high/immediate 2) low and/or for future consideration. Finally, the Table details the 'strawman' US plan for FY2005 KSTAR collaborations developed by the *Workshop* organizers and other US representatives following completion of the Korean and US presentations.

TABLE 1: Summary of US Collaboration Proposals, KSTAR Priorities and FY05 Plan

Category or Collaboration Topic	**Total US Cost** (1) ($)	**KSTAR Priority** (2) 1 = high/immediate; 2 = low/future	**Planning Basis for FY2005** (3) ($)
1) Steady-State Technology			
LHCD launcher	5.8 M	1	150 K
ECCD launcher + transmission lines	8.0 M	1	150 K
W-brush divertor targets	15.8 M	2	---
Repetitive pellet injector + guide tube	0.54 M	1	70 K
2) Control, Stability and AT Modes			
RWM physics design validation	0.55 M	1	150 K
Advanced KPCS development	0.75 M	1	150 K
AT Scenario physics design	0.18 M	1	50 K
3) Conventional Diagnostics			
Thomson Scattering	2.5 M	1	150 K
MSE	1.9 M	1	150 K
CERS	2.1 M	1	150 K
Intense Diagnostic Neutral Beam	4.8 M	2	---
4) 'Advanced' Diagnostics			
BES imaging	1.3 M	1	50 K
ECE and MRI imaging	1.5 M	1	150 K
5) Grid Collaboratory + Remote Ops			
Development for KSTAR	1.25 M	1	250 K
Total (all US proposals)	**47.0 M**	---	---
Total (KSTAR priority 1)	**26.4 M**	---	**1.62 M**

1) Total labor and ODC costs for each program, over 3- to 5-year program span
2) Based upon discussions among US and Korea delegations during and after Workshop
3) 'Strawman' collaboration plan recommended for FY2005 based upon discussions among US *Workshop* participants

This Table demonstrates a number of significant conclusions that emerged during and after the course of the *Workshop*. First, Korean/KSTAR priorities for the proposed US collaboration topics are well matched to the majority of the US-proposed initiatives. With regard to KSTAR priorities, the KSTAR team voiced a clear distinction between tasks they judged ‘important/essential’ for timely development of KSTAR baseline and advanced performance capabilities (priority 1) and those intended ‘for future support of ITER’ (priority 2). The tungsten-brush divertor target PFC test and the IDNB development and test in KSTAR fall into this latter category. Immediate KSTAR interest in these ‘for-ITER’ initiatives is, quite understandably, lower than for the KSTAR-focused collaborations that directly advance development of KSTAR initial and full-performance operation capabilities.

Second, the presentations solicited for the Workshop and summarized in Table 1 now give a clearer idea of the fiscal costs and focus areas for an expanded US –> KSTAR collaboration. Collaboration on major rf systems such as LH and EC and on major conventional diagnostic systems will necessarily, even with Korean and/or other-party cost sharing, will require major US human resource and fiscal commitments. Total US labor and ODC cost for the proposed KSTAR priority-1 selections is about $26M, or about $5M per year if a level annual funding profile were to apply. This $5M per year magnitude represents a 10-fold increase over the present $0.5M annual funding for US –> KSTAR collaborations.

The *Workshop* organizers and participants recognize that the US collaborations proposed during the *Workshop* cannot be and should not be considered in isolation. The KSTAR team is negotiating with their counterparts in the Japan and EU fusion programs for expanded Japan –> KSTAR and EU –> KSTAR collaborations that are, like the proposed US –> KSTAR collaborations, intended to accelerate realization of KSTAR research capabilities. The outcome of these bilateral negotiations will (the organizers hope) become clearer within this year. The same hope for near-term resolution applies to the on-going negotiations to finalize international commitments to proceed with ITER. The potential for impact of any and/or all of these negotiations on US –> KSTAR collaboration plans is significant.

The proceedings of the Workshop also establish that it will be essential to coordinate the international efforts on KSTAR so that both ex-Korea and Korea resources can be effectively used to ensure timely progress in making KSTAR into a world-class research facility. Exactly how this coordination will be effected — with or without ITER — remains to be determined. But in the interim, *Workshop* participants have developed a provisional ‘strawman’ fiscal plan, as detailed in Table 1, that provides for three-fold increase in overall funding, to about $1.6M per annum in US FY05. As Table 1 demonstrates, this strawman plan will support physics design activities and preliminary system and hardware engineering design work in all of the high-priority ‘urgent-need’ collaboration topics identified by the KSTAR team.

Agenda:

US-Korea Workshop

Opportunities for Expanded Fusion Science and Technology Collaborations with the KSTAR Project

May 19-20, 2004; Room 15-019
General Atomics, San Diego, California, USA

May 19: Korea and US Presentations

I. Intro and KSTAR Presentation		**J. Wesley (GA*)***
08:30 – 08:40	Welcome and Opening Remarks	E. Oktay (DOE)
08:40 – 08:50	US position of US-KSTAR collaboration	R. Nazikian (PPPL)
08:50 – 09:25	Korea position of US-KSTAR collaboration Current Status and Joint Utilization Plan of KSTAR Project	G.S. Lee (KBSI)
09:25 – 09:40	Preparation and Positioning of Korea for the ITER Project	J.H. Han (KBSI)
09:40 – 10:05	Status of the KSTAR Diagnostics and Control System Development for the 'Accelerated' Plan of Operation	M. Kwon (KBSI)
10:05 – 10:25	Status of KSTAR ICRF and NBI System Development	B.G. Hong (KAERI)
10:25 – 10:45	Status of KSTAR ECH and LHCD System Development	W. Namkung (POSTECH)
10:45 – 11:00	***Break***	
11:00 – 12:00	Discussion on KSTAR program	M. Kwon & KSTAR team
12:00 – 13:30	***Lunch***	

II. US Presentations (20 minutes, including 5 minutes for questions + discussion)		**H. Park (PPPL*)***
13:30 – 14:30	**Steady-State technology**	
	LHCD	J. Hosea (PPPL)
	ECCD	R. Prater (GA)
	Wall interaction	M. Ulrickson (Sandia)
14:30 – 15:30	**Control, Stability &AT modes**	
	Steady state physics simulation	C. Kessel (PPPL)
	Stability Optimization: IC coil and passive plate design	S. Sabbagh (Columbia)
	Basic and MHD control	D. Humphreys (GA)
15:30 – 15:45	***Break***	
15:45 – 17:45	**Conventional diagnostics and technology development**	
	Thomson Scattering system	D. Johnson (PPPL, GA)
	CER	D. Hillis (ORNL)
	MSE	F. Levinton (Nova Photonics)
	Pellet Injector	L. Baylor (ORNL)
	Diagnostic Neutral Beam	J. Park (LANL)
19:30	***Dinner at Korean House Restaurant***	

May 20: Conclusion of US Presentations; Joint Discussion and Collaboration Planning

III. Conclusion of US Presentations		**H. Park (PPPL)**
08:30—09:10	**Advanced diagnostics for MHD and transport**	
	Visualization diagnostics (BES)	G. McKee (U. Wisconsin)
	Visualization diagnostics (MIR and ECEI)	N. Luhmann (UCD, PPPL)
09:10 – 10:10	**Grid-based Collaboratory for KSTAR application**	
	Visualization and control tools	D. Schissel (GA)
	MDS-Plus data security and transfer	M. Greenwald (MIT)
	Global physics analysis with TRANSP	D. McCune (PPPL)
	Live demonstration	D. Schissel (GA)
10:10 – 10:20	***Break***	

IV. Discussion on logistics and philosophy **R. Nazikian (PPPL)**

10:20 – 10:50	Collaboratory concept	Schissel *et al*
10:50 – 11:20	Steady state technology	Hosea *et al*
11:20 – 11:50	Control & Stability	Sabbagh *et al*
11:50 – 12;30	Diagnostics and technology	Luhmann *et al*
12:30 – 13:30	***Lunch***	

V. Executive and Collaboration Planning Discussions

13:30 –17:00	Discussion and Plan Drafting	US + KSTAR representatives