Fusion Energy Division
American Nuclear Society
June 2000 Newsletter

The June 2000 newsletter of the American Nuclear Society (ANS) Fusion Energy Division (FED) has been archived on the ANS-FED Web site: http://fed.ans.org/. Please share this newsletter with your colleagues. If you did not receive this newsletter directly and would like to subscribe to the ANS-FED newsletter or provide us with a change in the E-mail address, simply reply to this message and include your contact information. We send this E-mail to fusion scientists in the U.S. and abroad. If you believe you are outside the fusion community, please inform the editor (elguebaly@engr.wisc.edu) and accept our apology for the inconvenience. A text version of the newsletter is appended below for those who do not have the capability to access the Internet. If you have a choice, please use the Web version as it contains formatting that is lost upon conversion to the text version. The topics for this issue include:

Message from the Chair, Clement Wong, General Atomics, San Diego, California

I would like to touch on three topics of interest to FED members. The first is the status of the fiscal year 2001 fusion budget, the second is the activity of generation IV Fission Power Systems, and the third is the fusion application of fission waste burning. I also add my observations on fusion development at the end of this message.

Fiscal Year 2001 budget (Quoted from Fusion Power Associate report)

In March of this year, 43 members of the U. S. fusion community signed and delivered a “Statement on the Fiscal Year 2001 Fusion Energy Science Budget" to the Subcommittee on Energy and Water Development of the Committee on Appropriations of the U.S. House of Representatives, chaired by Rep. Ron Packard (R-CA), asking the Committee to fund fusion research at a level of $300 million. In the statement, the group asked the Subcommittee to "fund the DOE/SC Office of Fusion Energy Sciences at $275M for FY2001, as authorized by the House Science Committee (last year), and that IFE related laser research be funded at $25M, to be allocated between DOE/DP Office of Inertial Confinement Fusion and the DOE/SC Office of Fusion Energy Sciences as deemed appropriate by the Subcommittee." The group said, "Such funding will allow the set of 5-year objectives established by the FESAC to be achieved in a timely fashion, without sacrificing the SEAB-recommended (Secretary of Energy Advisory Board) balance among elements in the program." (http://vm1.hqadmin.doe.gov/seab/)

Generation IV* Nuclear Fission Power Systems (Quoted from the joint statement after the workshop)

An International Workshop on Generation IV Nuclear Power Systems was held in Washington, D.C. on January 27-28, 2000. The attendees of the International Workshop, representing Argentina, Brazil, Canada, France, Japan, Republic of Korea, South Africa, United Kingdom, and United States of America, on Generation IV Nuclear Power Systems have reached a consensus view (http://www.ne.doe.gov/). They recognized significant growth in electricity demand will occur during the next 50 years, predominantly in developing countries. Currently, two billion people have no access to electricity, reducing the quality of life for that sector of the Earth's population. There are growing worldwide concerns about the consequences of air pollution and greenhouse gas emissions. Nuclear power currently provides 17 percent of the world's electricity without emitting air pollutants and greenhouse gases. Nuclear power continues to hold important electricity supply and clean air benefits for the future. Third-generation nuclear power technology will continue to provide a viable option for the nuclear power industry in some countries for the next two decades, although its cost-competitiveness must be improved. Future nuclear power technology should be developed in concert with future nuclear fuel cycles.

Future nuclear power technology development should take into account enhancements in economics, safety, energy supply security, waste management and nonproliferation. Such technology must be equally accessible to both industrialized and industrializing nations and provide for technology transfer to and economic participation by customer nations. Generation IV nuclear power systems should effectively address these issues in a fashion that will promote greater public acceptance, and particularly by providing a cost-competitive option.

Governments can foster the advance of nuclear power technology by:

- Conducting long-term research, development, and demonstration,
- Resolving waste disposition issues,
- Investing in human and technological infrastructure, and
- Assuring effective nuclear regulation for the twenty-first century.

Therefore, Generation IV Nuclear Power Systems should be investigated as an option for the future. Such an investigation should be pursued on a multilateral basis, involving both industrialized and industrializing countries and, as appropriate, intergovernmental organizations. As a next step, a technical group composed of representatives of the governments present will be assigned the task of further discussion on technology issues associated with Generation IV and making recommendations regarding potential future multilateral cooperation.

Subsequent to the above international workshop, the American Nuclear Society issued the following resolution on generation IV nuclear power plant:

> The American Nuclear Society Board of Directors supports the design, construction, and operation of a Generation IV nuclear energy plant in the near term to maintain United States leadership in nuclear energy, and to address the issues of carbon dioxide buildup in the environment, nuclear non-proliferation, and maintenance of our young generation's interest in entering the field of nuclear engineering, science, and technology.

Fusion Applications

At the February 2000 Fusion Energy Sciences Advisory Committee meeting in Washington, W. M. Stacey of Georgia Institute of Technology presented and summarized a white paper on "Neutron Transmutation of Spent Nuclear Fuel-- An Intermediate Term Objective For Magnetic Fusion," (co-authors are: D. E. Baldwin of General Atomics, R. R. Parker of MIT, and J. A. Schmidt of Princeton Plasma Physics Laboratory). They stated that they believe that transmutation of spent nuclear fuels is an appropriate objective for magnetic fusion in the intermediate term, which directly contributes to the long-term goal of fusion energy. Fusion energy, the white paper stated, could serve as one way for DOE to treat 87,000 tons of commercial spent nuclear fuel. Sen. Pete Domenici, R-N.M., has been a leading proponent of accelerator transmutation of waste (ATW). DOE has estimated it could cost $280 billion and take 117 years to treat the fission waste. Congress had allocated $9 million in FY-2000 funds for ATW activities (http://www.pnl.gov/atw/ReportToCongress).

The white paper recommended that fusion researchers should be involved in the ATW project, and provided detailed recommendations on such an involvement (http://www.frc.gatech.edu/pdf/transm1.pdf, http://www.frc.gatech.edu/pdf/transm2.pdf)

Observations

The three topics reported above represent some of the factors that will have impacts on the fusion power development in the U.S. The somewhat volatile state in the world energy supply, such as the recent increase of gasoline prices and various reports on the changes of the world's weather pattern, would remind people and politicians of the need for long-term energy policy and development with the inclusion of the fusion energy option. In parallel, fission power will continue to improve as noted by the Generation IV activities. At the same time, the interest of technical collaboration between the fission and fusion programs has been renewed, as evident by the nuclear waste disposal white paper. However, in order to advance the frontier of fusion research, in the near term, I believe that we need to have a serious assessment of the next step device. We should be looking for a device that has the possibility of addressing the needs for the scientific development of plasma physics and fusion technology. For MFE, three scenarios can be contemplated:

1. Participate in ITER and with parallel involvement in an international fusion neutron source device,
2. Support the development of an advanced tokamak concept, such as FIRE, and aim at the volumetric neutron source as an upgrade or follow on, and
3. Continue the support of the low aspect ratio concept development and the corresponding approach of fusion development facility including the capability of providing high neutron fluence for material and nuclear components development.

Cost and benefit, and inherent risks will have to be figured into the selection process. The obvious scenario is to consider any of these next step options to be constructed at a nuclear ready site. Such recognition would also bring in the necessary development of nuclear technology. Based on the assessment of the development cost of the next step option, additional budget support beyond the annual budget of $300M will be needed.

In the last six months, there were exciting developments in the use of liquid metal for the fusion power core design. Preliminary modeling results indicate that the presence of lithium in the plasma core could actually improve the plasma performance, which was also indicated by experimental results at PPPL in 1996. Another exciting development is the use of vaporizing lithium with refractory structural material. This could lead to high power density first wall and blanket concepts with high power conversion efficiency. These are innovative concepts at very early stage of evaluation, but they are showing new development directions and the unexpected benefits derived in the direct coupling of the development of fusion technology and plasma science.

* Footnote: "Generation IV" nuclear energy plants: these were defined as plants that were smaller, modular, cost-competitive, proliferation-resistant, and with improved safety levels over current nuclear plants.

Officers and Executive Committee List, Wayne Houlberg, Oak Ridge National Laboratory, Oak Ridge, Tennessee

We have a very capable set of officers and Executive Committee members representing the FED in ANS. For your convenience in contacting them, their terms and e-mail addresses are:

Chair:	Kathryn McCarthy (INEEL)	(00-01)	km3@inel.gov
VC/Chair-Elect:	James Stubbins (UIUC)	(00-01)	jstubbin@staff.uiuc.edu
Secy/Treas:	René Raffray (UCSD)	(00-01)	raffray@fusion.ucsd.edu
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	James Blanchard (UW)	(99-02)	blanchard@engr.wisc.edu
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	Dennis Youchison (SNL)	(00-03)	dlyouch@sandia.gov

FED Standing Committee Chairs:

Nominating	Clement Wong - Chair (GA)
Program	Steve Herring - Chair (INEEL)
Honors and Awards	Gerald Kulcinski - Chair (UW)

FED Special Committee Chairs:

Membership	Ken Schultz (GA)

FED Representatives on National Committees:

ANS Publications	Ken Schultz (GA)
ANS Public Policy	Bill Hogan (LLNL)

Editors:

Fusion Technology Journal	George Miley (UIUC)
Newsletter	Laila El-Guebaly (UW)

Liaisons to other organizations and ANS divisions:

Jim Anderson (DOE) - AAD
John Davis (Boeing) - MS&T
George Miley (UIUC) - IEEE

Web site maintenance: Mark Tillack (UCSD)

Treasurer's Report, Sandra Brereton, Lawrence Livermore National Laboratory, Livermore, California

As of April 2000, the Fusion Energy Division has a balance of $5,563. Income in 1999 included:

- $612 from membership
- $6233 carry forward from 1998.

Expenses in 1999 included:

- $500 for awards
- $500 donation to the Edward Teller endowment
- $442 for national meeting expenses (conference calls).

For 2000, our income will include approximately $600 from membership dues, carryover from 1999 (~$5400), and income from the 14th Topical Meeting on the Technology of Fusion Energy in October. Anticipated expenses in 2000 include:

- $500 for outstanding awards
- $1500 for new awards
- $1500 for student support
- $400 for national meeting expenses (conference calls).

The projected balance at the end of 2000 is approximately $4100.

14th ANS Fusion Technology Topical Steaming Ahead, Glen Longhurst, Idaho National Engineering and Environmental Laboratory, Idaho Falls, Idaho

The 14th ANS Topical Meeting on the Technology of Fusion Energy is developing into another excellent gathering in this series. This international meeting is sponsored by the ANS Fusion Energy Division, by the Idaho and NORCAL sections of the ANS and by the Fusion Engineering Division of the Atomic Energy Society of Japan. The focus will be on bringing together international leaders in both magnetic and inertial fusion research, to explore directions that will lead to viable fusion technology in this century. It will also be a great place to meet international colleagues and update personal contacts and familiarity with the interesting and groundbreaking work coming from fusion research efforts underway around the world. While travel plans have been uncertain for a number of potential participants, we note that this important topical meeting will be in the new U.S. fiscal year and will provide a significant forum for ideas and opinions as well as for new technical results.

Park City is one of the world's most scenic areas in the early fall. One of the non-technical highlights of the week will be the "Heber Creeper" steam locomotive train tour of the area between Park City and Heber City (some poetic license is taken in the second word in both names). Another highlight for guests and participants alike is access to factory outlets in Park City from many of the world's most famous clothiers, jewelers, and furniture makers. An organized shopping tour of these businesses is planned for Tuesday afternoon.

Park City is located about 30 miles east of Salt Lake City, Utah. Transportation to Park City from the Salt Lake City airport can be arranged through "All Resort Express", www.allresort.com. Learn more about the community at http://www.parkcityinfo.com.

The meeting site is the spacious Park City Marriott Hotel (http://www.parkcityutah.com). It will run from Sunday October 15 through Thursday October 19, 2000. The conference has reserved 175 rooms at the current U.S. Government perdiem rate. That rate is adjusted periodically and is presently $75 plus applicable taxes, double occupancy. These rooms are available at the conference rate until September 15, 2000 (ask for the IANS conference rate). After this date, rates are not guaranteed. Registration for these rooms is available by telephone (800-234-9003) and by fax (435-649-4852). The fax forms are available electronically at the conference web site, http://ev2.inel.gov/ParkCity/. Other hotels are available in Park City and in the surrounding area (http://www.parkcityinfo.com/lodging/hotelsWin.con.html)

On-site registration opens Sunday afternoon, October 15 from 4:00 pm to 8:00 pm, and each morning thereafter at 7:30 am. The opening plenary session will be Monday , October 16 at 8:30 am. Oral sessions will run Monday through Thursday from 8:30 am through 12:30 pm. Opening plenary sessions each day followed by three parallel oral sessions are planned, but details will be determined by paper submissions. Poster Sessions are planned from 2:00 - 5:00 pm Monday through Wednesday.

A reception will be held Monday evening from 7:00 - 9:00 pm with a no-host bar. A conference banquet will be held Wednesday evening from 7:00 pm to 9:00 pm with a choice of dinner entrée.

Technical sessions are planned on a wide range of subjects including:

Plasma Technology
- Plasma Engineering, Heating, and Current Drive
- Divertor Design and Experiments
- Plasma Fueling and Particle Control
- Plasma Facing Components Technology
- Plasma and Fusion Diagnostics
- Magnet Engineering and Superconductor Development

Fusion Materials
- Structural Materials
- Breeder Materials
- Optical and Diagnostic Materials
- Low activation Materials

Fusion Technology
- Fuel Cycle/Tritium Handling Technology
- Fusion Chamber Technologies

Neutronics Experiments and Analyses
Nuclear Testing and Design Studies
Safety and Environment
Remote Maintenance Technology
Next Steps (ITER and NIF)
Alternative and Advanced Concepts

Advanced Designs and Fusion Systems

Recent Results from Large Fusion Experiments
Fusion Power Reactors
Non-electrical Applications
Fusion Economics and System Studies

While the published abstract submittal deadline has passed, the organizing committee will continue to accept abstracts until June 1, 2000. Electronic submission is preferred at http://ev2.inel.gov/ParkCity/. Note that your web browser must be set to receive electronic mail for the electronic submission process to work properly.

KEY DATES

Abstracts due - June 1, 2000
Author Notification of Acceptance - July 15, 2000
Hotel Registration Rate Guarantee - September 15, 2000
Full Paper Submission for review (at meeting) - October 15, 2000
Final Paper Submission - December 15, 2000

REGISTRATION

Registration Fee (includes reception, banquet, proceedings)
ANS and AESJ Members: $450 before September 15, 2000, $500 after September 15, 2000
Nonmembers: $500 before September 1, 2000, $550 after September 15, 2000
Student Registration (meeting and reception only) members free, non-members $50
Extra Banquet Tickets $35
Guest Registration (Hospitality Room and Shopping Tour) $30
Heber Creeper Tour $40
VISA/ Master Card accepted

Register electronically at http://ev2.inel.gov/ParkCity/ or contact the conference secretary:

Marie Warnick
Bechtel BWXT Idaho, LLC
P.O. Box 1625
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Technology of Fusion Energy

FED Awards: Call for Nominations, Gerald Kulcinski, Fusion Technology Institute, University of Wisconsin-Madison

This is a repeat announcement for 3 awards to be given at the 14^{th} ANS Fusion Topical Meeting in Park City, Utah, October 15-19, 2000. These awards are:

* 2000 Outstanding Technical Accomplishments Award
* 2000 Outstanding Achievement Award
* 2000 FED Student Award for Fusion Science and Engineering

Descriptions of the selection criteria and deadlines for the nominations are posted on the ANS-FED Web site: http://fed.ans.org/.

Nomination deadline is July 30, 2000

Please make this announcement known to your colleagues and students. Thank you for your cooperation and I am looking forward to your submissions

Mail nominations to: Professor Gerald L. Kulcinski
Chair FED Honors and Awards Committee
University of Wisconsin-Madison
Department of Engineering Physics
1500 Engineering Drive, #443
Madison WI 53706-1687

Ongoing Fusion Research:

Plasma Technologies—Recent Progress and Future Directions, Stan L. Milora, Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee

Plasma technologies are those used to create, control and understand the plasma state. While they are normally associated with supporting the near-term needs of the science program experimental facilities, they, nevertheless, play an important role in the vision of an attractive fusion product primarily through the capability to achieve and sustain advanced plasma performance leading to improvements in fusion science metrics such as the fusion power density, $P_f \sim \langle\beta^2\rangle B^4$ and the minimum value of $n\tau T \sim (\beta/\chi)a^2B^2$ for ignition and burn. If we examine the parametric dependence of these two relationships, it is not difficult to identify certain front line technologies that contribute directly to the performance improvements; namely, higher-field lower-cost magnets, and an increasingly more sophisticated suite of plasma profile control technologies (heating, current drive, and fueling) to increase β and β limits and/or reduce transport (χ).

Equally important are technologies that enable devices to operate at their full performance potential and cope with the higher performance such as effective and reliable mitigation of disruptions and plasma facing components (PFCs) that handle the higher heat fluxes while maintaining edge plasma conditions conducive to stability and the formation of edge transport barriers.

The importance of plasma technologies in sustaining progress across the entire range of scientific issues associated with the portfolio of magnetic fusion energy concepts, and the integration of those issues into their steady-state and burning plasma embodiments was acknowledged at the 1999 Fusion Summer Study (Snowmass). Snowmass identified two overarching themes that cut across the various scientific disciplines and MFE concepts: (1) the need for physics understanding and predictive capability to develop the scientific basis for fusion energy, and (2) the development and employment of "sharper" plasma profile control tools to enable scientific understanding and performance optimization.

The community's call for a science/technology partnership and innovative technology to help solve the major fusion science research challenges is closely aligned with the goals and objectives of the Plasma Technology program element of the Virtual Laboratory for Technology (VLT). Its mission is *to provide the tools and understanding for creation, confinement, and control of high-temperature plasmas.* This mission closely mirrors the Snowmass challenge to "develop control tools for detailed physics investigation" of the outstanding cross-cutting science issues (turbulence and transport, MHD stability, and plasma boundary physics).

The supporting R&D objective—*to provide the technological advances that enable existing and near-term plasma experiments to succeed in achieving their full performance goals and ultimate research potential* — addresses the other component of the Snowmass partnership theme; namely, the need to improve the performance of the MFE concepts portfolio currently operating and those that are anticipated or planned in the near future (i.e., steady-state and burning plasma devices).

For the remainder of the article we focus on recent results and future directions of the science/technology partnership emphasizing technology's role in scientific understanding and performance optimization.

Fueling

The first example, from the fueling area, summarizes the latest high-field side (HFS) pellet fueling results from the DIII-D tokamak. The fueling facility developed for DIII-D is the most powerful tool of its kind for investigating the physics of fueling and density profile control and it can do this from four different poloidal locations (mid-plane low field side (LFS) to mid-plane HFS).

In the typical LFS case, density is deposited up to the expected position of maximum pellet penetration, but the radial particle deposition profile is outwardly skewed. In contrast, HFS pellets penetrate only about half as far, but the peak of the particle deposition profile is observed well beyond the point where pellet evaporation is complete, and a significant amount of fuel is deposited at the magnetic axis. And this is accomplished with an injection velocity one fifth of that used in the LFS case. From the perspective of fueling, assuming that these results extrapolate to larger plasmas, this should result in higher operating density, better control of the density level and profile shape, and, of course, higher burn up fractions.

Deep fueling has perhaps an even more important consequence, namely, the generation of internal transport barriers via local turbulence suppression resulting in what has come to be known as the Pellet Enhanced Phase (PEP) mode. An important signature of the PEP mode is a region of strong central shear reversal where extremely steep density, temperature and pressure gradients exist. Through the radial force balance, this pressure gradient gives rise to strong radial electric field shear which in turn generates the sheared poloidal flows that decorrelate or suppress the turbulence. This situation is associated with and likely triggered by a very strong off-axis bootstrap current and the resulting strong negative central shear that is responsible for reducing the growth rates of the microinstabilities thereby providing conditions conducive to transport reductions and pressure profile steepening.

Another consequence of the reversed shear profile is an increased stability to ballooning modes which allows us to take advantage of the transport barrier by permitting an increase in the core pressure gradient and central β. Such improvements give rise to a substantially higher fusion power density that scales as β^2.

Heating and Current Drive

In the heating and current drive area, the technology program is responding to the community's call for a shift in reliance on the blunt instruments used in the past for bulk heating and current drive to more precise spatial and temporal control of the pressure and current density profiles. Recent examples of the science/technology partnership in this area include a phased array high-harmonic fast wave (HHFW) antenna developed jointly by ORNL and PPPL for the National Spherical Torus Experiment (NSTX) and the 1-MW long-pulse electron cyclotron current drive (ECCD) gyrotron developed by CPI (in collaboration with GA, MIT, Univ. Maryland, and Univ. of Wisconsin) for DIII-D. Both of these technologies are key elements in the respective facility's research program from both the operational and performance points of view. With its limited volt-second capability, NSTX will rely on non-inductive techniques to drive a large fraction of the plasma current. ECCD is being pursued on DIII-D for precise localized current drive to affect negative central shear and to stabilize MHD modes. As such, it is a mainstay of the DIII-D advanced tokamak program.

The NSTX twelve-strap antenna and its associated tuning and matching system represents a level of sophistication never before achieved. This leading edge technology is required in the HHFW system in order to match the phase velocity of the launched fast waves to the electron thermal velocity as the NSTX discharge evolves from a tenuous low-temperature start-up phase to the fully developed high temperature and high β H-mode phase. This requires real time control of the current strap phasing. The physics of heating/current drive on NSTX is also leading edge because of the rapidly varying shear and high beta. A high absorption rate of HHFWs in the high β NSTX plasma is expected, thereby providing NSTX with an off-axis current drive capability for sustaining shear reversal.

Precision current drive technologies will be required to achieve the high β equilibria of the advanced tokamak (AT) in particular. Transport simulations for DIII-D indicate that the required current density profile can be achieved by 10-MW of off-axis localized ECCD, leading to the desired shear reversal and consequent increases in β (higher stability limits) and reductions in turbulence inside the shear reversal radius.

Magnet Technology

Magnet technology is fundamental to all MFE concepts and is also essential to the development of the heavy ion beam inertial fusion energy (IFE) concept. The long-term goal of this program element is to improve overall cost and performance of magnet systems by approximately a factor of two within the next decade. For MFE this would be accomplished through both incremental and innovative improvements in materials (superconductors, conduit, insulation) and individual components (such as improved quench detection and protection systems) while for IFE the appropriate approach is the development of advanced superconducting quadrupole array prototypes for the heavy ion beam driver. Consistent with the fusion program emphasis on innovation is a high priority placed on concept exploration activities of both low- and high-temperature superconductors where the potential exists to reduce cable costs by a factor of three to ten.

Recent examples of innovation in this area include the development of the world's most powerful pulsed superconducting magnet—the 13-T, CS Model coil now undergoing testing in Japan—and the development of both innovative low- and high-temperature superconducting cables and conductors. High-temperature superconductors being developed by MIT and the American Superconductor Corporation offer the potential for higher performance (magnetic field) and increased stability for future applications.

The Magnet Technology program is also addressing the near-term needs of the fusion program. The floating dipole magnet for the Levitated Dipole Experiment (LDX) is being constructed using a new, highly advanced Nb_3Sn wire with critical current density 1.6 times higher than ITER wire in order to achieve long floating times. The program is also presently developing, with industry, the first application of high-temperature superconductor for the LDX levitation magnet. High-temperature superconductors are practical in the near term for specialized applications such as the LDX device and may soon be the conductor of choice for advanced tokamaks, next-step stellarators, and KrF laser diodes. Another example of how the program is addressing the near-term needs of the community is in the development of compact, low-cost, high-current density NbTi quadrupole magnets for heavy ion fusion drivers, such as the High Current Experiment (HCX) and the Integrated Research Experiment (IRE).

We now turn our attention to technologies that enable devices to operate at their full performance potential.

Disruption Mitigation Technologies

Techniques to control and mitigate disruptions were given high priority at Snowmass particularly with respect to the advanced tokamak. Present disruption mitigation technologies are closely related to pellet injection systems commonly used in fueling experiments. Recent exploratory studies with high-Z pellets on Alcator C-MOD, and DIII-D and high-pressure He gas injection on DIII-D in particular have demonstrated the ability of the technology to significantly lessen the effects of the thermal quench and reduce vacuum vessel forces during staged disruptions (vertical displacement event, VDE). By injecting a massive helium gas puff of 7000 Torr-liters, the line density on DIII-D can be increased to 10^{21} m^{-2} in 7 ms. This cools the plasma rapidly, increasing its resistive decay rate such that a large fraction of the current dissipates before the plasma contacts the vessel walls. The net effect is a twofold reduction in the halo current and a factor of two reduction in the toroidal peaking factor leading to a factor of four reduction in peak forces on in-vessel components.

In the near term, further progress in developing effective and reliable mitigation techniques and procedures will require a broad based research and development program involving multiple tokamaks to scope out physics parameters experimentally and a parallel development effort to explore the most promising technologies such as low-Z liquid jet injection. In the long term, disruption detection and mitigation systems will need to be integrated into the control systems of existing tokamaks for testing and to demonstrate reliability.

Plasma Facing Components/Plasma Materials Interactions

As discussed earlier, PFCs will have to deal with the consequences of this improved performance. To this end, dramatic progress has been made in the past five years in the area of heat removal capability and component reliability. Advanced heat removal devices, such as the tungsten rod divertor mockup developed for ITER, already operate routinely at a heat flux of 3 kW/cm^2 for thousands of thermal cycles, a performance level that was unimaginable just five years ago. This remarkable progress was made possible by the use of rods (which reduce thermal stresses) to conduct heat to an actively cooled copper substrate and improved joining techniques that bond the tungsten armor to the copper. A near-term goal of this program that addresses the need for improved power handling expected in future high performance plasma configurations is to develop PFCs with a 50% improvement in both heat flux and erosion lifetime. Candidate technologies that are being explored include high-pressure He gas cooling, and enhanced water cooling (higher critical heat fluxes). Liquid surfaces may offer the potential for even higher performance while essentially solving the problem of PFC lifetime. The near-term objective for this activity is to perform exploratory studies of this concept on a plasma facility such as the Current Drive Experiment Upgrade (CDX-U).

The Plasma Boundary Working Group at Snowmass identified as a key to achieving high-plasma performance the need to develop a better physics understanding of the coupling between the core and edge plasmas and the effect of plasma facing materials on plasma performance. This is captured by the program's long-range goal *to develop a theoretical code which couples a core plasma to the first wall while integrating all of the known major plasma/first wall interactions in order to provide a more complete theoretical understanding of wall interactions with the core plasma and allow for significant improvements in the design of more accurate alternate concept proofs-of-principle and new devices*.

Recent progress on this front has also been excellent as evidenced by our ability to measure and predict material erosion rates and to relate the results to plasma erosion mechanisms. Other areas which are being addressed in the R&D program include wall retention of hydrogen—a key to minimizing tritium wall inventories—and the generation and subsequent transport of impurities which is so important in understanding the effect of plasma facing materials on core plasma performance.

In summary, the MFE concept and cross-cutting science subgroups at Snowmass told us that in order to continue to progress in the direction of steady-state advanced performance and burning plasmas, we will need to sharpen our profile control tools across the board. The technology response to this challenge includes better gyrotrons and ion cyclotron launchers and control systems, faster inside launch pellets, lower-cost increased-performance magnets, fast reliable disruption detection, low-Z liquid or gas injection mitigation systems, and lower erosion/higher heat flux PFCs.

Z-Pinch for High Yield and IFE, Craig Olson, Sandia National Laboratories, Albuquerque, New Mexico.

The Z accelerator at SNL is the most powerful multi-module synchronized pulsed-power accelerator in the world. X-rays from a z-pinch can be used in a hohlraum configuration to drive an inertial confinement fusion (ICF) capsule target. Demonstration of a single-shot high-yield target is presently a goal of the ICF z-pinch program at SNL (funded by DOE Defense Programs). For Inertial Fusion Energy (IFE), a rep-rated fusion capability is needed. Recent developments have led to a viable conceptual approach for a rep-rated z-pinch power plant for IFE, as is discussed here. In addition, Z could presently be used for x-ray material response experiments relevant to all IFE scenarios.

Rapid development of z-pinch loads on Z has led to outstanding progress in the last few years, resulting in radiative powers of up to 180 TW in 4 ns, and a total radiated x-ray energy of 1.8 MJ. Z nominally provides a 20 MA current pulse for about 100 ns to a small cylindrical wire array (radius typically 1-2 cm, and length 1-2 cm) consisting of a large number (up to 300) of high-Z, low-mass wires. The magnetic pinch force accelerates the wires to the axis, where they stagnate, thereby producing a hot, dense, radiating plasma with temperatures up to 200 eV. This radiation can be "captured" in a hohlraum and used to drive a fusion target.

LASNEX computer calculations indicate that a pulsed power accelerator delivering about 60 MA could drive a high-yield ICF target with a yield above 500 MJ. Pulsed power technology is both very efficient (Z has a wall-plug to x-ray efficiency of 15 %) and relatively inexpensive. The current vision is to proceed from Z (20 MA), to Z-MOD (up to 28 MA), and then go either to an intermediate facility ZX (~40 MA) or directly on to X-1 (60 MA). Note that the high-yield driver goal of 60 MA is a factor of three higher in current (a factor of nine higher in energy) than the present 20 MA on Z. The increased current is used to drive a higher-mass z-pinch, but with the same or smaller convergence ratio as used on Z. Since the Rayleigh-Taylor instability (the main concern for z pinches) depends on the convergence ratio and not the mass, there should be no increased risk for this instability as the current increases from 20 MA to 60 MA. Given this plausible scenario for achieving high yield on a single-shot basis, the key question is "Could this be done on a rep-rated basis?"

Up until now, it has been assumed that z-pinch fusion could not be used to generate electricity because the fusion explosion would destroy a portion of the magnetically-insulated transmission line (MITL) near the target, which would have to be replaced after each shot. The existing z-pinch machines use a massive transmission line structure that would be prohibitively expensive to replace after each shot. However, a rep-rated z-pinch power plant concept has evolved that exploits the advantages of going to high yield (~ few GJ) at low rep-rate (~ 0.1 Hz) and uses a Recyclable Transmission Line (RTL) to provide the necessary standoff from the fusion target. The RTL could be cast out of a conventional power plant coolant material, such as Li or Flibe. Other rep-rated z-pinch concepts have been considered such as use of liquid-Li electrodes; or an ion or electron beam to transport power to a small convertor; or a high velocity projectile stopped by a flux compression current convertor. However, none of these concepts has the simplicity and attractiveness of the RTL approach.

For an IFE power plant using the RTL concept with a z-pinch target, the sequence of operation would begin with the lowering of the RTL into an empty chamber, the connection of it electrically to the driver, and the insertion of the z-pinch target at its center. Vacuum is required nominally only in the RTL, and this could be pumped down before loading. The chamber itself would then be filled with a liquid or solid-with-voids Li-bearing coolant, chosen to mitigate the effects of shock to the first wall. The RTL (constructed of Li or Flibe), and the Li-bearing coolant (such as Li or Flibe) absorb the heat from the fusion reaction and also breed tritium. The thickness of the Li-bearing coolant, based on calculations, would typically be greater than about 1 meter. This thickness is sufficient to absorb the bulk of the neutron energy, provide a tritium breeding ratio above unity, and effectively protect the first wall from neutron damage. After filling the chamber with the Li-bearing coolant, a lid would be placed on the chamber, and the z-pinch fusion capsule would be fired. After the shot, the chamber would be opened, and the molten mixture containing the Li-bearing materials would be forced out to other parts of the power plant for heat extraction and tritium removal. The radius of the cylindrical chamber would be in the range of 3 or more meters. Since large yields (~ few GJ) would be used, the rep-rate would be low (~ 0.1 Hz). Also, more than one chamber might be driven by the same pulsed power. In any case, there would be of the order of 10 seconds or more to perform the whole sequence of operations. [Conventional IFE power plant concepts operate at lower yields (~ few 100 MJ) and higher rep-rate (~ 5 Hz).] The time scale of 10 seconds or more appears to be reasonable for the operations involved, but this needs to be investigated in detail. Initial cost estimates by the Advanced Manufacturing Group at SNL for recycling the RTL ($0.70/shot) are already in an acceptable range. The RTL rep-rated z-pinch power plant concept is simple and robust, and already has several outstanding advantages:

(1) The RTL concept simply recycles the transmission line, which is made out of typical power plant coolant materials.
(2) Because the RTL can have bends, the vacuum insulator can easily be shielded from line-of-sight from the fusion reaction.
(3) There is essentially no chamber vacuum requirement (as compared to other IFE power plant concepts) since the RTL's can be pumped down before insertion into the chamber.
(4) Solid or liquid Li-bearing materials with voids can fill the chamber essentially directly up to the target, and be appropriately tailored to mitigate the shock to the first wall.
(5) Other materials, such as lead or tin, may also be used in the RTL, since these are immiscible with, e.g., the coolant Flibe.
(6) Multiple chambers may be used, and this would increase the time between shots in each chamber.
(7) This approach uses simple technology in a robust environment of metal and plastic, that works in a dirty environment, and can survive shocks and debris.
(8) The problem of a final optic/magnet (which is required for all laser or ion beam approaches to IFE) is completely eliminated.
(9) The problem of high speed target injection, and the problems of accurately pointing and tracking a large number of laser or ion beams to precisely hit the target, is also eliminated.
(10) The z-pinch target is hard-wired to the accelerator, essentially guaranteeing that it will work.

Key issues for this RTL concept that will be addressed in initial research include the following goals:

(1) Demonstrate that a suitable material exists for constructing the RTL that is compatible with the overall power plant concept. The RTL must have appropriate electrical and structural properties, be inexpensive to manufacture, and be compatible with the power plant operational cycle.
(2) Test actual candidate materials on the Saturn (~10 MA) and Z (~20 MA) accelerators at SNL.
(3) Calculate the breakup of the RTL into plasma, liquid, and solid projectiles and examine their effects on the coolant material and first wall.
(4) Investigate the use of tailored density gradients of liquid or solid coolants to mitigate the shock to the first wall.
(5) Consider the design of targets with directed venting of debris to minimize impulse loads to the RTL connection hardware.

(6) Develop a suitable rep-rated pulsed power concept to drive the power plant, drawing on expertise gained in the RHEPP (Repetitive High Voltage Pulsed Power) program at SNL.
(7) Refine the overall rep-rated RTL power plant concept, and systematically initiate a pre-systems analysis of the concept.

The RTL concept was presented at the Snowmass Fusion Summer Study in 1999, where it was listed as the prime candidate for CE (Concept Exploration) for IFE. The RTL concept is also listed as the prime candidate under CE on the IFE Road Map. A one-year Laboratory Directed Research and Development at SNL ($160k for FY00) has just been awarded (March, 2000) to begin research on the RTL concept with a collaborative team (SNL, UCB, UCD, UW). A three-year collaborative proposal has also been made to DOE OFES in response to their recent solicitation for IFE CE research. The results of this research will also be relevant to any concept that uses pulsed power directly to drive a fusion target, such as Magnetized Target Fusion (MTF).

In addition, Z could presently be used for x-ray material response experiments relevant to all IFE scenarios. These experiments could be "added on" to existing Z shots at relatively low cost. A collaborative proposal (SNL, UCB, UCSD, UW) has been made to DOE OFES in response to their solicitation for IFE chamber and target research. A broader collaborative proposal, that would establish Z and related pulsed power facilities at SNL (Saturn, RHEPP, IBEST) as a national users facility to support the mission and goals of the DOE OFES Enabling Technology program, has been submitted to the VLT (Dr. Charles Baker, Director). For example, Z can produce extremely high x-ray fluence levels (~3000 J/cm^2), and IBEST can produce very high ion fluence levels (~15 J/cm^2) over ~100 cm^2 with ion energies above 0.5 MeV. These facilities appear to be uniquely qualified to support the Enabling Technology program.

International Activities:

IAEA Activities, Tom Dolan, Head Physics Section, IAEA, Vienna, Austria

The following activities are planned by the IAEA in 2000 and 2001.
TCM = Technical Committee Meeting,
RCM = Research Coordination Meeting (for a Coordinated Research Project).

2000

– IFRC Subcommittee on Atomic and Molecular Data for Fusion, May 7-8, 2000, Vienna.
– TCM, Physics and technology of inertial fusion energy targets and chambers, June 7-9, Madrid, Spain
– TCM, Fusion Safety, June 13-16 , Cannes, France
– Consultant meeting, Coolant Technology for Subcritical Blankets of Fusion/Fission Hybrids, July 6-7, Moscow

– RCM, Comparison of Compact Toroid Configurations, July 10-14, Vienna
– International Fusion Research Council (IFRC), October 3, Sorrento, Italy
– 18th IAEA Fusion Energy Conference, October 4-10, Sorrento, Italy
– Workshop on Plasma Diagnostics and Industrial Applications at the International Centre for Theoretical Physics, October 12-14, Trieste, Italy
– TCM, Applications of fusion research to science and technology, 30 Oct.-3 Nov., Chengdu, China
– RCM, Elements of power plant design for inertial fusion energy, Fall, Vienna

2001

– TCM on Research Using Small Fusion Devices (RUSFD), April 2001, Brazil,
– TCM on H-mode Physics/Transport Barriers, September 2001, NIFS, Japan,
– TCM on Control, Data Acquisition and Remote Participation for Fusion Research (possible collaboration with IEA), July 2001, General Atomics, San Diego, USA,
– TCM on Steady-State Operation of Magnetic Fusion Devices (SSO), March 2001, France
– TCM on Energetic Particles in Magnetic Confinement Systems (former alpha particle workshop), October 2001, IPP, Garching, Germany
– TCM on Spherical Tori, June 2001, possible hosts: Brazil, Russia or UK
– TCM on Divertor Concepts (possible collaboration with IEA), September 2001, host: France
– TCM on High Average Power Drivers, GSI Darmstadt, Germany
– TCM on Plasma Theory, EPFL-Lausanne, Spring 2001. (Focus to be determined)
– IFRC meeting, June, Vienna
– RCM, Dense magnetized plasmas.

For further information about these meetings, please contact u.schneider@iaea.org

Calendar of Upcoming Conferences on Fusion Technology

ANS Annual Meeting
June 4-8, 2000, San Diego, CA, USA
http://www.ans.org/

FPA Annual Meeting and Symposium: Science and Technology for Fusion Power.
July 17, 2000, San Diego, CA, USA
fpa@compuserve.com

21st Symposium on Fusion Technology (SOFT)
Sep 11-15, 2000, Madrid, Spain.
http://21SOFT.ciemat.es/
i.girrido@ciemat.es

18th IAEA Fusion Energy Conference

Oct 4-10, 2000, Sorrento, Italy
http://www.iaea2000.enea.it/index.html/
t.dolan@iaea.org

ANS 14th Topical Meeting on the Technology of Fusion Energy
Oct 15-19, 2000, Park City, Utah
http://ev2.inel.gov/ParkCity/

ANS Winter Meeting
Nov 12-17, 2000, Washington, DC, USA
http://www.ans.org/

ANS Annual Meeting
June 17-21, 2001, Milwaukee, WI, USA
http://www.ans.org/

10th International Conference on Fusion Reactor Materials - ICFRM-10
October 19-24, 2001, Karlsruhe, Germany

ANS Winter Meeting
Nov 11-15, 2001, Reno, NV, USA
http://www.ans.org/

6th International Symposium on Fusion Nuclear Technology - ISFNT-6
April 7-12, 2002, San Diego, CA, USA

ANS Annual Meeting
June 9-13, 2002, Hollywood, FL, USA
http://www.ans.org/