

FUSION ENERGY DIVISION NEWSLETTER

December 2009

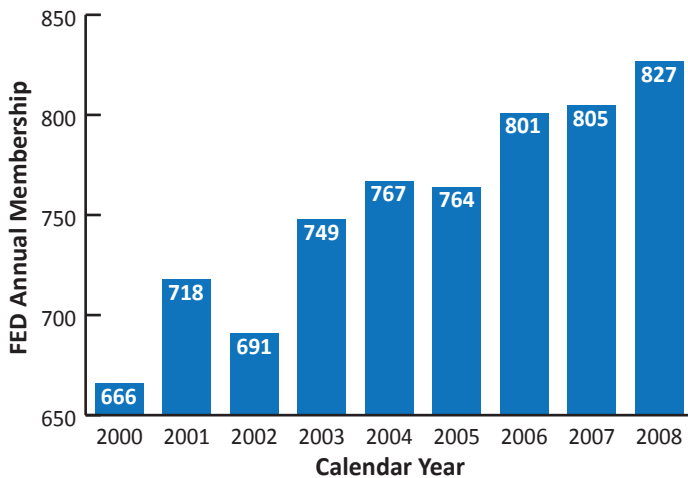
A Division of the American Nuclear Society

Letter from the Chair

Lance Snead

Materials Science and Technology Division
Oak Ridge National Laboratory, Oak Ridge, TN.

AS THE SUBJECT of this letter I would like to bring the Fusion Energy Division (FED) membership up to speed on some of the metrics for our division. I am also happy to do so as the previous Chairs have made our division look quite good. For those of you who are not intimately plugged into the American Nuclear Society (ANS), the overall society membership has been remarkably constant over the 2000 decade with total membership of approximately 10,800. As can be seen from the figure below, the membership of the FED over that period has had a significant increase, for which the Division receives high marks.



The ANS has recently invested great effort into evaluating the strength of each Division and has devised a set of metrics by which they can determine where improvements need to be made and which of the 22 Professional Divisions are becoming subcritical. For this effort, they are using a "Measures of Vitality System." The vitality of the Fusion Energy Division is given in the color-coded figure (Fig. 1, next page) for calendar year 2008. Green is "good-above average", white "average" and red "needs ANS attention." As you see from Fig. 1, the FED is largely green, and in fact is the only Division which has received no red marks. I will comment that it was clear that in the initial draft of the metrics the FED was not getting credit for much of the good work we were involved in such as meeting participation, scholarships, etc. In any event, both the growing membership

and the best metrics in the society put us in a good position going forward.

Currently, we are working on updating the FED Rules and Bylaws to comply with the overall ANS goal of unifying the professional division bylaws. We are also going to explore the possibility of starting a new student scholarship. Also, we will continue to discuss the nomination of additional FED members to Fellow status. At present, of our 827 members, 22 are Fellows of the society and an additional 16 are Emeritus Fellows. While this proportion of Fellows within the Division is consistent with the ANS as a whole, we have had relatively few Fellows over the past several years and overall, our society is heavy academically, which should naturally bias towards a greater proportion of Fellows.

I look forward to any input or suggestions you might have in any of these areas.

In this Issue...

- | | |
|--|--|
| 1 Letter from the Chair
<i>Lance Snead</i> | Special Section: Ongoing Fusion Research |
| 2 New ANS "Fusion" Fellows
<i>Nermin A. Uckan</i> | 6 Recent Advances in High Temperature Superconductors
<i>Joseph V. Minervini</i> |
| 3 Slate of Candidates for 2010/2011 FED Executive Committee
<i>Farrokh Najmabadi</i> | 8 Highlights of US Fusion-Fission Hybrid Workshop
<i>Jeffrey Freidberg</i> |
| 3 19th ANS Topical Meeting on the Technology of Fusion Energy
<i>Farrokh Najmabadi</i>
<i>Shahram Sharafat</i> | Special Section: International Activities |
| 4 Call for Nominations, ANS-FED Awards
<i>Neil B. Morley</i> | 10 US ITER Report
<i>Ned Sauthoff</i> |
| 4 Fusion Award Recipients
<i>Laila El-Guebaly</i> | 11 Report on IAEA Technical Meetings on "First Generation of Fusion Power Plants: Design and Technology" and "Fusion Power Plant Safety"
<i>Guenther Mank</i>
<i>Richard Kamendje</i> |
| 5 News from Fusion Science and Technology (FS&T) Journal
<i>Nermin A. Uckan</i> | |

Division Meetings	Division Governance	Division Contributions to Society	Division Services to Membership
National Meeting Participation 2008 Embedded Topical co-sponsor: 1 plenary, 0 panel 2008 Winter: 1 session, 0 panel	Succession Planning Included in 2004–2008 Strategic Plan	ANS Position Statements 12 Fusion Energy, Revised 2008 (Active)	Professional Development Established Program Committee — 2006 P. Wilson on ANS Prof. Devel. Comm. National Ignition Facility Workshop at 2008 TOFE
Class I/II Topicals +25% Attendance (135⇒200) 15 th Topical: TOFE 2004 (142 full papers) 18 th Topical Meeting on Technology of Fusion Energy	Membership Trends 2006: +4.8% (764⇒801) 2007: +0.5% (801⇒805) 2008: +2.7% (805⇒827)	Participation With Outside Professional Societies Fusion has liaison with IEEE Publishes in other journals	Scholarships No scholarship established 2008 contributed to ANS NEED scholarship
Class III Topicals (embedded) 15 th Fusion Topical — Nov. 2002 17 th Topical Meeting on Technology of Fusion Energy (TOFE — Nov. 2006) 157 full papers Embedded Topical co-sponsor Nuclear Fuels (111 summaries)	Communications 2 Newsletters in 2008 Website updated in 2008	Society Leadership 4 of 4 PDC: 75% Exec. Comm. All NPC Presentation to BoD June 2008	Peer/Recognition Awards Edward Teller FED Awards (Achievement & Technical Accomplishment) Best Student Paper Award
	Division Planning 2004–2008 Strategic Plan submitted to PDC Chair 2006 Reviewed budgeting process	Non-Meeting Publications Fusion Science & Technology Journal	Student Support 2008 Student Travel 2008 Student Conference
		Division's Commitment to YMG Appointed P. Calderoni, Liaison	

Figure 1. Professional Division Metrics: Fusion Energy Vitality Measures — Calendar Year 2008.

New ANS “Fusion” Fellows

Nermin A. Uckan

FS&T Editor

Oak Ridge National Laboratory, Oak Ridge, TN.

IT IS A PLEASURE to report that we have a new ANS “Fusion” Fellow added to the honors role: Dr. **A. René Raffray**. Congratulations.

René Raffray, ANS member for 8 years, was recognized as a Fellow of the American Nuclear Society during the ANS Winter Meeting in Washington, D.C., November 2009.

René Raffray has been a Research Scientist in the Mechanical and Aerospace Engineering Department and Center for Energy Research, University of California San Diego. Recently, he joined the ITER Organization in Cadarache, France as the Blanket Section Leader, responsible for the design and procurement of the ITER blanket and first wall.

René Raffray earned the highest grade of ANS membership “for his pioneering computational modeling research that helped solve show-stopper issues for fusion chambers, including opening the IFE dry wall design window through inclusion of ion time of flight effects and use of nano-structured tungsten armor; and understanding the tritium behavior in ceramic breeder blankets.”

The election to the rank of Fellow within the ANS recognizes the contributions that individuals have made to the advancement of nuclear science and technology through the years. Selection comes as a result of nomination by peers, careful review by the Honors and Awards Committee, and election by the Society’s Board of Directors. The list of current Fellows, nomination steps, guidelines, nomination forms can be found at <http://www.ans.org/honors/va-fellow>.

FED has two dozen or so Fellows. FED Officers/Executive Committee has been encouraging all FED members to actively

engage in nominating deserving colleagues to the fellowship grade. FED “red-team” Fellows will be happy to provide guidance and help review nomination packages. Please feel free to contact uckanna@ornl.gov for questions.

Slate of Candidates for 2010/2011 FED Executive Committee

Farrokh Najmabadi

Center for Energy Research
University of California-San Diego, La Jolla, CA.

Vice-Chair/Chair-Elect:

Minami Yoda (Georgia Tech)

Executive Committee:

Paul W. Humrickhouse (INL)

Keith R. Rule (PPPL)

Mark Tillack (UCSD)

19th ANS Topical Meeting on the Technology of Fusion Energy

Farrokh Najmabadi

University of California-San Diego
and

Shahram Sharafat

University of California-Los Angeles, CA.

CONSISTENT WITH OUR PRACTICE of alternating Topical Meetings between “stand-alone” and “embedded”, the 19th Topical Meeting on the Technology of Fusion Energy (TOFE) will be held November 7–11, 2010 in Las Vegas, Nevada as an embedded meeting within the ANS Winter Meeting. Prof. Farrokh Najmabadi is the General Chair and Prof. Shahram Sharafat is the Technical Program Chair. The Technical Program Committee, along with the list of sessions, will be published soon. The meeting website, <http://www.19tofe.com> is under construction and will be available at the beginning of the new year.

Plans are moving along nicely for the 19th TOFE. The meeting will be held at the Riviera Hotel in Las Vegas. The hotel is located about 10 minutes from the McCarran International Airport and near world-class golf courses. It offers a perfect setting for the TOFE meeting with its 160,000 square foot Convention Center — a self-contained full service conference facility. The Top of the Riviera hotel offers sweeping vistas of the Las Vegas Strip.

This is an exciting time for fusion technology due to the development of ITER and NIF. At the time of the meeting, it is expected that NIF will have demonstrated its first breakeven shots and the media will still be abuzz with excitement of fusion’s latest achievement. Therefore, we anticipate that the 19th TOFE will be very well attended.

The meeting will begin with a reception at the conference center on the evening of Sunday, November 7, 2010, and the technical program begins on Monday, November 8. The meeting banquet will be held on the afternoon of Wednesday, November 10, at 6 PM. Technical sessions will resume

on Thursday, November 11, and the conference will adjourn before noon that day. During the meeting banquet, the Honors and Awards Committee of the Fusion Energy Division (FED) of the American Nuclear Society (ANS) will distribute awards for Outstanding Technical Accomplishment, Outstanding Achievement, and the Best Student Paper. Each award consists of a cash prize and a plaque. For details regarding nomination procedures please see the award article in this newsletter or refer to <http://fed.ans.org/awards.shtml>. To be eligible for the student award, students must be the lead author on a technical paper, must be enrolled in an undergraduate or graduate degree program, and must submit the full written paper before the meeting. The call for papers will go out before the end of this year (December 2009) and a fully functional meeting website will be available shortly thereafter.

Technical Program

The 19th TOFE will be a three day meeting with plenary, oral, and poster sessions. There will be plenary papers, with a mix of invited and contributed oral papers, and a substantial number of poster papers. We expect many fusion technology professionals from the US and abroad to attend the 19th TOFE to share their recent results.

The overarching theme of the plenary talks is “Progress of Major Experiments and Next Facilities on the Pathway to DEMO” — ITER, NIF and other experimental machines: DIII-D, NSTX, JET, Tore Supra, KSTAR, EAST, etc. In addition, special sessions are being planned on various topics (e.g., ITER, Fusion Relevant Neutron Sources, Pathways to DEMO, etc.).

Topics

The scope of the TOFE meeting is to provide a forum for the discussion of new results in fusion technology as they relate to present fusion research and to future fusion energy applications. The list of session topics includes:

- Progress of major experiments — ITER, NIF and other experimental machine such as DIII-D, NSTX, JET, Tore Supra, KSTAR, EAST, etc.
- Materials and components test facilities
- Alternate fusion concepts
- Computational tools and validation experiments
- Divertors and high heat flux components
- Fabrication, assembly and maintenance
- First walls, blankets, shields
- Fuel handling and processing
- IFE driver and chamber technology
- IFE target design, fabrication and injection
- Magnets
- Materials development and modeling
- Non-electric applications of fusion
- Next step facilities and the DEMO power plant
- Nuclear analysis and experiments
- Plasma diagnostics
- Plasma engineering
- Power conversion

- Power plant studies and pathways to fusion energy
- Safety and environment

Key Dates

The following key dates have been determined:

December 15, 2009	— First Announcement
January 15, 2010	— First Call for Papers
February 15, 2010	— Second Call for Papers
March 15, 2010	— Third Call for Papers
April 1, 2010	— Abstracts Due.

We look forward to another highly successful TOFE meeting.

Call for Nominations, ANS-FED Awards

Neil B. Morley

University of California-Los Angeles, Los Angeles, CA.

THE HONORS AND AWARDS COMMITTEE of FED/ANS is seeking nominations for Fusion Energy Division of ANS Awards:

- 1) Outstanding Achievement Award:** This award is for recognition of a continued history of exemplary individual achievement requiring professional excellence and leadership of a high caliber in the fusion science and engineering area.
- 2) Technical Accomplishment Award:** This award is for recognition of a specific exemplary individual technical accomplishment requiring professional excellence and leadership of a high caliber in the fusion science and engineering area.

Detailed descriptions of the awards and past recipients can be found at <http://fed.ans.org/awards.shtml>. Note that nominees will only be considered for the particular award for which they are nominated, and that nominees from 2008 will be automatically reconsidered.

Deadline for nominations is August 1, 2010 for the awards to be presented at the 19th ANS Topical Meeting on the Technology of Fusion Energy, embedded in the ANS Winter Meeting and Nuclear Technology Expo to be held November 7–11, 2010 in Las Vegas, Nevada.

Nominations can be made by individuals and submitted anytime to the FED Honors and Awards Committee Chair (N. Morley). Nomination package should include:

- Nominee's CV
- A description of exemplary achievement(s)
- Support letters (and/or co-signature on the nomination form)

Details are available at the URL provided above. Please send nominations to:

Neil B. Morley
43-133 Engineering IV
Mechanical and Aerospace Engineering, UCLA
Los Angeles, CA 90095-1597
morley@fusion.ucla.edu

Electronic submission via email is encouraged.

An Outstanding Student Paper Award will also be given at the TOFE meeting; all indicated student papers will be automatically considered. Details will be forthcoming in conjunction with the meeting announcements.

Fusion Award Recipients

Laila El-Guebaly

Fusion Technology Institute

University of Wisconsin-Madison, Madison, WI.

FUSION AWARDS have been established to formally recognize outstanding contributions to fusion development made by members of the fusion community. The following awards (listed in alphabetical order) were available to the newsletter editor at the time of publishing this newsletter. We encourage all members of the fusion community to submit information on future honorees to the editor (elguebaly@engr.wisc.edu) to be included in future issues. The ANS-FED officers and executive committee members congratulate the honored recipients of the 2009 fusion awards on this well-deserved recognition and our kudos to all of them.

APS Awards

Prof. **Miklos Porkolab**, Director of the MIT Plasma Science and Fusion Center, has been selected to receive the **2009 James Clerk Maxwell Prize** by the American Physical Society (APS). The prize was established to recognize outstanding contributions to the field of plasma physics and honors Prof. Porkolab for pioneering investigations of linear and nonlinear plasma waves and wave-particle interactions; fundamental contributions to the development of plasma heating, current drive and diagnostics; and leadership in promoting plasma science education and domestic and international collaborations.

FPA Awards

2009 Distinguished Career Award: Prof. **Weston M. Stacey, Jr.**, Callaway Regent's Professor of Nuclear Engineering at Georgia Institute of Technology, has received this award for his decades of outstanding career contributions to fusion research and development, including his pioneering contributions to power-producing fusion reactor designs, to the INTOR design which was a forerunner for ITER, and to conceptual designs of fusion-fission systems.

2009 Leadership Award: Dr. **G. S. Lee**, President of the Korean National Fusion Research Institute (NFRI), has received this award for his leadership of the KSTAR tokamak project, of Korean participation in the ITER project, and of the International Fusion Research Council (IFRC).

2009 Excellence in Fusion Engineering Awards: Drs. **Darren Garnier** of Columbia University and **Jeff Latkowski** are the recipients of these awards. Dr. Garnier was recognized for the contributions and leadership he has provided for the design, fabrication and operation of the Levitated Dipole Experiment (a joint Columbia-MIT project located at MIT) and

his contributions to the diagnostics and control systems for that experiment. Dr. Latkowski is cited for the contributions and leadership he has provided for the LIFE fusion-fission project, the NIF Final Safety Analysis, and to LLNL contributions to the non-laser portions of the national High Average Power Laser (HAPL) program.

IFSA Awards

Drs. **Ed Moses** (LLNL) and **Ricardo Betti** are the recipients of the **2009 Edward Teller Medal**, sponsored by the American Nuclear Society. The medals were presented at the 6th International Conference on Inertial Fusion Sciences and Applications (IFSA) meeting in San Francisco on September 10, 2009:

Dr. Moses was cited for his “leadership in the development and completion of the National Ignition Facility” (NIF). As principal associate director for NIF and Photon Science at Lawrence Livermore (LLNL), he has overseen the construction of NIF, the world’s largest and most energetic laser, and is leading an international effort to perform the first ignition experiments on NIF in 2010.

Prof. Betti was cited for his “seminal contributions to the theory of hydrodynamic instabilities, implosion dynamics and thermonuclear ignition in inertial confinement fusion.” A professor at the University of Rochester and director of the Fusion Science Center for Extreme States of Matter, Dr. Betti has devised new ignition concepts and theoretical models for inertial fusion implosions and scaling laws for ignition. These scaling laws are the basis for present experiments on the OMEGA laser and future research on NIF.

MA-FNT Award

The **Miya-Abdou Fusion Nuclear Technology (MA-FNT) Award** was presented at the International Symposium on Fusion Nuclear Technology (ISFNT) in recognition of outstanding scientific contributions and leadership qualities of young researchers in fusion nuclear science and technology. This year’s award was presented at ISFNT-9 (held October 2009 in Dalian, China) to Dr. **Koichiro Ezato** of the Japan Atomic Energy Agency (JAEA) in recognition of his contributions, especially in the area of ITER divertor and international activities on plasma facing components.

Nuclear Fusion Award

The winner of the **2009 Nuclear Fusion Award** is **Steven A. Sabbagh** et al. for their paper on “Resistive wall stabilized operation in rotating high beta NSTX plasmas.” The authors, working on the National Spherical Torus Experiment (NSTX), have demonstrated the advantages of low aspect ratio geometry in accessing high toroidal and normalized plasma beta. This is a landmark paper, which not only reports record parameters of beta in a large spherical torus plasma, but also presents a thorough investigation of the physics of Resistive Wall Mode (RWM) instability beyond the no-wall limit. The paper addresses an issue of critical importance, using a spherical torus, with direct relevance to conventional tokamaks. The

fusion power in the technology phase of ITER will depend on the degree of RWM stabilization that can be achieved, which underlines the importance of the authors’ contribution. The winning paper will be freely available until the end of May 2010 at <http://herald.iop.org/nfaward/m26/1jc/131548/link/3083>.

News from Fusion Science and Technology (FS&T) Journal

Nermin A. Uckan

FS&T Editor

Oak Ridge National Laboratory, Oak Ridge, TN.

DURING THE PAST 12 MONTHS (from October 1, 2008 to September 30, 2009), FS&T received a total of 253 manuscripts: 78 are from North America, 111 are from Asia, 62 are from Europe (including Russia), and 2 are from Others. During this period, FS&T also received 43 camera-ready papers from the 2008 Open Systems Conference (OS2008), published in FS&T Transactions. OS2008 papers are not included in paper counts.

The following dedicated issues have been published during the period 10/1/08 to 9/30/09:

- ARIES Compact Stellarator Study — FS&T Oct. 2008
- Selected full papers from EC-15 — FS&T Jan. 2009
- Open Systems 2008 — FS&T Transactions Feb. 2009
- Selected papers from 18th IFE Target Fabrication — FS&T Apr./May 2009
- TOFE08 Proceedings (parts 1 & 2) — FS&T Jul./Aug. 2009
- Tore Supra Tokamak (Cadache, France) — FS&T Oct. 2009

The following issues are confirmed for 2010:

- LHD Stellarator (JA) 10th Anniversary Special Issue — FS&T double issues
- 9th Carolus Magnus Summer School 2009 Proceedings — FS&T Transactions
- Selected papers from APS-DPP 2009 Mini-Conf. on Mirrors — FS&T regular issue
- Selected papers from 6th Fusion Data Processing, VV & Analysis — FS&T regular issue

The following issues are planned for 2011 and 2012:

- Selected papers from 2010 EC-16 — FS&T regular issue(s) (2011)
- JT-60U (update of JT-60 Special 2002) — FS&T regular issue (2011)
- 19th TOFE 2010 Proceedings — FS&T double issues (2011)
- 9th Tritium 2010 Proceedings — FS&T double issues (2011)
- Open Systems 2010 Proceedings — FS&T Transactions (2011)

- Cluster of fusion papers from ICFRM 2011 — FS&T regular issue (2012)
- ICENES 2011 Proceedings — FS&T Transactions (2012)
- 10th Carolus Magnus Summer School 2011 — FS&T Transactions (2012)

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SPECIAL SECTION: ONGOING FUSION RESEARCH

Recent Advances in High Temperature Superconductors

Joseph V. Minervini

Massachusetts Institute of Technology, Cambridge, MA.

Introduction

Magnet systems are the ultimate enabling technology for magnetic confinement fusion devices. Powerful magnetic fields are required for confinement of the plasma, and, depending on the magnetic configuration, steady state and/or pulsed magnetic fields are required for plasma initiation, ohmic heating, inductive current drive, plasma shaping, equilibrium, and stability control. Almost all design concepts for power producing commercial fusion reactors rely on superconducting magnets for efficient and reliable production of these magnetic fields. Several fusion machines that use superconducting magnets are either operational or under construction in many countries throughout the world. These magnet systems were built exclusively with so-called low temperature superconductors (LTS). These are made from either the ductile alloy, NbTi or the brittle intermetallic compound, Nb₃Sn. These superconducting materials have been developed and optimized over the past four decades, and are optimized to near their ultimate limits of performance.

The new high temperature superconductor (HTS) materials potentially offer a revolutionary path forward in the design of magnetic fusion devices that could lead to very high performance in compact devices, with simpler maintenance methods and enhanced reliability. These materials are already sufficiently advanced to consider for next-step fusion applications. The game-changing opportunities offered by these types of superconductors include the ability to optimize the magnetic fusion device for very high field plasma performance and/or to operate the device at relatively high cryogenic temperatures.

They can be used with any magnetic field configuration including 3-D shaped devices. Since these materials can operate at cryogenic temperatures approaching that of liquid nitrogen (77 K), one can consider as realistic the option to build electrical joints into the winding cross-section that can be connected, unconnected, and reconnected in the field. The significance of this capability is that a fusion device can be more easily disassembled and reassembled in the field to allow for ease of maintenance and change of components inside the vacuum vessel.

High Temperature Superconducting Materials

Over the decades, several experimental magnetic confinement fusion devices have been built with superconducting magnets. As the magnetic field requirements have increased, the superconducting materials in use have evolved from NbTi for relatively low peak field devices (up to ~ 7 T at 4.5 K), to the present use of Nb₃Sn in ITER toroidal field (TF) and central solenoid (CS) magnets operating at peak field of 13 T, at 4.5 K.

As we look to the future, we note that ITER magnets are based on technology developed primarily in the 1980s and 1990s. If DEMO is to follow ITER on the roadmap, it is unrealistic to expect to be using this same technology decades later. A new opportunity that could significantly change the economic and technical status of superconducting magnets is to use high temperature superconductors (HTS). Experimental insert coils have already demonstrated operation in fields > 30 T in small bore solenoid geometries. HTS materials are not yet developed to the level required by the complex and extremely demanding radiation environment of fusion devices, but they are showing significant and rapid progress at a rate that qualifies them for consideration for use in future power plants, especially if a robust program of development is begun now.

HTS are a new class of superconductors made from oxide ceramic materials with a transition to the superconducting state at a critical temperature, T_C , much greater than that of the metallic compounds such as Nb₃Sn. Presently, the most developed types of these materials are Bi₂Sr₂Ca₂Cu₃O₁₀ (bismuth-strontium-calcium-copper-oxide, or BSCCO-2223) with a critical temperature of 108 K, and YBa₂Cu₃O₇ (yttrium-barium-copper-oxide, or YBCO) with a critical temperature of 93 K. The major significance of these materials is the critical temperature for both is greater than 77 K, the boiling point of liquid nitrogen. This then opens up the possibility of operating magnets at temperatures much higher than saturated liquid helium at 4.2 K, thus simplifying the cryogenic requirements as well as significantly increasing thermodynamic refrigeration efficiency. More importantly for fusion, YBCO has an upper critical magnetic field in excess of 100 T at 4.2 K. The expanded operating envelope offered by YBCO is shown in Fig. 1.

Fusion Magnet Requirements

Most practical applications of HTS until now have evolved in the realm of electric power utility applications and low loss current leads for LTS magnets. The majority of these devices use BSCCO-2223. Recently, the long-range outlook for YBCO

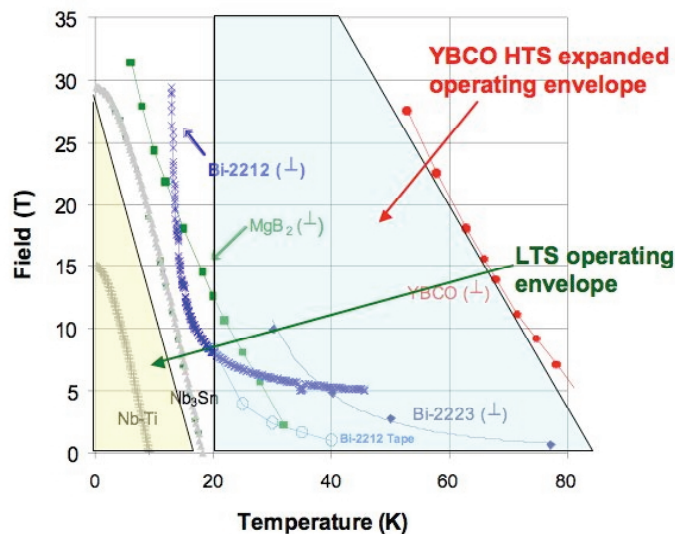


Figure 1. Critical surface of magnetic field versus temperature for several types of low temperature superconductors and high temperature superconductors. [Courtesy of David Larbalestier, FSU-NHMFL].

devices became very attractive for a variety of reasons including the potential for much lower production costs, long piece lengths, high strength, and excellent performance in magnetic fields at reasonably high temperatures. In the US, there are two companies producing HTS, SuperPower in Albany, NY and American Superconductor Corp. in Devens, MA. Both companies have abandoned production of BSCCO conductors in favor of the much better performance and economic value of YBCO conductors. Of the two materials, YBCO seems the better suited for high field magnet applications.

The YBCO conductors can presently only be made by thin film coating processes in tape form, typically 4–10 mm wide and 0.1–0.2 mm thick. The superconducting layer is only ~ 1 μm thick, with at least half of the cross-section made up of ~ 50 μm of a high strength nickel alloy, either Hastelloy™ or nickel-tungsten. The remaining thickness is comprised of several buffer layers of various compounds that provide the structural texture required to align the superconducting crystals to allow a high, longitudinal transport current. Although useful for many power utility applications, this geometry is not ideal for fusion magnets, where very high current conductors are required. The present state-of-the-art YBCO tapes (4 mm \times 0.1 mm) can be made in piece lengths greater than 1000 m, with a critical current of ~ 280 A at 77 K without applied field giving a figure of merit of ~ 300 kA-m. An advanced fusion magnet would require HTS conductors that can carry on the order 30–70 kA at fields in the 12–16 T range, and at an operating temperature somewhere between 20–60 K. This can only be achieved if thin tapes can be bundled or cabled into many strand (~ 1000) cables or flexible conductors as is presently done with round, multifilamentary wires of NbTi and Nb₃Sn. A focused development program is required to develop conductor concepts that are relevant for fusion magnets.

Fusion Magnet Applications

Properties and production lengths are now sufficient to use in even low-field fusion devices, e.g. a spherical tokamak, or with non-planar coils, e.g. helical or stellarator configurations. The ability to operate at relatively high cryogenic temperatures and the use of relatively simple structural configurations provide very highly stable operation that, in turn, allows consideration of demountable joints. Demountable high-temperature superconducting coils promise unique advantages for tokamaks and alternate configurations. They would enable fusion facilities in which internal components can be removed and replaced remotely, similar to vacuum vessel sector and blanket module removal. Once such connection methods have been developed, this would provide major advantages for the difficult challenges of reliability, availability, maintainability, and inspectability (RAMI) of fusion power plants.

In a working power plant, nuclear heating and radiation damage of the main plasma confinement coils are a major concern. The heating issue is significantly mitigated by the use of HTS conductors. Radiation damage to the insulation is presently the life-limiting factor. If the radiation life of the insulation system can be increased, for example, by developing ceramic, or other inorganic insulation systems, the superconducting material then becomes the life-limiting factor. The intrinsic physical properties of these superconducting materials make it unfeasible to increase the radiation damage lifetime.

Epoxy resin insulation systems reach the limits of its radiation resistance at the ITER fluence level of 10 MGy (10^{22} n/m²). Instead, the TF coils of ITER will use a new radiation resistant resin based on cyanate ester. This resin can provide a radiation life of over 100 MGy, 10-fold the original ITER requirement. For Nb₃Sn, the maximum fluence (at the maximum critical current density before a very fast drop off) is about 10^{23} n/m² [1]. As in Nb₃Sn, the critical current density of YBCO increases with fluence, especially at higher fields, allowing a lifetime limit of about 2×10^{22} n/m² (Fig. 2) or better [2]. However, the more restrictive critical temperature may limit the YBCO neutron fluence to $\sim 10^{22}$ n/m² (Fig. 3) [3,4].

Superconductors have always been very expensive relative to copper, with HTS conductors much more expensive than LTS conductors. LTS conductors are often priced on a cost per weight basis. This is not a good way to compare conductors because of the relative differences in absolute performance between them. But typically, one can say that at 4.2 K the highest performing NbTi wire is in the \$200/kg range at a 5 T point, and Nb₃Sn is in the range of \$800–1000/kg at the 12 T point. The cost of HTS conductors is very difficult to determine because of the rapidly changing manufacturing and performance gains. Since they are usually priced on a cost-performance basis, an approximate value to use today is \sim \$400/kA-m (77 K, self-field only). One can see how it is difficult to make a direct comparison. Roughly speaking though, the relative costs for HTS are at least 1 order of magnitude higher than LTS wires. Through constant development this ratio is being reduced, but it is important to consider overall system costs, performance, and life-cycle costs, as well as other performance

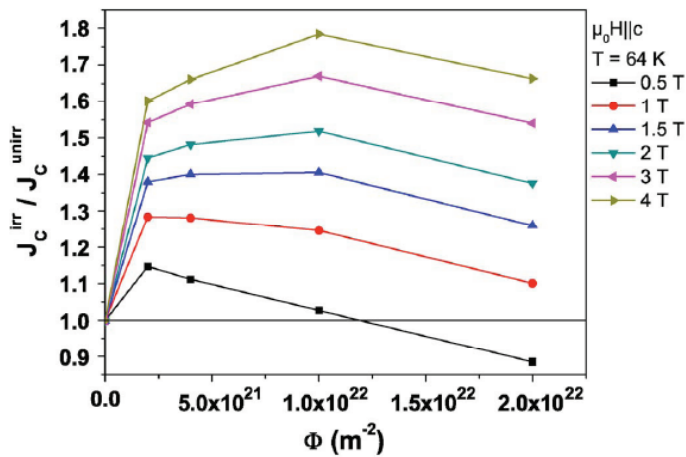


Figure 2. Ratio of the critical current density of YBCO before and after fast neutron irradiation to various fluences, and as a function of magnetic field [2].

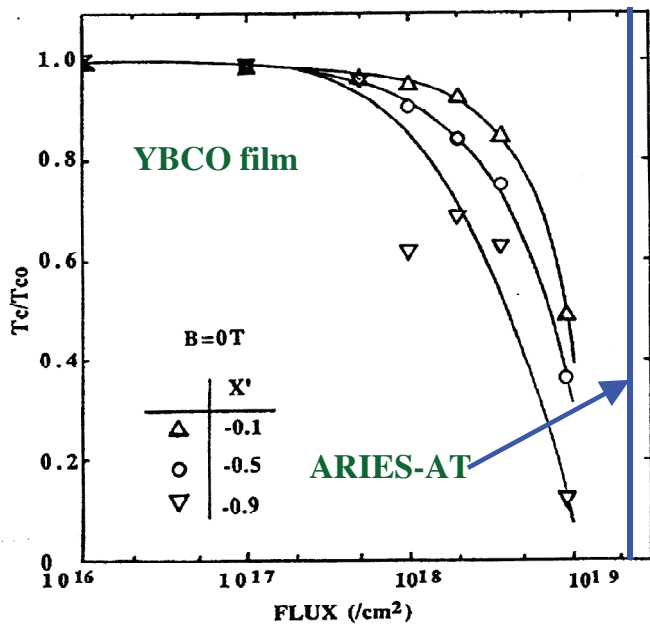


Figure 3. Ratio of the critical temperature of YBCO before and after fast neutron irradiation to various fluences [3,4].

and RAMI issues in order to choose the best superconductor for the application.

Second generation YBCO high temperature superconductors are under constant and rapid performance development in industry. The rate of progress is very impressive, yet good enough even now to begin considering for fusion applications. This is a revolutionary material that requires a focused development effort to provide a realistic vision for making an economical commercial fusion power plant.

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Highlights of US Fusion-Fission Hybrid Workshop

Jeffrey Freidberg
Massachusetts Institute of Technology, Cambridge, MA.

LARGELY IN ANTICIPATION of a possible nuclear renaissance there has been an enthusiastic renewal of interest in the fusion-fission hybrid concept, driven primarily by members of the fusion community. A fusion-fission hybrid consists of a neutron producing fusion core, surrounded by a fission blanket. Hybrids are of interest because of their potential to address the main long term sustainability issues related to nuclear power: fuel supply, energy production, and waste management.

As a result of this renewed interest, the US Department of Energy (DOE), with involvement of Office of Fusion Energy Sciences (OFES), Office of Nuclear Energy (NE), and National Nuclear Security Administration (NNSA), organized a three day workshop in Gaithersburg, Maryland from Sept. 30-Oct. 2, 2009. There were several goals to be achieved. At the highest level, it was recognized that DOE does not currently support any R&D in the area of fusion-fission hybrids. The question to be addressed was whether or not hybrids offer sufficient promise to motivate DOE to initiate an R&D program in this area. At the next level, the workshop participants were asked to define the research needs and resources required to move the fusion-fission concept forward.

The answer to the high level question was given in two ways. On the one hand, when viewed as a standalone concept, the fusion-fission hybrid does indeed offer the promise of being able to address the sustainability issues associated with conventional nuclear power. On the other hand, when asked whether these hybrid solutions have the potential to be more attractive than contemplated pure fission solutions (i.e. fast burners and fast breeders), there was a general consensus that this question could not be quantitatively answered based on the known technical information. That is, pure fission solutions are based largely on existing technology while hybrid concepts rely on assumed advances in technology, thereby prohibiting a fair side-by-side comparison.

Another important issue addressed at the workshop was the time scale on which long term sustainability issues must be solved. There was a wide diversity of opinions and no consensus was possible. One group, primarily composed of members of the fission community, argued that the present strategies with respect to waste management (i.e. on-site storage) and fuel supply (i.e. from natural uranium) would suffice for at least 50 years, the main short term problem being the economics of light water reactors. Many from the fusion community believed that the problems, particularly waste management, were of a more urgent nature and that we need to address them sooner rather than later.

There was rigorous debate on all the issues before, during, and after the workshop. Based on this debate the workshop participants developed a set of high level Findings and Research Needs and a comparable set of Technical Findings and Research Needs. In the context of the Executive Summary it is sufficient to focus on the high level issues which are summarized below.

High Level Findings

- 1) **The potential role of fusion-fission hybrids:** A fusion-fission hybrid might potentially contribute to all components of nuclear power – fuel supply, electricity production, and waste management.
- 2) **Ideas put forth by hybrid proponents:** The idea of the fusion-fission hybrid is many decades old. Several ideas, both new and revisited, have been investigated by hybrid proponents. These appear to have attractive features, but require various levels of advances in plasma science and fusion and nuclear technology.
 - a) **A waste transmuter based on the leading magnetic fusion and fast burner reactor technologies:** One tokamak-based proposal combines ITER physics and technology (the leading magnetic fusion technology) with sodium-cooled fast burner reactor technology plus the associated fuel reprocessing/refabrication technologies (the leading related burner reactor technologies). By building on the most advanced systems in both fusion and fission, this hybrid concept would require the minimal amount of advanced technology development. However, the duty factor of ITER is limited to only a few percent, well below that required for a hybrid system, so significant fusion technology reliability advances would still be required (as for any fusion concept), and the technology to integrate the two systems (e.g. dealing with a liquid metal in a magnetic field) would need to be developed. A reprocessing fuel cycle was proposed in which the actinides from LWR spent fuel were burned to greater than 90% in the hybrid.
 - b) **A waste transmuter with a removable fusion core:** This is a spherical tokamak-based concept that utilizes a compact replaceable fusion core which can be extracted as a single unit from the fission reactor. The goal is to minimize the electromagnetic and mechanical coupling between the fusion and fission systems. Maintenance and repairs would be simplified by periodically removing the fusion core to a remote bay and replacing it with another in the fission reactor. Also to minimize the MHD problems, the fission blanket is located outside the toroidal magnetic field coils. The fuel cycle of interest, which could be used by other hybrid concepts as well, uses a fusion-enhanced version of the two-tier process. Actinides are first reprocessed from spent fuel, then 75%-burned in an intermediate stage light water reactor (LWR) using inert matrix fuel (IMF) and finally burned in a hybrid, thereby providing a high support ratio. However, a new inert matrix fuel would need to be developed and a full systems analysis is required to assess the overall economics including the contributions of the intermediate stage IMF LWRs. Lastly, at least one additional physics development step is required before an ITER-equivalent neutron source prototype could be built.
 - c) **Once-through burn-and-bury energy producers:** A very deep-burn fuel cycle, based on laser fusion, has been proposed in which nuclear fuel is almost completely burned. The initial fuel does not require enrichment. Perhaps even more important the deep burn has the attractive feature that, if successful, no reprocessing would be required. However, a very deep burn fuel form needs to be developed and nearly the full capabilities of pure fusion systems would be required. Also, high-power, high rep-rate lasers need to be developed to produce high average power.
 - d) **Efficient LWR fuel breeders:** These are concepts in which fissile fuel is produced in a flowing liquid blanket. The fissile fuel is removed online in order to suppress its subsequent fission in the hybrid system. An efficient fuel breeder for LWRs has the advantage of enabling a long term sustainable fleet of LWRs requiring only a relatively few hybrids for fuel production. However, in addition to fusion technology developments, this concept requires the development of continuously flowing fuel systems. The use of hybrids to produce fissile fuel is applicable to both MFE and IFE systems. It was studied in great detail during the 1980's by MFE mirror advocates. The mirror configuration may need to be revisited because of recent progress in related plasma performance in the international fusion program.
- 3) **Repositories:** Any waste management strategy, using either pure fission technology, or fusion-fission hybrid technology will still require a long term geological repository for the final remaining long-lived waste.
- 4) **A political problem:** Although technologically deployable, long-term solutions to fuel and waste management may not be needed for half a century, there is a short term political problem facing the nation. With work on Yucca Mountain halted, there is no perceived progress on addressing the waste management problem on any time scale.

- 5) Economic comparison of pure fission vs. fusion-fission hybrid solutions:** There was general consensus that a hybrid capable of producing a certain amount of fusion power would be noticeably more expensive than an equivalent LWR. Economic comparisons thus have to be made on an overall systems basis. For example, what is the overall cost of a group of LWRs plus necessary hybrids vs. a combination of LWRs plus perhaps a larger number of fast reactors with each system producing the same amount of power and reducing the waste to the same level?
- 6) An intermediate step to pure fusion electricity:** Advocates suggest that a fusion-fission hybrid can be developed on a shorter time scale than for pure fusion electricity because the required plasma physics and some technology requirements are substantially reduced. Some of the panels and also the skeptics argued that some technology may be more complicated in a hybrid because of the integration of fusion and fission technologies. Perhaps more importantly, the pace of development will be dominated by engineering and technology and not plasma physics. They believe that the time scales for development will be comparable for both.
- 7) The international fusion-fission hybrid program:** There were concerns expressed by some of the experts at the workshop as to the slow pace of development of fusion-fission hybrids in the US program. However, such concerns were not shared by our international colleagues. Indeed, several countries are considering the option to develop neutron sources as a first step toward building hybrids. These include the Russian Federation, South Korea, and China.
- 8) Proliferation:** Hybrids produce significant quantities of fissile materials, generally not retained in individually accountable fuel rods, and hence raise significant proliferation concerns

High Level Research Needs

- 1) Comparison Between Fission-Based and Hybrid Solutions:** The first step that needs to be carried out is a side-by-side systems analysis comparison of proposed pure fission and fusion-fission hybrid solutions to the problems of waste management, fuel supply, and electricity production. The basic ground rules are that comparable assumptions (e.g. material properties, fuel forms, etc.) must be used for each design.
- 2) Fusion Engineering and Technology:** There appeared to be widespread consensus that neither pure fusion nor fusion-fission hybrids could be developed, even in 50 years, unless the fusion engineering and technology programs were restarted in OFES. Of particular concern was the need for an expanded materials research program. Without strong fusion engineering and technology programs, the US will continue to be unable to have a defined timetable for a fusion power plant and thus will fall further and further behind our international colleagues — they will be the leaders and we the followers.

SPECIAL SECTION: INTERNATIONAL ACTIVITIES

US ITER Report

Ned Sauthoff
US ITER Project Office
Oak Ridge National Laboratory, Oak Ridge, TN.

THE ITER COUNCIL RECENTLY MET for a two-day meeting in Cadarache to address a range of issues, including consideration of the ITER baseline scope, cost, and schedule. The Science and Technology Advisory committee had performed a review of the technical aspects, including consistency between the overall ITER mission and the requirements and design. The Management Advisory Committee had reviewed cost and schedule. Much effort was dedicated to specifying the conditions for acceptance of a realistic schedule, taking into consideration technical and cost risks. The Council directed the ITER Organization to work with the Domestic Agencies to develop two dates: an early-finish date and a late-finish date. The early-finish date should be based on a schedule that incorporates opportunities for accelerating the schedule, incorporating the probability that the risk mitigation approaches that are currently being pursued will be successful, and reflecting a schedule that the Domestic Agencies assess as being realistically achievable. The late-finish date should assume less optimistic assumptions. Achieving Deuterium/Tritium operation as early as realistically possible is a priority.

The Council also selected chairs for key parts of the Council organization:

- Evgeny Velikhov, Russian Federation, was elected Chair of the ITER Council for the next term.
- Yuanxi Wan, China, was appointed Chair of Science and Technology Advisory Committee.
- Gyung Su Lee, Korea, was appointed Chair of Management Advisory Committee.

On the US front, the US Domestic Agency recently awarded contracts to Oxford and Luvata for a total of \$33M of superconducting strand. This long-lead material will be used to fabricate the US's 8% of the Toroidal Field Conductor. Future work in this area will include procuring other materials, forming the strands into cable, inserting the cable into the stainless steel conduit and compacting the composite.

Report on IAEA Technical Meetings on “First Generation of Fusion Power Plants: Design and Technology” and “Fusion Power Plant Safety”

Guenter Mank

and

Richard Kamendje

Physics Section

International Atomic Energy Agency, Vienna, Austria.

THE 3RD IAEA TECHNICAL MEETING (TM) on “First Generation of Fusion Power Plants: Design and Technology” was held in combination with the 9th IAEA Technical Meeting on “Fusion Power Plant Safety” from 13–17 July 2009 at the IAEA Headquarters in Vienna. The agenda of the respective meetings was prepared so as to allow common presentations on 15 July and separate presentations on “Fusion Power Plants: Design and Technology” on 14 July and on “Power Plant Safety” on 16–17 July. July 13 was dedicated to a discussion session on proposed further activities. The purpose of these series of TMs was to assess the progress and outline general guidance and recommendations on issues related to the design, technology, and safe operation of the first generation fusion power plants as well as their environmental and socio-economic implications. A total of twenty-two oral presentations were given during the combined TMs. A panel discussion on “How fast commercial fusion can be reality assuming no funding constraints” took place on 14 July.

First Generation of Fusion Power Plants: Design and Technology

The topics covered during this meeting included power plant concepts and systems analysis, materials analysis/components design/plasma requirements and non-electric applications of fusion. Several presentations outlined the research needs, efforts and technology choices and discussed results and current challenges in various countries. In the presentation “40 Years of Power Plant Studies: Brief Historical Overview and Future Trends,” L. El-Guebaly (US) summarized the magnetic fusion history, by emphasizing the US and international activities, and gave a brief look into the future. In the early 1950s, there were only four magnetic confinement fusion concepts pursued internationally: tokamak, stellarator, mirror, and pinch. The tokamak, stellarator, and pinch concepts have experienced substantial modifications over the past 60 years. The mirror concept was suspended in the US in 1986, while continuing at a very low level in Japan and Russia. During the 1970–2008 period, more than 50 conceptual power plant design studies have been conducted in the US, EU, Japan, Russia, and China for both magnetic and inertial confinement concepts, covering a wide range of new and old design approaches: tokamaks, stellarators, spherical tori, field-reversed configurations, reversed-field pinches, spher-

maks, tandem mirrors, and laser/light and heavy-ion/Z-pinch driven inertial fusion. Internationally, the D-T fuelled tokamak is regarded as the most viable candidate for magnetic fusion energy generation. Its program accounts for over 90% of the worldwide magnetic fusion effort. The fusion roadmaps take different approaches internationally, depending on the degree of extrapolation beyond ITER. Several tokamak DEMOs should be built in the US, EU, Japan, China, Korea, and other countries to cover a wide range of near-term and advanced fusion systems. As an example of the present worldwide status of fusion power plant design and technology, K. Feng (China) outlined in his talk “Study Activities of DEMO Plant at SWIP” the special need for China to develop new types of energy sources due to the huge demand of energy. A first step will be a DEMO reactor to demonstrate the safety, reliability and environmental feasibility of fusion power plants, while demonstrating the prospective economic feasibility of commercial fusion power plants. The helium-cooled ceramic breeder (HCSB) was chosen under the conditions of meeting the requirement of the neutronics, thermal-hydraulics and mechanics aspects. The DEMO development strategy and related design and R&D activities based on China’s fusion power plant program were presented. A conceptual design of an HCSB-DEMO reactor was carried out with major parameters being 2000 MW fusion power and a neutron wall loading of 2.6 MW/m². Lithium orthosilicate (Li₄SiO₄) pebbles are used as a breeding material and a beryllium binary pebble-bed as a neutron multiplier material. The R&D on the development of functional materials, structural materials and the helium test loop construction were presented. The Chinese low activation ferritic/martensitic steels (CLF-1), the structural materials for the Chinese HCSB-DEMO concept, are currently developing towards industrially compatible manufacture. Beryllium and Li₄SiO₄ pebbles for HCSB-DEMO have been fabricated at the laboratory level.

Fusion Power Plant Safety

The main focus of the 9th IAEA Technical Meeting on “Fusion Power Plant Safety” was on:

- a) Safety assessment (safety requirements, barriers, accident analysis, environmental impact, safety of normal operation, failure database, verification and validation),
- b) Management strategy and materials characterization (safety of fuel cycle, structural and functional components, waste, tritium, pathway facilities to fusion power plants), and
- c) Socio-economic implications (regulations, emergency response, human resource development, natural resources, return on investment).

The objective of the safety meeting was to examine in an integrated way all safety and environmental aspects anticipated to be relevant to ITER, and to the first power plant prototype.

I. Non-Proliferation and Fission-Fusion Hybrids

As summarized by R.J. Goldston (US), nuclear proliferation risks from fusion associated with access to weapon-usable materials can be divided into three main categories:

- 1) Clandestine production of weapon-usable material in an undeclared facility,
- 2) Covert production of such material in a declared and safeguarded facility, and
- 3) Use of a declared facility in a breakout scenario, in which a state begins production of fissile material without concealing the effort.

The paper addresses each of these categories of risks from fusion. Ultimately, if designed to accommodate appropriate safeguards, fusion reactors would present low proliferation risk compared to fission. There is not a credible technique for clandestine production of significant quantities of weapons materials using fusion research facilities. Detection of the covert use of a declared and safeguarded fusion power plant to produce small amounts of plutonium or ^{233}U appears to be straightforward. The breakout scenario for fusion is qualitatively different from that for fission, because no weapons material is available at the time of breakout. Goldston estimated that the world community would have 1–2 months to respond and prevent the production of weapons materials.

II. Waste Management

Recycling of materials and clearance (i.e. declassification to non-radioactive material) were presented as the recommended two options, in an integrated approach from the US viewpoint (by L. El-Guebaly et al.) and from the European viewpoint (by B. Kolbasov et al.), for reducing the large amount of fusion waste, while the disposal as low-level waste could be an alternative route for specific materials and components. Such an approach requires further refinement, approval of the national authorities, and a dedicated R&D program to address the identified critical issues. This implies a complete consideration of most of the parameters involved in such a materials management system, by investigating and comparing different designs and material compositions, in view of their impact on the environment, particularly if assigned for geological disposal. Recycling and clearance are technically feasible for any fusion device employing low-activation materials, using advanced radiation-resistant remote handling equipment, and having clearance guidelines for slightly radioactive materials. However, such approaches are relatively easy to envision and apply from a science perspective, but a real challenge from the policy, regulatory, and public acceptance perspectives. In

the near future, the US fusion development program will be set up to accommodate this new recycling/clearance strategy as proper handling of activated materials is important to the future of fusion energy. One important and relatively immediate issue affecting public perception of fusion is the waste handling and disposition strategy for ITER. The host party, France, has taken responsibility for reception and disposal of the amount of waste produced by ITER, an unavoidable fact given the experimental nature of the device.

III. ITER Safety and Licensing

N. Taylor (ITER) presented a report on “Key Issues in the Safety and Licensing of ITER”. A preliminary safety report for the ITER facility at Cadarache has been prepared as part of the licensing submission. Following advice received from the nuclear safety authorities, the report is now being updated to provide additional information and further safety analyses in many areas. In the course of preparation of this report, a number of technical issues have been addressed which are of particular importance in the safety case, in order to provide the required level of justification that the safety provisions taken in the ITER design are adequate. The principal safety functions in ITER are the confinement of radioactive material (tritium and the products of neutron activation, including in-vessel dust), and protection from exposure to radiation. The confinement function is provided by two confinement systems, comprising static barriers and dynamic systems. For the in-vessel inventory, the vacuum vessel and its extensions provide the first barrier. Challenges to this barrier from possible over-pressure in accidents are considered, including in-vessel coolant leaks or hydrogen and dust explosions. The ITER approach is based on multiple provisions to mitigate such events, by pressure relief, limiting hydrogen production and air ingress, and maintaining low temperatures by heat removal. Other internal hazards such as fire, and external events such as earthquake, are also taken into account by design provisions.

Conclusion

The informative presentations, paired with fruitful discussions during these meetings, contributed to clarify the need for a forum of an international expert group on Fusion Power Plant Designs, which should serve as platform for exchange of expertise and definition of R&D priorities.

FED Newsletter Editor in Chief:

Laila El-Guebaly (elguebaly@engr.wisc.edu)

FED Newsletter Graphics & Layout Editor:

Thad Heltemes (taheltemes@wisc.edu)

FED Newsletter Technical Editor:

Dennis Bruggink (bruggink@engr.wisc.edu)

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