American Nuclear Society
Fusion Energy Division
December 2014 Newsletter

Letter from the FED Chair, Susana Reyes, Lawrence Livermore National Laboratory, Livermore, CA.

In my very first opportunity to deliver the “Letter from the Chair”, I would like to start by wishing you and your families a happy 2014 holiday season, on behalf of the Fusion Energy Division (FED) officers. I also would like to thank our past Chair, Professor Minami Yoda, for her outstanding job as Division leader over the past two years and her continued support and guidance in her new role as FED Past Chair.

Since I started my Chairmanship in June of the present year, this has been a quite vibrant period for the American Nuclear Society (ANS), and for the Fusion Energy Division. As we approach the middle of the decade, we are witnessing more and more interest in nuclear power being expressed worldwide. The ANS Summer Meeting that took place last June in Reno, NV, with title “The U.S. Role in a Global Nuclear Energy Enterprise," recognized that while for many years, the U.S. has led the development and deployment of nuclear power worldwide, we should now be prepared to explore the expectation for this to continue, and what domestic and international forces could impact this leadership in the future. International developments in waste management and safety regulations, for example, are already having a very visible impact on how the U.S. regulators, policy makers, utilities and other nuclear power stakeholders develop their own strategies.

In the fusion arena, I would like to do a brief introspection regarding this very same topic. Throughout its history, the quest for controlled fusion energy has been a global enterprise with strong U.S. leadership. Now half of the world is engaged in the international burning plasma experiment, ITER, and simultaneously our international colleagues are building other large-scale facilities with capabilities that complement ITER to help pave their respective exciting roadmaps towards the ultimate goal of fusion energy. Meanwhile, in the domestic front, the decreasing budget for domestic fusion research is frustrating for many U.S. researchers. Nevertheless, it is of extreme importance that we continue to strive for a robust and well-balanced domestic fusion science and technology programs, and that we keep our commitment towards international collaborations to help maintain the major role of the U.S. in the development of fusion energy.

Next, I would like to highlight a few recent FED related activities. In the first place, I would like to offer my most sincere congratulations to the organizers of the recent 21st Topical Meeting on the Technology of Fusion Energy (TOFE) that took place in November 9-13, in Anaheim, CA. In particular, I would like to thank Brian Wirth, Vincent Chan, Rajesh Maingi and the rest of the organizing committee for making the 2014 TOFE meeting a success. I am very excited to report that ANS FED was able to provide financial support enabling eight students to attend this meeting, and that the conference proceeds will contribute towards our Division’s goal of creating an endowment fund to support a typical ANS annual scholarship for a student in both fields of fusion science and engineering. I am also thrilled to announce that Princeton Plasma Physics Laboratory will be hosting the 2016 TOFE meeting (August 22-25, Philadelphia) with additional support from the ANS Northern California Local Section. Although I cannot advance many details, I assure you that the FED leadership will work hard to help the conference organizers make this TOFE another success. Other FED co-sponsored conferences to keep under the radar include ICENES 2015 (May 10-14, 2015, Antalya, Turley) and Tritium 2016 (April 17-22, 2016, Charleston, SC), so please mark your calendars accordingly.

Finally, over the last year, much emphasis has been directed towards engagement of new members and young members in overall ANS activities, through the Professional Divisions, the Local Sections and other governance committees. As part of this initiative and as some of you may have noticed, the FED welcome letter to new ANS members now includes an invitation upon RSVP, to join one of our Executive Committee meetings in order to get introduced to our FED activities and to motivate further involvement of new members in such activities. Whether you are a former or a new member, please do not hesitate to contact me if you would like to pursue further involvement in the FED or the broader Society.

Thank you all for supporting the ANS FED.

New ANS Fusion Fellows – November 2014, Nermin A. Uckan, FS&T Editor, Oak Ridge National Laboratory, Oak Ridge, TN.

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, and nomination forms can be found at http://www.ans.org/honors/va-fellow.

It is a pleasure to report that we have a new ANS "Fusion" Fellow added to the honors rank: Dr. **Richard J. Kurtz**, a materials science researcher at the Pacific Northwest National Laboratory (PNNL). Congratulations for a well-deserved honor.

Richard Kurtz earned the highest grade of ANS membership "*For demonstrating research excellence and program leadership for more than three decades leading to significant advances in the development of damage tolerant structural materials for nuclear energy applications, including improved nondestructive inspection techniques and evaluation methods to ensure structural integrity*."

Richard Kurtz is a PNNL Laboratory Fellow in PNNL Energy and Environmental Research Division. He is an internationally recognized expert in the field of reactor materials, particularly in the fusion reactor materials. Currently, he leads a program focused on developing durable, stable materials that will withstand the fusion reactor environment.

Richard Kurtz has been recognized as a Fellow of the American Nuclear Society during the ANS Annual Meeting, held in Anaheim, CA, Nov 9-13, 2014

FED has two dozen or so Fellows and the FED Officers/Executive Committee have been encouraging all FED members to actively engage in nominating deserving colleagues to the fellowship grade. Please remember that one cannot get recognized for any award or elevated to Fellow status, unless nominated. The FED “red-team” Fellows will be happy to provide guidance and help review nomination packages. Feel free to contact uckanna@ornl.gov for questions.

Slate of Candidates for 2015 FED Election, Minami Yoda, Georgia Institute of Technology, Atlanta, GA.

At the beginning of 2015, the ANS headquarters will e-mail an announcement about E-ballots to all ~900 members of the FED. Please remember to E-vote by April, or if you do not have e-mail address, to return your ballot by postal mail. The outcome of the election will be announced before the next FED Executive Committee meeting in June 2015. The FED Nominating Committee is always looking for fusion professionals, like those listed below, who are willing to serve the division. If you are interested in becoming active in the division governance, please contact any Executive Committee member.

The present ExCo officers are in the middle of their 2-year terms. We would like to thank the ExCo members who are completing their terms in June 2015: Satoshi Konishi (Kyoto U.), Jacob Leachman (WSU), and Juergen Rapp (ORNL).

We have an excellent set of fusion researchers running for these three executive committee seats in this election. Their willingness to contribute their time and talents to the division is appreciated by the FED. Our list of candidates (in alphabetic order) for the coming election is:

Ahmad Ibrahim (ORNL)
Takeo Muroga (NIFS)
Keith Rule (PPPL)
Chase Taylor (INL).

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 2013, 2014, and 2015 fusion awards on this well-deserved recognition and our kudos to all of them.

ANS-FED Awards

The 2014 ANS-FED Outstanding Achievement Award has been awarded to Mr. **Brad Merrill** (Idaho National Laboratory) "for his lifelong pioneering and impactful contributions in the development of international fusion safety analysis tools that have formed the foundation for fusion nuclear safety assessments."

Dr. **Larry Baylor** and Dr. **Steve Combs** (ORNL) received the 2014 ANS-FED Technical Accomplishment Award "in recognition of a long history of creative technology solutions in the areas of plasma fueling and disruption mitigation for present and future (ITER) fusion energy experiments and reactors."

The winner of the 2014 ANS-FED Outstanding Student Paper Award is **Juliusz Alexander Kruszelnicki** (University of Florida) for his paper titled "Impact of Focusing Grids and Pulsed Power on Modified IEC Fusion Device."

APS-DPP Awards

The recipients of the APS 2014 John Dawson Award for Excellence in Plasma Physics Research are:

- Prof. **Chris Hegna** (University of Wisconsin-Madison) for the theoretical prediction and experimental demonstration of neoclassical tearing mode stabilization by localized electron cyclotron current drive.
- Dr. **Hartmut Zohm** (Max Planck Institute fur Plasmaphsik) for the theoretical prediction and experimental demonstration of neoclassical tearing mode stabilization by localized electron cyclotron current drive.
- Prof. **James D. Callen** (University of Wisconsin-Madison) for the theoretical prediction and experimental demonstration of neoclassical tearing mode stabilization by localized electron cyclotron current drive.
- Prof. **Olivier Sauter** (Ecole Polytechnique Federale de Lausanne) for the theoretical prediction and experimental demonstration of neoclassical tearing mode stabilization by localized electron cyclotron current drive.
- Dr. **Robert J. LaHaye (General Atomics)** for the theoretical prediction and experimental demonstration of neoclassical tearing mode stabilization by localized electron cyclotron current drive."

FPA Awards

The Fusion Power Associates (FPA) Board of Directors has selected the recipients of its 2014 Distinguished Career, Leadership, and Excellence in Fusion Engineering Awards:

- The 2014 Distinguished Career Awards are presented to Prof. **Ronald C. Davidson** (Princeton University) and to Rep. **Rush Holt** (U.S. House of Representatives). **Davidson** is cited for his many years of dedication to advancing the prospects for fusion power, noting especially the decades of outstanding career contributions as a scientist, educator, manager and advisor in the areas of both magnetic and inertial confinement fusion. **Holt** is cited for his decade-long dedication to advancing the prospects for fusion power earlier in his career, followed by his dedication to public service for more than a decade as a member of Congress, noting especially his efforts to improve the Nation's educational opportunities for young people, to improve our environment, and to provide support for scientific research.

- The 2014 Leadership Awards are presented to Dr. **John Edwards** (Lawrence Livermore National Laboratory) and to Prof. **Martin Greenwald** (MIT). **Edwards** is cited for his many scientific contributions and the managerial leadership to national and international research efforts on inertial confinement fusion and high energy density plasma physics, noting especially the leadership of the scientific program on the National Ignition Facility (NIF) for both high energy density physics and for the eventual achievement of ignition leading towards a commercial fusion power source. **Greenwald** is cited for the many scientific contributions and the managerial leadership to national and international research efforts on plasma and fusion science, noting especially the role in the achievement of the Lawson n-tau in Alcator-C, the role in the understanding of turbulent transport and its role in determining tokamak density limits, and more recent, the leadership of the US Fusion Energy Sciences Advisory Committee (FESAC).
- 2014 Excellence in Fusion Engineering Awards are presented to Dr. **Daniel Sinars** (Sandia National Laboratories) and to Dr. **Ann E. White** (MIT). **Sinars** is cited for the leadership to high energy density physics experiments on the Z facility at Sandia, for many scientific contributions to understanding wire-array implosions for indirect drive inertial confinement fusion, and for magnetically-driven implosions being studied for the MagLIF approach to inertial confinement for fusion energy applications. **White** is cited for the leadership to the world effort to understand turbulent transport in tokamaks – a critical feasibility requirement for tokamak-based fusion power plants, for many other scientific contributions to the field of fusion research, and for devotion to training the next generation of fusion scientists and engineers.

IEEE Awards

The Institute of Electrical and Electronics Engineers (IEEE) has named Prof. **Noah Hershkowitz** (University of Wisconsin-Madison) the recipient of the 2015 IEEE Marie Sklodowska-Curie Award for outstanding contributions to the field of nuclear and plasma sciences and engineering, with the following citation: "For innovative research and inspiring education in basic and applied plasma science."

Nuclear Fusion Journal Award

The International Atomic Energy Agency has awarded an annual prize to honor exceptional work published in its Nuclear Fusion journal:

- The winner of the 2013 award is Dr. **D.G. White** (MIT). His ground breaking paper, presenting results from Alcator C-Mod, enhances the understanding of the formation of energy transport barriers and temperature pedestals, without particle barriers, through the I-mode regime. The discovery of a stationary ELM-free improved confinement regime with no impurity accumulation in a metallic high field tokamak, like ITER, has implications that will stimulate much future research. The 2013 winning paper is: I-mode: an H-mode energy confinement regime with L-mode particle transport in Alcator C-Mod **D.G. Whyte**, A.E. Hubbard, J.W. Hughes, B. Lipschultz, J.E. Rice, E.S. Marmar, M. Greenwald, I. Cziegler, A. Dominguez, T. Golfinopoulos, N. Howard, L. Lin, R.M. McDermott, M. Porkolab, M.L. Reinke, J. Terry, N. Tsujii, S. Wolfe, S. Wukitch, Y. Lin and the Alcator C-Mod Team 2010 Nucl. Fusion **50** 105005.

- The winner of the 2014 award is Dr. **P.S. Snyder** (General Atomics). His paper on Pedestal height will have a dramatic impact on overall fusion performance in next-step devices. This outstanding paper presents a compelling model for the edge pedestal width and height based on coupling peeling-ballooning theory for stability and kinetic ballooning transport theory. Comparison is made to experimental observations across a range of devices and convincing agreement is demonstrated. This model, therefore, has the potential to significantly focus the predictions of performance in future devices. The winning papers will be free to read until March 2015: A first-principles predictive model of the pedestal height and width: development, testing and ITER optimization with the EPED model **P.B. Snyder**, R.J. Groebner, J.W. Hughes, T.H. Osborne, M. Beurskens, A.W. Leonard, H.R. Wilson and X.Q. Xu 2011 Nucl. Fusion **51** 103016

News from Fusion Science and Technology (FS&T) Journal, Nermin A. Uckan, FS&T Editor, Oak Ridge National Laboratory, Oak Ridge, TN.

During the period October 1, 2013 to September 30, 2014, FS&T received a total of 136 regular issue manuscripts; plus 118 camera-ready papers accepted from the Tritium 2013 – a total of 254. Online submission/processing of about 60 papers from Open Systems & Plasma Materials Interactions (OS/PMI 2014) has been deferred to Oct. 2014, and not included in statistics of this period.

Statistics for FS&T regular issue manuscripts (136): 35 from North America, 31 from Europe and Russia, 62 from Asia, and 8 from Others, with the following breakdown: 77 have been accepted, 19 are under review/revision, and 40 have been rejected/withdrawn.

Statistics for camera-ready special issue papers accepted from Tritium 2013 (118): accurate statistics are not available for papers rejected/withdrawn from pre-review/pre-selection of papers - status and regional breakdowns will be sorted during the publication process in early 2015.

Following dedicated issues were published during the period 10/1/13 to 9/30/14:
- Selected lectures from 6th Int. ITER School 2013 – FS&T Jan. 2014
- Selected papers from 2nd IAEA-ITER Materials Technol. – FS&T Mar./Apr. 2014
- Selected papers from ICFRM-16 2013 – FS&T Jul./Aug. 2014.

Following dedicated issues are scheduled for 2015:
- ARIES-ACT Power Plant Study – FS&T Jan. 2015
- Selected papers from Tritium 2013 (camera-ready) – FS&T (early 2015)

- NIF-NIC Special Issue – FS&T (mid 2015)
- Selected papers from OS/PMI 2014 – FS&T (mid-late 2015)
- Selected papers from TOFE 2014 – FS&T (late 2015).

Following dedicated issues are being scheduled for 2016 and beyond:

- Target Fabrication 2015 special issue – FS&T (early/mid 2016)
- Selected papers from ICFRM 2015 – FS&T (2016)
- Selected papers from Tritium 2016 – FS&T (2017)
- Selected papers from TOFE 2016 – FS&T (2017)
- JA-EU-KO ITER Broader Approach & KSTAR (Korea) – FS&T (in planning)
- Physics and Technology for Steady-State Operation – FS&T (in planning).

New with FS&T in 2014/2015: ANS start assigning DOI numbers to articles starting with the January 2014 issue. There is no timetable yet for historical/back issue DOI assignments. Also, ANS will be introducing 'first-look' article-based publishing in 2015. In preparation for 'first-look,' during the second-half of 2014, ANS start testing the online posting of 'preprint' copies well ahead of the formal print copies.

As noted before, ANS has completed scans/upload of historical pre-1997 back issues and electronic access to FS&T is now available from 1981-to-current. As always, tables of contents and abstracts of papers can be accessed at http://www.ans.org/pubs/journals/fst/. Individual and library subscribers can access the full text articles at http://epubs.ans.org/.

Please send your comments on FS&T contents and coverage as well as suggestions for potential future topical areas that are timely and of interest to fst@ans.org.

ONGOING FUSION RESEARCH

Configuration Studies for an ST-Based Fusion Nuclear Science Facility,

Jonathan Menard, Princeton Plasma Physics Laboratory, Princeton, NJ.

There are several pathways from ITER to a commercial power plant. One option is a fusion demonstration power plant (DEMO) [1] with an engineering/electricity gain $Q_{eng} \sim$ 3-5 and other parameters approaching those of a first of a kind power plant. Another option is a "Pilot Plant" which is a potentially attractive next-step towards fusion commercialization by demonstrating generation of a small amount of net electricity $Q_{eng} \geq 1$ as quickly as possible and in as small a facility as possible in a configuration directly scalable to a power plant [2]. However, there are significant challenges to achieving net electricity and tritium fuel production – in particular the blanket technology used for thermal power conversion and tritium breeding. Such challenges have motivated consideration of a Fusion Nuclear Science Facility (FNSF) / Component Test Facility (CTF) [2-8] to provide fusion-relevant neutron wall loading (1 MW/m^2) and neutron fluence 6 $MW\text{-}yr/m^2$ to develop and test fusion blankets. This article describes recent assessments of the Spherical Tokamak (ST) approach for an FNSF/CTF and in particular the achievable missions as a function of device size. Key questions addressed include:

(1) What are the device and component lifetimes? (2) How large must an ST device be to achieve tritium breeding ratio TBR ≥ 1? (3) How much externally supplied tritium would be needed for a smaller ST that cannot achieve TBR ≥ 1?

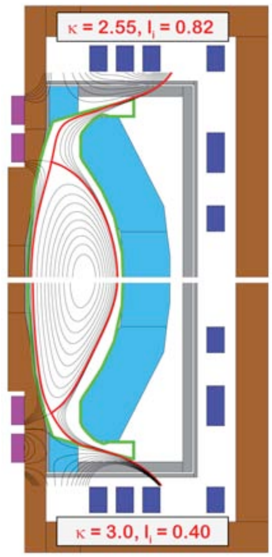

Figure 1 - *R_0 = 1.7m ST-FNSF: TF coils (brown), divertor / outboard PF coils (purple / dark blue), vessel and shielding (gray), breeding blankets (light blue), limiter outline (green), and plasma poloidal flux contours (black and red). Upper / lower plots are l_i = 0.82 / 0.40 and κ = 2.55 / 3.0.*

Physics Design

A key constraint on the design of an ST-based FNSF is the achievable shaping – namely the plasma boundary elongation (κ) and triangularity (δ) as a function of plasma aspect ratio, current profile peaking (l_i), normalized pressure, and normalized beta. The ST-FNSF design assumptions used here are chosen to be consistent with shaping achieved in the National Spherical Torus Experiment (NSTX) and/or anticipated in the near-term in NSTX Upgrade. In the last several years, substantial progress has been made in identifying a magnetic field coil set with attractive features:

1. All equilibrium poloidal field (PF) coils are outside the vacuum vessel to simplify maintenance and improve coil shielding. This coil set supports a wide range of plasma equilibrium internal inductance and pressure values.
2. Divertor PF coils in the ends of the central toroidal field (TF) coil to support strongly shaped plasmas with high triangularity for stable high-beta plasma operation.
3. Increased strike-point radius which reduces divertor heat flux to acceptable levels and partially shields the divertor with the blankets. This configuration combines features of the Snowflake [9,10] and Super-X divertor [11-13] to be tested soon on MAST-U [14].
4. Divertor strike-points at large major radius also leave space for breeding near the center-stack (CS) ends which is important for maximizing the tritium breeding ratio (TBR).

Another very important consideration for ST-FNSF is the choice of heating and current drive. Due to the typically over-dense plasma conditions of the ST, most RF schemes are challenging or inapplicable, so neutral beam injection (NBI) heating is one of the few potential options. Indeed, nearly all the present high-performance ST physics basis has been developed using NBI heating. Negative neutral beam injection (NNBI) current drive efficiency is found to increase with injection energy and tangency radius of injection, and for a R_0 = 1.7 m ST device, the optimal injection energy is approximately 0.5 MeV with optimal injection radius between R_0 and 1.4 times R_0. It is anticipated ST-FNSF could leverage NNBI research and development being carried out for JT-60SA (0.5 MeV) and ITER (1 MeV).

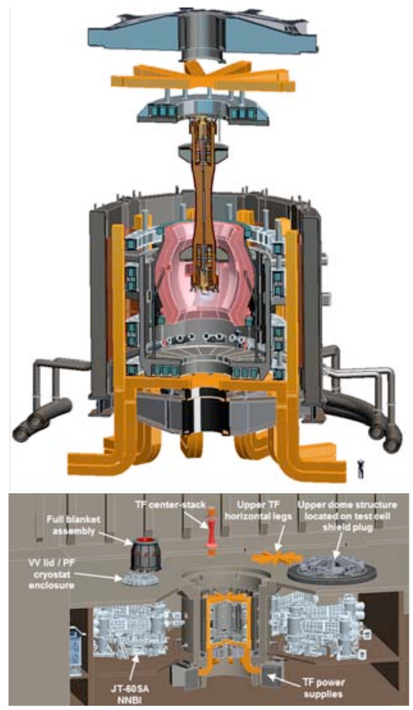

Figure 2 *– (Top) Cross-section of R_0 = 1.7m ST-FNSF showing vertical maintenance strategy, (bottom) example layout of test-cell and components during maintenance.*

Device configuration

With the above definition of the plasma equilibrium, PF and TF coil location and size, vacuum vessel layout, blanket and divertor geometry, and NBI tangency radii, 3D CAD models of the ST-FNSF have been generated. A key feature of the design is that the top superstructure, horizontal TF legs, and top PF coils and lid, can all be removed vertically. The TF center-stack and/or full blanket assembly or individual blanket modules can be removed independently. Divertor cooling and pumping and breeder/coolant manifolds exit the device diagonally from the bottom and side of the device, and copper leads for the TF coils and the associated power supplies are located underneath the machine in a lower test-cell chamber.

Radiation shielding and tritium breeding

Using the device configuration described above, the shielding effectiveness and tritium breeding potential have been analyzed with sophisticated 3-D neutronics codes. In particular, the 3-D CAD models have been coupled with MCNP using the University of Wisconsin DAGMC code [15] to accurately represent the entire torus. No approximations have been utilized in this analysis, and many configuration details are retained. Two ST devices (R_0 = 1 m and 1.7 m) have been analyzed for shielding and TBR. Both configurations provide 1 MW/m^2 surface-average neutron wall loading. For both sizes the assumed plant lifetime is ~20 years with an availability ranging from 10-50% with an average value of 30% equivalent to 6 full power years (FPY) of operation.

Assuming MgO insulation and Cu conductors for both the divertor PF coils at ends of the centerstack and also the most inboard of the top and bottom divertor region PF coils, the neutron dose is well below (by an order of magnitude) the present best estimate of the allowable limit of 10^{11} Gy [16]. This shielding margin is also adequate to shield the divertor PF coils in the smaller R_0 = 1 m ST. The computed peak outboard dpa of 15.5 dpa / FPY implies 93 dpa total damage to the outboard first-wall for 6 FPY of operation.

This total dpa level is 9 times the current limit of 10 dpa for ferritic steel and calls for the development of more radiation resistant ferritic steel structures that can handle 100 dpa or more. Test Blanket Modules (TBMs) and Materials Testing Module (MTM) are incorporated at the outboard midplane in ST-FNSF and are subject to a fusion-relevant nuclear environment and will develop and test materials and components for fusion power production applications [17,18].

For the R_0 = 1.7 m device, the innermost segment of the outboard dual-coolant lead-lithium (DCLL) blanket provides a TBR of 0.81, while the outer-most segment provides 0.15 for a total outboard blanket TBR of 0.96. Thus, to achieve TBR > 1 even with no penetrations or ports, additional breeding regions are needed. A key advantage of the large strike-point radius divertor is the ability to breed in the top/bottom centerstack end regions which increases the total TBR to 1.03. The TBMs provide breeding nearly as efficiently as the DCLL base blanket with an overall TBR reduction of only 1% (0.25% per TBM). In contrast, the MTM does not provide breeding which leads to a TBR reduction of 2% per port. Each of the 4 NNBI ports is sized to support 20 MW of NBI power and the total TBR reduction from all 4 NNBI ports is 3%, i.e. an average of 0.75% per NNBI. Including all 4 TBMs, 1 MTM, and 4 NNBI ports results in an overall TBR of 0.97. It is highly desirable to demonstrate tritium self-sufficiency in an FNSF device, and the calculated TBR for the R_0 = 1.7 m ST-FNSF of 0.97 is very close to unity. Several ideas/options have been identified to further increase TBR to values above 1 including: additional breeding in the divertor PF coil shield region, having a smaller opening to the divertor to reduce neutron leakage, and additional optimization of the outboard blanket thickness and cooling. It is expected that some combination of these options will enable achievement of TBR ≥ 1 at the R_0 = 1.7 m size.

The TBR for the R_0 = 1 m configuration is found to be 0.88 which is far enough below 1 that even if similar options to increase TBR are exploited, the TBR will very likely still be below 1. Despite this (expected) inability to achieve TBR ≥ 1 in the relatively small R_0 = 1 m device, TBR of 0.88 is still very substantial and would reduce the external supply of T by over a factor of 8 relative to not breeding any tritium.

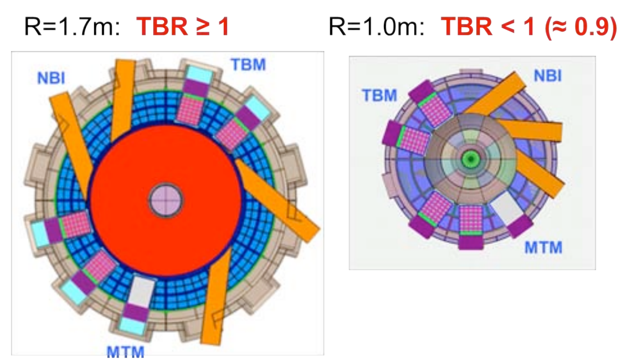

Figure 3 *– Side-by-side comparison of mid-plane sections of R_0=1.7m and 1m ST-FNSF devices showing TBR and TBM, MTM, and NBI ports.*

For the R_0=1 m device it will be necessary to purchase ~0.4-0.55 kg of T/FPY from outside sources at a cost of \$30-100k/g of T, implying a total cost of \$12-55M/FPY. Since the expected average duty factor is 0.3, the estimated annual average cost for T is \$4-17M per year which is likely an acceptable operating cost for a major nuclear device and associated program. However, there is uncertainty in relying on external sources to supply T fuel (~3 kg over 6 FPY) for such a program. Future work could assess such size/cost trade-offs in more detail.

References

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INTERNATIONAL ACTIVITIES

The Search for Compact Fusion Energy, Alan Sykes, Tokamak Energy Ltd, UK.

When Thompson and Blackman at Imperial College patented their Fusion Reactor [1] in 1946, they assumed classical confinement, and fusion using deuterium appeared relatively straightforward in a small device – indeed the potential appeared so great that the subject was classified for security purposes. Early ‘pinch’ experiments in pyrex toroids showed major instabilities on a rapid timescale (Cousins and Ware at Aldermaston, Fig. 1) but these could be mitigated by the use of a conducting shell; and in 1958 British scientists announced that fusion had been achieved in the ZETA device, and newspapers reported that electricity would be virtually free in 20 years: a triumph that excited the author and persuaded him to pursue a career in fusion research!

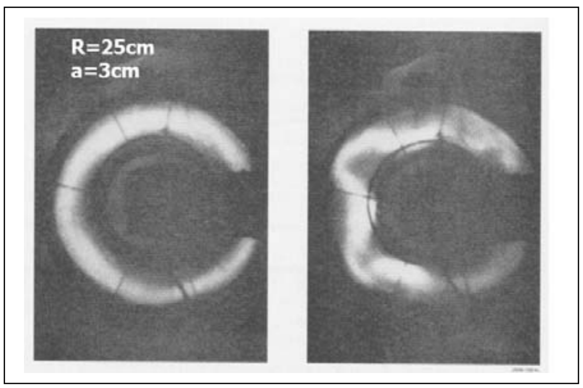

Fig. 1: Gross kink instability rises in 20 μsec.

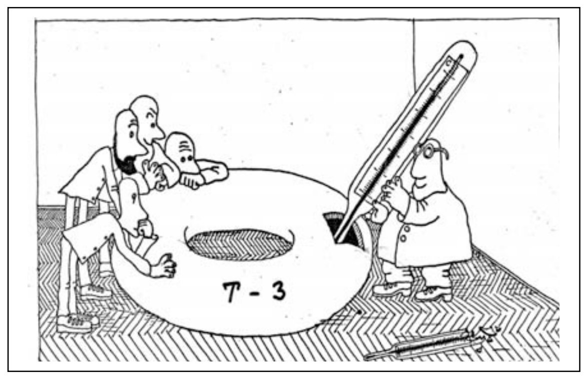

Fig. 2: Culham scientists at the Kurchatov (as seen by Kadomtsev)

Alas, the neutrons produced were not of thermonuclear origin; energy confinement was several orders of magnitude lower than expected; and it became obvious fusion energy was far away. At the famous Geneva ‘Atoms for Peace’ meeting in 1958, the subject was declassified; it became known that the Russian team at the Kurchatov Laboratory had added a large toroidal field to the pinch and greatly improved stability and energy confinement – the latter proved by a team of British scientists from Culham Laboratory, led by Robinson and Peacock, who measured very high plasma temperatures in the T-3 ‘tokamak’ (Fig. 2).

Magnetic confinement flourished with tokamaks of ever increasing size, advancing (Fig. 3) towards the goal of an ignited plasma, where energy produced from D-T fusion is sufficient to maintain the fusion process (the original concept of D-D fusion, although highly desirable, requires much higher temperatures).

Major instabilities can be largely avoided by choice of operating parameters; however underlying small scale microturbulence is still not fully understood, and indeed energy confinement time is represented by empirical scalings derived from many experiments.

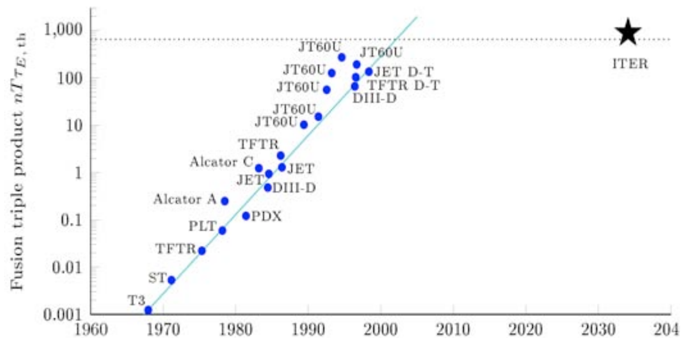

Fig. 3. 'Moore's Law' applied to Tokamaks.

The Problem with Size

For almost four decades progress towards ignition followed a similar path to the Moore's Law predicted and observed for integrated circuit performance; however, whereas Moore's law has continued unabated for microchips, there is a dramatic flattening of fusion progress as shown in Fig. 3. This can be explained by the huge size of recent tokamak experiments; they take decades to build, require international collaboration on funding; and they also consume a large proportion of the total resources allocated to fusion research. The growth in size arises partly from the perceived need for gigawatt level output; the 'triple product' nTtau of density (n), temperature (T), and energy confinement time (tau) has to exceed a certain critical value for sufficient energy gain to occur; but n and tau increase with size – and so massive devices seemed inevitable, leading to ITER.

ITER is presently under construction in Cadarache in southern France; the decision to proceed as a world experiment followed a meeting of Reagan and Gorbachev in 1986 – but initial operation is not now expected until the mid 2020's, with fusion D-T plasmas several years later. After ITER, an even larger device, DEMO, is planned to demonstrate electricity production. Can fusion be made to work on a smaller, faster scale?

Compact Fusion

A whole series of compact confinement devices were studied in the early decades of fusion research, and in recent years several of these ideas have re-emerged from several different teams; for example, General Fusion in Canada (fast adiabatic compression of compact toroids); Tri-Alpha in California (field reversed configuration); and very recently, a new development from the Spheromak team at the University of Washington [2], and the recently announced Lockheed 'skunkworks' project which uses a mix of ideas [3]. In each case, it is believed that present results fall far short of the necessary triple product; but one of these schemes may just work, and the reward for success is potentially huge.

Two groups however have not discarded the tokamak, which has emerged as the clear winner in terms of achieving high nTtau, as a potential device for compact fusion. These are the MIT team lead by Prof. Dennis Whyte, and Tokamak Energy Ltd in the UK, which originates from the Spherical Tokamak group at CCFE Culham Laboratory. Both realise that the main problem is the huge size of a tokamak reactor.

Several features, not apparent in 1986, may help reduce the size of the tokamak. These include the discovery of high temperature superconductors in 1987, the advent of the 'Spherical' tokamak (announced by Peng & Strickler in the US in 1986, and developed on START at Culham in the 1990's); the realisation that a series of low power fusion modules may be more efficient (certainly capable of much more rapid development) than gigawatt size devices; and a re-interpretation of the ITER databases.

The Compact Tokamak Approach

After 60 years of development of the tokamak, it is now known that n, T and tau of the triple product are not independent entities; they are constrained by various operational limits on density, efficiency β (where β is the ratio of plasma pressure to magnetic field pressure), and magneto-hydro-dynamic stability. It has been shown (e.g. [4]) that under fusion conditions, fusion power:

$$P_{fus} \sim \beta^2 B_t^4 V \qquad \qquad \text{…………………(1)}$$

where V is volume – subject to engineering constraints on wall loading. And of course for any device to be viable and produce net power, the energy gain Q_{fus} (fusion power out / power into plasma) must be high enough; indeed it must exceed ~9 as the efficiencies of both electricity extraction from heat, and of current drive and plasma heating, are around 1:3.

A significant advance has recently been made by Costley, Hugill & Buxton [5]. By reinterpreting the ITER confinement scalings and with evaluations by means of a specially developed system code they found that, at commonly used fractions of the density, beta, and safety-factor limits, the energy gain Q_{fus} has only a weak dependence on plasma size, and is mainly proportional to H^2 x P_{fus}, where H is the confinement improvement over the ITER98pby2 scaling:

$$Q_{fus} \sim H^2 \times P_{fus} \qquad \qquad \text{……………………(2)}$$

This remarkable result is confirmed by theoretical analysis [5].

This implies that a small scale fusion reactor may be a real possibility - a huge advantage! Fusion could be available in small units, ideal for rapid and (relatively) inexpensive development – akin to the rapid development of fission. For a small device, P_{fus} is limited (via wall loading) by the surface area; the available H-factor then determines the energy gain, Q_{fus}. As a consequence, if high H can be achieved, small devices can potentially have the same fusion gain as larger devices. If the achievable H-factor is not high enough, P_{fus} must be raised until Q_{fus} exceeds about 10, and the increased wall loading will require an increase in device size – however almost certainly far smaller than ITER. We note that we have returned to realise the essential role that confinement plays.

An additional benefit highlighted in the Costley et al paper [5] is the probability, seen from special parameter scans on JET and DIII-D, that the ITER scalings for beta, which imply that high beta devices have reduced confinement, are inaccurate. Instead, the scalings should probably be independent of beta: this result gives a further boost to confinement in Spherical Tokamaks.

Sorbom et al. at the Massachusetts Institute of Technology (MIT) propose ARC [6], a JET-sized tokamak of volume ~140 m^3 and conventional aspect ratio (Fig. 4-a). Consistent with eq. (1) they obtain P_{fus} ~ 525 MW by supplying the high field of 9 T made possible by the use of ReBCO HTS magnets at a neutron wall load of 2.5 MW/m^2. FLiBe molten salt can be used both as neutron shield and tritium breeder. High energy gain Q_{fus} depends on energy confinement, which remains to be determined; but comparison with the I-mode confinement observed on the high field C-mod tokamak appears promising. A tritium breeding ratio of ~1.1 is provided.

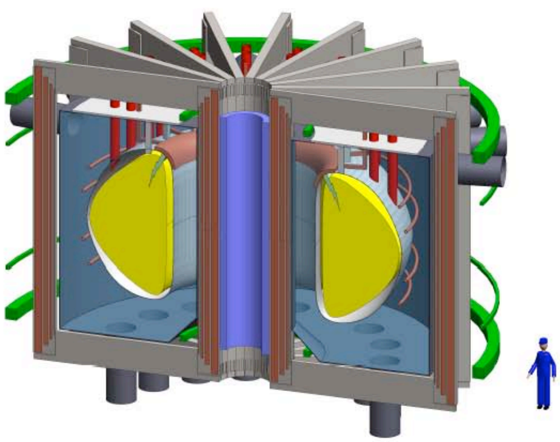

Fig. 4-a. ARC concept (MIT).

Fig 4-b: HTS testing on ST25(HTS).

The Tokamak Energy (TE) team also use the remarkable high-field features offered by high temperature superconducting magnets; the restricted centre column space of an ST limits field to 3-4 T but by virtue of the high β available in an ST (see eq. (1)) they propose a prototype pilot plant of volume ~40 m^3, with fusion power of 185 MW at a wall loading of 1.8 MW/m^2.

The Importance of Confinement Time

The work of Costley et al. shows that energy confinement (or more precisely, 'H'– the H-factor increase over ITER98pby2 scaling) is key to obtaining the high gain Qfus essential for producing net power. The ARC design relies on I-mode enhanced confinement, associated with low shear. The TE approach considers two methods of obtaining high confinement: high field combined with the high shear of the ST, and the lithium wall concept.

It is predicted theoretically, with some supporting evidence from the MAST and NSTX spherical tokamaks, that the combination of high magnetic shear and high magnetic field in a Spherical Tokamak may provide stabilisation of some forms of the microturbulence that bedevils tokamaks, leading to a higher H-factor over the ITER prediction. To test this important prediction, Tokamak Energy propose to develop a high field ST denoted ST40, obtaining 2-3 Tesla (STs to date have been low field devices <1 T).

An alternative route to high H plasmas may be lithiumisation [7,8], advocated by Zakharov and Majeski at Princeton Plasma Physics Laboratory (PPPL), and being evaluated on the Lithium Torus (LTX) and NSTX experiments. Small amounts of lithium are effective in gettering impurities, providing a useful increase in confinement; larger amounts can lead to 'lithium walls' if the walls are hot, and this (if it can be achieved in practice) reduces recycling and thus stops the cooling of the plasma edge – the increased edge temperature then producing excellent confinement.

Modelling for the TE design of an R=1.35 m prototype pilot plant described in [5] reveals the importance of the H-factor (Fig. 5): using a value of H=1.8 (which has been obtained in the MAST and NSTX STs) we find that Q_{fus}=5 is predicted. However if H=2.1 can be achieved (as in the recent lithium experiments on DIII-D [7]) Q_{fus} ~10 appears possible.

High Temperature Superconducting (HTS) magnets

In a commercial reactor, it will be essential to use superconducting magnets as otherwise too big a fraction of the generated power will be spent on resistive losses. Conventional superconductors (as used in ITER) generally require cooling below 4 K. ReBCO HTS becomes superconducting below ~90 K; however performance greatly improves at lower temperatures and an optimum is generally around 20-30 K. These ReBCO (where Re=Yttrium or Gadolinium) 2nd generation high temperature superconductors were discovered in the late 1980's and have very promising properties, being able to carry high currents at very high magnetic fields. The tapes require protection from neutron bombardment, a particular problem in an ST because the space for shielding the centre column is limited. A compromise must be made between shield thickness and device lifetime.

It is very useful to have a step-by-step approach to a commercial reactor, and there are interesting possibilities for STs with HTS magnets at say 20 K, in that a small R~60cm device with 10 cm of tungsten carbide shielding can operate in D-T until the HTS warms up to reach 40 K. MCNP modelling [10] suggests that this should give several seconds of pulse, sufficient to demonstrate fusion. We also note that because D-D fusion produces far less neutrons and of lower energy, the 10 cm shield would allow long pulses in a D-D device; and D-D performance is relatively easy to organise, cheap to fuel and also provides a good indicator of potential D-T performance.

Research Programme at Tokamak Energy (www.tokamakenergy.co.uk)

A sequence of experiments are underway or in planning to investigate key aspects of the compact tokamak fusion concept. Tokamak Energy is operating ST25(HTS), the world's first all-HTS tokamak (Fig. 4-b); at present (late 2014) we are preparing to convert the cooling system from helium gas (involving high consumption of expensive helium) to cooling primarily by closed-circuit cold head units. Experiments will investigate HTS performance under tokamak conditions. In parallel with this, we are building ST40, a larger ST (Fig. 6) to investigate the key question of energy confinement time in a high field ST of ~3 T. This will use copper magnets, since copper is at present much cheaper and more readily available than HTS.

There are also further plans to build a high-field magnet using HTS; to test lithiumisation in an existing small tokamak; and to test the concept that a high-field HTS magnet ST can be operated in pulsed mode, as described in the previous section.

Based on results from these experiments, it is proposed to build then a prototype pilot plant using D-T and producing ~185 MW of fusion power, of size R~1.35m and aspect ratio ~1.8 using HTS magnets. The precise size of this device will be influenced by our on-going research programme. Preliminary design work has been done for TE by Menard and Brown at PPPL (Fig. 7). Performance is crucially dependent upon H-factor; if H=2.1 is assumed, Q_{fus} ~10 is predicted. Neutronics modelling using MCNP [10] indicates that a tungsten carbide shield of 32 cm in this device would limit heating in the central HTS magnet to ~50 kW, requiring ~3 MW of cooling cryogenic power to run steady-state. Remarkably, moderate neutron bombardment improves performance by flux pinning if the tape is below ~60 K, this result holding at least until $2.3 \times 10^{22}\ m^{-2}$ [11].

Eventual tape damage will limit continuous operation of the magnet; assuming a limit of $3 \times 10^{22}\ m^{-2}$ would enable continuous operation of at least a few months. Tests of higher radiation on the HTS tape are awaited.

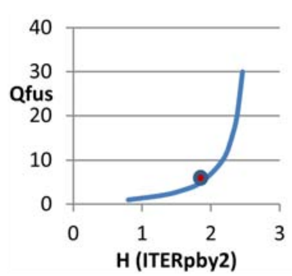

Fig. 5. Sensitivity of Q_{fus} to H-factor.

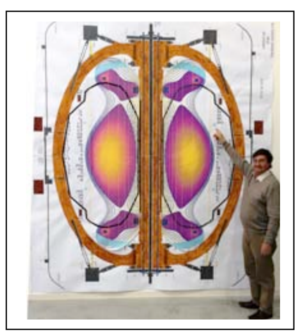

Fig. 6. Outline of proposed ST40.

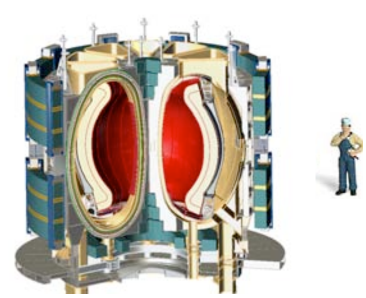

Fig. 7. Preliminary design of ST135 by Menard & Brown (PPPL).

Private Investment in Fusion

The energy market is vast and investors immediately see the potential of Compact Fusion. The scale of ITER or its successor DEMOs is beyond the resources of individual investors – even companies. Compact sustained fusion could be more difficult than we expect by extrapolation from present data – but it might be easier – for example there are good reasons to expect that high field spherical tokamaks will be more stable than present designs. The benefits to investors are that Compact Fusion can provide rapid results, with an iterative approach to success.

Summary

Compact Fusion is becoming increasingly popular especially as concern grows over the high cost and long timescales of achieving commercial fusion with the very large machines such as ITER and DEMO. A variety of confinement schemes are under investigation, mostly funded privately. Recent innovations and discoveries suggest that the tokamak route may be possible on a much smaller scale than that implied by the JET-ITER-DEMO family, and therefore can be developed rapidly, benefitting from the past 60 years of tokamak research, and attracting private investment.

Acknowledgements

The author is indebted to colleagues at Tokamak Energy Ltd, and to helpful discussions with Dennis Whyte (MIT), Dick Majeski, Jon Menard and Tom Brown (PPPL).

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

The Fall 2014 ITER governance meetings (Management Advisory Committee, Science and Technology Committee, and Council) are celebrating the completion of the B2 basement floor and the arrival of the first "plant" systems to the ITER site, and are reviewing progress and refining plans on the development of an updated resource-loaded schedule (to be presented to the Council in June 2015) and on actions responding to the 2013 Management Assessment.

In July, the French regulator authorized the pouring of the 1.5-meter-thick floor of the "inner building" which is supported on the 493 seismic isolators to reduce the impacts of earthquakes on the ITER tokamak itself, and which itself supports the cryostat which houses the ITER tokamak. Within hours, the European Domestic Agency starting pouring and completed that floor in about a month – in a shorter duration than originally planned. The reinforcing steel for the walls is now being installed, and the Tokamak building is taking shape.

In September, the US domestic agency (USDA, "US ITER") delivered the first plant components, steady-state electric system equipment, which is now housed in the Poloidal Field Coil Building awaiting installation by the European Domestic Agency. Five 400 kV transformers are being completed by the USDA and will be shipped in the next few months. In the winter and spring, the USDA will be shipping 5 large nuclear-qualified drain tanks. The transformers and the drain tanks will be the first large, heavy loads to be carried by the Logistics Service Provider using a complex many-wheeled carrier on the ITER itinerary (cf., http://www.iter.org/transport).

Addressing a key barrier for ITER, a new entity, called the ITER Chief Executives Team has been created to improve decision-making; consisting of the Director General, the Director of the ITER Project, and the 7 Domestic Agency heads, this entity includes the managers for all the ITER resources; this forum aims at integrating the visions of the senior managers of the project-execution team and developing approaches that achieve the ITER mission within the constraints of the ITER team.

Planning for assembly, installation and commissioning is underway, providing a framework for the integrated schedule. Several workshops and a new-dedicated team are identifying approaches to improving the processes and accelerating the schedule.

In each of the seven domestic agencies, factories are being established and components are being fabricated. In the USDA, a magnet development facility is being completed at General Atomics (GA) near La Jolla, CA, for the fabrication of the seven Central Solenoid modules. These magnets use Nb_3Sn conductor provided by the Japanese Domestic Agency. At GA, the spools of conductor are wound into a spiral pancake, heat-treated to react the many adjacent Nb and Sn strands into Nb_3Sn, turn-insulated, and then vacuum-impregnated. Also in the US, the US-share of the strand for the toroidal field magnets has been completed by Luvata in Connecticut and Oxford Superconductor in New Jersey. Cable is being prepared at New England Wire Technology in New Hampshire. And the cable is being jacketed at High Performance Magnetics in Florida. Similar activities in six of the ITER domestic agencies will fabricate the stainless-steel-jacketed conductor for fabrication into the TF coils by the European and Japanese domestic agencies.

For further information about the international project, please visit the ITER website www.iter.org and its newsletter (http://www.iter.org/whatsnew). For information on the US project, see www.usiter.org.

FUSION CONFERENCES

Summary of the 21st ANS Topical Meeting on the Technology of Fusion Energy, Brian D. Wirth, University of Tennessee, Knoxville, TN.

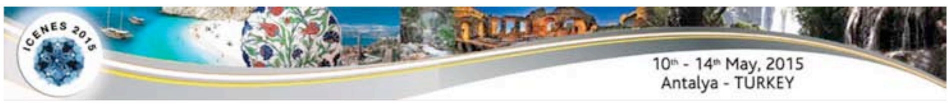
The 21st ANS Topical Meeting on the Technology of Fusion Energy (TOFE) was held on November 10-13, 2014 and embedded in the ANS Winter meeting at the Disneyland Hotel and Resort in Anaheim, California. I was very pleased with the quality of the technical program, which encompassed 3 ½ days, with a total of 166 presentations. Plenary oral sessions were held on each morning of the meeting on November 11-13, with very interesting and informative updates in the first plenary sesssion on the plans and status of the Chinese CFETR, the Korean K-DEMO, and the National Ignition Facility at Lawrence Livermore National Laboratory. On the second day, the plenary focused on the status of ITER, and a European analysis of the technological roadmap to DEMO. The plenary session on the final day of the meeting focused on materials science research needs as well as the U.S. Department of Energy Office of Fusion Energy sciences perspective on materials technology development, in addition to an overview of fusion engineering in Japan.

While I have not received attendance numbers from ANS, I felt that the meeting was well attended and well received by the community. Unfortunately, DOE travel restrictions combined with difficulties in obtaining visas by some Asian participants resulted in about 22 cancellations during the meeting. But, again, the technical quality of the oral presentations and the 89 posters presented in two different poster sessions was quite high, and stimulated lots of discussion. I would like to express my gratitude and thanks to the following members of the Technical Program Committee for their efforts to ensure a successful meeting, namely: Dr. Rajesh Maingi (PPPL), Dr. Vincent Chan (General Atomics), Dr. Arnold Lumsdaine (ORNL), Dr. David Hill (LLNL), Dr. Laila El-Guebaly (University of Wisconsin), and Dr. Chuck Kessel (PPPL), in addition to all of those whom contributed.

Dr. Susana Reyes, the chair of the Fusion Energy Division, handed out the Division awards at the plenary session on Wednesday November 12. It was also announced that the next TOFE would be organized by the Princeton Plasma Physics Laboratory, and will be a stand-alone meeting in the August 2016 timeframe. Finally, the proceedings will be published as a special issue of the Fusion Science and Technology journal, with a manuscript submission deadline of November 30, 2014. I would like to express my thanks and gratitude to the editor, Dr. Nermin Ucken (ORNL), for her dedicated efforts in ensuring that the resulting publication is of high quality and published in a timely manner.

Thanks again to all, whom participated in the meeting, for helping make it a success.

ICENES-2015 Call for Papers, Sümer Şahin, ATILIM University, Ankara, Turkey.



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Dear Colleagues and Friends,

It is my pleasure to invite you to attend the 17th International Conference on Emerging Nuclear Energy Systems (ICENES2015), which will take place in 10-14 May 2015 inclusive, in Antalya, Türkiye.

This conference will consist of an informative and comprehensive scientific program, featuring oral and poster presentations and a commercial exhibition. This will provide a unique opportunity to become familiar with the most recent advancements in innovative nuclear energy systems, as well as looking at "bold" and "unthinkable" ideas on a sound scientific-technical basis. The forum will also be open to intellectual debate leading to practical applications around innovative non-nuclear technologies, such as hydrogen energy, solar energy, deep space exploration and others.

Earlier conferences were held in Graz (Austria), Lausanne (Switzerland), Helsinki (Finland), Madrid (Spain), Karlsruhe (Germany), Monterey (USA), Chiba (Japan), Obninsk (Russia), Tel-Aviv (Israel), Petten (The Netherlands), Albuquerque (USA), Brussels (Belgium) and İstanbul (Türkiye), Ericeira (Portugal), San Francisco (U. S. A.), Madrid (Spain). It has been the tradition of the ICENES conference series to select conference venues with unique features. For 2015, one of the most beautiful and most attractive touristical regions of Türkiye will host ICENES2015, where see and mountains embrace each other.

We feel sure that you will enjoy the meeting facilities at the congress venue. You will enjoy our assistance to ensure your stay with us is fascinating, rewarding and memorable. I am confident you will all be delighted with your stay in Antalya where you will have the opportunity to experience the renowned Turkish hospitality.

The conference web address is: http://www.icenes2015.org
A selection of ICENES2015 papers will be published in special editions of the "International Journal of Hydrogen Energy".
http://www.sciencedirect.com/science/journal/03603199
and in the "International Journal of Fusion Energy"
http://www.springer.com/physics/particle+and+nuclear+physics/journal/10894

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RECENTLY PUBLISHED FUSION BOOKS

Jeffrey Freidberg, **Ideal MHD**
http://www.cambridge.org/us/academic/subjects/physics/plasma-physics-and-fusion-physics/ideal-mhd.

Laila El-Guebaly and **Lee Cadwallader**, "**Perspectives of Managing Fusion Radioactive Materials: Technical Challenges, Environmental Impact, and US Policy**." Chapter in book: **Radioactive Waste: Sources, Management and Health Risks**. Susanna Fenton Editor. NOVA Science Publishers, Inc.: Hauppauge, New York, USA. ISBN: 978-1-63321-731-7 (2014).
https://www.novapublishers.com/catalog/product_info.php?products_id=51057

CALENDAR OF UPCOMING CONFERENCES ON FUSION TECHNOLOGY

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35th Fusion Power Associates Annual Meeting and Symposium: Fusion Energy: Recent Progress and The Road Ahead
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http://fusionpower.org

2015:

39th International Symposium on Advanced Ceramics and Composites (for Sustainable Nuclear Energy and Fusion Energy)
January 25-30, 2015, Daytona Beach, Florida, USA
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http://ece.unm.edu/ppcsofe15/

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June 7-11, 2015, San Antonio, TX, USA
http://www.ans.org/

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http://icm12.com/programme/symposia/#materials-for-fission-and-fusion-h

12th International Symposium on Fusion Nuclear Technology - ISFNT
September 14 – 18, 2015, Jeju Island, S. Korea
http://www.isfnt-12.org/sub01

17th International Conference on Fusion Reactor Materials – ICFRM-17
October 11-16, 2015, Aachen, Germany
http://www.fz-juelich.de/conferences/ICFRM2015/EN/Home/home_node.html

ANS Winter Meeting
November 8-12, 2015, Washington, DC, USA
http://www.ans.org/

57th American Physical Society - Division of Plasma Physics (APS-DPP) meeting
November 16-20, 2015, Savannah, GA, USA
http://www.apsdpp.org

2016:

ANS Annual Meeting
June 12-16, 2016, New Orleans, LA, USA
http://www.ans.org/

11th International Conference on Tritium Science and Technology – Tritium-2016
April 17-22, 2016, Charleston, S. Carolina, USA

ANS 22d Topical Meeting on the Technology of Fusion Energy – TOFE-2016
August 22-25, 2016, Philadelphia, PA, USA
http://www.ans.org/

29th Symposium on Fusion Technology – SOFT-2016
September 5-9, 2016, Prague, Czech Republic
http://www.SOFT2016.EU

ANS Winter Meeting
November 6-10, 2016, Las Vegas, NV, USA
http://www.ans.org/