American Nuclear Society
Fusion Energy Division
December 2015 Newsletter

Letter from the FED Chair, Arnold Lumsdaine, Oak Ridge National Laboratory, Oak Ridge, TN.

The "Letter from the Chair" this month is a bit of a misnomer. The Fusion Energy Division (FED) Chair is still in the capable hands of Susana Reyes, but has been on maternity leave the past few months. So, as acting Chair, I will do my best to pass on the news from the Division and maintain the high standard that Susana has set.

The ANS Winter Meeting & Expo was held on November 8-12, 2015, in Washington DC, with the theme, "Nuclear: The Foundation of Sensible Policy for Energy, Economy, and the Environment." Our Division sponsored one session (with seven papers), and co-sponsored two other sessions – one with the Reactor Physics and the Accelerator Applications Divisions, and one with the Radiation Protection and Shielding Division. This is our most substantial participation in a national meeting for as long as I have been involved in the society (with the exception of embedded topical meetings). The FED primary session was well attended, had quality presentations, and led to some interesting interactions. Hopefully, quality sessions from the fusion community will be a common occurrence in National Meetings for a long time to come.

Two other items of interest: First, as the FED treasury has surpassed the required funds to establish a scholarship, we have begun the process of getting the scholarship in place. Leigh Winfrey (University of Florida) has agreed to chair the scholarship committee, and along with Ahmad Ibrahim (ORNL) and Susana Reyes (LLNL) have put a proposal together that was submitted to the ANS Scholarship Policy and Coordination Committee. The committee cannot approve new scholarships until their June meeting, but the proposal was well received, and we hope to have the first scholarship awarded for the Fall 2017. Second, the Division has a newly designed web site – http://fed.ans.org. The site was re-designed as a response to an ANS-wide effort to use a common template for all Division pages. Along with the rollout of the new site, we are also rolling out a new Webmaster! I want to extend a heartfelt thanks to Mark Tillack (UCSD), who has served as Webmaster for many years. Mark's service to FED extends well beyond this activity, and I speak for the entire Division in expressing our appreciation for his years of service. He is passing the baton to Kelsey Tresemer (PPPL) who has already been involved in working with Mark to port content to the new platform, and who has some great ideas for making the content more dynamic. Many thanks to Kelsey for taking on this role.

Speaking of topical meetings – mark your calendars and plan to attend the 22nd Technology of Fusion Energy (TOFE) meeting, (organized by Princeton Plasma Physics Laboratory), in Philadelphia, PA on August 22-25, 2016 (http://tofe2016.ans.org). Abstracts are due February 15, 2016. FED is also sponsoring the Tritium 2016 meeting in Charleston, SC in April 17-22, 2016 (http://tritium2016.org).

Susana will be back to write the next Letter from the Chair in June. In the meantime, I wish you a happy holiday season, and thank you for your continued support of the ANS Fusion Energy Division.

Slate of Candidates for 2016 FED Election, Minami Yoda, Georgia Institute of Technology, Atlanta, GA.

ANS HQ will send an e-mail announcement about E-ballots to all the members of the FED at the beginning of 2016. Please remember to E-vote by April, or if you do not have E-mail, return your ballot by postal mail. The outcome of the election will be announced before the next FED Executive Committee meeting in June 2016. 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 of the members of the Executive Committee.

The current ExCo officers will be completing their 2-year terms in June 2016, as will the following three members of the Executive Committee: Jean-Paul Allain (UIUC), Kevin Kramer (PPPL), and Kelsey Tresemer (PPPL).

We have an excellent set of fusion researchers running for the officer positions, as well as the 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 for the coming election, which was approved by the current Executive Committee at its recent meeting on November 8, 2015, is:

Vice Chair:	Keith Rule (PPPL)
Secretary/Treasurer:	Kelsey Tresemer (PPPL)
ExCo seats:	Nicole Allen (PPPL)
	Lauren Garrison (ORNL)
	Leigh Winfrey (University of Florida).

2016 ANS-FED Awards – Call for Nominations

The Honors and Awards Committee of Fusion Energy Division of American Nuclear Society [ANS-FED] is seeking nominations for two ANS-FED Awards:

- **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.
- **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 (purpose, criteria, and procedure) and past recipients can be found at http://fed.ans.org/awards

Note that the nominees will only be considered for the particular award for which they are nominated.

- **Nomination deadline is: March 1, 2016**

The awards will be presented at the 22nd ANS Topical Meeting on the Technology of Fusion Energy (22nd TOFE), in Philadelphia, PA, August 22-25, 2016.

Nominations can be made by individuals and submitted anytime to the ANS-FED Honors and Awards Chair electronically at uckanna@ornl.gov.

Nomination package must include:

1. The nomination letter including a description of the exemplary achievements and the recommended citation to appear on the award plaque.
2. Additional letters supporting the nomination (a minimum of three and a maximum of five, including the nominator letter).
3. Nominee's CV and publication list.

Incomplete submissions will not be considered. Complete details are available at http://fed.ans.org/awards

Please send complete nomination packages electronically to:

Nermin A. Uckan
ANS-FED Honors & Awards Chair
uckanna@ornl.gov

Nominators of 2014 nominees are encouraged to update their 2014 nomination packages and re-submit electronically.

Outstanding Student paper award will also be given at the 22nd TOFE meeting through a separate process under the auspices of 22nd TOFE. Details will be forthcoming in conjunction with the meeting announcement.

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

FPA Awards

The Fusion Power Associates (FPA) Board of Directors has selected the recipients of its 2015 Distinguished Career, Leadership, and Excellence in Fusion Engineering Awards. All awards including a Special Award will be presented this year at the FPA 36th Annual Meeting and Symposium, December 16-17, 2015 in Washington, DC.

- The 2015 Distinguished Career Award will be presented to Prof. **Gerald L. Kulcinski** (University of Wisconsin). Prof. **Kulcinski** is cited for his "many years of dedication to advancing the prospects for fusion power" and noting especially "your decades of outstanding career contributions as a scientist and educator in the areas of both magnetic and inertial confinement fusion."

- The 2015 Leadership Award will be presented to Prof. **Hiroshi Azechi** (Osaka University). Prof. **Azechi** is cited for his "many scientific contributions and the managerial leadership you are providing to national and international research efforts on inertial confinement fusion and high energy density plasma physics" and noting especially "your leadership of the scientific program at the Institute of Laser Engineering, Osaka University, for both high energy density physics and for the eventual achievement of ignition, leading towards a commercial fusion power source."
- The 2015 Excellence in Fusion Engineering Awards will be presented to Dr. **Susana Reyes** (Lawrence Livermore National Laboratory) and to **Francesco Volpe** (Columbia University). Dr. **Reyes** is cited for "the leadership you have been providing to both magnetic and inertial fusion efforts in many areas, including safety and licensing, tritium systems, and power plant designs" and especially noting "the important roles you played in the National Academy's panel on Prospects for Inertial Confinement Fusion Energy Systems and as Chair of the American Nuclear Society Fusion Energy Division." Dr. **Volpe** is cited for "the contributions you have been providing to fusion science and engineering in many areas, including MHD stability and RF heating" and noting especially "the leadership role you are playing in innovations for stellarator and tokamak-torsatron hybrid configurations."
- A Special Award will be presented to Dr. **Wayne Meier** (Lawrence Livermore National Laboratory) "in recognition of your many contributions to advancing the science, technology, and integrated assessments of potential fusion power plants, and for your broad support of the fusion community in leadership positions within the ANS and IEEE, as well as your role on journal editorial boards."

IEEE Awards

The Institute of Electrical and Electronics Engineers (IEEE) has named Dr. **Chuck Kessel** (PPPL) the recipient of the 2015 Fusion Technology Award. The honor, from the IEEE Nuclear and Plasma Sciences Society, recognizes outstanding contributions to fusion engineering and technology.

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, 2014 to September 30, 2015, FS&T received a total of 251 manuscripts. Papers received for 2015 Target Fabrication Meeting (TFM2015) special issue are not included in this count.

Of the 251 manuscripts, 79 were from North America, 43 from Europe (including Russia), 115 from Asia, and 14 from others, with the following breakdown: 156 have been accepted, 71 have been rejected/withdrawn, and 24 are under review/revision.

The following dedicated issues were published during the period 10/1/2014 to 9/30/2015:

- ARIES-ACT Power Plant Study – FS&T Jan. 2015
- Selected paper from Tritium 2013– FS&T Mar. & Apr. 2015
- Selected paper from OS2014 – FS&T Jul. 2015
- Selected papers from TOFE2014 – FS&T Sept. & Oct. 2015.

The following issues are scheduled/planned for 2016 and 2017

- NIF-NIC Special Issue – FS&T Jan./Feb. 2016
- Target Fabrication 2015 special issue – FS&T (mid 2016)
- 1st IAEA-TM on Fusion Data Processing, Validation, Analysis – FS&T (mid 2016)
- Selected papers from Tritium 2016 – FS&T (2017)
- Selected papers from TOFE-2016 – FS&T (2017).

New with FS&T: 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 introduced 'first-look' article-based publishing in 2015 with posting of 'preprint' copies ahead of formal print issue: see http://www.ans.org/pubs/journals/fst/firstlook/. These pre-publication articles are peer reviewed, copyedited, and proofread and can be cited using DOI.

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

Neutron Sources for Fusion Applications

Since the early 1970s, fusion researchers have been concerned about the effects of 14 MeV neutrons on components of D-T fuelled fusion devices. Each 14 MeV neutron will produce orders of magnitude more displacements per atom (dpa) and helium and hydrogen gaseous atoms than a fission neutron. It has been widely recognized that unless the safe operation of the fusion structural components in a 14 MeV neutron environment can be experimentally demonstrated, nuclear regulators will not allow the construction of commercial D-T fusion DEMO or power plant. For over 50 years, the materials community has been looking for an irradiation facility that can provide a fusion neutron spectrum to test fusion materials over a sufficiently large volume and can be built in a reasonable time before constructing a DEMO.
In the absence of such a 14 MeV neutron source, it is not possible to predict the fusion component performance and lifetimes into the anticipated high dpa (> 100 dpa) and He

production (> 1000 appm) regimes. A considerable body of irradiation effects data derived from fission reactors, and heavy ion and spallation neutron facilities which, combined with predictive modeling, indicates that significant changes in the mechanical behavior could occur at 20-30 dpa and 200-300 appm helium over the range of predicted operating temperatures for 14 MeV neutron exposures. However, such facilities, incapable of generating a fusion-specific He/dpa ratio of 10, were found not favored by the materials community. In the mid 1970s, the US proposed FMIT – a fusion relevant neutron source based on Li(d,xn) nuclear reactions [1]. In the early 1990s, the International Energy Agency (IEA) reviewed the proposed fusion irradiation facilities and concluded that the D-Li neutron source is the preferred concept. The International Fusion Materials Irradiation Facility (IFMIF) [2] has been the reference concept for a fusion relevant neutron source since the 1990s, offering 500 cm^3 of testing volume and 20-50 dpa/FPY. The recently designed EU DEMO suggests a lower dpa dose to the RAFM structure. This position stirred an interest in Europe to construct DONES [3] – a simplified version of IFMIF offering >300 cm^3 of testing volume and 10-20 dpa/FPY.

In the US, several reports recognized the IFMIF mission and the need to assess the potential for alternative facilities [4]. The 2009 ReNeW report [5] cited several fusion-relevant neutron sources as examples of options that need to be further evaluated and selected based on technical attractiveness and cost effectiveness. ReNeW also recognized the possibility for a Fusion Nuclear Science Facility (FNSF), but emphasized that bulk material property data from a fusion relevant neutron source would inform the design, construction and licensing of FNSF.

The following table compares several key parameters for the pre-DEMO neutron sources and/or facilities that have recently been proposed by China and the US. The radiation damage parameters are for RAFM alloys. Detailed description of HINEG, PNL, and FNSF are available in the following articles.

References

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[2] J. Knaster et al., “The Accomplishment of the Engineering Design Activities of IFMIF/EVEDA: The European-Japanese Project Towards a Li(d,xn) Fusion Relevant Neutron Source,” Nuclear Fusion (2015) 55 086003.

[3] A. Ibarra et al., “A Stepped Approach from IFMIF/EVEDA toward IFMIF,” Fusion Science and Technology 66, 252-259 (2014).

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[5] R. Hazeltine et al., “Research Needs for Magnetic Fusion Energy Sciences,” DOE Report (2009). http://science.energy.gov/~/media/fes/pdf/about/Magnetic_fusion_report_june_2009.pdf.

Neutron Sources	HINEG (China)	PNL (USA)	FNSF (USA)
Neutron Yield (n/s)	$10^{14} \sim 10^{15}$	10^{15} - 10^{16}	10^{27} - 10^{28}
Available Volume to irradiate sample(s)	>100 cm^3	1,300 cm^3	1 m x 1 m x 0.5 m
Achievable dpa/FPY	10 @ 2 cm^3, 2 @ ~30 cm^3, 1 @ ~70 cm^3	4-8 @ 150 cm^3, 1-2 @ 1,150 cm^3	15 @ outboard first wall
Cumulative peak dpa		160 @ 20 FPY (22 y)	126 @ 8.5 FPY (37 y)
He/dpa ratio	10	10	10
H/dpa ratio	40	40	40
Estimated Cost ($M)	$20M	$27M*	N/A
Expected Start of Construction	2013	2018	~2025
Expected Year of Operation	2018	2020	~2033

* Including $6M for development.
N/A means not available.

Status and Prospect of Neutron Sources for Fusion Applications in China,

Yican Wu, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, China.

Neutron sources are essential test platforms for the development of nuclear technology and nuclear safety. The majority of neutron sources for fusion applications employ accelerator-based D-T fusion neutron generators, fission reactors, and spallation neutron sources. Since the neutron energy spectra of fission reactors and spallation neutron sources are very much different from that of fusion, it is necessary to check the equivalency of fusion neutrons and fission/spallation neutrons in terms of the neutronics performance, irradiation effects on materials, etc. To conduct such tests, fusion neutron sources with high intensities are needed. This article focuses on the status and prospect of fusion neutron sources in China.

Operational Fusion Neutron Sources in China

In China, several fusion neutron generators were built and have been applied to fusion research, as shown in Table 1.

Table 1. Main Accelerator-based D-T Fusion Neutron Sources in China

Name	Neutron Yield (n/s)	Voltage (kV)	Beam on Target (mA)
CPNG-6	10^{11} (10^{10})*	550 (300)*	1 (30μA)*
ZF-300	3.3×10^{12}	300	1
PD-300	2×10^{11} (4×10^{9})*	300	2

* The values in brackets are data for the pulse mode.

CPNG-6 is a 600 keV neutron generator developed by China Institute of Atomic Energy in 2000[1]. There are two operational modes for CPNG-6: steady mode and pulse mode. The neutron yield of the steady mode can reach up to 10^{11}n/s. For the pulse mode, the width of the pulse is shorter than 1.5 ns and the frequency is about 1.5 MHz.

ZF-300, developed by the Lanzhou University in 1988, is a D-T neutron generator with a maximum neutron yield of 10^{12} n/s, using the large-area rotating target [2].

China Academy of Engineering Physics developed a series of neutron generators: PD-300, K400, and NS200. Among them, PD-300 is the most advanced one and achieved a maximum neutron yield of 2×10^{11} n/s in the steady mode and that of 4×10^{9} n/s in the pulse mode.

Experiments have been conducted for fusion applications, mainly focusing on the validation of neutronics analysis methods and nuclear data using the neutron generators mentioned above. For instance, the nuclear data of ^{7}Li, ^{9}Be, ^{27}Al, ^{56}Fe, etc. was validated [3,4], and the tritium breeding of $LiSiO_4$ induced by fast neutron was investigated [5,6]. However, the intensity of the current fusion neutron sources is quite low, and the accuracy and capability of performed experiments are limited. A higher intensity fusion neutron source becomes urgently needed for the development of both fusion nuclear technology and safety.

Development of High Intensity D-T Fusion Neutron Sources

The Institute of Nuclear Energy Safety Technology (INEST), Chinese Academy of Sciences (CAS) has launched the High Intensity fusion Neutron Generator (HINEG) project to develop an accelerator-based D-T fusion neutron generator with the neutron yield higher than 10^{14}-10^{15}n/s [7,8]. The HINEG project includes two phases. During the first phase (HINEG-I), a D-T fusion neutron generator is developed with both steady and for pulse modes. The maximum neutron yield of the steady beam mode can reach 10^{12} n/s for the steady state mode, while the full width at half maximum of neutron pulse is < 1.5 ns for the pulse mode. At present, all components have been developed. The installation of HINEG-I has been finished (see Figure. 1) and is commissioning in December 2015.

HINEG-I will focus on the basic research of neutronics, including nuclear data measurement, verification and validation (V&V) of the methods and code, etc.. For example, it can be used for the measurement of the (n, p), (n, α) cross sections of transmutation reactions that produce gases and affect the service performance of structure materials in fusion reactors, and the (n, γ) reaction which contributes to the nuclear heating deposition in superconducting coils [9-11]. It is also a significant platform to perform the V&V for the neutronics simulation software, such as SuperMC, and its applicability to fusion neutron environment [12]. Note that the SuperMC code was developed by the INEST/FDS team and has been validated by ~2000 benchmarking cases for both fission and fusion reactors.

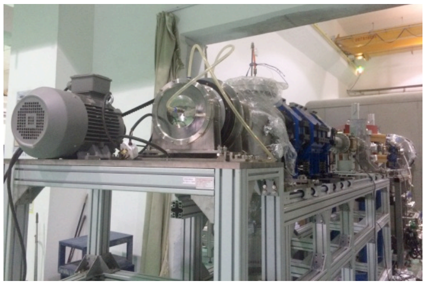

Fig. 1-a. Steady beam line.

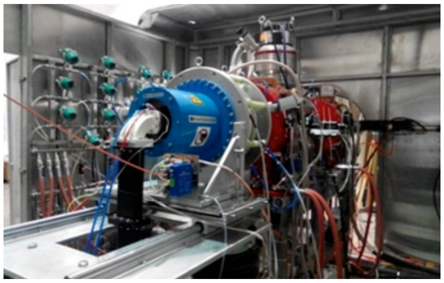

Fig. 1-b. Ion injector of HINEG-I.

During the second phase (HINEG-II), in order to reach a neutron yield higher than 10^{14} n/s, several key technologies have been developed, such as the spraying impingement cooling for the target as well as a high intensity ion source. The feasibility of technological route is demonstrated. Furthermore, the neutron yield of 10^{15}~10^{16}n/s is expected to be achieved through adopting accelerator-array and upgrading the rotating target. The concept design and development of key components of HINEG-II is ongoing. HINEG-II will focus on fundamental phenomena of nuclear technology, including mechanism of material irradiation damage and neutronics performance of key components. For example, a series of material irradiation experiments will be performed to study irradiation effects on the mechanical properties of the China Low Activity Martensitic steel (CLAM) – the primary candidate structural material for CN ITER TBM (Test Blanket Module) – in high energy and high intensity neutron environment [13]. A series of experiments for TBM (such as the Dual Function Lithium Lead liquid TBM and Helium Cooled Ceramic breeder TBM) will be performed to confirm whether the neutronics performance (such as tritium breeding ratio, nuclear heating deposition and material activation behavior) is consistent with the design or not.

Other applications of HINEG include coupling with the China LEAd-based zero-power Reactor (CLEAR-0). HINEG could be used for neutronics physics verification and control technology of CLEAR (China LEAd-based fission power Reactor) series [14] as well as fusion-fission hybrid reactors. HINEG could also be used to support the research on nuclear technology applications, such as fast neutron radiography, fast neutron activation analysis, and medical radioactive isotope production.

Prospect of Fusion Neutron Sources for Fusion Development

In order to simulate a real fusion reactor environment, the INEST/FDS team further proposes a high-flux volumetric fusion neutron source (VFNS), which will be applied for integral testing of components nuclear performance, such as multi-physics coupling test. One of the optional concepts for VFNS is a Gas Dynamic Trap device (GDT), which has a complex multi-physics environment like the real fusion reactor, and able to reach more than 10^{18} n/s of neutron flux intensity. Its fusion test volume can reach several m^3 of magnitude. Other features include compact structure, steady-state operation, easy upgrade and maintenance, etc.

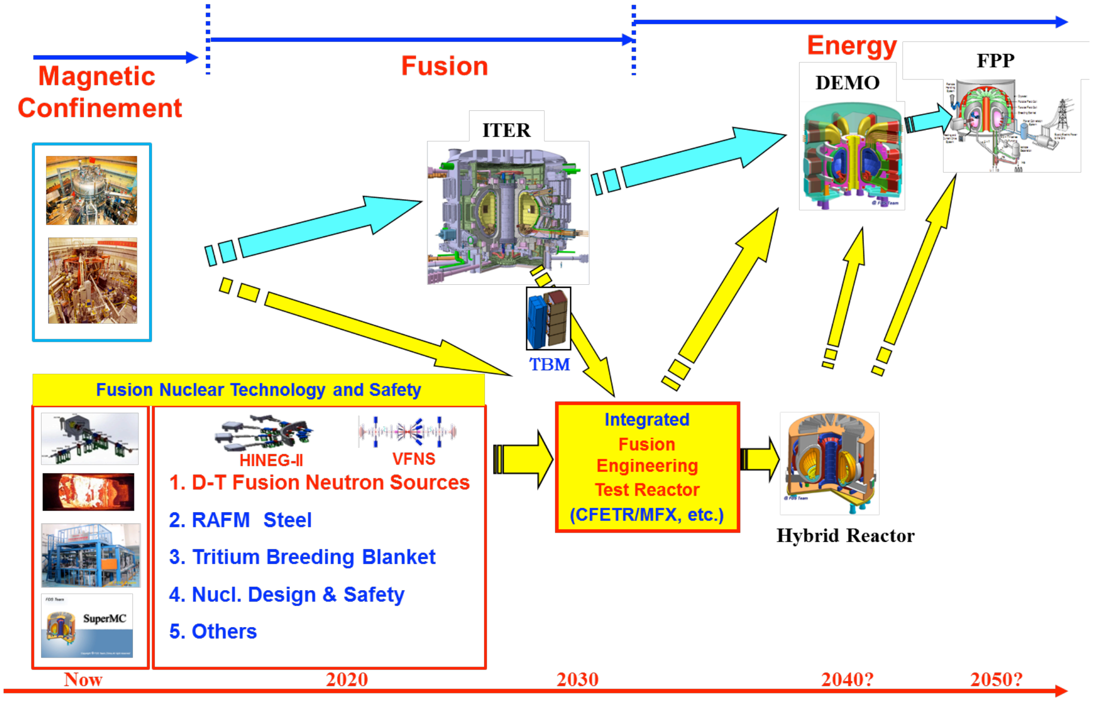

Figure 2 Proposed Roadmap of Fusion Nuclear Technology Development in China

In the proposed strategy of fusion development in China, the fusion neutron sources play an important role in the V&V of neutronics, materials irradiation damage, neutronic performance of components, etc. To verify the fusion nuclear technology before DEMO construction, it is necessary to build a test reactor complementary to ITER, and validate tritium breeding self-sufficiency, fusion blanket reliability and nuclear safety. Several concepts of test reactors have been proposed in China, such as the Multi-Functional eXperimental Reactor (FDS-MFX) and the China Engineering Design Test Reactor (CFETR), etc.

References:

[1] G. R. Shen, X. L. Guan, H. T. Hong et al., “CPNG ns pulsed system for high current beam,” 25, Part 9, 730, (2002).

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Near Term, Low Cost, 14 MeV Fusion Neutron Irradiation Facility for Testing the Viability of Fusion Structural Materials,

Gerald L. Kulcinski (University of Wisconsin-Madison, Madison, WI), Ross F. Radel (Phoenix Nuclear Labs LLC, Monona, WI), Andrew Davis (University of Wisconsin-Madison, Madison, WI).

Phoenix Nuclear Labs (PNL) has built and delivered a number of high output neutron generators with measured yields of up to 3x10^{11} n/s (DD) [1-4]. One of the devices uses a gaseous tritium target. This beam target arrangement is used as the basis for the 14 MeV neutron source in the irradiation facility.

The 14 MeV neutron generator utilizes a custom 300 kV accelerator and a microwave ion source. The resulting D^+ ion beam is focused and directed into a gaseous 8 kPa (60 Torr) deuterium or tritium target. A pressure differential of approximately 10^6 is achieved between the gas target and the accelerator region that allows sufficient target density to stop the beam while keeping accelerator pressure low. The D^+ beam slows down over ~35 cm and the resulting line source of neutrons is ~1 cm in diameter.

The fusion neutron materials test facility builds upon the existing PNL neutron generator technology by utilizing a large number (12 to 16) of DT neutron line sources around a materials test capsule. This configuration allows for significantly higher neutron flux in the test capsule than is achievable with a single line source. In addition, PNL is working towards higher deuteron current operation, which would allow each beamline to produce

~10^{14} n/s (14 MeV) – double the neutron yield of systems currently under construction. Figure 1 shows a CAD drawing of the multi-beam test assembly.. The overall test facility is ~6 meters long without neutron shielding and Figure 2 shows two possible configurations of the beamlines. Configuration A has 12 beam lines surrounding a 30 cm diameter, 60 cm long test capsule, while Configuration B has 16 beams arranged in a square lattice such that the samples will be placed between the tubes.

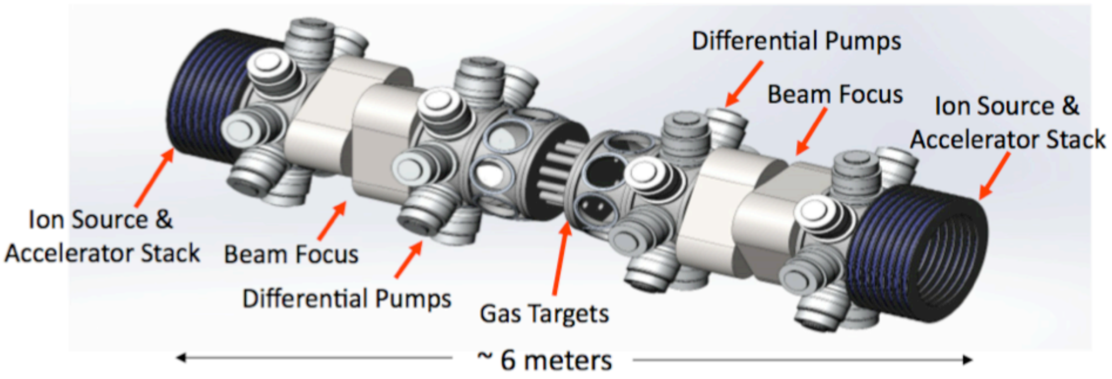

Fig. 1. A CAD rendition of a 14 MeV neutron irradiation facility with beams injected from both ends [1-4].

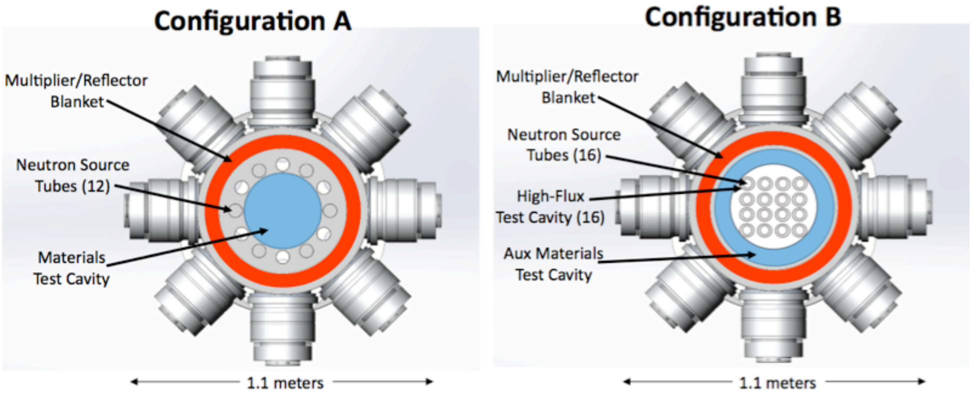

Fig. 2. Two possible configurations of multi-beam neutron generators. Samples could be placed in a central test cavity, an exterior cavity, or between beams. Other configurations are also possible.

Neutronic calculations on several multi-beam configurations have been performed using the Monte Carlo N Particle (MCNP) code. In these simulations, the 14 MeV neutron source region is surrounded by 10 cm Be to increase the total number of neutrons impinging on the sample and to soften the spectrum. The neutron spectra for the proposed source (labeled UW-PNL), ITER [5], and the Spallation Neutron Source (SNS) at ORNL [6] are given in Figure 3. It is seen that below 9-10 MeV, both the UW-PNL and SNS sources do a good job of duplicating a DT reactor spectrum.

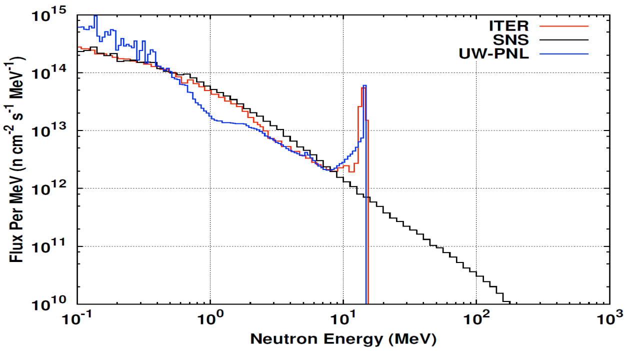

Fig. 3. Neutron spectra from three nuclear test facilities.

The PNL neutron facility also does a very good job of duplicating the ITER spectrum from 9-14 MeV, whereas the SNS spectrum is approximately 50 times lower than the ITER spectrum at 14 MeV. Above 14 MeV (where there are essentially no neutrons in a real DT environment), the SNS facility has neutrons of up to several 100 MeV bombarding the samples. These neutrons will cause transmutations in the samples that would not be produced in a fusion reactor with unknown consequences to the radiation damage behavior.

Table 1 lists the critical damage parameters for the Configuration B in Figure 2. The peak dpa values are ~8 dpa /Full Power Year (FPY) and the helium production is 80 appm/FPY, exactly the ratio of He/dpa for the first wall of DT fusion facilities [7]. As shown in Figures 4 and 5, the rate at which the PNL neutron facility generates both the correct He production rate and displacement damage rate allows the full lifetime of ITER damage to be accumulated in < 1 FPY and 3 MW-y/m^2 damage levels to be produced in ~4 FPYs for current DEMO/Fusion designs [5].

Table 1- Current Parameters for the PNL 14 MeV Neutron Facility are Relevant to ITER [5] and DEMO [8]

Parameter	Value
Peak Displacement Damage Rate	8 dpa/FPY
Peak Helium Production Rate	80 appm/FPY
Useful Irradiation Volume	1,300 cm3
Projected Operating Time/Cal. Year	90%
Projected Time to Implementation	4 years
Projected Capital & Licensing Cost	\$21 M
Projected Development Cost	\$6 M

The unique relationship between displacement damage (dpa) and helium production (appm He) is important to duplicate in order to determine the useful lifetime of fusion reactor materials. See Figure 4. While the Rotating Target Neutron Source (RTNS) [10] has close to the 10 to 1 (appm He/dpa) ratio, the absolute rate of damage in the RTNS is roughly 100 times lower than would be experienced in a DT fusion reactor. Fission reactors can produce high damage rates but the He/dpa ratios are ~100 times too low.

The 14 MeV PNL neutron facility can produce the correct He/dpa ratios and can duplicate ITER lifetime damage in less than 1 FPY.

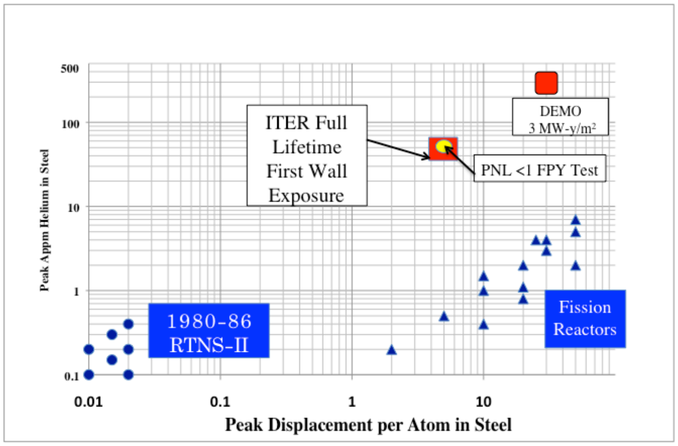

Fig. 4. Comparison of dpa and He appm provided by candidate fusion material test facilities. RTNS and fission reactor data from Zinkle [9] and Bloom [11].

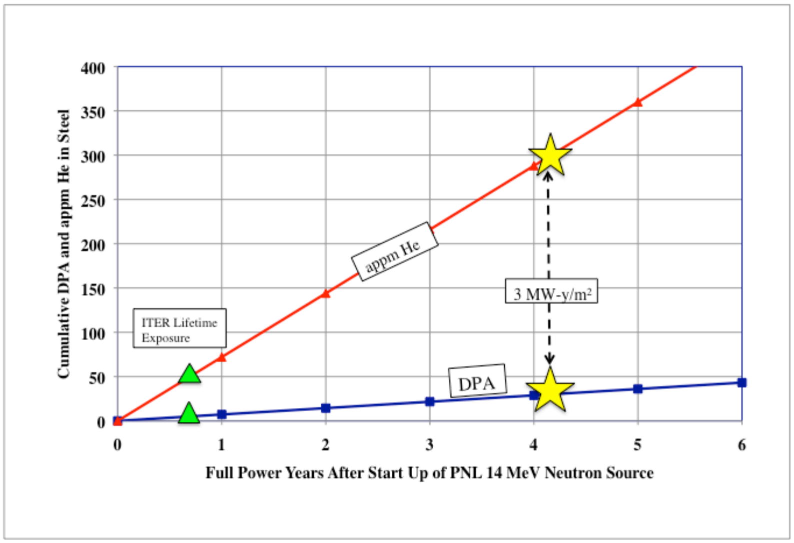

Fig. 5. The PNL 14 MeV neutron facility can simulate 3 MW-y/m^2 in ~4 FPY.

An important feature of the proposed test capsule is that the flux variation across the high dpa/FPY test volume is less than a factor of 3. This will allow for larger samples, or large numbers of smaller samples, to be simultaneously irradiated in a fairly uniform environment. The experimental facilities have already shown that over a 24 hour period, the ion beam has a >95% capacity factor. Finally, on the basis of current system costs, it is estimated that the PNL 14 MeV neutron irradiation facility could be constructed and tested in < 4 years for a capital cost of ~$20 M. This cost includes the neutron generator and tritium handling/safety equipment, plus a simple bunker and balance of plant costs. If a development project started in 2016, the production facility could be operational by ≈2020. This aggressive schedule is possible due to the established nature of the core neutron generator technology and the relatively simple requirements of the facility with respect to construction and licensing. This timeline means that one FPY exposure in DEMO (≈3 MW-y/m^2) to steel specimens could be tested by ~2025, well before the final design of the DEMO or other magnetic fusion facilities are finished. To conclude:

- Phoenix Nuclear Labs (PNL) has developed an intense neutron generator that has demonstrated DD fusion neutron yields of 3×10^{11} n/s. This technology is well established, multiple units have been delivered, and conversion to DT is currently being demonstrated.
- PNL, along with the Univ. of Wisconsin, has developed a conceptual design for a multi-beam DT version of this core technology to provide intense DT flux on a sample volume for fusion material irradiation.
- The PNL neutron source is the first low cost, near term, 14 MeV neutron test facility to be proposed that can provide high fidelity experimental data on ITER structural components before DT is introduced into the reactor.
- It is also the only known facility that could provide 3 MW-y/m^2 of typical fusion reactor exposure to DEMO relevant materials by 2025 (before the design phase of the DEMO is completed).
- The success of the PNL 14 MeV neutron test facility described here does not require any major plasma physics breakthrough and could be designed using current materials and classical physics principles.

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Taking Advantage of the Fusion Neutron Environment in the FNSF for Materials Testing,

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The Fusion Nuclear Science Facility (FNSF), a toroidal confinement device, is viewed as an essential element of the US fusion developmental roadmap. It is desirable to have a materials testing module on the FNSF to expose a wide range of specimens in a relevant fusion neutron environment, which can be contrasted with those of IFMIF and DONES or other accelerator-based neutron environments. As part of the larger FNSF material testing strategy, the test modules play a pivotal role to expose newer materials not yet qualified for use in the FNSF and to expose qualified materials (used in blankets, divertors, vacuum vessels) to higher neutron fluence levels than will be reached in the FNSF program.

In recent years, a number of proposals have been made for an FNSF type device [1-4] to enable integrated testing and development of fusion technologies under prototypical fusion conditions. Such facilities will display the complex integration of fusion components and subsystems in relevant multi-factor fusion environment: 14 MeV neutrons, surface and volumetric heating, helium and hydrogen generation in materials, relevant stresses, high pressures and temperatures with significant gradients, and strong magnetic fields. A CAD drawing of the tokamak-based FNSF (currently being developed by the Fusion Energy System Study team) is shown in Fig. 1. The facility mission requires very long pulse operation [1] to achieve the goal of testing and qualifying key power core elements. This entails a peak neutron wall loading of 1.5 MW/m^2, with achievable dpa and He production of 15 dpa per full power year (FPY) and 150 He appm/FPY, respectively. Reference 1 outlines the proposed testing program of FESS-FNSF as a series of seven phases of operation with time frames, neutron exposure, plasma on/off times, and duty cycle. The first two phases are He/H and D, while phases 3-7 are DT, and reach maximum dpa's of 7, 19, 26, 37, and 37-74, respectively. The dose regimes to the steel-based structure are displayed in Fig. 2.

An essential task for the US materials community will be to provide further irradiation data, well before the start of construction of an FNSF, to confirm that the GEN-I reduced-activation ferritic/martensitic (RAFM) alloys (such as F82H and EUROFER) will indeed survive the 4th phase of FNSF operation, which reaches ~20 maximum dpa on the outboard first wall This confirmation could possibly be derived from irradiation experiments utilizing the spallation neutron source (SNS) experiment [5], the High Flux Isotope Reactor (HFIR) [6], and heavy ion facilities to partially simulate the fusion irradiation environment. The existing simulation experimental database [7,8] indicates that radiation damage begins to have significant effects on properties for damage levels of 20-30 dpa / 200-300 appm helium. However, irradiation performance data derived from these facilities must be regarded as an approximate assessment of the dpa and helium levels that could be tolerated by the current GEN-I RAFMs. Establishing the engineering database required to support the design, construction and licensing of FNSF and DEMO will depend on the timely deployment of 14 MeV neutron facilities such as DONES-IFMIF.

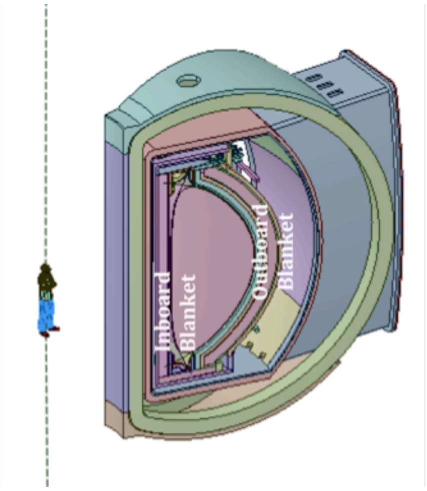

Figure 1. Preliminary layout of FESS-FNSF components.

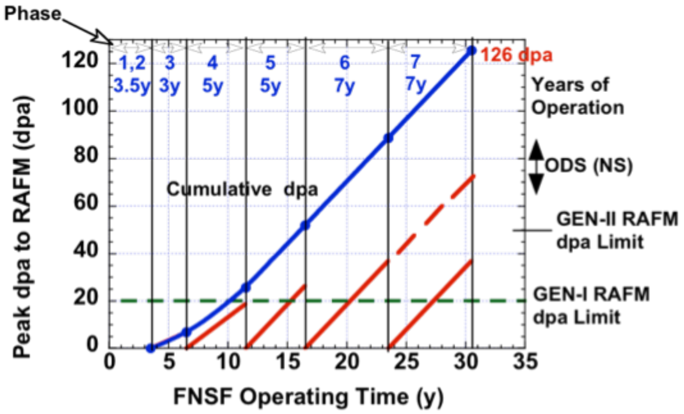

Figure 2. Peak dpa and lifetime of steel-based structure of FNSF outboard blanket.

Based on the fission experience, the development of high performance materials progresses in stages, depending on the need. In the future, the development of GEN-II RAFMs based on nano-structured microstructures generated via conventional fabrication technologies will provide higher creep strength sufficient to permit the extension of the operating regime up to ~650ºC. In addition, the microstructures of these alloys are being designed to provide more efficient trapping of helium and point defects to improve the overall tolerance to radiation damage. A further stage in the advancement of improved structural alloys is the development of nano-structured Oxide Dispersion Strengthened (ODS) alloys [9] containing 12-14% Cr. In addition to providing even higher levels of radiation-damage tolerance via more efficient trapping of point defects and helium atoms, the exceptional thermal stability of their nano-scale microstructures would provide enhanced tolerance to off-normal temperature excursions during an accident. To meet operational goals of the phased FNSF program, both of these higher performance materials will need to be in the developmental pipeline and fully qualified, including comprehensive evaluation in a 14 MeV neutron facility, prior to the construction of the FNSF.

The performance goals for the structural materials will be to survive the various phases of the FNSF. After each phase, and even at intermediate points in a phase, the blanket, divertor, and structural ring components are removed and taken to a hot cell to be disassembled, cut and examined. A clear advantage of developing more radiation resistant structures is to allow the structure (and other materials) to survive higher fluence without property degradation, thus enabling higher plant availability in the DEMO and commercial power plant. A set of alloy development goals (for radiation damage tolerance and to expand the operating temperature window) has been considered in FNSF for three classes of alloys:

1. GEN-I RAFMs (20 dpa/200 appm He). This would enable the structure to survive the 4th phase without replacement (refer to Fig. 2)
2. GEN-II RAFMs (50 dpa/500 appm He) needed to be deployed for the structure to survive through Phase 5
3. ODS (65 dpa/560 appm He) needed for Phases 6 and 7.

Validation of these goals and the development of an engineering design database for FNSF are entirely dependent on the timely deployment of fusion relevant neutron facilities, such as DONES and IFMIF. However, the FNSF itself will provide the only opportunity to extend the understanding of materials behavior into the realm of the integrated multi-effects fusion environment, combining the fusion neutron spectrum, temperature gradients, cyclic operating history, etc. To take advantage of this unique fusion neutron environment produced in the FNSF, it is proposed that a materials testing module (MTM) be embedded in the outboard blanket of the FNSF to contribute to the comprehensive multi-materials database with the potential to reach neutron exposures up to 126 dpa in Phase 7, see Fig. 2. A wide variety of materials and test specimens could be accommodated simultaneously. For example:

- New generations of structural steels, if not tested before the FNSF, including:
    - GEN-II RAFMs designed for operation up to 650ºC,
    - RAFM variants with reduced susceptibility to radiation-induced DBTT shifts for operating temperatures < 385ºC,
    - Nanostructured ODS steels (12-14% Cr) with enhanced radiation damage tolerance and high temperature capability
- Multi-material PbLi corrosion capsules
- SiC/SiC composites for advanced blanket designs
- W alloys for divertor and stabilizing shells (W-TiC, WL10, W-K, W/W composites, VMW, etc.)
- Low-temperature and high-temperature magnet materials: superconductors, jackets, insulators, etc.
- New materials variants arising from:
    - Continuing development of improved compositions/microstructures
    - Application of advances in fabrication technologies (additive manufacturing, precision casting, joining technologies, etc.).

Figure 3 displays a proposed layout of material samples within a 1x1 m MTM. Samples within individual compartments are not structural, will be exposed to higher dpa than the full sectors would reach, and could vary in shapes, sizes, thicknesses, etc. The RAFM structural frame would be replaced upon reaching the dpa limit while some fraction of the specimen inventory would be re-installed after change outs in order to accumulate progressively higher damage levels and accelerate the qualification of materials for later phases.

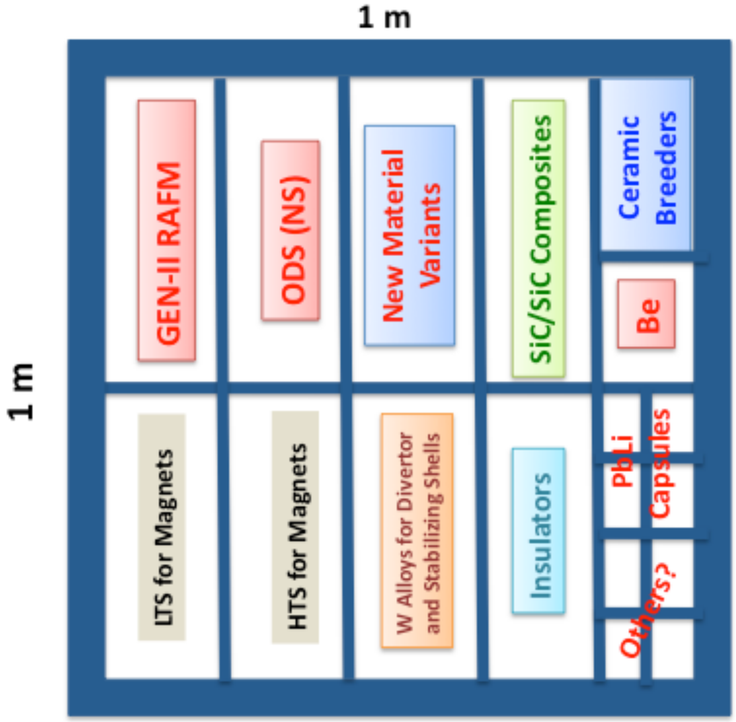

Figure 3. Layout of material samples within 1x1 m MTM.

As mentioned earlier, the data developed with continuous radiation sources (SNS, DONES, IFMIF, fission reactors, ion accelerators, etc.) are essential for developing the science-based understanding of neutron radiation damage phenomena that underpins the development of damage-resistant materials. Data from such facilities will also form the basis for developing the engineering database for designing and licensing FNSF. The FNSF itself, with fully integrated components operating in the multi-factor environment provides the ONLY access to the complete fusion environment, and these components will be dismantled and cut to provide samples for the full range of material tests. Meanwhile, the MTM on the FNSF is a complementary source of fusion neutron irradiation data in the actual fusion neutron spectrum, and is critical to quantifying the differences with accelerator-based exposure data. The FNSF is the only facility with the combined radiation damage and fusion environmental conditions needed for engineering qualification of materials and components prior to the DEMO design and construction. The most important attributes for MTM would be the relevant He/dpa ratio and the much larger specimen volumes compared to the 10-500 mL range available in the SNS/IFMIF/DONES/HFIR series of neutron sources.

In summary, the MTM potentially provides a means of:

- Testing in fusion relevant neutron environment with the correct He to dpa ratio of 10, H to dpa ratio of 40, transmutant production rates, and PKA parameters
- Testing a range of specimen geometries (tubes, flat and curved plates, etc.)
- Testing larger sized mechanical property specimens, particularly pressurized creep tubes and fracture toughness specimens with a range of section thicknesses and crack geometries
- Validation of data derived from highly miniaturized specimens irradiated in SNS/IFMIF/DONES/HFIR
- Carrying a higher multiplicity of test specimens for improved statistical analyses
- Conducting a critically important surveillance program to track materials performance using a range of specimen geometries to monitor radiation-induced changes in mechanical properties and dimensional stability of first wall, blanket and divertor plasma facing structural materials
- Evaluation and testing of welded/bonded joints with various geometries
- Irradiation testing of new material variants arising from continuing development of improved compositions and microstructures and from the application of advances in fabrication technologies (such as additive manufacturing, precision casting, alternative joining/bonding technologies, etc.)
- Providing radiation effects data in a pulsed neutron environment and comparing behavior of identical materials irradiated in steady state 14 MeV neutron sources.

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INTERNATIONAL ACTIVITIES

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

Since the appointment of Bernard Bigot as ITER Director General in March 2015, the ITER project has focused on the Director General's action plan, including reorganization, team building, resolution of long-standing technical issues, and development and execution of the integrated project schedule.

The Director General re-shaped the organization to emphasize the transition from a design project to an integrated construction project. Deputy Directors General G.S. Lee (Korea) and Eisuke Tada (Japan) were nominated by the Director General and approved by the ITER Council. The restructured organization is now led by a set of Department Heads with experience in their requisite areas.

The Director General is working toward achievement of a strong project culture with a sense of urgency, discipline and timely decision-making aimed at countering previous causes of significant delay. A key element of his action plan for improved project decision-making is the Reserve Fund that provides funding for changes driven by the ITER Organization, preempting the impasses that were previously experienced.

Both the ITER Organization's Central Team (the group at the ITER site) and the seven Domestic Agencies have refined plans and prepared a revised integrated resource-loaded schedule based on the combined detailed schedules from the Central Team and the Domestic Agencies. This activity has brought together the systems engineers, system hardware designers, the fabricators, the assembly team and the commissioning team to define the network of activities necessary to achieve the First Plasma configuration and beyond. At the November ITER Council meeting, the Director General presented this plan, including scope, cost and schedule, to the Council for their consideration; the Council recognized the improved understanding of the scope, sequencing, risks, and costs of the ITER Project achieved by this process. The Members are now digesting the inputs, and the Council has commissioned a team to review the overall schedule and associated resources. The Council plans to complete these reviews and reach agreement on the overall schedule through First Plasma by June 2016.

Meanwhile, the project team has made considerable progress in the fabrication and delivery of hardware components:

- Construction progress made onsite by the European Domestic Agency, with the completion of the framing of the Assembly Hall and the platform for the first level of the Tokamak – as well as progress on magnets, neutral beam injector, remote handling, and other ITER components;
- India's completion of the fabrication, pre-assembly, and shipment of the initial components of the ITER cryostat, for subsequent assembly in the already completed cryostat building onsite, as well as the first cooling water piping for ITER's chilled water and heat rejection systems;
- On-site delivery and installation of four US-procured 400 kV transformers; and of five US-procured drain tanks for the cooling water and neutral beam systems;

- China's completion of the manufacturing and testing of the first batch of pulsed power electrical network equipment; and China's meeting qualification milestones in the manufacturing of magnet feeders, correction coils, and the blanket first wall.

For further information, please visit the ITER website: www.iter.org.

CALENDAR OF UPCOMING CONFERENCES ON FUSION TECHNOLOGY

2015:

36th Fusion Power Associates Annual Meeting and Symposium: Strategies to Fusion Power
Dec 16-17, 2015 Washington, DC, USA
http://fusionpower.org

2016:

11th International Conference on Tritium Science and Technology – Tritium-2016
April 17-22, 2016, Charleston, S. Carolina, USA
http://tritium2016.org

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

ANS 22nd Topical Meeting on the Technology of Fusion Energy – TOFE-2016
August 22 -25, 2016, Philadelphia, USA
http://tofe2016.ans.org/

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

5th International Conference on Nuclear and Renewable Energy Resources (NURER)
September 18-21, 2016, Hefei, China
http://nurer2016.org.cn/dct/page/1

26th IAEA Fusion Energy Conference,
October 17-22, 2016, Kyoto, Japan
http://www-pub.iaea.org/iaeameetings/48315/26-th-IAEA-Fusion-Energy-Conference

58th American Physical Society - Division of Plasma Physics (APS-DPP) meeting
October 31-November 4, 2016, San Jose, CA, USA
http://www.aps.org/units/dpp/meetings/

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

2017:

ANS Annual meeting
June 11-15, 2017, San Francisco, CA, USA
http://www.ans.org/

13th International Symposium on Fusion Nuclear Technology - ISFNT
September 25 – 29, 2017, Kyoto, Japan

18th International Conference on Fusion Reactor Materials (ICFRM)
October 2017, Aomori, Japan

18th International Conference on Emerging Nuclear Energy Systems (ICENES)
2017, Hefei, China

59th American Physical Society - Division of Plasma Physics (APS-DPP) meeting
October 23-27, 2017, Milwaukee, WI, USA
http://www.aps.org/units/dpp/meetings/

ANS Winter meeting
October 29-November 2, 2017, Washington, DC, USA
http://www.ans.org/