

# **Abstracts for Oral Presentations**

**Wednesday, May 18**



## **Nuclear Energy beyond Base-Load Electricity: The Other 75% of U.S. Energy Demand**

Charles W. Forsberg

*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*  
*cforsber@mit.edu*

Electricity production is about 40% of U.S. energy demand. Base-load electricity is two thirds of total electricity production. If the use of nuclear energy is limited to base-load electricity, nuclear energy can meet only a quarter of U.S. energy needs. We have examined what is technically required if nuclear energy is to meet total electricity needs and eliminate dependence on crude oil with the concurrent objective to minimize greenhouse gas releases to the atmosphere.

Assuming all electricity is generated by nuclear plants operating at base load, the new base-load electricity demand in the U.S. would be 50% greater than today's base-load electricity demand from all sources. If there were ideal electricity storage technologies in an all-nuclear system, only 7% of all electricity would need to go to storage to meet peak electricity demand. Several "electricity" storage technologies have been identified to meet peak electricity demand. Large steam accumulators can store energy for periods of hours. Nuclear hydrogen and nuclear-geothermal heat storage systems can store energy to meet hourly, weekly, and seasonal variations in electricity demand. Different technologies are preferred for different storage periods. A similar analysis was done for all wind and all solar electricity systems.

The production of liquid fuels requires a carbon-containing feedstock and an energy source (heat and/or hydrogen) to convert that feedstock into gasoline and diesel fuel. Greenhouse gas emissions are minimized if that energy source does not emit carbon dioxide. We examine the use of three feedstocks (heavy oil, biomass, and carbon dioxide from air) for production of liquid fuels with nuclear energy as the energy source. Heavy oil is three times more abundant than light crude oil; but, 20 to 40% of its energy content is used in recovery and conversion to liquid fuels. There is sufficient available biomass to meet U.S. liquid fuel needs as a feedstock, but not sufficient biomass to be both the feedstock and the energy source to convert biomass to liquid fuels. Ultimately carbon dioxide in air can be used as a liquid fuel feedstock; but, it requires energy to capture and convert that carbon dioxide into gasoline and diesel fuel. The technologies and nuclear energy requirements (heat, hydrogen) for these alternative methods of liquid fuels production are described and compared.

It is concluded that all of these options are technically feasible; but, there remain significant R&D challenges to develop economic systems and understand what technologies are most appropriate under different conditions.

**IFE / Inertial Fusion R&D at Osaka**

H. Azechi

*Institute of Laser Engineering, Osaka University, Osaka Japan  
azechi@ile.osaka-u.ac.jp*

After 50 years journey from the innovation of lasers, controlled ignition and subsequent burn will be demonstrated within a couple of years at the US National Ignition Facility (NIF). Fast ignition has the high potential to ignite a fuel using only about one tenth of laser energy of NIF [1]. One of the most advanced fast ignition programs is the Fast Ignition Realization Experiment (FIREX) [2]. The goal of its first phase is to demonstrate ignition temperature of 5 keV, followed by the second phase to demonstrate the ignition-and-burn. The first experiment of FIREX-I, reported here, gives a confidence that one can achieve ignition temperature at the heating laser energy of 10 kJ.

Given the demonstrations of the ignition temperature at FIREX-I and the ignition-and-burn at NIF, the inertial fusion research would then shift from the plasma physics era to electric power era.

1. E.I. Moses, *Nucl. Fusion* **49** (2009) 104022.
2. H. Azechi et al., *Nucl. Fusion* **49** (2009) 104024.

## ITER Project: Progress and Plans

Ned R. Sauthoff<sup>1</sup>

<sup>1</sup>*Oak Ridge National Laboratory, Oak Ridge, TN USA  
sauthoffnr@ornl.gov*

The ITER Project is an international partnership aimed at demonstrating the scientific and technological feasibility of fusion energy, producing 500MW of fusion power with only 50MW of auxiliary heating power for periods of 400 seconds or more, using strong magnetic fields in the tokamak configuration. Partners include China, European Union, India, Japan, South Korea, Russian Federation, and the United States.

ITER has made significant progress in the areas of governance, design, and construction/fabrication.

In July 2010, the ITER Council approved the baseline: scope, schedule and cost, transitioning the project into construction. Director General Motojima's proposed restructuring of ITER Organization management was approved, and he commissioned a cost-reduction activity aimed at seeking ways to achieve the ITER mission at lower cost while preserving the schedule of First Plasma in 2019.

The ITER design has advanced with early systems moving from final design to fabrication: buildings, cryostat, vacuum vessel, and magnets. Progress, status and plans in these and other systems will be described. Safety/licensing documents have been submitted to the French regulator and have been accepted for detailed assessment.

On-site civil construction progress includes completion of the excavation for the tokamak building, and starts of the construction for the poloidal-field-coil building and the office building. Industrial contracts are being put into place by Members' Domestic Agencies for completion of design and fabrication. Superconducting strand and conductors are in production.

**Fusion Nuclear Science Research to Establish the Basis for Fusion Nuclear Science Facility**

Mohamed Abdou<sup>1</sup>, Neil Morley<sup>1</sup>, Alice Ying<sup>1</sup>, Sergey Smolentsev<sup>1</sup>

<sup>1</sup>*University of California, Los Angeles, CA USA*

*abdou@fusion.ucla.edu, morley@fusion.ucla.edu, ying@fusion.ucla.edu,*

The primary mission of a Fusion Nuclear Science Facility (FNSF) is to provide a relevant and scalable environment in which the functions, integration, and reliability of in-vessel fusion nuclear components can be tested, measured, understood and improved. The most common vision of such a facility for magnetic fusion is a small, low power, plasma-driven based fusion core that can provide sufficient neutron irradiation, surface and volumetric power density, and other relevant operational conditions such as magnetic fields necessary to fully test blanket, first wall, divertors, RF antennas and other internal components.

There is a need for a vigorous Fusion Nuclear Science (FNS) research program that can establish the basis for the successful operation of a low-Q FNSF. The research needs are diverse and numerous, but can be classified into two central categories: (1) that needed to understand, design and interpret fusion nuclear science experiments in FNSF, and (2) that needed to enable the fabrication, operation and licensing of the base FSNF machine.

Firstly, advancing FNS knowledge at the fundamental scientific level is needed in many areas to establish the basic phenomenological and constitutive models and fill out the separate and multiple effects database necessary to understand and predict the behavior of in-vessel components for fusion. Basic needs in areas such as liquid metal coolant magnetohydrodynamics, tritium chemistry and transport, thermomechanical characteristics of relevant structural and functional materials, interactions of volatile breeder and multiplier compounds with air and water, etc. are discussed in more detail in the paper. An intensive program of laboratory scale experiments, model development, and diagnostic and experimental techniques that can address these research needs is envisioned, proceeding from the separate effect to more multiple effect and unit cell experiments. This research should complement that done in support of ITER and utilize both ITER TBM and fission reactors as partially integrated test environments. It is essential to do this with the nimbleness to adapt and even change course when indicated by new discoveries and better ideas.

Secondly, FNSF suffers from the well known quandary of fusion, that the operation of the machine and fulfillment of the testing mission will require the successful operation of the very components and technologies that it was designed to test. FNSF must have full breeding blanket for testing as well as breeding the tritium necessary to operate FNSF. To address this, serious research to establish the essential material engineering and fabrication technologies must be done in advance of any final design. Material engineering research and component prototyping with relevant ferritic/martensitic steels is identified as an essential effort. Similar fabrication and characterization efforts are needed for the many functional materials (breeders, insulators, mirrors, armors, secondary structures, etc.) that are also essential to the function of diverse in-vessel components. Experiments and modelling are required in many fundamental areas related to simultaneous tritium breeding and energy extraction at high temperature. Examples of issues to be addressed are MHD thermofluid phenomena, interfacial phenomena, tritium extraction and control, and interactions between the plasma and blankets and PFC systems.

## A Fusion Nuclear Science Facility Based on the Advanced Tokamak to Enable DEMO

A.M. Garofalo, V.S. Chan, R.D. Stambaugh, J.P. Smith, and C.P.C. Wong

*General Atomics, San Diego, California, USA*

[garofalo@fusion.gat.com](mailto:garofalo@fusion.gat.com), [chanv@fusion.gat.com](mailto:chanv@fusion.gat.com), [stambaugh@fusion.gat.com](mailto:stambaugh@fusion.gat.com),  
[smithj@fusion.gat.com](mailto:smithj@fusion.gat.com), [wongc@fusion.gat.com](mailto:wongc@fusion.gat.com)

A fusion nuclear science facility based on the advanced tokamak approach (FNSF-AT) with normal conducting magnetic field coils is proposed in order to fill, together with ITER, the scientific and nuclear technology gaps between current experiments and an advanced performance fusion demonstration power plant (DEMO). Also designated as Fusion Development Facility [1], this FNSF-AT is envisioned with the dual mission to carry forward advanced tokamak physics and enable development of fusion's energy applications. The two elements of the mission are interrelated. AT physics enables the design of a compact steady-state machine of moderate gain that can provide ten times the neutron fluence as ITER, required for FNSF-AT's nuclear science development objective, while consuming only a moderate quantity of the limited supply of tritium fuel before the technology for breeding tritium is in hand.

FNSF-AT has a goal of demonstrating net tritium production and building a supply for the start up of DEMO. Neutronics calculations [2] show net tritium production in the baseline scenario, with a breeding blanket in the inboard, outboard, and divertor regions. In port blanket modules, the development of blankets suitable for both tritium production and electricity can be made. With neutron wall loading at the outer midplane of 1-2 MW/m<sup>2</sup> and a goal of an annual duty factor of 0.3, FNSF-AT can produce fluences of 3-6 MW-yr/m<sup>2</sup> in 6-10 years, sufficient to enable the irradiation qualification of materials and components for at least the first few years of DEMO operation.

The FNSF-AT core is conceived as a double null plasma with high elongation and triangularity, predicted to allow good confinement of high plasma pressure. High normalized pressure is required in order to utilize full noninductive, high bootstrap current scenarios to demonstrate continuous operation for periods up to two weeks, a necessary step before DEMO and essential to a blanket development mission. The peak exhaust power flux density is kept manageable by high core radiation and strong tilting of the divertor plates. FNSF-AT relies on near term AT-physics for its baseline operating modes, and can further develop all elements of AT physics, qualifying them for an advanced performance DEMO.

Key to FNSF-AT's ability to carry out all its science and technology studies is the baseline vertical maintenance scheme enabled by jointed copper toroidal field coils. FNSF-AT is conceived with the flexibility and maintainability to allow several changeouts of the main full tritium producing blanket, and precision alignment of the divertor toroidal ring structures, in order to assure uniform heat flux deposition with strong target tilt. FNSF-AT would be the next major U.S. facility, running in parallel with ITER.

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1. V.S. Chan, et al., "Physics basis of a Fusion Development Facility utilizing the tokamak approach," *Fusion Science and Technology* **57**, 66 (2010).
2. M.E. Sawan, et al., "Neutronics analysis in support of the Fusion Development Facility design evolution," to appear in *Fusion Science and Technology* (2011).

### **Technology Developments at KIT towards a Magnetic Confinement Fusion Power Plant**

K. Hesch, J. Aktaa, S. Antusch, L.V. Boccaccini, C. Day, D. Demange, W. Fietz, G. Gantenbein, A. Möslang, P. Norajitra, M. Rieth

*Karlsruhe Institute of Technology (KIT), 76021 Karlsruhe, Germany*

*klaus.hesch@kit.edu, jarir.aktaa@kit.edu, steffen.antusch@kit.edu, lorenzo.boccaccini@kit.edu, christian.day@kit.edu, david.demange@kit.edu, walter.fietz@kit.edu, gerd.gantenbein@kit.edu, prachai.norajitra@kit.edu, michael.rieth@kit.edu*

Complementing its intense efforts towards the finalization of the design, and the realization, of key components for ITER, the Karlsruhe Institute of Technology is pursuing vigorously also a number of important long-term technology developments towards a magnetic confinement fusion power plant. While ITER still will be an experimental device with a total run-time of only few percents of its total operation period, a power plant will have to be designed for (quasi-) continuous operation with severe implications on neutron doses, heat load cycles, and throughputs. Fundamental issues that cannot be solved by ITER nevertheless have to be addressed, due to their long lead time, already now in order to have the appropriate options prepared when the coherent design of a demonstration power plant will be started.

To this end, KIT is developing, within the overall EURATOM fusion programme, structural materials for fusion on the basis of both low-activation steels and refractory metals, in particular to withstand the neutron and thermo-mechanical loads the in-vessel components will be exposed to. On this basis, concepts for breeding blankets and divertor designs are being developed and verified step-wise, along with the development and qualification of suitable manufacturing and joining technologies. In parallel, KIT contributes to the engineering design and validation phase of the Fusion Materials Irradiation Facility (IFMIF) which will be needed for qualifying the materials to be used in a power plant. The specific characteristics of a fusion power plant fuel cycle, i.e., the processing of substantial tritium quantities within huge mass flows of exhaust gases and the related tritium compatible high throughput vacuum and pumping technologies, are being determined and translated into viable engineering approaches. As the cooling requirements of the superconducting magnet coils confining the fusion plasma will have a strong impact on the balance of plant and hence, on the overall efficiency, high temperature superconducting solutions are being developed, currently at the stage of strands, conductor cables and current leads. In order to increase the wall-plug efficiency of plasma heating, also critical for overall efficiency, advanced gyrotron tubes with power levels significantly beyond what is envisaged for ITER are being developed along with a frequency tuneability option for efficiently counteracting plasma instabilities.

The current status of these developments at KIT will be reported.

## Pilot Plant Options for Magnetic Fusion Development\*

G. H. Neilson<sup>1</sup>

<sup>1</sup>*Princeton Plasma Physics Laboratory, Princeton, NJ, U.S.A.  
hneilson@pppl.gov*

A potentially attractive next-step towards magnetic fusion commercialization is a “pilot plant”, defined here as an R&D facility that would integrate key science and technology capabilities of a fusion power plant. [1] Targeted characteristics of such a facility are: 1) capability for fusion nuclear science and technology research, including component development, 2) demonstration of a maintenance scheme applicable to a power plant, and 3) capability for net electricity production. A pilot plant would operate with a steady-state burning plasma generating a surface-averaged neutron wall load  $\geq 1 \text{ MW/m}^2$ . It would exhibit a level of reliability and maintainability sufficient to provide  $4\text{-}6 \text{ MW-yr/m}^2$  accumulated neutron fluence for blanket development. It would have a prototypical blanket, thermal conversion, and helium processing system capable of achieving tritium self-sufficiency and generating electricity. Efficient magnet, thermal conversion, plasma control, and plant systems will be required to demonstrate plant energy breakeven, i.e. net electricity generation.

Three magnetic confinement configurations are being examined for the pilot plant application: the advanced tokamak (AT), spherical tokamak (ST), and compact stellarator (CS). Each of these has advantages that motivate its consideration: the tokamak presently has the most well-developed physics basis, the ST offers the potential for simplified maintenance and reduced cost, and the CS offers disruption-free operation with low re-circulating power.

The pilot plant can be an attractive step on the roadmap to commercial MFE. It could accelerate the commercialization of magnetic fusion by carrying out a high neutron fluence component testing mission and demonstrating an efficient maintenance scheme, both of which are critical to ultimately achieve high availability in fusion systems. By demonstrating net electricity generation, it would demonstrate the successful integration of power plant physics regimes and technologies, and would establish the viability of magnetic fusion as an energy source for society.

1. J. Menard, *et al.*, “Prospects for pilot plants based on the tokamak, spherical tokamak, and stellarator,” 23rd IAEA Fusion Energy Conference, Daejeon, Republic of Korea, 11-16 October 2010, paper FTP2-2.

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## Fusion Nuclear Science and Engineering Research Motivation and Required Capabilities

Y.K.M. Peng<sup>1</sup>, J.M. Canik<sup>1</sup>, S.J. Diem<sup>1</sup>, S.L. Milora<sup>1</sup>, J.M. Park<sup>1</sup>, A.C. Sontag<sup>1</sup>, P.J. Fogarty<sup>2</sup>, A. Lumsdaine<sup>1</sup>, T.W. Burgess<sup>1</sup>, M.J. Cole<sup>1</sup>, Y. Katoh<sup>1</sup>, K. Korsah<sup>1</sup>, B.D. Patton<sup>1</sup>, J.C. Wagner<sup>1</sup>, G.L. Yoder<sup>1</sup>, V. Chan<sup>3</sup>, R. Stambaugh<sup>3</sup>, G. Staebler<sup>3</sup>, J. Navratil<sup>4</sup>, M. Sawan<sup>5</sup>

<sup>1</sup>*Oak Ridge National Laboratory, UT-Battelle LLC, Oak Ridge, Tennessee, U.S.A., [pengym@ornl.gov](mailto:pengym@ornl.gov)*

<sup>2</sup>*Innovative Design Inc., Oak Ridge, Tennessee, U.S.A., [fogartypj@ornl.gov](mailto:fogartypj@ornl.gov)*

<sup>3</sup>*General Atomics, La Jolla, California, U.S.A., [chanv@fusion.gat.com](mailto:chanv@fusion.gat.com)*

<sup>4</sup>*Columbia University, New York, New York, U.S.A., [gan2@columbia.edu](mailto:gan2@columbia.edu)*

<sup>5</sup>*University of Wisconsin, Madison, U.S.A., [sawan@engr.wisc.edu](mailto:sawan@engr.wisc.edu)*

A compact ( $R_0 \sim 1.2\text{-}1.3\text{m}$ ), low aspect ratio, low-Q ( $< 2.5$ ) Fusion Nuclear Science Facility (FNSF) was recently proposed [1] to provide, *for the first time*, a fully integrated, deuterium-tritium-fueled, continuously driven plasma, volumetric nuclear environment of copious fusion neutrons. This environment would be used to carry out discovery-driven research in fusion nuclear science and engineering, in parallel with and complementary to ITER. This research would aim to test, discover, and understand new synergistic interactions involving plasma material interactions, neutron material interactions, tritium fuel breeding and transport, and power extraction, and to find and innovate solutions for the DEMO component designs. A compact, normal aspect ratio design [2] is also a viable option for the low-Q FNSF.

Such a facility properly designed could provide, initially using conservative JET-level D-T plasmas in Hot-Ion H-Mode with pressures  $\sim 30\%T$ ,  $Q < 1$ , and an outboard fusion neutron flux of  $\sim 0.25 \text{ MW/m}^2$  (fusion power of  $\sim 20 \text{ MW}$ ). If the research, facility operation, and component solutions were successful, the performance could be extended toward  $1 \text{ MW/m}^2$  (fusion power  $\sim 76 \text{ MW}$ ) by reaching for twice the JET plasma pressure and Q. High-safety factor q and moderate- $\beta$  plasmas would be chosen to minimize plasma-induced disruptions, and deliver reliably a neutron fluence of  $1 \text{ MW-yr/m}^2$ , if duty factors of  $\sim 10\%$  can be achieved.

Such duty factors would therefore require time-efficient installation and replacement of all components using remote handling (RH). These in turn would require modular designs for all internal components, including a single-turn toroidal field coil center-post with RH-compatible bi-directional sliding joints. These would further dictate placement of support structures and vacuum seal welds behind the internal and shielding components, providing opportunities for R&D in Reliability, Availability, Maintainability, Inspectability (RAMI) in an integrated fusion nuclear environment. RH-enabled hot-cell laboratories would enable *ab initio* preparation and *post ex facto* investigations of internal test components.

The scientific and technical basis for such an FNSF, and the research needed in the next decade to manage the potential risks in its research capabilities, are described.

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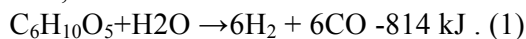
1. Y.K.M. Peng et al, "Remote handling and plasma conditions to enable fusion nuclear science R&D using a component test facility," *Fusion Science and Technology*, **56**, 957 (2009).
2. V.S. Chan et al, *Fusion Science and Technology*, "Physics Basis of a Fusion Development Facility Utilizing the Tokamak Approach," **57**, 66 (2010).

## Waste Biomass Conversion by Nuclear Energy

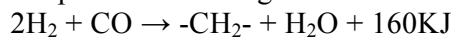
Satoshi Konishi<sup>1</sup>

<sup>1</sup> *Institute of Advanced Energy, Kyoto University, Uji, Kyoto, Japan*  
*s-konishi@iae.kyoto-u.ac.jp*

While global climate change is concerned worldwide and nuclear energy is expected, use of the nuclear is mainly limited for base load electricity. However current and future energy demand for gas and liquid fuels are several times larger than electricity, particularly in developing countries where large fraction of consumption is anticipated. Nuclear hydrogen from water is being developed, but current infrastructure and end consumer demands substitute of fossil fuels. Even if electric vehicles will increase, large scale engines, air and surface transport, and fuel cells will continue to require fuels. This paper proposes a new energy supply scenario from nuclear energy by the conversion of waste biomass into liquid and gaseous fuel. The authors have proposed a fuel production process from waste biomass at high temperature. Experimental results confirmed that biomass (represented by cellulose and lignin) is converted to H<sub>2</sub>-CO mixture at high reaction efficiency over 90% by the reaction;



This is an endothermic reaction and the measured heat absorption agreed with this theoretical value. This product H<sub>2</sub>-CO gas mixture can yield artificial oil, such as diesel, kerosene or jet fuel.



the well-known Fischer-Tropsch Synthesis reaction with existing technology. This fuel product, ether gas or oil cause little carbon dioxide emission, because the raw material of waste biomass is regarded as carbon neutral, while they can substitute existing commercial fuels. Thus, these energy products (fuels) can replace fossil, and reduces carbon dioxide emission.

Because of the nature of this endothermic chemical reaction (1), nuclear heat is converted to chemical energy without being limited by the thermal cycle efficiency that discards more than half of external energy supplied as heat. Moreover by adding the original chemical energy of the waste biomass, total apparent energy conversion efficiency to the product chemical energy as a form of gaseous fuel by reaction (1) approaches 270%. This process can be applied for VHTR as a near future nuclear energy source. The authors has also developed an Intermediate Heat Exchanger for high temperature made of SiC composite that is a key element of the process. With current nuclear energy that cannot generate high temperature heat, electricity at night or load adjustment can be used as heat for this reaction, and found to be economically feasible.

For fusion, with high temperature blanket being developed, due to the energy multiplication feature of the reaction, the “biomass-fusion hybrid” concept makes net energy output easier. Near future fusion technologies, both magnetic and inertial, those suffer poor energy multiplication, have a chance to be utilized faster than what expected for pure fusion electricity.

The supply chains of waste biomass were analyzed and found to satisfy considerable part of the current fuel market with existing sources such as urban garbage, agricultural byproduct, and forestry waste that are available in both developed and developing countries. The analysis also suggests the product is economically competitive. Thus nuclear bio-fuel will replace fossil and commercially deployed taking advantage of the existing social infrastructure, and expand the possibility of nuclear energy market several times larger. It also immediately and drastically decrease CO<sub>2</sub> emission that is expected by the public, and will eventually make it zero.

## A Clean Nuclear Energy Using Hydrogen and Condensed Matter Nuclear Science

Xing Z. Li, Zhan M. Dong, Chang L. Liang, Han Yi, Yun P. Fu

*Department of Physics, Tsinghua University, Beijing, 100084, CHINA  
lxz-dmp@tsinghua.edu.cn*

Nuclear energy is supposed to be accompanied by nuclear radiations. Neutron and gamma radiation are particularly concerned for their nuclear contamination. Transforming nuclear energy into hydrogen energy was proposed to avoid the nuclear contamination on site of application; however, we are always searching for the clean nuclear energy without strong nuclear radiation using hydrogen technology. This is Condensed Matter Nuclear Science which has been developed in the past twenty years.

Both nuclear fission and nuclear fusion are heavily relied on nuclear resonance for thermal neutrons, because the resonance would greatly enhance the cross-section of nuclear reaction. Indeed, the resonance of thermal protons might play key role in enhancing the cross-section of nuclear reaction as well. The wave nature of the thermal protons inside the metal-hydrides might greatly enhance the tunneling through Coulomb barrier due to the resonant tunneling when thermal proton wave has resonance with the energy level inside the nuclear potential well.

6 major fusion reactions (d+t, d+d, d+He3, t+T, t+He3, and p+D) are used as an example for justifying this resonant tunneling model [1]. The key issue is to identify if there is any low lying nuclear energy level which might be in resonance with thermal protons inside the metal-hydrides.

Lithium-6 has a large cross-section with thermal neutron. It is a good hint to study the resonant tunneling for thermal proton in p+Li6 fusion reaction. The primary calculation would be presented to show that p+Li6 fusion cross-section data are just fit with the resonant tunneling model. Moreover, p+Li6 fusion reaction cross-section data reveal clearly that there is indeed a low lying energy level for p+Li6, which may match the energy levels inside the metal-hydride. Thus we may expect to watch the fusion products of p+Li6 reaction inside the metal-hydride.

The experimental data show that the ratio of isotope abundance (Li7/Li6) in the palladium hydrides deviates from its natural ratio far beyond the experimental errors. The palladium samples from three laboratories in 3 countries are analyzed in silicon valley. This is a good evidence of the p+Li6 fusion reaction due to resonant tunneling of thermal protons inside the palladium hydrides.

There is no neutron or gamma radiation from this low energy p+Li6 fusion reaction. Thus the hydrogen technology today might be enough to explore a clean nuclear energy using hydrogen and Condensed Matter Nuclear Science.

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## Study for Tritium Production for Fusion Reactor using High-Temperature Gas-Cooled Reactor

H.Matsuura<sup>1</sup>, T.Yasumoto<sup>1</sup>, S.Kouchi<sup>1</sup>, H.Nakaya<sup>1</sup>, S.Shimakawa<sup>2</sup>, Y.Nakao<sup>1</sup>,  
M.Goto<sup>2</sup>, S.Nakagawa<sup>2</sup> and M.Nishikawa<sup>3</sup>

<sup>1</sup>*Quantum Physics and Nuclear Engineering, Kyushu University  
Motooka 744, Fukuoka 819-0395, Japan  
mat@nucl.kyushu-u.ac.jp*

<sup>2</sup>*Japan Atomic Energy Agency, Oarai 4002, Ibaraki 319-1394, Japan*

<sup>3</sup>*Graduate School of Engineering Science, Kyushu University,  
Hakozaki 6-10-1, Fukuoka 812-8581, Japan*

How to stably supply a sufficient amount of tritium to experimental fusion devices and the initial startup of future power generation reactors is an important problem to be solved in early stages [1]. At this moment, the tritium production by Canadian operated CANDU has been considered to be one of the most promising candidates. Considering the considerably small cross sections of neutron capture reaction by deuterium, however, we can not deny its inefficiency. In the high-temperature gas-cooled fission reactor, according to its unique fuel-pellet structure, it is well known that enough space can be available to load plenty of transmutable nuclear compounds just by the <sup>235</sup>U-fuel region. In this paper, the performance of the high-temperature gas-cooled reactor for the purpose of tritium production is investigated.

The gas turbine high-temperature reactor of 300MWe nominal capacity (GTHTR300) [1] has been assumed as a typical calculation target of gas-cooled reactor. On the basis of the continuous-energy Monte Carlo transport code MVP-BURN [2], the burn-up calculations for whole-core region of GTHTR300 have been carried out considering its unique double heterogeneity structure. The effectiveness of the use of the high-temperature gas-cooled reactor for tritium production for fusion reactors is presented and a stable operation scenario to avoid rapid variation of the multiplication factor is discussed. An optimal system construction and necessarily derived technical problem to be overcome are shown.

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## **The Effects of the Reactor Outlet Temperature on Integrating Nuclear Heat to Industrial Processes**

Michael G. McKellar<sup>1</sup>

*<sup>1</sup>Idaho National Laboratory, Idaho Falls, ID, USA  
Michael.McKellar@inl.gov*

A high-temperature gas reactor, HTGR, can produce industrial process steam, high-temperature heat-transfer gases, and/or electricity. In conventional industrial processes, these products are generated by the combustion of fossil fuels such as coal and natural gas, resulting in significant emissions of greenhouse gases such as carbon dioxide. Heat or electricity produced in an HTGR could be used to supply process heat or electricity to conventional processes without generating any greenhouse gases. Process heat from a reactor needs to be transported by a gas or fluid to the industrial process.

Using the HYSYS process modeling software, a parametric study was made to determine the effects of the reactor outlet temperature on the integration of nuclear heat to industrial processes. The model consists of a primary reactor cooling loop and a secondary process heat loop. Two gases were considered in this study: helium and steam. For this analysis, it was assumed that steam was delivered at 17 MPa and 540°C and helium was delivered at 7 MPa and at a variety of temperatures.

From this analysis the following effects were found. The temperature of the gas returning from the industrial process and going to the HTGR must be within certain temperature ranges to maintain the correct reactor inlet temperature for a particular reactor outlet temperature. The returning gas may be below the reactor inlet temperature, but not above. The optimal return temperature produces the maximum process heat gas flow rate. Maximum process flow rates and process return temperatures result in the least number of HTGRs needed for heat integration.

## **One Mega Electrical Power Grid Based on Nuclear Energy**

N.I. Mukul<sup>1</sup>

*<sup>1</sup>Bechtel Power Corporation, Fredrick, Maryland, USA  
nimukul@bechtel.com*

We have connected the whole world in wireless tele-communication.  
We have connected the whole world in land, sea, or air transportation.  
We have connected the whole world in internet.  
So, why should NOT we be connected in electrical power grid?

With the above various industry's' globalization success in mind, the question arises, is it possible to create one electrical Power Grid for the whole world? The answer is YES. If mankind wants to live in peace and prosper, we have to do business together, think together, and act together. One MEGA ELECTRICAL POWER GRID will be a giant step towards an accelerated globalization of business and solving the present climate and environmental crisis as well as present un-equal distribution of energy. To achieve this goal, Nuclear Energy can play a vital role because it can be produced abundantly without threatening the climate and environment. Using Nuclear Energy as the "base load", it is possible to stabilize one global Power Grid. Therefore, first we have to build the Nuclear Power Plants in suitable locations in all the continents of the world. Since the nuclear age began, the globalization of atomic production has been much discussed, but never attempted. The recent vote on a global nuclear fuel bank – taken in Vienna by the 35 countries of International Atomic Energy Agency (IAEA) that make up the board of the atomic energy agency, an arm of the United Nations – comes as dozens of developing countries have expressed interest in nuclear power. This is a breakthrough in global cooperation which provides the green signal for Global Operation and Distribution of Nuclear Energy.

## **Integration of High Temperature Gas Reactors with In Situ Oil Shale Retorting**

E.P. Robertson<sup>1</sup>, M.G. McKellar<sup>1</sup>, L.O. Nelson<sup>1</sup>

<sup>1</sup>*Idaho National Laboratory, Idaho Falls, ID, USA  
eric.robertson@inl.gov, michael.mckellar@inl.gov, lee.nelson@inl.gov*

We have completed an evaluation of integrating a high-temperature gas reactor (HTGR) to an in situ oil shale retort operation. The evaluation looked at generating the large amount of heat required to produce 50,000 bbl/day of refinery-ready crude oil from an in situ shale operation using an HTGR, which replaced heat generated by the combustion of fossil fuel (natural gas or coal). Three cases were considered: a base case which includes no nuclear integration, an HTGR-integrated case using helium as the heat transfer medium, and another HTGR-integrated case using steam as the heat transfer medium.

The HTGR was assumed to be physically located near the oil shale operation such that heat losses during surface transport of the heating fluid were negligible. Transferring the required retort heat for all three cases to the underground oil shale was modeled by a series of closed-loop pipes. The pipes ran from the surface to the desired subsurface zone where the majority of the heat was transferred to the oil shale; the cooled fluid was then returned to the heat source at the surface for reheating. The heat source was a natural gas fired boiler for the base case and was an HTGR for the other two cases. The fluid and heat flow through the systems were modeled using Hyprotech's HYSYS.Plant™ process modeling software.

A model was developed in Excel™ that was used to evaluate the natural gas usage, electricity requirements, heat requirements, electricity produced, CO<sub>2</sub> emissions, and shale oil production for each of the three cases. The HTGR-integrated case using steam as the heat transfer medium was superior to the case that used helium. Integrating an HTGR to an in situ oil shale retort operation appeared quite feasible and had some notable advantages over the base case. The steam HTGR-integrated case produced roughly twice as much natural gas and one-eighth of the CO<sub>2</sub> as the base case, while producing the same amount of refinery-ready oil.