Abstracts for Oral Presentations

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Fluoride Salt-cooled High Temperature Reactors – Technology Status and Development Strategy

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Fluoride salt-cooled high temperature reactors, or "FHRs", are a promising new class of thermal-spectrum, high-to-very-high temperature reactors. FHRs are characterized by their use of tri-isotropic (TRISO) coated particle graphite fuels and graphite moderator materials similar to those employed in gas-cooled reactors, together with liquid fluoride salt coolants, near-atmospheric operating pressures, and operating temperatures ranging from 600 ºC to perhaps as high as 1000 ºC. FHR concepts have been developed and are being optimized for a variety of sizes and applications ranging from large (> 2000 MWt) plants for high-efficiency central station electricity generation [1], to small (125 MWt) modular units designed for process heat and hybrid process heat / electricity production missions [2]. Core geometries that have been considered include prismatic fixed cores [1], cylindrical "stringer" fuel assemblies [3], removable plate-type removable fuel assemblies [2], and pebble-bed concepts [4]. Both loop-type and integral primary system concepts are under investigation.

Current FHR system concepts are briefly surveyed, along with their principal operational and safety characteristics. Although FHR systems leverage a number of well-developed technologies from the gas-cooled and molten salt reactor arenas (as well as employing the low-pressure pool type core configuration of liquid metal-cooled reactors), the successful development and deployment of commercial FHR systems will necessitate a variety of technology development and demonstration activities. Present technology status and principal technology development needs are identified in the areas of nuclear fuels and coolants; structural materials; instrumentation and controls; and major components such as pumps, heat exchangers, thermal energy storage devices, and power conversion technologies. Finally, an integrated multi-decade strategy for development and deployment of transformational FHRs is presented.

1. D. T. Ingersoll, et al, "Status of Preconceptual Design of the Advanced High-Temperature Reactor (AHTR)," ORNL/TM-2004/104, Oak Ridge National Laboratory, May 2004
2. S. R. Greene, et al, "Pre-Conceptual Design of a Small Modular Fluoride Salt-Cooled High Temperature Reactor (SmAHTR), ORNL/TM-2010/26178, Oak Ridge National Laboratory, December 2010.
3. C. W. Forsberg, "Refueling Options and Considerations for Liquid-Salt-Cooled Very High-Temperature Reactors", ORNL/TM-2006/92, June 2006.
4. P. F. Peterson, Pebble-Bed AHTR Design Review, Design Status Update, UC-Berkeley, October 7, 2009 (http://www.nuc.berkeley.edu/PB-AHTR/resources.html,)

Fusion Power Plants: Visions and Development Pathway

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Conceptual design and analysis of fusion power plants have been carried out since the early days of fusion research to understand the characteristics of potential fusion energy systems. Maturity of fusion science and technologies in recent years has transformed these conceptual design studies. Detailed and integrated design and assessment of fusion concepts as power plants have allowed these studies synthesize a wide variety of fusion R&D results, and provide direction on on the scientific problems that carry greatest leverage for fusion energy. As such, they have been increasingly utilized as valuable tools in guiding the research programs and illuminating the fusion development paths.

During the past ten years, the ARIES Team, a national US team involving universities, national laboratories, and industry, has studied a variety of magnetic fusion power plants (tokamaks, stellarators, spherical torus, and RFP) with different degrees of extrapolation in plasma physics and technology from present database.

In this paper, I will present the top-level requirements and goals for commercial fusion power plants developed with consultation with US utilities and industry. I will review several ARIES designs and discuss the candidate options for physics operation regime as well engineering design of various components (*e.g.,* choice of structural material, coolant, breeder). For each option, we will discuss (1) the potential to satisfy the requirements and goals, and (2) the feasibility (*e.g.,* critical issues) and credibility (*e.g.,* degree extrapolation required from present data base).

In addition to scientific data, I discuss what fusion R&D programs should generate in order convince the power industry to invest in a fusion system, the licensing authority to license such a device, etc. I will use “Technical Readiness Levels” (TRL) as a quantitative measure to compare physics, engineering, and technology needs of a power plant with present-day achievements. The R&D requirements for an attractive fusion power plant together with the TRL structure for assessing maturity of fusion concepts provide the basis for developing a “roll-back” frame-work for fusion development path.

High Power Hadron Accelerators: Applications in Support of Nuclear Energy

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New generation high power hadron accelerators are more and more required to produce intense fluxes of secondary particles for various fields of science: radioactive ions for nuclear physics, muons and neutrinos for particle physics, and of course neutrons for many applications like condensed matter physics, solid-state physics, or irradiation tools. This paper will focus on the applications of such accelerators in support of nuclear energy, and in particular on the two following cases: the International Fusion Materials Irradiation Facility (IFMIF), which asks for a 10 MW, 40 MeV deuteron beam, and the ADS (Accelerator Driven System) application for transmutation of long-lived radioactive wastes, which typically requires a 600 MeV - 1 GeV proton beam of a few mA for demonstrators, and a few tens of mA for large industrial systems. In this respect, the status of the accelerator proposed for the European MYRRHA project will be detailed and discussed.

Single and Multi-ion Beam Facilities and their Application to Nuclear Energy

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Nuclear energy faces challenges with regards to our ability to accurately predict materials performance. Relevant issues include life extension of the existing reactor fleet, development of advanced fast reactors with design lifetimes of several decades or longer, high burn-up fuels, and fusion energy materials. Ion-beam studies of materials have played an important role in the development of nuclear energy materials in the past. With new interest in nuclear energy the need for much more intensive research focused on key mechanisms that can inform multi-scale models becomes paramount. Single and multi-ion beam facilities provide flexible platforms for significantly accelerating the investigation of the underlying physics of radiation tolerance and actinide fuel evolution. We will review the various facilities currently in operation around the world, review important experiments that have been conducted, and indicate where the US programs in nuclear energy might benefit from a coordinated and intensive use of ion beams for nuclear energy materials development.

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Irradiation Facilities for Fusion Materials Development

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The extreme materials environment in a fusion power plant requires exploring, characterizing and qualifying a range of new materials for structural and functional applications, which can only be addressed with facilities presently not fully available for the scientific community.

In this work, it will be analyze the requirements of the facilities needed for the characterization of radiation effects in the materials and it will be review the main characteristics and status of the two complementary approaches presently used:

i) IFMIF, the international project for the construction of a fusion-like neutron source, presently under design and validation, aimed for the qualification of fusion materials, with a reduced capability for development of new materials, and

ii) the use of other irradiation sources (fission reactors, spallation sources and, mainly ion accelerators) for the development of a better understanding of the materials behavior. In this aspect special emphasis will be made for the case of triple-beam irradiations and specifically on the MARIAM project, the triple-beam irradiation facility included in the Spanish TechnoFusión Project.

The IFMIF Project

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Future fusion reactors using the DT-reaction will create a high flux of energetic neutrons. The materials of the reactor vessel will suffer from this neutron irradiation resulting in activation and material fatigue. For economic reasons materials are necessary which can withstand the irradiation for several years. To test new materials a neutron source is required which provide a sufficient high flux with an appropriate energy spectrum.

IFMIF (International Fusion Material Irradiation Facility) is an accelerator based neutron source fulfilling these requirements. A 250 mA cw deuteron beam with an energy of 40 MeV hits a target of liquid lithium. Because of the very high beam current two RF linear accelerators are used in parallel. Because of the required cw operation a superconducting solution has been chosen. The main part of the linac (5-40 MeV) will consist of superconducting half-wave resonators (HWR) arranged in two groups optimized for a specific particle velocity. In a first step the 9 MeV front-end is presently under construction to demonstrate the feasibility.

The overall project and the status of the accelerator are reported. Additionally an alternative design based on superconducting CH-cavities will be presented.

Feasibility Studies on Once Through Subcritial Cores Driven by Accelerator Driven Spallation Neutrons

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The proliferation resistance of the nuclear fuel cycle would be increased if one could eliminate the need for both uranium enrichment and spent fuel reprocessing. Heavy-water and graphite moderated critical reactors can extract energy from natural uranium but offer a very low uranium utilization (low discharge burnup). The objective of the present study is to explore the feasibility of achieving high fuel utilization without resorting to enrichment and reprocessing using spallation neutron source driven subcritical reactors. Three different high burnup once through subcritical nuclear systems are investigated: a fluoride salt cooled high temperature reactor (FHR) with pebble fuel, a helium cooled core with sphere pack fuel based on General Atomics' EM^2 reactor concept, and a sodium cooled fast reactor that is loaded with fuel discharged from a high burnup Breed-and-Burn (B&B) fast reactor that is fed with depleted uranium, after removing the gaseous fission products and inserting the voided fuel rods into a new clad (without removing the old one).

The pebble fuel design and fuel cycle for the FHR concept was optimized for maximum electric power multiplication using natural thorium fuelled subcritical core. The maximum attainable power multiplication was not high enough to merit future studies.

The optimal discharge burnup of the fuel in the EM^2 type subcritical core was found to be approximately 30% FIMA and the corresponding power multiplication was found higher than in the FHR but still not high enough for practical applications.

Significantly better performance was obtained from the sodium-cooled source-driven core that is fed with fuel discharged at 20% FIMA from a critical B&B fast reactor that underwent recladding. The maximum attainable power multiplication was found to be greater than 10 while fissioning approximately 20% of the loaded heavy metal.

Recent Trends in Nuclear Education and Training to Match the Needs

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Since the publication of the OECD/NEA report "Nuclear Education and Training: Cause for Concern?" [1], it is apparent that the general outlook of the nuclear energy industry has substantially changed, shifting from one of a sector suffering stagnation and decline to one with a healthy perspective of revival. The required average technical level of the nuclear workforce was and remains very high, emphasizing the need for comprehensive and sustainable education and training, with an overarching priority to safety. The paper reviews some of the many initiatives around the world that have been launched to stop the decline of the available well educated and well trained workforce influx.

In particular, the paper addresses two categories of human resources necessary to run a nuclear power plant: (1) People with an adequate background in a relevant area (e.g. mechanical, electrical, civil engineering, etc.) and a general knowledge of the technical and organizational nuclear environment in which they have to apply their knowledge and skills; (2) People with a specialized background in nuclear subjects (e.g. nuclear engineering, radiochemistry, radiation protection, etc.).

For category (1), as illustrated in the paper, Industry has responded to the shortage by recruiting people with adequate competencies in a relevant area, but without any nuclear background, and by organizing specific trainings for these new recruits. People of category (2), whose needed influx is smaller, are crucially important for the operation of nuclear installations. For them, education in nuclear engineering and/or nuclear physics is a mandatory prerequisite. This education is provided by higher education institutions through two different channels: a regular bachelor or master programme or a postgraduate programme. In addition, training on simulators and on the job is required before reaching full professional maturity. Doctoral programmes are necessary to educate a number of specialists of nuclear technologies who are indispensable for R&D in Industry and Research Institutions. The paper reviews some of the recent initiatives shown by the universities and associations of universities around the world, with the support of the nuclear sector and/or the public authorities.

An analysis of the use of research reactors and thermal-hydraulic facilities for educational purposes is presented, and recommendations are made to make them more accessible to larger groups of students.

The nuclear industrial, research and regulatory activities have considerably increased, but at the same time the numbers of students attracted in science and technology disciplines have not increased. The result is a persisting gap between supply and demand. Additional efforts are thus needed, in particular to facilitate the mobility of young professionals.

1. "Nuclear Education and Training: Cause of Concern?" Nuclear Energy Agency, OECD, 120p., (2000).

ENEN's Challenges in Response to the Industry and Regulatory Needs

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The European Nuclear Education Network (ENEN) Association is a non-profit organization established by the consortium of the EU 5th Framework Programme (FP) ENEN project in 2003. Its main objective is the preservation and further development of expertise in the nuclear fields by higher education and training. As of December 2010, the ENEN has 56 members in 18 European countries, South Africa, Russian Federation, Ukraine and Japan.

Based on the mutual recognition and adoption of the European Credit Transfer and Accumulation System (ECTS) within the EU, the ENEN has provided support to its members and European students/young professionals to organise and participate in selected Education and Training (E&T) courses in the nuclear field. The ENEN also developed a reference curriculum in nuclear engineering, consisting of a core package of courses and optional substitute courses in nuclear disciplines, to be realised in order to obtain the "European Master of Science in Nuclear Engineering (EMSNE)", the ENEN Certificate, which has been implemented from 2005. Expansion of the scope of EMSNE is currently under discussion towards other nuclear disciplines such as radiation protection and waste management.

Since 2009 the ENEN has been involved in three FP7 European Fission Training Scheme (EFTS) projects, i.e. ENEN III on nuclear engineering, PETRUS II on waste management and ENETRAP II on radiation protection, in order to establish a common certificate for professionals at European level. The EFTS is a significant development aimed at structuring training and career development across the EU. The ultimate objective of each EFTS is to develop a European passport for training, using the European Credit system for Vocational Education and Training (ECVET) approach, which is in fact a portfolio of learning outcomes. Once established, this concept will be applied to all ENEN and other appropriate training courses for achieving the harmonization of professional training over Europe.

In 2009 the ENEN launched the EUJEP project for exchange of Master level students and faculty members with Japan. Two 7th FP projects for mutual recognition of nuclear E&T with Russian Federation and China are expected to be launched in 2011.

It has also organised several European events for further promotion of the mutual recognition of nuclear E&T over the EU, such as the annual PhD Event and the Post-FISA Workshop 2009 on E&T.

In December 2008 the European Council welcomed the existence within the EU of coordinated teaching and training leading to qualifications in the nuclear field, provided notably by the ENEN, and expressed its hope that, with the help of the EU, ENEN and its members will continue to develop the coordination of nuclear education and training in Europe.

Education of Nuclear Energy Systems at Åbo Akademi

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The Finnish universities were "privatized" starting January 1, 2010. However, the main obligations have remained unchanged, since according to the University Law 645/1997, 4§, the universities should "provide skilled persons for the society", the so-called "third obligation" - in addition to doing research and highest teaching based thereupon.

An explicit case is the growing future need for personnel in the existing, as well as the coming, nuclear power plants. This has been clearly pointed out for about a decade already, but little, if anything, has happened. The universities that have presented teaching or research in nuclear physics/technology are Helsinki (HUT), Lappeenranta (LUT) and Jyväskylä, the latter basic nuclear physics only. Since some years, Åbo Akademi has joined the group.

Today Finland has 4 nuclear plants running, 2 in Olkiluoto (TVO) north of Turku, 2 in Loviisa (Fortum) east of Helsinki, and a fifth is being constructed in Olkiluoto. Further, two additional ones have got the right to present advanced plans for construction; Teollisuuden Voima (TVO) and Fennovoima [1].

Therefore, in addition to a "retirement wave" - the running 4 units were all started at almost the same time - there will be (and has started in TVO-3) need for personnel for the new units. Åbo Akademi has started education with those needs in focus, but there are problems related to the teaching of a fairly complicated, many-faceted subject like (future) nuclear energy systems, especially in a small university like Åbo Akademi:

- there is a shortage of personnel if many different subjects are pursued,
- there is an economical shortage since the department has graduation obligations, and
- this leads to concentration in only a few subjects and
- larger companies are unwilling to sponsor, since the unit is "too small to be effective".

The presentation reviews the existing courses, and especially, it presents the new courses developed for the above purpose. Including the Special Assignment and Master's Thesis, the total volume of nuclear-physics-like education is presently 101 credit points (cp) out of a Master's degree totaling 300 cp! A very positive feedback is that when the Faculty of Technology starts a new MTech program, Energy and Environmental Technology, in Fall 2011, these physics courses will be explicitly included [2].

1. Home pages for the mentioned companies: tvo.fi, fortum.com, fennovoima.fi.
2. K. Fagervik, Process technology, private communication

Asset Management: Time for an Integrated Approach

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Information has been collected and evaluated regarding the status of asset management for nuclear power plants in the United States. The current condition if measured by plant capacity factors is fundamentally sound. On average; a value around 90 % is stabilizing with the highest quartile being in the range of 95 %. Examples of motivations for continued enhancement and improvement of these solid plant capacity factors include: (1) organizational attention to continuous improvement, (2) movement from a lower quartile of unit performance to a higher quartile as well as (3) avoidance of the pitfalls of complacency associated with excellence.

An integrated approach to asset management will involve technical actions that are proper and properly timed, accomplished correctly, and carried out in a structured and repeatable manner.

The evolution into this integrated approach should confront the feedback collected from utilities and elsewhere in the industry including observations such as:

(a) Needing a better focus of maintenance expenditures on critical systems and components
(b) Integration between engineering and work management
(c) An interest in good, accurate assessments
(d) Addressing if the “run to failure” category of components are being evaluated well and populated fairly
(e) The challenge of maintenance resources as a precious commodity not to be wasted.

Effort is underway to assess current conditions at nuclear power plants and the benefits that are hoped to be achieved from this systematic approach to asset management. Some examples of benefits for which this work approach can deliver results include plant capacity improvement , reduced investments in maintenance expenditures, enhanced confidence in technical evaluations, rapid turnaround of equipment condition assessments, central location of relevant plant information, improved knowledge transfer to new personnel, and reduced manpower burdens to perform related tasks. Challenges to success will include the recognition and need to a committed task approach to transition management of such a change including involvement of the work force in appreciating the value of this approach, related user requirements, and effective training and training materials . Incorporation of an integrated approach is expected to be applicable to operating fleets as well as new reactors.

The presentation will include a current status of the incorporation of integrated asset management at nuclear power plants in the US. For emerging interests in nuclear power generation, the maximum effectiveness and benefits of an integrated asset management attention are best achieved through leveraging approaches occurring elsewhere and apply this experience early in the planning and design process.

Fifty Years of Fusion Research: Historical Overview of Power Plant Studies and Discussion of Future Trends

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Since the 1950s, scientists and engineers have been seeking means to effectively control the fusion process for peaceful energy production. Numerous experiments and conceptual power plant designs have been developed for all magnetic and inertial fusion concepts. Although fusion science has progressed significantly, it has been demonstrated only on relatively small-scale devices. ITER in France and NIF in the US are the largest experiments that respectively use magnetic and inertial confinement methods to achieve and control the plasma.

Only four magnetic confinement concepts were pursued internationally in the 1950s: tokamak, stellarator, pinch, and mirror. These magnetic concepts experienced substantial modifications over the past five decades. Beginning in the late 1960s, numerous studies have been conducted worldwide for the four original and three new approaches: spherical torus, spheromak, and field-reversed configuration.

Shortly after the invention of the laser in the early 1960s, scientists suggested the implosion of D-T filled targets by laser beams for net energy production. The following decades witnessed serious research when more powerful and efficient lasers made inertial fusion appear more practical for generating net energy. Besides the laser driven system, other drivers have been identified: light ions, heavy ions, and Z-pinches. Like magnetic fusion concepts, all inertial fusion concepts are at an early stage of development. More simulations, experiments, and testing have yet to be done to solve and validate the key engineering issues and remaining challenges.

Over the years, power plant studies remained an essential element of the fusion development process in order to understand the future trends. More than one hundred large-scale magnetic and inertial fusion power plants have been developed since the early 1970s by research teams in the US and abroad. Basically, these studies help the fusion community identify the major physics and technology problems and provide guidance for R&D programs to deliver a viable end product. Most studies employed the D-T fuel cycle, since it has the least demanding physics conditions to reach ignition. The stress on fusion safety stimulated worldwide research on fuel cycles other than D-T that would produce much fewer neutrons.

Among the eleven fusion concepts developed to date, the tokamak and laser-driven system are regarded as the most viable candidates for magnetic and inertial fusion energy, respectively. The main progress in these concepts has been directly connected to physics-oriented experimental facilities built in various countries with varying missions and scopes. No country has yet offered a firm commitment to build the next step machine after ITER and NIF. Fusion advocates in their developmental plans manifested the fusion pathways in quite varied philosophies, depending on the degree of assumed technology readiness, the extent of physics and technology extrapolation beyond ITER and NIF, and the desired economic competitiveness of the power plant. Several countries projected operating a Demo in 20-30 years from now. If the energy market favors accelerating the development of fusion with a substantial increase in funding and governmental support, commercial production of fusion energy could be achieved as early as 2030.

Heavy-Ion Driven IFE

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Accelerators have long been considered attractive options for inertial fusion energy, and the upcoming National Academy of Sciences (NAS) review will soon revisit the candidacy of heavy ion fusion.

There are three types of heavy ion fusion targets that set requirements on the accelerator: indirect drive, direct drive (polar drive with shock ignition), and direct-drive fast ignition (X-target, as well as several types of accelerators and target chamber options. A tri lab consortium of LANL, LBNL, and LLNL successfully completed a large induction linac (DARHT-II) for radiography at LANL in 2008, which validates many features of induction linacs that could be applied to heavy ion fusion. The X-target may expand accelerator options for heavy ion fusion to include high gradient RF linacs. A Workshop on Accelerators for Heavy Ion Fusion is being planned for spring 2011 (see Peter Seidl [PASeidl@lbl.gov]) to take a fresh look at accelerator-driven inertial fusion.

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New Laser Fusion by Intense Laser

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A feasibility of new approach of laser fusion in plasma without implosion has been proposed and is discussed using an intense laser. The cross section of nuclear reaction is increased by the enhanced penetrability of nuclei through Coulomb barrier. In this approach, intense laser field more than 100PW was required to distort the Coulomb barrier to obtain enough penetrability. Energy gain even with Deuterium - Deuterium reaction can be obtained using this scheme in Deuterium plasma. Reactor with neutron and direct conversion of charged particle beam individually is proposed. Charged particles from d-d reaction are guided at the end of reactor and directly converted by a MHD scheme into electric energy. The energy recover rate is so high and required smaller laser energy, which may make that of this energy cost cheaper than that of a fission reactor.

Time-Dependent Fusion Reaction Rates in the Mechanical Adiabatic Compression of a Dense Plasma

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Fusion by mechanical adiabatic compression refers to the rapid compression by a piston of a deuterium gas subjected to external electric and magnetic fields. The fields serve to reduce the degrees of freedom of the gas and hence a higher final temperature can be achieved for a given energy input. Previous calculations, which considered only primary fusion reactions and which assumed the temperature increase and the fusion reactions to occur only at the end of the compression process, demonstrated that, for a sufficiently dense gas, appreciable fusion rates can be attained at temperatures much lower than those required for standard magnetic confinement techniques [1-3]. The present study considers increases in temperature and the effects of both primary and secondary fusion reactions to take place throughout the compression. Final temperatures and fusion reaction rates are computed for 1, 2 and 3 degrees of freedom and are compared with those reported in the earlier studies for both ideal and van der Waals gases. Additional fusion enhancement mechanisms are discussed.

1. David W. Kraft and Lloyd Motz, “Mechanical Adiabatic Compression of a Dense Plasma”, *Current Trends in International Fusion Research – Proceedings of the Third Symposium*, E. Panarella, ed. (NRC Research Press Ottawa, 2002), p. 475.
2. David W. Kraft and Lloyd Motz, “Fusion by Mechanical Adiabatic Compression of a Dense Plasma”, *Current Trends in International Fusion Research – Proceedings of the Fourth Symposium*, C. D. Orth and E. Panarella, eds. (NRC Research Press Ottawa, 2007), p. 505.
3. David W. Kraft, “Thermonuclear Fusion by Mechanical Adiabatic Compression of a Dense Plasma”, *Proceedings of the 13th International Conference on Emerging Nuclear Energy Systems, ICENES 2007*, Istanbul/Türkiye (3-8 June 2007) S. Sahin, ed. ISBN-978-975-01805-0-7.

Axisymmetric Magnetic Mirror Applications – Neutron Source to Fusion Power Plant

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Axisymmetric magnetic mirrors are a potential game-changer for magnetic fusion energy. They are inherently steady state. The axisymmetric structure leads to simpler circular magnets, and opens the possibility of using thick-liquid walls to reduce, or eliminate issues of neutron damage to materials [1]. All magnetic mirrors eliminate: disruptions, because there is no significant plasma current; and high-power density on strike plates, because the exhaust power can be spread over arbitrarily large end walls. Axisymmetry eliminates neo-classical radial diffusion, which is characteristic of toroidal devices and non-axisymmetric mirrors. Electron axial heat loss is small in mirrors with a large expansion ratio of the magnetic field in the end tanks to eliminate secondary emission of electrons as an issue, and fast vacuum pumps to eliminate gas ionization as an issue. The major issues are to demonstrate micro-stability and MHD stability at sufficiently high electron temperatures. Microstability has been demonstrated with the aid of sloshing ions, warm plasma, or a larger radius plasma. Axisymmetric mirrors have been MHD stabilized by the pressure of out-flowing plasma in good-curvature regions between the outer mirrors and the end walls, or by a rotating plasma stabilization technique; as demonstrated on the Gas Dynamic Trap (GDT) at the Budker Institute of Nuclear Physics. The outflowing plasma limits the electron temperature, which restricts Q to ≤ 1 [Q=(fusion power)/(heating power)]. Straightforward extrapolation of the GDT to a Deuterium-Tritium Neutron Source, DTNS, provides stability with a DT-fusion neutron flux of 2 MW/m^2 over 1 m^2, at a power-plant efficiency of $Q \sim 0.07$. (A DTNS enables development and testing of materials and sub-component structures for fusion power plants [2].) Further extrapolation yields a $Q \leq 1$ facility that can profitably burn minor actinides (mainly Np, Am, and Cm), and perhaps Pu [3]. Even further extension to a pure-fusion axisymmetric-tandem-mirror power plant, requiring $Q \geq 10$, demands the use of different stabilization techniques that are not dependent on out-flowing plasma, a number of which have been proposed, and some of which have been tested. These simple tandem mirrors, with high-field end-cells, can provide Q's of 10, perhaps more, without the added complexity of thermal barriers. With tandems, helium ash removal becomes an issue. The GDT, or a new similar device, could provide a test-bed for these issues.

1. R. W. Moir and T. D. Rognlien, Fusion Sci. Technol. **52**, 408 (2007).
2. 2. T. C. Simonen, Fusion Sci. Technol. **57**, 305 (2010); A. W. Molvik, et al., ibid, p. 369.
3. 3. D. D. Ryutov, A. W. Molvik, T. C. Simonen, J. Fusion Energy **29**, 548 (2010)

The Economic and Environmental Prospects of Fusion and Fission in the Long Term

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Electricity demand is expected to increase. Growth is driven by the economic performance especially in the fast growing countries in Asia and South America and by a shift of the end energy carriers with electricity being the winner of this shift. With the expected advent of electric cars, increasing public transport in urban areas and high speed trains the role of electricity is also increasing in the transport sector. Electricity is still mainly produced by fossil fuels, especially coal, while wind and solar energy increase at very high rates but remain globally still on a rather modest level.

The paper will start with a detailed discussion of the expected global electricity demand. Technological and economic drivers of the demand will be discussed and different scenarios will be presented. In the past electricity demand and economic growth were strongly correlated. One way to increase the overall energy efficiency is often the increased use of electricity. This means that a primary energy demand reduction can well go along with an increase of the electricity demand.

The discussion of the production side will start with a short overview of the possibly generation options: nuclear (fission and fusion), renewable and fossil. While shortly technological and economic specificities will presented for the individual technologies, emphasis of the discussion will be on the integration of the different technologies in a larger system. Here especially renewable intermittent production sources require special attention. Central issue of analysis is the role of fusion and fission in a nuclear-renewable hybrid system. As an example a broader discussion of a European “supergrid” will be presented, before results for a global scene are presented.

A General Approach to Nuclear Fission Sustainability and the Need for Specific Solutions – A Case Study on a New Coolant.

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Nuclear Fission has undergone a first phase of exploitation through Thermal Reactors, mainly Light Water Reactors (LWR) which contribute to generate about 16 % of World's electricity and have a good safety record, in spite TMI-2 accident.

However, LWR are not well suited for exploiting nuclear raw fuels.

Extensive exploitation of nuclear raw materials requires the use of "nuclear breeding", which is a phenomenon that can be attained in fast reactors. However, those reactors have had a complex history with some drawbacks and some important political attacks, as the INFCE initiative launched by President Carter in 1978. Two points were very relevant in that context: the extensive use of plutonium recycling and an inherent property of fast reactors that could induce positive feedback between reactivity and thermal-hydraulics. In fact, a partial or total loss of coolant could convey a tremendous injection of reactivity, which could produce a catastrophe.

An alternative to breeding in critical fast reactors is presented by hybrids [1], which are sub-critical reactors which need an external neutron source for keeping their neutron population alive. In fact, those reactors could be designed either for stimulating energy generation in the reactor itself, or to breed fissile nuclei to be burnt in other reactors [2]. The interest for that alternative has not been explored so far in depth, and it related to the very good safety standards expected in Gen 3 reactors (as AP 1000 and ESBWR) because they will embody lessons learned in TMI-2 and Chernobyl-4. But they will need a feeding reactor: a breeding hybrid.

Anyway, a reply to the challenges presented by Nuclear Fission Sustainability must rely on specific choices and designs. There is not too much that can be done in nuclear fuel, because natural ores are composed by uranium and thorium, and the bred nuclei are Pu-239 and U-233 respectively. So, attention must be paid to coolants, and this is the case of an initiative to feature beryllium fluoride as a coolant for hybrids [3] in an attempt to reach high final burn-ups in a single cycle, without needing recycling, and avoiding positive reactivity feedback by loss of coolant or coolant void accidents. First series of results are promising in neutronics, particularly for thorium, although additional studies are needed to characterize it from the point of view of material compatibility and damage effects.

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Sustainable Energy Security: Need for a Comprehensive Systematic Integrated Approach

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While multiple independent energy projects can improve US energy security, a more comprehensive systematic and integrated approach is recommended. Technology and engineering solutions, as good as they are or potentially can be, are greatly needed but they alone cannot bring about the change needed to ensure US Energy Security. There is a need to rethink our approach to a sustainable energy security and then take deliberate actions to achieve it.

Embedding Emerging Nuclear Systems in Sustainable Development: the Shadow of Nuclear Past and a Potential Dark Side of Nuclear Future

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Last 50 yrs the conventional Nuclear Power (NP) witnessed several periods of optimistic expectation for NP growth. Nevertheless, no one scenario was completely realized, and periods of high expectation followed by NP stagnation. Apparently, this proves that not only economic but also social and geopolitical environment is at least not fully favorable to the conventional NP.

Being nuclear, an Emerging Nuclear System (ENS) inherits this unfavorable environment. The ENS should therefore cope with the sigma of nuclear past and a potential dark side of nuclear future.

The paper reviews several international studies of the global nuclear legacy performed last decade and the implication of the legacy on generic perspective of NP.

Further, the paper identifies and discusses unresolved problems of nuclear fuel cycle, which can feed threat of proliferation and emerging face of nuclear terrorism.

Finally, the paper formulates some recommendations that would help proponents of emerging nuclear energy systems to govern identified problems and thus helps to embed NP in sustainable development.

Long-term Planning for Nuclear Power's Development in Japan for a Zero-carbon Electricity Generation System by 2100

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Nuclear power is expected to contribute to the realization of a zero-carbon electricity system much more than the intermittent, complicated and costly renewable energy in the future in Japan. Therefore, in the present study, nuclear power development for a future zero-carbon energy system was studied through scenario analysis. The study was conducted in three steps to (i) estimate future electricity demand and electrical load pattern by 2100; (ii) determine the contribution of nuclear power to the electricity generation based on various constraints including construction space, nuclear fuel availability, advanced reactor technologies, and so on; and (iii) test the feasibility of the nuclear-based electricity system in term of supply-demand balance. An integrated computer software platform was developed to conduct the analyses.

In the first step, the electricity demand reduction was estimated based on the performance improvement of thermal insulation of buildings and efficiency of air-conditioners for cooling and heating in summer and winter respectively. On the other hand, the newly-added controllable electrical loads represented by electric vehicles (EV) and heat pump (HP) were considered. The final electrical demand and load by 2100 were obtained based on present electrical load, future predicted demand reduction and newly-added loads. In the second step, two scenarios with maximum and minimum nuclear power are calculated separately to determine the contribution of nuclear power to a zero-carbon electricity generation system for meeting the obtained electricity demand. The available construction space was estimated considering the increase of reactor capacity from 1GW per set to 1.7 GWe. The nuclear fuel availability was studied based on Fast Breeder Reactors (FBR), nuclear fuel recycling, extracting uranium from seawater and thorium utilization technology. Furthermore, the ADSR (Accelerator Driven Subcritical Reactor) was assumed to be used to transmutate high level nuclear waste with a long half-life. In the third step, hour by hour simulation was conducted to examine the supply-demand balance of the nuclear power based electricity system with the help of batteries in EV and hydrogen for electricity storage under smart control technologies.

The analysis results show that comparing with 2005, the total electricity demand will increase by 50% by 2100. Nuclear power contributes 60%-100% of total electricity production and its capacity factor needs to be enhanced from the present 60-70% to 80-90%. The necessary construction space, nuclear fuel utilization and replacement schedule were studied based on various nuclear fuel and reactor technologies. The obtained nuclear power based electricity system was proven to be feasible in terms of the supply-demand balance.

Fusion Demo Program of Korea

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The strategic plans of the Fusion DEMO Program of Korea, of which the total capital investment and duration are expected to be 5 to 11 billion US dollars and around 27 years respectively, were developed [1] and introduced [2]. In line with the strategic plans, to facilitate R&D portfolio management, the Program is divided into the phased Sub-Programs that are the DEMO Preparatory Program from 2009 through 2011, the DEMO R&D Program from 2012 through 2021 and the DEMO Construction Program from 2022 through 2036. The strategic plans define the vision, mission, strategic goals, key strategies and strategic initiatives with the implementing measures for the strategic initiatives. The implementation plans define the scope of works of, time lines of and resources required for the Sub-Programs.

The top tier requirements and limitations of the DEMO Fusion Power Plant (DEMO FPP) including, but not limited to, the user requirements and material development are studied, defined and assumed. With these top tier requirements and limitations, studies on thermal cycle, heat transfer medium and material selection are carried out: DEMO Reactor is to use pressurized light water to transfer the heat from the Fusion DEMO Reactor (DEMO Reactor) to its secondary side through two steam generators; adopt a super critical steam cycle, with the power generation capacity of 600 MWe, for the secondary side; use the material characteristics with moderate enhancement from the contemporary materials. Cross-cuttings ideas are discussed and incorporated in the selection of thermal cycles and definition of the concept of DEMO plant.

With the concept of DEMO Plant defined, DEMO Reactor systems, engineered safety features and balance of plant systems are identified to develop the Preliminary WBS of DEMO Plant and make the DEMO R&D activities pulled from the final deliverables. Technologies and materials required for the design, fabrication and construction of the components and systems of each element of the WBS are studied to set the desired goals for each WBS element. The gaps between the contemporary technologies and desired goals are studied and studies to fill the gaps with KSTAR, ITER and global DEMO consortium are also conducted. The global DEMO R&D consortium proposed in DEMO Program of Korea is not to confront with the Broader Approach of EU and Japan but to supplement the efforts of EU and Japan as to expedite filling the gap and commercialization of Fusion Energy. The front-end R&D activities including the researches on the concept of the kinetics of control system of DEMO Reactor and licensing of DEMO Plant are identified and launched. The test facilities required for the validation of the design methods to be developed to fill the gaps are also identified.

The DEMO Construction Sub-Program is to be carried out in two phases to avoid the logical dilemma of “the material first or the DEMO first”. In the first phase DEMO Plant the tests, which cannot be carried out without DEMO, on the materials, components and systems will be conducted. The economic feasibility will be verified at the second phase DEMO.

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Conceptual Design Study and Strategy toward Fusion Demonstration Plants

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A report in 2005 by the Atomic Energy Commission of Japan has stated an expectation to secure the prospect of putting fusion into practical use by the middle of 21st century. A roadmap based on this policy was developed in 2008. The roadmap consists of a breakdown list of works which has shown and categorized the R&D issues required to construct the DEMO plants.

Two tokamak concepts, SlimCS[1,2] and Demo-CREST[3], have been proposed in Japan as possible DEMO designs which will fit in the policy. The major radius of the SlimCS (R=5.5m) is smaller than the ITER (R=6.2m) and the aspect ratio A is 2.6 which is similar to the plasma of JT-60SA. The radius of Demo-CREST (R=7.3m) is larger than the ITER but the aspect ratio is similar to ITER. The engineering requirement for both designs is close, while the required plasma performances are somewhat different.

In the concept of SlimCS, the CS (Central Solenoid) has a small radius (0.7m), being capable of plasma shaping and plasma current ramp of 3.8MA (23% in operating current). Although such small CS size causes a constraint in operation, it has advantages to allow us to introduce a thin toroidal coil and contributing a reduction of the reactor size and its cost. The SlimCS also adopts the sector transport hot cell maintenance scheme, which minimizes time required for the maintenance, and then results in the low operation cost. The blanket of DEMO is required to have continuity with the Japanese ITER-TBM program in which water-cooled solid breeder blanket will be developed. The blanket system of SlimCS satisfies this requirement. The temperature and pressure of the coolant are one of the key issues in the blanket design. The PWR conditions (15 MPa, 285-325ºC) will be problematic in that the required large amount of coolant can detract the TBR (tritium breeding ratio). Use of supercritical water (25 MPa, 280-510ºC) is anticipated to cause serious corrosion of law activated ferritic steel (F82H). Considering these points, the subcritical water condition of ~23MPa and 290-360ºC (ΔT=70K) is chosen for SlimCS. The local TBR can attain 1.42, corresponding to the net TBR of 1.05.

The unique feature of Demo-CREST concept is the two phase operations, i.e. demonstration phase (1st phase) and development phase (2nd phase). In the 1st phase, net electric output less than 500MWe is planned with minimum extension from the ITER technology. This design policy results in the size larger than ITER. The 2nd phase will be offered to demonstrate the economic competitiveness with advanced design blanket and higher plasma performance. It has been considered how to start up this demo-plant if no initial inventory of tritium is secured[4,5]. In the initial stage of commissioning, the DD reactions with external power injection by neutral beams produce tritium and neutrons. Tritium produced by the DD reaction together with that produced in the blanket is re-circulated into the plasma, then, the D/T ratio increases from 100/0 to 50/50 within about 100 days. Since no natural resource of the tritium is available, such 'tritium free' start-up scenario will reduce anxiety on the fuel security of the fusion energy[4].

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Energy Synergism: A Framework for Energy Stability

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Energy scenario in the twenty-first century is rather complex. Most countries in the world depend on external energy sources, and economic development and population increase are boosting a new process in the frame of environmental protection and reduction of CO_2 emissions.

European Union energy policy is mainly based on its very limited endogenous natural resources. Energy priorities have been focused on the reinforcing of a more stable framework with traditional suppliers, Russian Federation and OPEC countries, and the establishing of a pragmatic cooperation with some Central Asia republics and Caspian Littoral States. This cooperation is aimed at a sustainable development of their energy sectors, as well as at the diversification and expansion of export routes, demand and supply structures.

Energy security, together with Kyoto Protocol commitments, have led European countries to redefine its energy policy. EU demand of fossil fuel energies (consumption minus national production) is presently 55%, twice the US demand. This implies an energy problem that must be solved as soon as possible. With this approach, European countries have established different R&D programs to develop alternative energy sources, both renewable and nuclear, considering the present fission energy and, in a future, fusion energy. High temperature solar energy has an important future perspective in the efficient production of electrical power and new photovoltaic cells are under R&D.

Related to nuclear fusion, the Working Group on Inertial Fusion Energy was established in the European Union more than ten years ago, being one of its objectives the research coordination of the main laboratories in the field. The encouraging way opened after the NIF success, together with the forthcoming MJL, will bring nuclear fusion future closer. Our Institute of Nuclear Fusion (DENIM) has been working during 25 years in the development of simulation codes for pellet design and fast ignition (ARWIN), atomic physics (ABACO), materials (MDCASK) and activation analysis (ACAB).