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## SYNERGIES BETWEEN GENERATION-IV AND ADVANCED FUSION POWER PLANT RESEARCH PROGRAMS

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*For the first time since the early 1990's, the U.S. Department of Energy has long term research and development programs in both nuclear fission and nuclear fusion, the Generation IV program and the ARIES program, respectively. The Generation IV program has introduced a safety goal for future fission reactor systems that has long been reflected in the ARIES mission: no off-site emergency response to any design basis accident. This change, in concert with the overall departure from light water reactor technology, will drive a change in the regulatory framework for both Generation IV reactors and fusion power plants of the future. Further, both fission and fusion power plants will have to compete in similar future energy markets with uncertainties in energy prices and the development of alternative energy products. Enabling the success of nuclear energy, advanced materials will be a cornerstone to both programs, driven both by higher temperatures and heat fluxes and by a desire for longer lifetimes in high radiation environments. The synergies created by these increasingly parallel programs open the door for renewed collaborations that will increase the total effectiveness of research needed in both.*

### I. INTRODUCTION

The Generation IV[1] fission reactor development program and the advanced fusion power plant design studies have a great deal of overlap in their goals and their fundamental research needs. This situation is, in part, reflected in the 2001 National Energy Policy that explicitly recognized the near-term contributions of nuclear fission and the long-term value of nuclear fusion. In particular, the Generation-IV program represents a new vision for fission research in the U.S. and coincides with a general rebound in funding levels from the lows of the late 1990s. Similarly, the fusion community is benefiting from an increase in the number of advanced power plant design efforts and a return to participation in the ITER project.

### I.A. The Generation IV R&D Program

William Magwood, IV, Director of the U.S. Department of Energy's Office of Nuclear Energy, Science and Technology, coined the term "Generation IV" in order to refer to a set of reactor technologies that would be deployable by 2030 and aimed at aggressive goals that would set them apart from existing reactors. At the same time, he was recognizing the three distinct generations of reactors that are already in use: a first generation of demonstration and prototype power reactors, a second generation representing the majority of installed U.S. nuclear reactors (and most of those around the world), and a most recent third generation of reactors that features advanced safety systems and have so far been deployed only overseas. The goals for the Generation IV program are broadly defined as:

- Highly economical: competitive with other ways of generating electricity and other energy products,
- Enhanced safety: further reducing potential human impacts,
- Minimized wastes: optimizing fuel cycles to reduce quantity and hazard of waste streams, and
- Proliferation resistance: allowing international deployment while maintaining global security.

The Generation IV program is being pursued by a growing global partnership including Argentina, Brazil, Canada, the European Union, France, Japan, South Korea, South Africa, Switzerland, Great Britain, and the United States. The research and development roadmap was developed following an extensive review of over 100 specific concepts contributed by research teams from around the world. The evaluation of these concepts led to the development of general conceptual directions and a down selection to six specific concepts described in Figure 1.

Of these, the first four are receiving the most attention in the United States and recent budget increases in nuclear energy research and development have been steered to directly support them.

Very High Temperature Reactor [VHTR]:
focused primarily on high temperatures for the efficient production of $H_2$,
Supercritical Water-cooled Reactor [SCWR]: focused on improved economics with an extension of today's technology,
Gas-cooled Fast Reactor [GFR]
focused on actinide management with enhanced safety,
Lead-cooled Fast Reactor [LFR]
focused on small/modular "battery" concepts with long-lived cores,
Sodium-cooled Fast Reactor [SFR]
building upon decades of international experience for actinide management, and
Molten Salt-cooled Reactor [MSR]
a liquid-fueled concept that addresses actinide management and resource extension.

Figure 1. Six Generation IV Concepts being explored in R&D Roadmap

### I.B. Advanced Fusion Power Plant Design Programs

Historically, the development of potential fusion plant designs has been centered in the ARIES [Advanced Research, Innovation and Evaluation Study] program. This program, active since about 1986, has a long history of studying Tokamaks, Stellarators and other toroidal magnetic devices, and most recently inertial fusion energy concepts[2]. Among other contributions, the ARIES program has been responsible for integrating advances in understanding of plasma physics into new engineering designs in order to optimize the performance of fusion power plants in terms of economics and environmental impact. Most importantly, the ARIES program has interacted with other elements of the fusion energy program to identify engineering weaknesses and the gaps in physical understanding which drive them.

More recently, congressional interest has developed in two specific inertial fusion design efforts. Beginning in 2003, the High Average Power Laser [HAPL] program[3] is focusing on a complete power plant design based on recent advances in laser technology, identifying the most critical obstacles to the success of laser fusion energy. Just this year, a new program was initiated to explore the possibility of a fusion energy system based upon a Z-pinch/pulsed power driver, the Z-Pinch Power Plant program.

### I.C. Overview of Synergies

The synergies between the reinvigorated fission R&D program and the ongoing fusion power plant studies are found first in the increasing convergence of the programs' goals, primarily those of safety, environmental impact and economics. However, synergies arise upon deeper exploration into the technical details and obstacles of the research programs. Nowhere is that more true than in the field of materials. Perhaps true of most engineering fields, the development of advanced materials offers the promise of significant performance improvements for both fission and fusion systems, in the latter case opening a window of technical and economic feasibility. This paper explores the synergies that arise from the increasing convergence of the program goals and their similar need for advanced materials development.

## II. THE ENVIRONMENT, SAFETY AND REGULATION

Increasingly, developers of new technology (of any kind) are required to consider the impact of that technology on both the natural and man-made environments in which they exist. This is certainly true for nuclear technology and highlighted by the goals of the Generation IV project with respect to safety and the environment.

High-level radioactive waste [HLW] has long been a point of division between fission and fusion power systems. Where fission systems will always have to deal with the creation of highly radioactive material, regardless of the sophistication of the fuel cycle, fusion power plant studies have used the avoidance of HLW as a design constraint[4]. While this will continue to be true, new nuclear fuel cycle developments seek to greatly reduce the HLW produced by fission systems, whether by improving the power plant performance or by implementing new fuel cycles under the closely related Advanced Fuel Cycle Initiative[5]. (Interestingly, some researchers have even suggested fusion systems as neutron sources for the transmutation of fission waste to further reduce this issue.[6])

Both fission and fusion systems will have comparable quantities of low-level waste [LLW], but their life-cycle waste streams will be dominated by so-called *clearable material* that has activity levels below regulatory limits but is often considered "tainted" by its use in a nuclear system. Progress by the various compacts (affiliations of states organized under federal law to develop joint solutions to LLW disposal) in the development of LLW sites and changes in the societal and commercial views on clearable materials will have similar benefits for fission and fusion systems.

Perhaps more significant is the Gen-IV goal to eliminate the need for an offsite evacuation plan, bringing it on par with a similar goal that has been a constraint for the development of fusion systems for over 8 years[4]. The impact of such a goal will be felt throughout the design of a reactor, whether choosing fuel forms, designing safety systems, or building a containment (or confinement) structure. In addition to imposing design constraints, experimental evidence and analysis capabilities will have to be sufficient to inspire confidence in regulators and the public that this goal can be met by a nuclear system.

As already alluded to above, most improvements in the environmental impact and safety performance of nuclear systems will have to be implemented in concert with changes in the regulatory structure. Because today's US nuclear fleet consists entirely of light water reactors, the regulatory framework is slanted towards the successful regulation of such systems. Specific design limits, analysis techniques and accident scenarios have been developed under this framework to give an ever increasing confidence in the safe operation of nuclear power and in our ability to make the safety assessments themselves. The current regulatory environment is the result of many decades of continuous improvement, including specific enhancements following the accident at Three Mile Island, a light water reactor. Even early conceptual designs for Generation IV reactors anticipate significantly different engineered systems and correspondingly altered safety strategies. For example, there is an effort to design gas cooled reactors in which decay heat can be removed adequately by natural circulation. Therefore, in addition to an arguably simpler passive safety strategy, the choice of coolant might allow a smaller containment structure with a different purpose from an LWR containment. Modular liquid metal cooled plants aim to have the plants passively follow balance of plant demand using reactivity feedbacks and natural circulation flow. These plants would be designed such that the balance of plant has no safety function, thus simplifying licensing. Regulations will need to be developed to allow licensing of these design features.

Fusion power plants will also include such significant departures from the current basis for nuclear power plant regulation. Whether they are similar to Generation IV plants in their specifics (gas-cooled blankets or natural circulation decay heat removal) or in their design philosophies (no offsite evacuation requirements), changes in the regulatory framework will be necessary for fusion power plants to achieve their economic and safety performance goals. Hence, in this area of regulatory reform, not only are there potential synergies with respect to the specific changes in regulation, but the act of changing the regulatory framework will provide valuable lessons applicable to all future nuclear power systems.

## III. ECONOMICS AND ENERGY PRODUCTS

The economic climate for energy systems of the future is increasingly uncertain as oil and natural gas prices reach new highs, electricity market deregulation and restructuring occurs at differing paces and in different forms around the country, and global interest in alternative energy products increases. Nevertheless, nuclear systems, both fission and fusion, will need to compete in these markets with similar financial profiles: capital-intensive, operating and maintenance costs that eclipse fuel costs, and available to supply a wide variety of energy products. As such, any improvements in the economic performance of one type of system, or in the understanding of its important financial parameters, may be useful for the other.

Given the many decades of experience with the construction and operation of nuclear fission power plants, for example, nuclear reactor vendors have recognized that their future systems, including Generation IV reactors, will need to minimize capital costs and construction times. Not only do these have a clear and primary impact on the final levelized cost of electricity, but they also play a secondary role in contributing the financial risk that is involved for investors. A recent study by the University of Chicago, motivated in part by the renewed interest in nuclear fission R&D, discussed the various sources of risk premium associated with nuclear power plant construction and concluded that new nuclear plants would face a 3 percent risk premium due to uncertainty in construction times, energy market fluctuations and licensing hurdles. This value was arrived at even after taking credit for successful overseas construction experience and an improved licensing regime. To be sure, new nuclear fusion power plants would initially face an even greater premium due to the utility market's lack of familiarity with the technology.

One component of new fission reactor development is focused upon methods to ensure lower capital costs and faster construction times. One approach is to maximize the fraction of the plant that can be fabricated in a controlled factory environment and then transported to the site for rapid assembly. AECL has already demonstrated this in the recent CANDU power plants built in China where even pieces of the containment building were prefabricated and shipped to the construction site[7]. The construction of large engineering structures by the assembly of pre-fabricated modules would be a virtual necessity for fusion power plants given their large and complex components and the high energy neutron fluxes that limit component lifetime. In fact, many fusion power plants are designed for the regular replacement of large components[8,9] throughout the life of the system such that developments in this field of modular construction could impact both the construction and operation costs of a fusion power plant.

The economic performance of nuclear systems will also benefit from policy-driven financial incentives such as loan guarantees or production tax credits. While it is outside the scope of this paper to fully discuss the range and impact of these policy implications, near term developments for new fission power plants (pre-Gen-IV) would set possible precedents for the support of nuclear energy of all kinds.

Another way for nuclear systems to improve their economic performance is to be effective participants in newly opened energy markets. While there is likely a role for nuclear energy systems in the desalination of water to ensure global fresh water supply, the predicted hydrogen economy of future decades offers a valuable role for nuclear energy systems. The largest single effort in the U.S. Generation-IV program is devoted to the development of the very high temperature reactor as a heat source for high-temperature thermo-chemical processes for the production $H_2$. Coupled with the Nuclear Hydrogen Initiative[10,11], this area of research offers the promise of large quantities of $H_2$ with no airborne emissions. The temperatures required by these reactors are much higher than the typical temperatures of current light water reactors, but not unusual for fusion reactors. The development of technology and markets for nuclear generated hydrogen will easily allow fusion to make an early entry into the market of $H_2$ production.

## IV. MATERIALS

While there are certainly many common enabling technologies and synergies between fission and fusion (e.g. improvements in remote handling, power conversion cycles or various energy products, etc) none is clearer than the need for the development of advanced materials for radiation environments.

In order to realize the goals of both the Gen-IV and advanced fusion power plant development programs, the systems will have to operate in environments that are more taxing than the current fleet of nuclear reactors. The fusion materials community has spent considerable effort on developing low activation structural materials capable of withstanding the high temperatures and large irradiation doses necessary for economic and efficient operation of a potential fusion reactor. Under the Gen-IV program, future fission reactors will be driven by some of the same concerns. Table I summarizes some of the major parameters that limit material performance in current nuclear reactors, fusion reactors and Gen-IV reactors. Both advanced fission and fusion systems are considering alternative coolants that may be more chemically aggressive than light water coolant that forms the current basis for nuclear materials experience.

The materials of construction must demonstrate adequate mechanical strength, ductility, and toughness, must demonstrate adequate dimensional stability, must maintain adequate thermophysical properties, and must have acceptable resistance to corrosion and stress corrosion attack from cooling media[12]. The development and testing of materials to meet these requirements requires a robust experimental program. Realistically, experimental programs cannot cover the breadth of materials and irradiation conditions for the proposed fusion and Generation IV fission reactor designs. A set of tools is required to assist in a material selection process that will be performed based on an incomplete experimental database and that requires considerable judgment to carry out the necessary interpolation and extrapolation. Modeling and microstructural analysis can provide the intellectual foundation for these important decisions.

Table I. Advanced Fission and Fusion Operating Conditions[12]

| | Fission | Fusion | Gen IV |
|---|---|---|---|
| **Coolant** | $H_2O$, $CO_2$ | $H_2O$, He, Li, PbLi, FLiBe | $H_2O$(SC), He, Pb, PbBi, Na |
| **Particle Energy** | < 1-2 MeV | < 14 MeV | < 1–2 MeV |
| **Temperature** | <400˚C | 300-1000˚C | 300-1000˚C |
| **Max displacement damage** | <20 | ~ 200 | 15–200 |
| **He/dpa** | ~ 0.1 appm/dpa | >10 appm/dpa | ~ 0.1 appm/dpa |
| **Stresses** | Moderate, nearly constant | Moderate, nearly constant | Moderate, nearly constant |

Materials degradation from radiation starts with collisions between high-energy neutrons and lattice atoms and then develops into radiation-induced microstructures that degrade mechanical properties, dimensional stability, thermophysical properties, and resistance to environmental attack. This is true in both fission and fusion systems. A set of computational tools that adequately describes radiation events and subsequent microstructural development and provides from this microstructure an accurate description of property changes in engineering materials would be a tremendously valuable tool for system designers. While developing these computational tools to a true predictive capability is a difficult and time-consuming challenge, the knowledge gained from development of the individual components of the models will provide valuable insight to any on-going materials development and design effort. These models cannot be developed without a parallel set of validation experiments. The interplay between new experimental data and advanced theory or computational tools is critical to the development of accurate radiation response models.

While there are many similarities between fission and fusion systems, some important differences do exist. For example, the higher energy neutrons in fusion systems will lead to greater concentrations of the transmutation gasses helium and hydrogen. Additionally, certain Generation IV concepts use different coolants and may respond to changes in microstructure in a unique manner. These differences do not dramatically change the types of computation tools that need to be developed. The tools need to couple descriptions of radiation cascades all the way to bulk property changes and this basic set of tools will be valid for both fission and fusion. The differences in environment only dictate that a broader set of confirmatory experiments is required to ensure the models operate over the entire operating regime of fission and fusion systems.

## V. SUMMARY AND RECOMMENDATIONS

The advent of the Generation IV fission R&D program has introduced a new degree of convergence and similarity to the goals and promise of future fission and fusion energy systems. Both the Generation IV program and the advanced fusion power plant research and development programs have a long-term focus of delivering increased energy security with a commitment to environmental stewardship. At the same time, while there are certainly significant differences, both fission and fusion programs overlap in the obstacles and issues that will be vital to their long-term success. Most notable among these is the development of advanced materials for extreme environments. While the fusion program has always had a strong emphasis on the development of optimized materials, the ambitious goals of the Generation IV reactor concepts has increased the need to develop new materials for fission reactors too. Common ground can also be found in the realm of safety and regulation where the Generation IV program is responsible for advancing the goals of fission to be similar to the long-stated goals of the fusion development program. Recognizing the full benefits of these advanced safety strategies will require reform of regulations that are currently strongly oriented towards the light water reactor technology that forms the current nuclear fleet. Finally, the economic profile of future fission and fusion plants – capital intensive, generally unsusceptible to fuel price fluctuations and arguably competitive with alternative baseload systems – is subject to great uncertainty, both in the realization of expected improvements in economic performance and in the external energy markets in which these systems must compete.

Consequently, an increased interaction between the fission and fusion communities would probably result in gains for both. Given the range of expected deployment dates for the Generation IV reactor concepts, they can be viewed as valuable stepping stones on the path to a nuclear future that includes fusion. The lessons learned from the introduction of these gradually greater departures from a system of only light water reactors will be valuable in preparing the deployment of fusion reactors. Opportunities exist to increase the interaction between the small fusion technology community and the much larger fission research and development community, whether at professional meetings, within research groups, or via formal leveraging of funds for common research priorities. Exploring these opportunities could accelerate, or ultimately enable, the successful deployment of both the Generation IV fission concepts and fusion power plants.

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