NUCLEAR ENERGY INNOVATION AND THE NATIONAL LABS

HEARING

BEFORE THE

SUBCOMMITTEE ON ENERGY

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HOUSE OF REPRESENTATIVES

ONE HUNDRED FOURTEENTH CONGRESS

FIRST SESSION

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NUCLEAR ENERGY INNOVATION AND THE NATIONAL LABS

WEDNESDAY, MAY 13, 2015

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON ENERGY
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to call, at 10:05 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Randy Weber [Chairman of the Subcommittee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

FDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congreſs of the United States
House of Representatives
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
2321 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, DC 20515-6301
(202) 225-6371
www.science.house.gov

Subcommittee on Energy

Nuclear Energy Innovation and the National Labs

Wednesday, May 13, 2015
10:00 a.m. – 12:00 p.m.
2318 Rayburn House Office Building

Witnesses

Dr. Mark Peters, Associate Laboratory Director, Energy and Global Security, Argonne National Laboratory

Mr. Frank Batten, Jr., President, The Landmark Foundation

Mr. Nathan Gilliland, CEO, General Fusion

Dr. John Parmentola, Senior Vice President, Energy and Advanced Concepts Group, General Atomics

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON ENERGY

HEARING CHARTER

Nuclear Energy Innovation and the National Labs

Wednesday, May 13, 2015
10:00 a.m. – 11:30 a.m.
2318 Rayburn House Office Building

Purpose

The Energy Subcommittee will hold a hearing titled *Nuclear Energy Innovation and the National Labs* on May 13th at 10:00 a.m. in room 2318 of the Rayburn House Office Building. This hearing will discuss research activities and infrastructure within the Department of Energy's national laboratories and how the private sector leverages those capabilities for investments with near-term payoff. This hearing will focus on research to advance nuclear energy technology.

Witnesses

- **Dr. Mark Peters**, Associate Laboratory Director, Energy and Global Security, Argonne National Laboratory
- **Mr. Frank Batten, Jr.**, President, The Landmark Foundation
- **Mr. Nathan Gilliland**, CEO, General Fusion
- **Dr. John Parmentola**, Senior Vice President, Energy and Advanced Concepts, General Atomics

Background

The Department of Energy (the Department) currently owns seventeen national laboratories (labs or the national labs), sixteen of which are operated by contractors as Federally Funded Research and Development Centers (FFRDCs).[1] These government-funded labs provide unique research capabilities to advance scientific research and development (R&D). In certain research areas, private sector companies invest in cooperative R&D with national labs with the goal of commercializing certain technologies. The national labs recruit researchers while also overseeing the construction and operation of research facilities.

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[1] See the complete list of FFRDCs here: http://www.nsf.gov/statistics/ffrdclist/

The Department's open-access user facilities comprise one of its most prominent offerings to enable cutting edge research. User facilities are capital intensive, one-of-a-kind machines that enable a specific type of research. For example, Oak Ridge National Laboratory in Tennessee operates the Spallation Neutron Source, a billion dollar assembly that provides the most intense pulsed neutron beams in the world for scientific research purposes.[2] Another example at Argonne National Laboratory is the Advanced Photon Source, an ultra-bright x-ray beam.[3] Research ranging from materials science to pharmaceuticals relies on these user facilities that require large capital investments that the private sector cannot undertake on its own.

Nuclear energy technology development relies heavily on the capital intensive and unique systems at the national labs, partially because of its technological complexity and also due to the high regulatory cost to license civilian nuclear activities. The Nuclear Regulatory Commission (the NRC) regulates all civilian activities involving nuclear material with the exception of the Department's research facilities, which are not regulated by the NRC.[4] A private company or researcher seeking to construct and operate a reactor, even for noncommercial research purposes, must obtain a license from the NRC which may costs hundreds of millions of dollars and require decades of processing time.

Historically, the Atomic Energy Commission and the Department (as its successor) enabled the advancement of nuclear energy technology by using its authority to construct and operate reactors for research purposes. There has been much debate in recent years about whether the Department has lost its competence to continue this work and to what extent the Department continues to fulfill its mission to enable investment and further research for advanced nuclear energy technology.

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[2] See Oak Ridge National Laboratory website here: https://neutrons.ornl.gov/sns

[3] See Argonne National Laboratory website here: https://www1.aps.anl.gov/About/Overview

[4] See Nuclear Regulatory Commission website here: http://www.nrc.gov/about-nrc.html; See also "The Department of Energy research reactors are not regulated by the NRC" here: http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/research-reactors-bg.html

Chairman WEBER. Subcommittee on Energy will come to order. Without objection, the Chair is authorized to declare recesses of the Subcommittee at any time. Welcome to today's hearing, entitled "Nuclear Energy Innovation and the National Labs." I now recognize myself for five minutes for an opening statement.

Good morning, and I've already welcomed you to the Committee Hearing this morning. We appreciate you all being here. Today's hearing will focus on the Department of Energy's National Laboratories' research capabilities, and the working relationship with the private sector to advance nuclear energy technology, both fission and fusion. The Department of Energy owns 17 national laboratories, 16 of which are operated by contractors as federally funded research and development centers. The government owned contractor operated model allows the labs flexibility to think outside of the box when tackling fundamental scientific challenges. The Department of Energy labs grew out of the Manhattan Project, and today provide the critical R&D infrastructure that will enable researchers in academia and the private sector to develop the technologies of tomorrow.

It's pretty clear that the challenges in nuclear science can be quite complicated, and we'll hear more about that from our expert witnesses on our panel today. That said, not being a nuclear physicist or anything of that sort, I'm going to do my best to simplify what we intend to discuss in today's hearing. We hope to get a better understanding of what the DOE labs do, and how their unique research machines and talented group of researches can enable companies to develop new products. This is especially relevant for nuclear energy R&D, which requires large up-front costs, but may lead to revolutionary technology with long term rewards.

Folks, I would add that the United States has a definite national interest in maintaining our position at the forefront of nuclear technology development. Nuclear energy, as you know, is in a class of its own, with the highest energy density of any fuel, and yet yields zero emissions, the big goose egg. It is also highly regulated, often a centerpiece of global, especially national, politics, and is associated with the world's strongest economies. In the United States we invented this technology, and cannot forego, we must not forego the opportunity to export more efficient and safer reactor systems that will mitigate proliferation concerns, while increasing global stability by providing a reliable energy source.

Today we're going to hear from the president of a charitable organization that has co-invested with a DOE lab to advance a specific nuclear fuel treatment process to convert nuclear waste into a useable fuel. We will also hear from the Argonne National Lab, which invented this fuel treatment process, as well as private companies developing fusion, and advanced fission reactors. Needless to say, this is a unique panel of witnesses. I thank the witnesses for participating in today's hearing, and I look forward to their testimony.

[The prepared statement of Chairman Weber follows:]

PREPARED STATEMENT OF SUBCOMMITTEE ON ENERGY CHAIRMAN RANDY K. WEBER

Good morning and welcome to today's Energy Subcommittee hearing on nuclear energy innovation. This hearing will focus on the Department of Energy's national laboratories' research capabilities and working relationship with the private sector to advance nuclear energy technology—both fission and fusion.

The Department of Energy owns seventeen national laboratories, sixteen of which are operated by contractors as federally funded research and development centers. The government-owned, contractoroperated model allows the labs flexibility to think outside of the box when tackling fundamental scientific challenges. The DOE labs grew out of the Manhattan project and today provide the critical R&D infrastructure that will enable researchers in academia and the private sector to develop the technologies of tomorrow.

It's pretty clear that challenges in nuclear science can be quite complicated and we'll hear more about that from our expert witnesses. That said, I will do my best to simplify what we intend to discuss today.

We will get a better understanding of what the DOE labs do and how their unique research machines and talented groups of researchers can enable companies to develop new products. This is especially relevant for nuclear energy R&D, which requires large up-front costs, but may lead to revolutionary technology with long-term rewards. The United States has a national interest in maintaining our position at the forefront of nuclear technology development. Nuclear energy is in a class of its own with the highest energy density of any fuel, and yields zero emissions. It is also highly regulated, often a centerpiece of global politics, and associated with the world's strongest economies.

In the United States, we invented this technology and cannot forgo the opportunity to export more efficient and safer reactor systems that will mitigate proliferation concerns and increase global stability by providing reliable energy.

Today, we will hear from the president of a charitable organization that has co-invested with a DOE lab to advance a specific nuclear fuel treatment process to convert nuclear waste into usable fuel. We will also hear from Argonne National Lab, which invented this fuel treatment process, as well as private companies developing fusion and advanced fission reactors.

Needless to say, this is a unique panel of witnesses. I thank the witnesses for participating in today's hearing and I look forward to their testimony.

Chairman WEBER. Mr. Grayson of Florida, you're recognized for five minutes.

Mr. GRAYSON. Thank you, Chairman Weber, and—for holding this hearing, and thank you to our witnesses for agreeing to participate this morning.

For decades the federal government has provided critical support for energy research and development. From solar, to wind energy, to natural gas recovery, many of the technologies allowing us to transition toward a clean energy economy, and creating entire new industries, would not be possible without Federal support, and the same is true for nuclear energy. This morning we will listen to you all regarding the Federal role in developing the next generation of nuclear energy technologies.

I'm particularly pleased that, as part of this discussion, we will learn more about innovative future fusion energy concepts, concepts that have the potential to accelerate the development and deployment of commercial fusion reactors dramatically. Fusion holds the promise of providing a practically limitless supply of clean energy to the world. In a sense, we're already dependent upon it, because the energy that we get from that fusion reactor called the sun, in the sky, is essential to the existence of life on Earth. It's proving difficult for people to replicate what the stars are able to do through sheer gravity, but based upon several developments in recent years that we'll be hearing about in part today, I am confident that we'll get there, and I hope far sooner than people may realize.

I do have my reservations about fission, another subject that we'll be discussing today. Not about the physical process itself, but the applicability of that to our energy needs. I have described fission, in a sense, a failed technology. There is a problem with spent fuel that doesn't seem to have a solution after many decades of consideration. We've had three nuclear disasters worldwide. But the answer to that may not be the German solution of simply scrapping. The answer to that may be to do further research, and try to find solutions to these problems.

In any event, I'm a strong supporter of fusion energy research, which is entirely different, in terms of its impact and potential problems, than fission. I believe that now is the time to build and operate experiments that are capable of demonstrating that manmade fusion systems can consistently produce far more energy than it takes to fuel them. I'm eager to learn about both the costs and the benefits of a wide range of new nuclear technologies, and I also look forward to hearing how nuclear energy can play an important role in developing a modern clean energy economy. Again, I want to thank you all, our witnesses, for providing your insights today, and I look forward to hearing from the Chairman and working with the Chairman on nuclear energy issues moving forward. Thank you. I yield back the remainder of my time.

[The prepared statement of Mr. Grayson follows:]

PREPARED STATEMENT OF SUBCOMMITTEE ON ENERGY MINORITY RANKING MEMBER ALAN GRAYSON

Thank you, Chairman Weber, for holding this hearing, and thank you to our witnesses for agreeing to participate this morning.

For decades, the federal government has provided critical support for energy R&D. From solar and wind energy to natural gas recovery, many of the technologies that are helping us transition to a clean energy economy and creating entire new industries wouldn't be nearly as far along as they are today, or would not exist at all, without the benefit of federal support and public-private partnerships. The same certainly holds true for nuclear energy.

This morning we are here to discuss the federal role in developing the next generation of nuclear energy technologies, and how this support may be better structured going forward. I am particularly pleased that, as part of this discussion, we will be learning much more about some innovative new fusion energy concepts that have the potential to dramatically accelerate the development and deployment of commercial fusion reactors.

Fusion holds the promise of providing a practically limitless supply of clean energy to the world. We're actually already dependent on it—the energy we get from that fusion reactor in the sky, better known as the sun, is essential to the existence of life on Earth, including us. Of course, it's a bit trickier for people to replicate what the stars are able to do with sheer gravity. But based on several developments in recent years that I know we'll be hearing more about today, I am confident we will get there—and perhaps far sooner than many realize. This is why I am such a strong supporter of fusion energy research, and I believe that now is the right time to build and operate experiments that can finally demonstrate that a manmade fusion system can consistently produce far more energy than it takes to fuel it.

That said, I am eager to learn more about the costs and benefits of a wide range of new nuclear technologies over the course of the hearing.

I certainly support an "all of the above" approach toward a clean energy economy and achieving safer, more cost-effective, and environmentally friendly ways to utilize nuclear energy can play an important role in this mix. We just need to make sure that we are making the smartest investments we can with our limited resources, and that they are in the best interests of the American people.

Again, I want to thank the witnesses for being willing to provide their insights today, and I look forward to working with the Chairman and with all of the stakeholders in this critical area moving forward.

Thank you, and I yield back my remaining time.

Chairman WEBER. I thank the gentleman from Florida, and now recognize the gentleman from Texas, the Chairman of the full Committee, Chairman Smith.

Chairman SMITH. Thank you, Mr. Chairman. In today's hearing we'll examine opportunities for advances in nuclear fission and fusion energy technologies. We will hear from the Associate Laboratory Director at Argonne National Lab, the home of the world's first reactor to demonstrate a sustainable fission chain reaction. Argonne National Lab is responsible for foundational research and development in nuclear energy that has led to many operating reactors and reactor concepts that will be discussed today. These include the integral fast reactor, and pyroprocessing. We will also hear from witnesses who represent private companies and a charitable organization, all of whom have invested in the development of advanced fission or fusion reactor designs.

Nuclear energy provides reliable zero emission power. This technology represents one of the most promising areas for growth and innovation to increase economic prosperity and lower the cost of electricity over time. This will help keep the United States globally competitive. The Department of Energy's national laboratories provide vital opportunities for the private sector to invest in innovative energy technologies. This includes its open access user facilities, which are one of a kind machines that allow researchers to investigate fundamental scientific questions. These facilities enable a wide array of researchers from academia, defense, and the private sector to develop new technologies without favoring one type of design. This represents a better approach than simply picking winners and losers through energy subsidies.

DOE's labs also provide the fundamental research capabilities that lead to scientific publications or proprietary research. In this public/private partnership, private companies take on the risk for commercializing technology, while the government enables researchers to conduct specialized research that would not be possible without Federal support. DOE's national labs keep America's best and brightest scientists working on groundbreaking research here in the United States, instead of moving to research projects overseas.

I am hopeful that today's hearing can demonstrate the importance of foundational research capabilities in the national labs that will lead to the next generation of nuclear energy technology. Inevitably, and I hope sooner rather than later, all Americans will benefit from this research.

Now, Mr. Chairman, before I yield back, I just want to apologize to our witnesses, I have another Subcommittee meeting of another Committee that I need to go to briefly, and then hope to return, so—but do look forward to meeting and hearing what the witnesses have to say today.

[The prepared statement of Chairman Smith follows:]

PREPARED STATEMENT OF FULL COMMITTEE CHAIRMAN LAMAR S. SMITH

Today's hearing will examine opportunities for advances in nuclear fission and fusion energy technologies. We will hear from the associate laboratory director at Argonne National Lab, the home of the world's first reactor to demonstrate a sustainable fission chain reaction.

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Inevitably, and I hope sooner rather than later, all Americans will benefit from this research.

Thank you Mr. Chairman and I yield back.

Chairman WEBER. Thank you, Mr. Chairman. Let me introduce our witnesses. Our—Dr. Mark Peters, our first witness today, is the Associate Laboratory Director for Argonne National Laboratory's Energy and Global Security Directorate, which includes Argonne's programs in energy research and national security. Dr. Peters has worked with the national labs for 20 years. In addition, he serves as a senior advisor to the DOE on nuclear energy technologies and nuclear waste management. Dr. Peters received his Bachelor's Degree in geology from Auburn University, and his Ph.D. in geophysical sciences from the University of Chicago. Welcome, Dr. Peters.

Our next witness is Mr. Frank Batten, Junior, Chairman and CEO of Landmark Media Enterprises, and President of the Landmark Foundation. The Landmark Foundation focuses its efforts on helping local education and human service organizations. Mr. Batten received his Bachelor's Degree in history from Dartmouth, and his MBA from the University of Virginia. Welcome, Mr. Batten. Am I pronouncing that right?

Mr. BATTEN. Yeah.

Chairman WEBER. Our next witness is Mr. Nathan Gilliland, okay, Chief Executive Officer of General Fusion. Before joining General Fusion, Mr. Gilliland served as an entrepreneur-in-residence with Kliner, Perkins, Caufield, and Byers, one of the world's largest venture capital firms. In addition, he was the president and co-founder of Harvest Power, a renewable energy company that turns organic waste into natural gas and electricity. Mr. Gilliland received his Bachelor's Degree in political science from the University of California, Berkeley. Welcome, Mr. Gilliland.

Our final witness today is Dr. John Parmentola, Senior Vice President of General Atomics' Energy and Advanced Concepts Group. Dr. Parmentola oversees a team of nearly 475 from over 90 institutions worldwide who lead the way in international nuclear fusion and fission research and development. Before joining General Atomics, Dr. Parmentola served as Director of Research and Laboratory Management for the United States Army. In addition, he served as Science and Technology Advisor to the Chief Financial Officer of the Department of Energy. Dr. Parmentola received his Bachelor's Degree in physics from Polytechnic Institute of Brooklyn, and his Ph.D. in physics from MIT. Welcome, Dr. Parmentola.

We're going to turn to our witnesses now, and you all are recognized for five minutes. We ask that you keep your testimony to five minutes. Dr. Peters, we'll start with you.

TESTIMONY OF DR. MARK PETERS, ASSOCIATE LABORATORY DIRECTOR, ENERGY AND GLOBAL SECURITY, ARGONNE NATIONAL LABORATORY

Dr. PETERS. Good morning. Thank you, Mr. Chairman. I would like to thank Chairman Smith, Chairman Weber, Ranking Member Grayson, Congressman Lipinski, Congressman Hultgren, and the other distinguished members of the Subcommittee for your invitation to testify here today on this important subject. My name is Mark Peters, and I am the Associate Laboratory Director for Energy and Global Security at Argonne National Laboratory. And, Mr. Chairman, I've prepared a detailed written testimony that I request be submitted for the record, and I'll summarize it here.

Chairman WEBER. Without objection.

Dr. PETERS. The history of nuclear energy development in the U.S. is one of cooperation amongst the federal government, its DOE national labs, universities, and industry. The breakthroughs and designs achieved by the scientists and engineers of the national laboratory complex, and Argonne in particular, inform and drive every nuclear reactor design in the world today.

The U.S. continues to be the lead source of innovation globally for the current generation of light water reactors, or LWRs, and small module reactors, or SMRs, as well as leading in regulatory process, independence, and rigor. But a 30 year hiatus in the construction of new U.S. reactor projects has impacted domestic production capacity, investment in technology and innovation, and the domestic supply chain.

The country's leadership in global nuclear energy could be further compromised as the world begins to move beyond the current generation of nuclear reactors to new designs, known as advanced, or generation four, reactors that can address the future challenges of nuclear energy. Other countries are forging ahead with new reactors that, when coupled with advanced fuel cycles, can address long running challenges with nuclear waste management, make significant gains in efficient use of fuel, and operate even more safely than current generation reactors, further addressing lingering public acceptance and confidence challenges.

Without a commitment to advanced reactor technology development and demonstration in the U.S., our country runs the risk of defaulting on the return of 7 decades investment in nuclear SMT and infrastructure. That lead position has allowed the U.S. to become the recognized world leader of efforts to control nuclear proliferation, ensure the security of nuclear materials, and promote safe and secure operation of nuclear power plants. If the U.S. is to ensure its rightful place at the forefront of advanced nuclear energy systems, it will require a new commitment to the type of public/private partnership that led to the creation of our current fleet of light water reactors.

Our national labs and universities continue to work closely with industry to accomplish much of the research necessary to facilitate advanced reactors, but substantial work remains. A new generation of advanced reactors will require refinement and demonstration of new technologies, as well as a test reactor and demonstration test bed for demonstration of advanced reactors. More work remains to be done on advanced fuel cycles and providing options to close the fuel cycle, decreasing the amount of waste that must be stored, and simplifying geologic disposal requirements.

Perhaps no effort better illustrates how cooperation between national laboratories and industry can enable important breakthroughs in nuclear energy than the long running collaboration between Argonne and General Electric, Hitachi Nuclear Energy. This collaboration stretches back to the '50s, in the days when we were working on experimental boiling water reactors in collaboration with GE, and more recently in GE's advanced reactor design known as Prism, which also has its root in this public/private partnership. And Prism was created using principles demonstrated at Argonne's Experimental Breeder Reactor II, or EBR–II, and further refined in the Integral Fast Reactor, or IFR.

With the creation of EBR–II, and the following design of IFR, the march towards continued U.S. leadership seemed inevitable, however, in the 1970s and '80s, a variety of developments coalesced to move the U.S. away from nuclear energy and next generation reactors, and closing the fuel cycle. Today this is buried beneath the fight—rising levels of greenhouse gases in our atmosphere, and once again drive the U.S. to regain its place at the forefront of nuclear technology.

So our vast nuclear energy infrastructure, developed over decades with the combined capabilities of industry and the federal government, is at a crossroads, where existing nuclear reactors are set to be retired over the coming decades. While light water cooled SMRs can serve as a bridge to the next generation of advanced reactors, many issues remain that can be addressed by advance reactor technology. If we wish to charter a way forward towards those solutions, we must once again engage our public and private resources in a new effort to build the next generation of reactors. Much of the technology is developed and demonstrated on a small scale, although substantial work remains. The next logical step is to unify these technical efforts and successfully deploy a test reactor and test bed to demonstrate the advanced reactor systems.

The time we have to demonstrate this technology is short, due to the age of our current light water reactor fleet. Action over the short term is required to demonstrate new technologies by 2030, when retirement of existing nuclear power plants will accelerate. Thank you, and I look forward to answering any questions you might have.

[The prepared statement of Dr. Peters follows:]

Nuclear Energy Innovation and the National Laboratories

Testimony to U.S. House of Representatives

Committee on Science, Space, and Technology – Subcommittee on Energy

Mark T. Peters, Argonne National Laboratory

May 13, 2015

Summary

The history of nuclear energy development in the U.S. is one of cooperation amongst the federal government, its Department of Energy (DOE) national laboratories, universities, and industry. For 70 years, these groups worked closely together to develop the technology, designs, and licensing basis necessary to place the U.S. at the forefront of nuclear technology worldwide. The breakthroughs and designs achieved by the scientists and engineers of the national laboratory complex inform and drive every nuclear reactor design in the world today. Many of those breakthroughs were made by Argonne researchers.

The U.S. continues to be the lead source of innovation globally for the current generation of Light Water Reactors (LWRs) and Small Modular Reactors (SMRs), as well as leading in regulatory process, independence, and rigor. But a 30-year hiatus in the construction of new U.S. reactor projects has impacted domestic production capacity, investment in technology innovation, and the domestic supply chain.

The country's leadership in global nuclear energy could be further compromised as the world begins to move beyond the current generation of nuclear reactors to new designs – known as advanced or Generation IV reactors – that can address the future challenges of nuclear energy. Other countries are forging ahead with new reactors that – when coupled with advanced fuel cycles – can also address long-running challenges with nuclear waste management. These new designs have the potential to make significant gains in efficient use of fuel, thereby reducing costs and ensuring global supplies of resources. Advanced designs make these reactors even safer than current-generation reactors, further addressing lingering public acceptance and confidence challenges.

Many of these new reactor designs and much of the science that underpins them were developed in the U.S. under the leadership of DOE's Office of Nuclear Energy (DOE-NE). In fact, our national laboratory complex designed, built, and operated earlier versions of the reactors that form the basis of the advanced reactor programs in many countries.

Without a commitment to advanced reactor technology development and demonstration in the U.S., our country runs the risk of defaulting on the return of seven decades' investment in nuclear science, technology, and infrastructure, as well as forfeiting the legacy of the many brilliant minds that put the country at the forefront of nuclear energy technology. That lead position has allowed the U.S. to become the recognized world leader of efforts to control nuclear proliferation, ensure the security of nuclear materials, and promote safe and secure operation of nuclear power plants, all through the efforts of DOE and the National Nuclear Security Administration (NNSA).

If the U.S. is to ensure its rightful place at the forefront of advanced nuclear energy systems, it will require a new commitment to the type of public-private partnership that led to the creation of our current fleet of LWRs. Our national laboratories and universities continue to work closely with industry to accomplish much of the research necessary to facilitate advanced reactors, but substantial work remains. A new generation of advanced reactors will require refinement and demonstration of new technologies, as well as a test reactor and test bed for demonstration of advanced reactors. More work remains to be done on advanced fuel cycles, and providing options to close the fuel cycle, decreasing the amount of waste that must be stored and simplifying geologic disposal requirements.

An effort of this scope cannot be undertaken successfully by the national laboratories and universities or by industry alone. Only by pooling the best resources of the federal government and industry can the U.S. progress to the next generation of advanced nuclear energy systems.

Introduction

The 70-year development of the peaceful use of the atom is one of the most successful examples in U.S. history of how collaboration between industry and the federal government, through its national laboratories, can address national needs to greatly improve the lives of its citizens. Translating the atomic science breakthroughs of the first part of the 20th century into affordable and reliable electricity required a vast investment of public and private resources unlike anything that had been seen to that point. Facing huge challenges in science, technology development and maturation, safety, licensing, and regulation, government agencies, national laboratories, universities, and industry worked hand-in-hand to develop the nuclear plant infrastructure that today provides nearly 20 percent of the electricity generated in the U.S., including more than 60 percent of our zero-carbon energy.

But that vast energy infrastructure is at a crossroads, where existing nuclear reactors are set to be retired over the coming decades. Unresolved waste issues leave tons of used nuclear fuel in temporary storage at reactors across the country. Economic factors tilt the market away from nuclear, particularly in deregulated markets in which reliability of supply is not recognized, making nuclear energy's environmental benefits more difficult to justify. Public sensitivity to nuclear risk still colors perceptions of this technology's benefits.

To move nuclear energy into the next generation of advanced systems will require a re-energized commitment to the types of public-private partnerships that created our current reactor fleet. Construction of advanced reactors, along with advanced fuel cycles, will address many current concerns, but will require a strong collaboration on technology development and demonstration among the federal government, its national laboratories, universities, and industry.

That same collaborative approach with industry has fostered the development of small modular reactors (SMRs) that extend the use of nuclear energy to new markets and applications. For example, national laboratories and universities are supporting NuScale Power's efforts to achieve Nuclear Regulatory Commission design certification for its light-water-cooled SMR design. NuScale is currently in the pre-application review portion of the regulatory process and hopes to bring its first plant to production in 2023. Light-water-cooled SMRs can serve as a bridge to the next generation of advanced reactors.

Industry will not be able to do this alone, because of high financial risks and challenging technological barriers to developing a new generation of nuclear energy. For advanced reactors to become a commercial reality, the federal government must play a role in helping solve the science and technology questions and in deploying a test reactor and demonstration test bed that can prove the safety and effectiveness of these advanced concepts. A licensing and regulatory structure also must be established to accommodate these new, more efficient, and safer reactors.

Industry must do its part, for it is only through private investment that commercial-scale advanced nuclear power plants will be built. Industries with decades of experience designing and deploying reactors will translate the innovations developed by the national laboratories, universities, and their own researchers into concrete plans, designs, and, eventually, operating advanced reactors. These reactors will allow the U.S. to keep its position at the forefront of nuclear technology, a position it has held since the dawning of the atomic age at a graphite reactor built under the stands of Stagg Field at the University of Chicago, then later brought to Argonne National Laboratory.

Research and Development in Advanced Reactors and Fuel Cycles

The atomic age dawned in 1942 at the Metallurgical Laboratory of the University of Chicago, where Enrico Fermi and his fellow scientists built the world's first nuclear reactor. The MetLab, as it was known, later became Argonne National Laboratory, which quickly established itself as the epicenter for nuclear energy research in the U.S.

In the ensuing 70 years, Argonne worked with industry, universities and its sister national laboratories, including Idaho and Oak Ridge National Laboratories, on the science and technology that underpin every nuclear reactor operating in the world today. That unbroken chain of cutting-edge reactor research and design led to multiple "firsts," including the first man-made, self-sustaining neutron chain reaction and the first electricity generated from nuclear energy.

That first electricity was generated by the Experimental Breeder Reactor I (EBR-I), which was the predecessor of EBR-II, both designed, built, and operated by Argonne. EBR-II is the foundation upon which today's advanced fast reactor designs are based. EBR-II was a sodium-cooled fast reactor designed and operated at Argonne West (now known as Idaho National Laboratory's Materials and Fuels Complex) to demonstrate a complete fast reactor power plant with onsite reprocessing of metallic fuel. It accomplished that mission admirably from 1964-1969, then moved on to demonstrate many other breakthroughs that inform today's advanced reactors, before shutting down in 1994.

In 1986, EBR-II underwent a series of safety tests in which it demonstrated its unique ability to have truly "passive" safety systems, allowing the plant to automatically shut down, without operator assistance, even if safety systems failed. The successful safety tests simulated a loss of coolant flow with normal shutdown devices disabled. The reactor safely shut down without reaching excessive temperatures anywhere in the system. These types of inherent safety systems are hallmarks of the next generation of advanced reactors envisioned by researchers at national laboratories and in countries across the globe.

EBR-II was the prototype for the Integral Fast Reactor (IFR), designed to encompass all the benefits of advanced fast reactors with a closed fuel cycle in a single facility. IFR was designed to maximize the use of fuel, while minimizing waste, by recycling used fuel repeatedly. In addition to reducing the volume of used fuel, this approach burned most of the transuranics, the most long-lived radioactive elements, thereby simplifying the geologic disposal requirements for the remaining nuclear waste. The IFR project was canceled in 1994, but much like EBR-II, the technology developed for the program remains a cornerstone of advanced nuclear technologies today.

As background, the nuclear fuel cycle is a cradle-to-grave framework that includes uranium mining, fuel fabrication, energy production, and nuclear waste management. There are two basic nuclear fuel-cycle approaches. An open (or once-through) fuel cycle, as currently envisioned by the U.S., involves treating used nuclear fuel as waste, with ultimate disposition of the material in a geologic repository (see Figure 1).

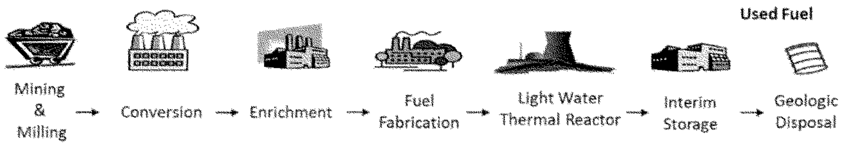

Figure 1. Open (or Once-Through) Nuclear Fuel Cycle

In contrast, a closed (or recycle) fuel cycle, as currently planned by other countries, treats used nuclear fuel as a resource, separating and recycling actinides in reactors and using geologic disposal for remaining wastes (see Figure 2).

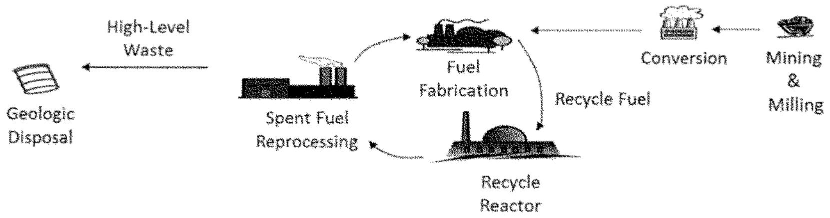

Figure 2. Closed Nuclear Fuel Cycle (or Reprocessing/Recycling)

In a closed fuel cycle, the useful constituents of the fuel are extracted and recovered to make fresh fuel. The unusable fission products are removed from the process and encapsulated in durable waste forms designed for geologic storage.

The most common commercial technique for reprocessing used fuel today is known as Plutonium and Uranium Recovery by Extraction (PUREX), a solvent extraction process that separates uranium and plutonium and directs the remaining minor actinides (neptunium, americium, and curium) along with all of the fission products to vitrified waste. Innovative processes are being developed in the national laboratories that minimize proliferation concerns about potential misuse of the PUREX process, which can generate a pure plutonium stream. Under current DOE advanced nuclear technology development programs, scientists at Argonne and other national laboratories have continued to advance the state of the art in used fuel processing.

Scientists and engineers at Argonne and other national laboratories have also actively continued work on advanced reactors under the direction of DOE-NE, and are engaged in innovative research to enhance safety while reducing capital and operational costs. Research and development areas include improved structural materials, advanced power conversion systems, improved inspection and maintenance technologies, design simplification, and improved computer modeling and simulation to optimize designs.

National Laboratories Approach to Cooperation with Industry

DOE has established multiple funding mechanisms that allow its national laboratories to work with industry. All cooperative projects with industry are reviewed and approved by DOE/NNSA, and are subject to the appropriate orders and regulations. Two of the more common arrangements are Strategic Partnership Projects (SPPs), where outside organizations pay the cost of research, and Collaborative Research and Development Agreements (CRADAs), where cost is shared between industry and DOE. Argonne and the other national laboratories also are involved in efforts to license inventions and copyrights to industry, ensuring the groundbreaking work of the laboratories is transferred to industry where it can be translated into products that impact the market and improve people's lives. Argonne's work with private entities also includes joint research projects, user agreements for Argonne's Scientific User Facilities, and Small Business Innovation Research.

The national laboratories' decades-long history of work with industry continues to this day, with dozens of ongoing science and engineering projects in pursuit of new technologies and new designs that both improve existing reactors and help address technical challenges to the creation of next-generation nuclear energy systems. Perhaps no effort better illustrates how cooperation between national laboratories and industry can enable important breakthroughs in clean, safe, and reliable nuclear energy generation than the long-running collaboration between Argonne and General Electric – Hitachi Nuclear Energy (GEH). The history of cooperation between Argonne and GEH reaches back to the 1950s and the Experimental Boiling Water Reactor (EBWR), which was designed, built, and operated at Argonne. The laboratory's researchers worked closely with GEH (then known simply as GE) to transfer the knowledge and design of EBWR to a commercial product. Today, boiling water reactors make up a third of the U.S. fleet.

Looking to the future, GEH's advanced reactor design, known as PRISM, was created using principles demonstrated at EBR-II and further refined in the IFR. PRISM was designed under the Advanced Liquid Metal Reactor (ALMR) program. ALMR was a government-funded effort that brought multiple U.S.-owned companies, including General Electric, together with the national laboratories to develop an advanced nuclear reactor design. One of PRISM's prime selling points is its "passive safety" based, in part, on the characteristics of metallic alloy fuel developed at Argonne. A metallic core expands as it heats in a loss-of-cooling situation; this expansion decreases the density of the fuel, slows the fission reaction, and maintains a safe temperature automatically. This technique was first demonstrated with EBR-II. The ALMR approach to partnership between private and public entities to achieve a large, long-term goal is a useful method and leveraged the best capabilities of all the collaborators to help create the PRISM design.

A more recent partnership in the nuclear sector involved a SPP with GEH to develop technologies for recycling scrap fuel material generated at the GEH fuel fabrication plant. The project resulted in detailed design and fabrication cost estimates for several key operations, information that allowed GEH to refine its nuclear fuel recycling strategy and cost model. The collaborative effort relied on experimental data and equipment concepts developed from the DOE-NE Fuel Cycle Technology program and its predecessor programs.

In another cooperative arrangement, Argonne was selected last year to participate in a set of DOE-funded projects to facilitate industry-led R&D solutions to significant technical challenges to the design, construction, and operation of next-generation nuclear reactors. As part of this program, GEH is partnering with Argonne to develop an updated safety assessment of the PRISM reactor. In addition, Westinghouse is also partnering with Argonne and the University of Pittsburgh to develop thermo-acoustic sensors for sodium-cooled fast reactors.

The Case for Advanced Reactors in the U.S.

With the creation of EBR-II and the follow-on design of IFR, the march toward continued U.S. leadership in advanced nuclear reactors seemed inevitable. However, in the 1970s and 1980s, a variety of developments coalesced to move the U.S. away from nuclear energy and end the nation's drive to build a next-generation reactor and close the fuel cycle. Public sentiment turned away from nuclear in the wake of accidents at Three Mile Island and Chernobyl. Market forces, a challenging regulatory environment, and high construction and capital costs made it difficult to finance new plants. Growing issues with long-term management of used fuel and the difficulty of siting a geological repository added cost and created safety concerns.

Today, however, we face a driver for new nuclear energy that may be sufficient to once again establish the U.S. as the world leader in next-generation nuclear reactor technology. That driver is the carbon-constrained future that is forcing the U.S. and the world to find ways to fight rising levels of greenhouse gases in our atmosphere.

In environmental terms, electricity production is often broken down by source, with "dirty" sources like fossil fuels on one side and "clean" sources, such as solar, wind, and hydropower on the other. Fossil fuels will be a part of our country's energy mix for decades to come, and significant research, development, and demonstration efforts need to continue to make electricity generated from fossil fuels "cleaner." Nuclear, with zero carbon output but lingering waste management challenges, is often thought of as its own category, without a clear place on either side. A scientific understanding of the realities of nuclear electricity generation would argue that nuclear energy should indeed be a part of the clean energy future. That status would be even further enhanced by the deployment of advanced reactors by mid-century.

Nuclear power plants currently generate just under 20 percent of the electricity in the U.S. and nearly 65 percent of the carbon-free electricity. Those generation numbers are not expected to change substantially in the future. The U.S. Energy Information Administration projects nuclear's share of the country's electricity mix at 16 percent in 2040, with renewables at 18 percent. With greenhouse gas emissions becoming an ever-increasing concern, allowing nuclear energy – the nation's largest contributor of carbon-free electricity – to lapse over the coming decades would have serious environmental consequences.

The primary environmental concern with nuclear energy is related to waste. Through more efficient use of fuel and recycling, advanced reactors would not only generate additional energy from the transuranics that create the most long-lived concern, they could also destroy those same transuranics by burning them in reactors.

Nuclear energy also suffers from a negative perception of environmental risk due to accidents. The nuclear industry has a remarkable safety record in comparison to other types of electricity generation, but public perception of the risk does not correlate with historical performance. The already high safety levels of the current generation of LWRs have been greatly increased by decades of cutting-edge research. The inherent safety features – many of them pioneered at Argonne and other national laboratories – built into next-generation reactors will raise the bar even higher.

Finally, as the leader of the global effort to control nuclear proliferation, ensure the security of nuclear materials, and promote safe and secure operation of nuclear power plants worldwide through DOE and NNSA programs, the U.S. has a major stake in assuring that future systems meet stringent safety and security standards. If the U.S. foregoes the timely development and commercialization of advanced reactors, future exports of advanced reactors will be left to other supplier nations, with potential adverse impacts on U.S. interests in nuclear safety, security, and nonproliferation. In fact, the U.S. is already at risk of falling behind due to the proactive efforts of other countries in deploying LWRs and advanced reactors, along with other nuclear technologies. Lack of U.S. participation in the next generation of nuclear reactors will also impact interest in the field among young scientists and engineers, reducing the trained workforce needed to sustain nuclear generation in the future. Moreover, the in-depth national expertise needed to ensure the effectiveness of international safeguards is unlikely to be sustained, and the U.S. risks ceding industrial capabilities and economic benefits to other countries.

Conclusion and Recommendations

Harnessing the extraordinary power of the atom for peaceful purposes was a daunting challenge with huge technical hurdles to overcome when President Dwight D. Eisenhower delivered his famous "Atoms for Peace" speech at the United Nations on December 8, 1953. Eisenhower eloquently expressed his desire that the power so recently unleashed in war be redirected toward bettering the lives of all humans. But to make that vision a reality would require "the miraculous inventiveness of man," as Eisenhower put it.

Over the ensuing decades, the U.S. tapped that miraculous inventiveness from minds in the federal government, the national laboratories, universities, and industry to create a nuclear energy industry that today provides nearly one-fifth of the nation's electricity. We used our great minds to create a fleet of technologically advanced nuclear reactors with unparalleled safety and innovative features that would be adopted worldwide. And we used our inventiveness to help restrict the spread of non-peaceful uses of the atom worldwide.

Now our country faces another critical moment in which we must once again tap our inventiveness if we wish to move forward and maintain our place at the forefront of nuclear energy innovation. Our nuclear reactors – the product of many decades of public-private partnership –will be retired over the coming decades. Challenges in waste and cost continue to confront the industry over the long term. Rising levels of greenhouse gases in our atmosphere challenge us to find new ways to power our homes and industry without contributing to environmental risks.

Advanced nuclear energy systems promise to answer those challenges. If we wish to chart our way forward toward those solutions, we must once again engage our public and private resources in a new effort to build the next generation of reactors. We are fortunate that the challenge, while substantial, is not as difficult as that faced in 1953. For decades the Department of Energy, through its Office of Nuclear Energy, has invested wisely in science and engineering that will enable advanced nuclear energy systems. Much of the technology is developed and demonstrated on a small scale, although substantial work remains. The next logical step is to unify these technical efforts and successfully deploy a set of test beds and reactors to test and demonstrate the advanced reactor systems. The time we have to demonstrate this technology is short due to the age of our current LWR fleet. Action over the short term is required to demonstrate new technologies by 2030, when retirement of existing nuclear plants will accelerate.

DOE-NE is using the resources of its national laboratories and universities to pursue the development of advanced nuclear energy systems. This research builds on concepts identified and developed over the past several decades and makes use of innovative solutions to address the technology challenges in designing a system that is safe, secure, sustainable, and economically competitive. These continued efforts, in collaboration with industry, will lead to the deployment of a system that ensures an affordable energy supply with minimal impact on the environment. If we choose to take this step as a country, the innovative minds at our national laboratories, universities, and industry stand ready to show the world that the U.S. still leads all countries in the peaceful use of the atom and that the greatness and inventiveness of our combined abilities can rise to this challenge.

MARK T. PETERS, Ph.D.

Position
Associate Laboratory Director, Energy & Global Security

Short Profile
Dr. Mark Peters is the Associate Laboratory Director for Energy and Global Security (EGS) at Argonne National Laboratory (ANL). He is responsible for the management and integration of the Laboratory's energy and global security programs. As the Associate Laboratory Director, he manages an organization of more than 800 staff with an annual budget of over 250 million dollars. Dr. Peters also serves as a senior advisor to the Department of Energy on nuclear energy technologies and research and development programs, and nuclear waste policy. As a recognized expert in nuclear fuel cycle technologies and nuclear waste management, Dr. Peters is called upon frequently to provide expert testimony to Congress and to advise in formulation of policies for nuclear fuel cycles, non-proliferation, and nuclear waste disposal.

Professional History
Previously, Dr. Mark Peters was the Deputy Laboratory Director for Programs at Argonne. He was responsible for the management and integration of the Laboratory's science and technology portfolio, strategic planning, Laboratory Directed Research and Development (LDRD) program, and technology development and commercialization. Prior to that, as a Deputy Associate Laboratory Director for Energy Sciences and Engineering, he was responsible for the development of new program opportunities at the Laboratory, particularly in the areas of energy storage, nuclear energy, nuclear safety, and waste management. He served as an expert advisor to the DOE Advanced Fuel Cycle Initiative (AFCI) and as the AFCI National Campaign Director for Waste Forms and Used Fuel Disposition.

As a scientist with Los Alamos National Laboratory in New Mexico, Dr. Peters served as the senior scientist to the Director of the Office of Civilian Radioactive Waste Management (OCRWM), and was the external spokesman for the OCRWM science and technology programs. Dr. Peters was widely recognized for his efforts in addressing and resolving sensitive policy and technical issues on used fuel disposition. He led many interactions with independent technical, oversight, and regulatory bodies, and was commended by the OCRWM Director for his efforts. In a prior position, Dr. Peters was with Los Alamos National Laboratory, where he managed the science and engineering testing program at the Yucca Mountain Project.

Before joining Los Alamos National Laboratory, Dr. Peters was a research fellow in geochemistry at the California Institute of Technology where his research focused on trace-element geochemistry. He has authored over 60 scientific publications, and is a recognized expert at national and international meetings.

Dr. Peters holds an adjunct faculty appointment in the Department of Earth and Planetary Sciences at Northwestern University and is a Senior Fellow in the Northwestern Argonne Institute of Science and Engineering. Dr. Peters serves also on several advisory boards and councils, including several that support innovation and economic development for the State of Illinois, greater Chicago area, and U.S. industry. These include the Illinois Smart Grid Advisory Council, Harman's Innovation Advisory Council, Energy Foundry Board of Directors (current Board Chairman), University of Illinois at Chicago College of Engineering Advisory Board, and the Scientific Advisory Committee for Notre Dame's Energy Frontier Research Center.

Dr. Peters is an active member of professional organizations including the Geological Society of America, where he served as a member of the Committee on Geology and Public Policy. In addition, he is a member of the American Geophysical Union, the Geochemical Society, the Mineralogical Society of America, and the American Nuclear Society (ANS). He serves on the ANS' Public Policy Committee and also served on the Executive Committee of the ANS' Fuel Cycle and Waste Management Division. His professional achievements have resulted in his election to Sigma Xi, the Scientific Research Society, as well as Sigma Gamma Epsilon, the Earth Sciences Honorary Society.

Education
Dr. Peters received his Ph.D. in Geophysical Sciences from the University of Chicago and his B.S. in Geology from Auburn University. He has also received extensive management and leadership education and training, including completion of the Strategic Laboratory Leadership Program at the University of Chicago Booth School of Business.

Chairman WEBER. Thank you, Dr. Peters.

Mr. Batten, you're recognized.

TESTIMONY OF MR. FRANK BATTEN, JR., PRESIDENT, THE LANDMARK FOUNDATION

Mr. BATTEN. Chairman Smith, Ranking Member Grayson, good morning. My name is Frank Batten, and I'm the President of the Landmark Foundation. We're a private foundation that supports educational, environmental, and human service organizations. I greatly appreciate the opportunity to testify today regarding a positive example of a near completed cooperative research and development agreement, or CRADA. And we did this with the Department of Energy's Argonne National Lab. The CRADA relates to what we believe should be an important component of our country's national energy policy, the—which is the recycling of used nuclear fuel through a demonstrated U.S. technology called pyroprocessing. We have no commercial interest in this area, and no financial agenda, but we believe that the U.S. can significantly benefit from recycling used nuclear fuel through pyroprocessing. While private industry can, and should, play a role, federal government R&D funds are essential if the benefits of this technology are to be realized.

Pyroprocessing has been the subject of Federal R&D for many years, and Argonne has led the way. The technology is now capable of recycling used fuel from the country's nuclear power plants for re-use to generate electricity in advanced reactors. Pyroprocessing is good energy policy, it's environmentally sound, it promotes effective use of resources, it can contribute to addressing climate change, and it holds the promise of significantly mitigating the country's used nuclear fuel disposition issue.

I would like to briefly summarize the success story of our partnership with Argonne, which relates to the design for a pilot reprocessing facility. I would also like to brief the Subcommittee on an analysis undertaken by Energy Resources International, or ERI. We commissioned and funded the ERI analysis outside of the CRADA. The ERI report analyzes the costs and benefits of using pyroprocessing and advanced reactors on a commercial scale. Now, I've attached a copy of the ERI report to my testimony, and ask that it be included in the hearing record.

The Landmark Foundation entered into the CRADA with Argonne over two years ago. We invested $5 million, and the federal government invested $1 million in the CRADA. The purpose of the CRADA is to develop the conceptual design and a robust cost estimate for a 100 metric ton per year pilot scale pyroprocessing demonstration facility. The CRADA is a particularly good use of the public/private partnership concept. It leverages prior government funded work, it takes that work to the next level, and it builds a bridge for the U.S. Government to move forward with the detailed design for the pilot facility. All of this, we hope, will spur additional federal funding for a pilot facility.

The ERI report provides a detailed assessment of the costs and technical factors associated with a realistic fuel cycle using pyroprocessing and advanced reactors. ERI concluded that the potential exists to reduce the volume of used commercial fuel, requiring permanent disposal by 50 percent or more, avoiding the need for a second geologic repository. Avoiding a second repository would save the U.S. Government tens of billions of dollars.

According to ERI, re-use of pyroprocessed fuel also would simply the design of a first geologic repository, and reduce the volume of repository space needed by more than 50 percent. This would significantly contribute to reducing the federal government's financial liability associated with its obligation to receive used fuel from its utility standard contract holders.

I'm pleased to be here today to talk both about the success of our partnership with Argonne, and the underlying benefits of further developing the pyroprocessing technology. Thank you for your time and attention.

[The prepared statement of Mr. Batten follows:]

NUCLEAR ENERGY INNOVATION AND THE NATIONAL LABS HEARING

BEFORE THE SUBCOMMITTEE ON ENERGY
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
UNITED STATES HOUSE OF REPRESENTATIVES

May 13, 2015

Testimony of Mr. Frank Batten, Jr. on Behalf of The Landmark Foundation

Chairman Weber, Ranking Member Grayson and other members of the Subcommittee. Good morning. My name is Frank Batten and I am Chairman and Chief Executive Officer of Landmark Media Enterprises, LLC, and also President of The Landmark Foundation. Landmark Media Enterprises is a diversified media and business services company providing print newspapers, classified advertising websites, software and data center services.

Our company funded The Landmark Foundation as a private foundation that supports educational, environmental, and human service organizations mostly in the Norfolk area, and I am here today on its behalf. I greatly appreciate the opportunity to testify before this Subcommittee, and I am honored to be part of this distinguished panel.

I am testifying today about public-private partnerships with the federal government, and in particular, a positive example of a cooperative research and development effort between The Landmark Foundation and a U.S. Department of Energy (DOE) National Laboratory. I am here to discuss The Landmark Foundation's near-completed Cooperative Research and Development Agreement, or "CRADA," with the DOE's Argonne National Laboratory (Argonne) relating to what we believe should be an important component of our Country's national energy policy: in particular, the recycling of used nuclear fuel through a demonstrated U.S. technology called "pyroprocessing."

Mr. Chairman, before I begin my testimony I would like to commend the Committee for its efforts on H.R. 1158, the Department of Energy Laboratory Modernization and Technology Transfer Act and in particular Section 104, Nuclear Energy Innovation. I believe this type of legislation will help to maintain the focus of the Department of Energy on nuclear energy technologies and to identify the opportunities for cooperative research and development projects with the private sector.

The Landmark Foundation has *no* commercial interest in this area – in other words, we have no financial "agenda" in promoting this nuclear fuel recycling technology. But we believe that the United States—as a country—can significantly benefit from recycling used nuclear fuel through pyroprocessing. While private industry can and should play a role, federal government research and development (R&D) funds, at least in the near and intermediate term, are essential if the benefits of this technology are to be realized.

Pyroprocessing of used nuclear fuel has been the subject of federal R&D for many years. DOE's Argonne National Laboratory has led the way with, among other things, its pioneering development of a first-of-a-kind pyroprocessing facility for used metallic fuel from its Experimental Breeder Reactor II (EBR-II). Argonne has treated more than four metric tons of used fuel using pyroprocessing. The technology is now capable of recycling used nuclear fuel from the country's nuclear power plants. This technology can and should be employed to beneficially re-use the existing U.S. inventory of commercial light-water reactor used fuel. Once the fuel is recycled, it can then be used again as fuel to generate electricity in advanced reactors.

This approach could result in a continued public-private partnership related to pyroprocessing for decades into the future.

Pyroprocessing technology development is good energy policy, environmentally sound, promotes effective use of resources, can contribute to addressing climate change, and holds the promise of significantly mitigating the used nuclear fuel disposition issue that currently confronts this Country.

I would like to cover two general but related topics today: (1) first, I will briefly describe the success story of our public/private partnership with Argonne, its general status, and the anticipated successful conclusion. Second, I will generally brief the Subcommittee on the benefits we see being derived from this technology when it is employed at full scale, based upon an analysis undertaken by Energy Resources International, Inc. (ERI). ERI is a highly-regarded, international consulting firm specializing in, among other things, independent resource, technology and market analyses; economic consulting; and strategic planning and procurement associated with the nuclear fuel cycle. The Landmark Foundation commissioned and funded the ERI analysis outside of the CRADA. The ERI report analyzes the costs and benefits of using pyroprocessing and advanced reactors on a commercial scale. I have attached a copy of the ERI Report to my testimony and ask that it be included in the hearing record.

The Landmark/Argonne CRADA

The Landmark Foundation entered into the CRADA with Argonne over two years ago, in March 2013. The CRADA involves a public/private cost sharing arrangement and use of Argonne's extensive technical expertise and resources. Landmark invested $5 million and the federal government contributed $1 million to the CRADA.

The purpose of the CRADA is to develop the conceptual design and a robust cost estimate for a *pilot scale* pyroprocessing demonstration facility for converting used commercial reactor fuel into a form that can be re-used as fuel in an advanced reactor. The pilot plant would be designed to recycle up to 100 metric tons per year. The basic technology was developed at Argonne and the conceptual design is based on the work previously performed at Argonne. Under the CRADA, Argonne's work includes developing process descriptions and requirements, equipment conceptual designs, facility layout, a safety assessment strategy, and cost and schedule estimates.

We feel that our CRADA with Argonne is a particularly good use of the public/private partnership concept. It leverages prior government-funded work, takes that work to the "next level," begins to evaluate regulatory options to make this effort a reality rather than just another academic exercise, and builds a bridge for the U.S. Government to move forward with the detailed design for the pilot facility. All of this, we hope, will spur additional federal funding for a pilot facility.

The CRADA is on budget and very close to completion.

Conclusions of the ERI Analysis

I also would like to discuss the ERI Report that we funded, which provides a detailed assessment of the costs and technical factors associated with a realistic "fuel cycle" using pyroprocessing and advanced reactors. Among other things, the ERI analysis concluded that the potential exists to reduce the volume of used commercial light water reactor fuel requiring permanent disposal by 50% or more, avoiding the need for a second geologic repository in the United States. As you may know, the Nuclear Waste Policy Act limits the capacity for a first permanent geologic repository to 70,000 metric tons. However, even if no new reactors are built in the United States, the existing fleet is projected to generate twice that amount, or 140,000 metric tons. Avoiding a second repository would save the U.S. Government tens of billions of dollars, and indeed, that avoided cost could "pay" for a pyroprocessing/advanced reactor fuel cycle.

According to ERI, re-use of pyroprocessed fuel also would simplify the design of a first geologic repository, as a result of an order of magnitude reduction in the radiotoxicity of the resulting waste product. At 1,000 years after discharge from a reactor and pyroprocessing, the waste to be disposed of would contain only 1% of the activity found in waste from the current once-through fuel cycle. The volume of repository space needed also could be reduced by over 50%. This would significantly contribute to reducing the federal government's financial liability associated with its obligation to receive the used fuel from its utility standard contract holders.

Let me conclude by quoting a summary conclusion from the ERI Report:

> There are significant potential cost savings and technical benefits associated with recycling nuclear fuel (*i.e.*, developing pyroprocessing and IFRs), compared to the current once-through fuel cycle. Key among these is eliminating the need for a second geologic repository at a cost savings in the range of $12 to $96 billion.
>
> However, adequate research and development funding, and deploying a pilot facility to demonstrate pyroprocessing in the U.S. is an important step in resolving remaining technical challenges prior to scaling up the technology to a commercial scale. Expanded research, development, and demonstration of pyroprocessing and IFR technology should continue in the U.S. to provide a sustainable alternative program for long-term waste management and nuclear power deployment.

As I said earlier, I am pleased to be here today to talk both about the success of our partnership with Argonne and the underlying benefits that can be derived if the technology that is the focus of that partnership is given the opportunity for further development. Thank you for your time and attention. While I am hardly the technical expert on this panel, I would be pleased to answer any questions you may have.

Biographical Information on Frank Batten Jr.

Frank Batten Jr., 56, is the president of The Landmark Foundation, an independent private foundation that supports human services and educational charities in the Norfolk, Virginia area.

Batten also is the chairman and chief executive officer of Landmark Media Enterprises LLC. A predecessor company of Landmark Media provided the funding that endowed The Landmark Foundation.

Landmark Media sells advertising and marketing services to real estate agents, to apartment communities, and to auto, truck, boat, motorcycle, recreation vehicle and heavy equipment dealers. Landmark Media also owns The Virginian-Pilot, the daily newspaper in Norfolk, and Expedient Data Centers, which operates nine data centers around the U.S.

Batten received a bachelor's degree in history from Dartmouth College and an M.B.A. from the Darden School of Business at the University of Virginia.

Frank Batten Jr.
150 Granby Street
Norfolk, Virginia 23505

757.351.8800 batten@Lcimedia.com

EDUCATION

1976-1979	DARTMOUTH COLLEGE, Hanover, New Hampshire A.B. in History
1982-1984	UNIVERSITY OF VIRGINIA, Charlottesville, Virginia M.B.A.

EMPLOYMENT

1979-1980	THE ROANOKE TIMES, Roanoke, Virginia Advertising sales representative
1980-1982	THE ROANOKE TIMES, Roanoke, Virginia Reporter
1984-1985	THE ASSOCIATED PRESS, London, England Reporter
1986-1987	THE NEWS-ENTERPRISE, Elizabethtown, Kentucky General Manager
1988-1989	THE NEWS-ENTERPRISE, Elizabethtown, Kentucky Publisher
1990-1991	THE VIRGINIAN-PILOT, Norfolk, Virginia Vice-President/Marketing
1991-1995	THE VIRGINIAN-PILOT, Norfolk, Virginia Publisher
1995-1997	LANDMARK COMMUNICATIONS, Norfolk, Virginia Executive Vice-President/New Ventures
1998-2008	LANDMARK COMMUNICATIONS, Norfolk, Virginia Chairman and CEO
2008-present	LANDMARK MEDIA ENTERPRISES, Norfolk, Virginia Chairman and CEO
2002-present	THE LANDMARK FOUNDATION, Norfolk, Virginia President

Chairman WEBER. Thank you, Mr. Batten.

Mr. Gilliland, you're recognized.

TESTIMONY OF MR. NATHAN GILLILAND, CEO, GENERAL FUSION

Mr. GILLILAND. Chairman Weber, Ranking Member Grayson, Chairman Smith, thank you very much for the opportunity to testify today about the emergence of new innovative fusion energy concepts, and the importance of governmental support in working with U.S. labs. My name's Nathan Gilliland, Chief Executive Officer of General Fusion, one of the leading private fusion energy companies. I'll make five point—key points today, and have done so in my written statement in more detail, which I would like to submit to the record.

First, I would echo what Ranking Member Grayson said. The game changing nature of fusion energy bears repeating. It's energy production that is safe, clean, and abundant. In a fusion reaction, one kilogram of hydrogen is equivalent to ten million kilograms of coal. It's the energy density comment that you made earlier. Humanity would have abundant energy for millions of years. There's also no long lived radioactive waste, no chance of meltdown in fusion reactions. The benefits to energy security can hardly be overstated.

Second, U.S. support for magnetic fusion programs like ITER, and inertial confinement programs like NIF, have created an enormously beneficial source of research. ITER and NIF have justifiably been the highlights of the U.S. fusion energy framework, and developed key insights into plasma behavior, material science, simulation codes, and many others. These programs should continue to be supported.

Third, because of this historical research, innovation in alternative pathways to fusion have accelerated. These alternative approaches, both in private companies and in labs and university, offer potentially faster and less expensive concepts, and demonstrable progress is being made, both in these labs, universities, and the private companies. Of particular note, work at Sandia, University of Washington, and Los Alamos are worth noting, as well as the three leading private companies, Tri-Alpha Energy, which is based in Southern California, Helion, which is based in Seattle, and ourselves, General Fusion. The progress of these alternative concepts was featured last summer in Science and Nature magazines. Novel fuels are being tested, new simulation tools developed, and we're all setting records for the stability of our plasma, so real progress is being made.

Increased commercial viability, lower cost power, and faster progress are common threads in these alternative fusion concepts. Alternative approaches are reducing costs by applying existing industrial technologies to the challenge of fusion, primarily avoiding costly large lasers, or costly superconducting magnets. Some have novel ways to protect the fusion reactor from neutrons, others have simpler ways to convert heat into electricity, but, of course, there are no silver bullets. These alternative approaches tend to be less researched and studied, and are simply newer. The physics have not been fully explored. But we would argue the viability and efficacy of these alternative approaches can be demonstrated for less money. Some will show rapid progress, and others will not, but, dollar for dollar, progress or failure can be demonstrated much more quickly.

Fourth, though the majority of fusion research has been publicly funded, there is a place, and an important place, for private companies who can build on previous research, and potentially innovate faster. The Human Genome Project is a great analogue, and a great example. The NIH built a core of research that was very strong, and from this private industry was able to efficiently and rapidly innovate to sequence the genome. We see parallels in fusion energy. World leading historical research is being done at labs and universities, and has led to rapid innovation. And just like every energy industry, oil and gas, solar, wind, there will be multiple approaches that succeed in fusion. It's not a winner-take-all industry.

Fifth, and finally, going forward we'd like to see more open innovation and information sharing across private industry labs and universities. For example, we all use computer simulation. It's a very important tool for us. We'd like to see co-development of simulation codes, more sharing of simulation codes. Another thing we'd like to see is greater emphasis on exchanges of physicists and Ph.D.'s across private industry and government labs. This leads to better sharing of historical research, current research, and the private sector would absolutely put resources into doing this. And labs and universities can help here at no cost to them.

Ultimately, more cooperation between government supported efforts and private industry can only accelerate progress. There is no value in silence. Let's push for more private/public partnerships, as Dr. Peters mentioned, and I'm sure Dr. Parmentola will as well. Let's push for more private/public partnerships to share data, build faster, and accelerate progress. The world needs fusion, and the faster the better. Thank you.

[The prepared statement of Mr. Gilliland follows:]

Written Statement of

Nathan Gilliland

Chief Executive Officer

General Fusion Inc.

Testimony before the House Committee on Science, Space and Technology

Subcommittee on Energy

United States House of Representatives

May 13th, 2015

INTRODUCTION

Chairman Weber, Ranking Member Grayson and Members of the Subcommittee, thank you for the opportunity to testify on the emergence of new innovative fusion energy concepts and the importance of governmental support for these concepts in parallel with longstanding fusion energy research activities.

My name is Nathan Gilliland, Chief Executive Officer of General Fusion, one of the leading private fusion energy companies. I have been asked to provide background on the value of General Fusion's partnerships and relationships with U.S. agencies, labs, universities and other institutions, as well as the emergence of innovative alternative fusion energy concepts.

Though it is mentioned frequently, the game-changing nature of fusion energy bears repeating: energy production that is safe, clean, and abundant that would change the landscape of energy forever and greatly enhance energy security. In a fusion reaction, one kilogram of hydrogen fuel has the equivalent energy of 10 million kilograms of coal—humanity would have abundant energy for millions of years. There is also no long-lived radioactive waste and no chance of meltdown in fusion reactors. Net energy gain from fusion energy has proven more difficult to achieve than expected, and more costly, however the benefits of reaching this milestone in a commercially viable reactor can hardly be overstated.

As the Committee knows well, the U.S. has been the leader in developing fusion energy for many decades, beyond the significant support for ITER, and similar concepts. The U.S. has also led the way in inertial confinement fusion, the culmination being the National Ignition Facility. ITER and NIF have justifiably been highlights of the U.S. fusion energy framework. The resources and time put into both pathways, though very different, have significantly expanded the knowledge-base for all fusion concepts, including a number of innovative alternatives. Though neither program has progressed on a perfectly straight line, the pathway that they have and are creating is unquestionably worth it.

INNOVATION IN FUSION ENERGY AND THE 'MIDDLE GROUND'

The depth and breadth of U.S. research in fusion energy has led to significant innovation, and the development of potentially viable alternative concepts. Nearly all of these concepts borrow ideas and research from ITER and other magnetic fusion programs, as well as NIF and related laser fusion programs. And just like ITER and NIF, each have their benefits and their drawbacks. All have challenges, whether they are scientific and engineering hurdles, speed or cost.

There is a wide arrangement of parameters used in these alternatives, from magnetic fields to compression to even the type of fuel used. The progress of these alternative concepts was featured last summer in both the journals *Science* and *Nature*.

As an example, Sandia's MagLIF experiment demonstrated impressive neutron production using their approach that combines a magnetized plasma with a Z-pinch compression, and published these results in 2014.[1] Though not yet fully proven, Z-pinch has the potential to be a cheaper reactor.

The University of Rochester has also tested a hybrid approach, and is collaborating with the MagLIF team. The University of Rochester used the OMEGA Laser Facility to perform experiments using magnetic field combined with laser compression and demonstrated improved neutron yield. Omega outlined their progress on laser-plasma interaction in December of 2014.[2]

The University of Washington's Helicity Injected Torus program has demonstrated a new mechanism for sustaining a stable plasma.[3] The team has proposed how the technology could be tested at larger scale, as well as an intriguing reactor concept, called a Dynomak, that could be more practical to implement than ITER-style plasmas

I will provide an on the three leading private companies in the fusion space as well.

Tri Alpha Energy, based in Orange County, uses a magnetic plasma configuration called an FRC and runs continuously to directly extract electricity. Unlike ITER or NIF, they do not plan to use just hydrogen as their core fuel, but rather hydrogen and an isotope of Boron. Though harder from a physics standpoint than using traditional fuels, this approach would avoid neutron damage to the reactor and produce electricity directly. They have extended the lifetime of this FRC plasma to a record five milliseconds, which is a solid step forward. These results were published in 2015. [4]

Helion, is another private company that has demonstrated progress. Located in Redmond, Washington, they also use an FRC plasma like Tri Alpha Energy. Instead of running continuously, Helion creates

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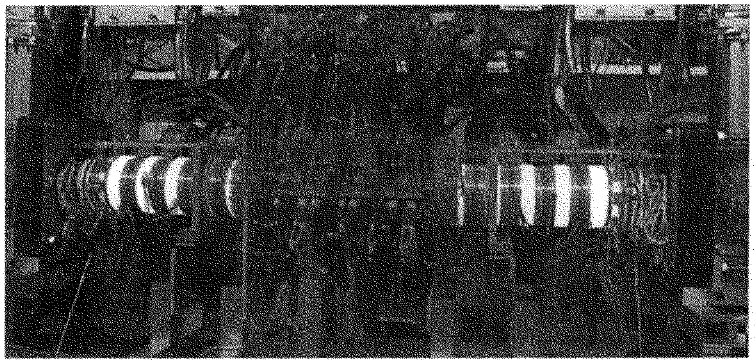
[1] Gomez, M. R. et al., "Experimental Demonstration of Fusion-Relevant Conditions in Magnetized Liner Inertial Fusion", *Physical Review Letters* Vol 113 (2014)

[2] Chang, P. et al., "Fusion Yield Enhancement in Magnetized Laser-Driven Implosions.", *Physical Review Letters* Vol 107 (2011)

[3] Jarboe, T.R. et al., "A Proof of Principle of Imposed Dynamo Current Drive: Demonstration of Sufficient Confinement.", *Fusion Science and Technology* Vol 66, No. 3 (2014)

[4] Guo, H. Y. et al., "Achieving a long-lived high-beta plasma state by energetic beam injection", *Nature Communications* Vol 6 (2015)

fusion reactions in a rapid pulse. Helion uses a strong magnetic field to compress this plasma to high temperature. They published reaching a temperature of approximately 35 million degrees Celsius[5],



Source: Helion Energy © 2015 Helion Energy

General Fusion, my company, also fits 'between' ITER and NIF, as we use magnetic field to contain heat, but use compression of this plasma to reach fusion conditions.

General Fusion fits into a category of fusion energy called Magnetized Target Fusion (MTF). We also use a specialized plasma, form it to specific temperature and density requirements, and then compress it in a pulsed reaction. We use an array of large, high-precision steam pistons to compress this plasma to fusion conditions. Using pistons to put energy into plasma has one key benefit: cost. Using steam to drive energy into plasma is less expensive than lasers, particle beams, or superconducting magnets. Additionally, we use a liquid metal blanket to surround the fusion reaction, protecting the reactor from neutrons produced and making it much simpler to extract energy.

In 2014, building on past research at SSPX (Lawrence Livermore National Laboratory) and CTX (Los Alamos), General Fusion produced the best thermal confinement ever in spheromak plasmas.[6]

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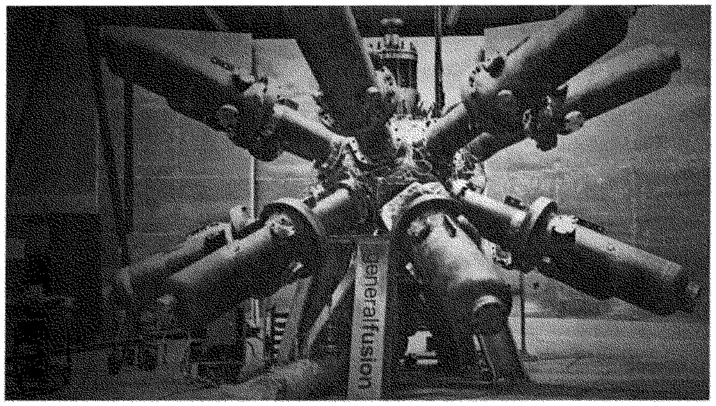
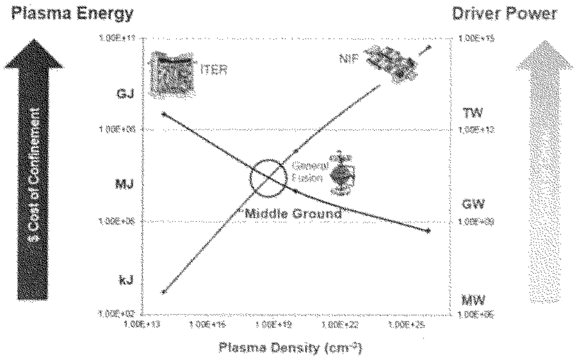
[5] Slough, J. et al., "Creation of a high-temperature plasma through merging and compression of supersonic field reversed configuration plasmoids.", *Nuclear Fusion* Vol 51, No. 5 (2011)

[6] Froese, A. et al., "Spheromak Compression Experiments at General Fusion", *Pacific Basin Nuclear Conference Proceedings*, (2014)



Source: General Fusion Inc.

I call MTF and some of these other approaches a 'middle ground,' in fusion research. What do I mean by that? While ITER uses a very low density plasma with magnetic field that runs continuously, NIF and other inertial confinement fusion concepts use no magnetic field but instead use a very rapid pulse reaction using lasers. MTF and other alternative concepts are pursuing a middle ground-- higher density than ITER, but less than NIF: compression like NIF, but at much, much lower speeds. The idea is that lower extremes in magnetic field or compression speed will lead to simpler, less expensive fusion reactors: less expense to confine plasma, and less expense to put energy into this plasma to create fusion conditions:



Source: General Fusion Inc.

Though the nuances of each fusion energy alternative are real, they have several key items in common:

1. Lower cost of confining plasma, and lower cost to put energy into plasma
2. Potentially lower cost commercial power plants
3. Simpler, and in some cases smaller, fusion reactors
4. Progress toward achieving break-even energy

Increased commercial viability, lower cost power, and faster progress are common threads in comparison to ITER and NIF. But of course there are no silver bullets. These alternative approaches tend to be less researched and studied, and are simply newer. Fewer resources, private or public, have been allocated to their study. The core physics of many of these alternatives is less explored – potentially faster, smaller and cheaper, but at an earlier stage in their development.

I would argue the viability and efficacy of these alternative approaches can be demonstrated for less money. Some will show rapid progress, others will not. Dollar for dollar progress or failure can be determined much more quickly.

As the Committee is likely aware, ARPA-E launched its first-ever fusion energy program announcement in 2014, targeting this 'middle ground.' ARPA-E is clearly cognizant of both the value of fusion as an energy source, but also the viability of these alternative approaches as potentially faster, less expensive pathways. As a proponent of this 'middle ground' set of approaches, we were impressed with the program they formulated. We would love to see additional DOE support of this regime in the future.

As an analog, I am aware this Committee has evaluated a number of types of energy storage options: lithium-ion batteries, lead-acid batteries, molten salts, flywheels and many others-options that are highly diverse in their cost and application. It is much too early to declare one dramatically superior. Each has its benefits and its drawbacks and they represent a basket of alternatives for a variety of situations and applications.

Further, like so many other new energy sources, whether fossil fuels, solar or wind, this is not a 'winner-take-all' industry we are developing. Small fusion reactors have certain applications, while large reactors can power cities. Some fusion reactors will be used to make industrial heat, while others electricity. There isn't one solar company or one oil & gas company, and there will be multiple fusion energy companies.

VALUE OF GENERAL FUSION'S PARTNERSHIPS WITH U.S. AGENCIES, LABS, UNIVERSITIES AND OTHER INSTITUTIONS.

The Committee also asked me to comment on my company--General Fusion—and its experience with U.S. labs, universities and agencies.

Founded in 2002, General Fusion is a private, venture-capital backed company with sixty employees based in Canada. The majority of our capital has been sourced privately, and totals nearly $100 million raised from a global investor base. We have also received support from various Canadian government programs.

Though the majority of fusion research has been publicly funded, there is a place for private companies, who can build on previous research and innovate faster. SpaceX and Celera Genomics are good analogs. The NIH led research and created the framework for the Human Genome Project. Private company Celera rapidly innovated, and ultimately led the way to what is today rapid and inexpensive gene sequencing. Large government-backed programs built the framework, and created the opportunity, but private industry was able to drive down cost, and move more quickly.

None of this is to say that the time has arrived to turn all fusion research over to private companies – it is too early for that step.

U.S. labs and universities engage in the world's leading research and much of the most advanced experimentation, and as a private company we are keen to draw on this expertise wherever we can.

To be specific, we have benefited in the following ways from U.S research efforts:

1. Our core concept is based on the ideas first developed in the LINUS program at the Naval Research Lab in the late 1970s and early 1980s.[7] Novel research and experimentation done by this group centered on using compressed gas pistons to compress plasmas. The concept was elegant for a variety of reasons, notably the ease of extracting heat. We continue to have an ongoing dialogue with Dr. Peter Turchi, one of the pioneers of Magnetized Target Fusion and this approach.
2. We have previously had a Cooperative R&D agreement with Los Alamos, and continue informal dialogue with current researchers.
3. We have Advisory Council members and consulting arrangements with individuals presently or previously affiliated with Lawrence Livermore National Laboratory, Los Alamos and Princeton.
4. We and others use a simulation code, NIMROD, extensively – this is a multi-lab project originally sponsored by the DOE's Office of Fusion Energy Sciences to create tools for fusion research.

However, if I could suggest one step as an industry we need to make, it is a change to our ethos. Often because of funding concerns, our industry is often dismissive of any other fusion concept. At times, ITER proponents don't support laser fusion. NIF proponents are quick to point out the flaws in tokamaks. The same is true in the basket of alternative pathways that I have discussed so far. We are at times quick to point out others' weaknesses – but we all have them. The world needs fusion energy, wherever we can get it. And the faster the better. I would like to see more initiative on the part of

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[7] Turchi, P. J., et al., "Linus fusion reactor design based on axisymmetric implosion of tangentially-injected liquid metal. Memorandum report.", *Naval Research Laboratory* (1981)

private companies as well as U.S. Labs to share best practices, share data, share simulation codes. There is no value in the silos that have been built.

ROLE OF U.S. LABS, UNIVERSITIES AND AGENCIES IN ALTERNATIVE FUSION CONCEPTS: WHAT IS NEXT?

Outside of funding for these alternative approaches, there are a number of more practical items, areas in which private companies would certainly invest:

Simulation codes. All fusion programs, big, small, longstanding or alternative use simulation codes. Two thoughts here. First, there are several codes that are validly restricted for national security reasons. I don't suggest opening these codes up completely, however, for private industry there ought to be a pathway to apply, be screened, and use these codes. An example is ALEGRA code, developed over many years by Sandia National Laboratory and designated "unclassified Export-Controlled Information". Let's find a pathway that protects the justifiable national security concerns, but allows for greater access. Companies like General Fusion are not only interested in using these codes, but are also prepared to commit resources to help develop and advance their capabilities for all users.

Additionally, all large fusion efforts generate huge volumes of data. Data from sensors, diagnostics, simulation and other sources. Private industry's capabilities in fast computing, analysis using "big data" tools and machine learning, have accelerated rapidly over the last five years. Use of these new tools would be beneficial to all of us. I believe a public-private partnership is in order here.

Entrepreneurial leave program. Some U.S. labs offer leave programs in which physicists can go into private industry for one to two years and return. This is a tremendous idea that should be offered more broadly, and incentives created to participate. This temporary transfer of experts could go both ways – from labs to industry, and from industry to labs. Knowledge and experience rest with people, and the movement of people will lead to greater information sharing and rapid advancement. General Fusion, and other private companies are prepared to commit resources to facilitate this program.

Information sharing is not as valued as it should be. This is true for U.S. laboratories in some cases, but it is true of the private fusion companies as well. We would like to see greater emphasis and initiative toward sharing experimental data--past and future—as there is no question it would benefit us all.

CONCLUSION

U.S. support for ITER and NIF have created a wealth of research data and experimental results which have significantly benefitted the entire fusion community. We encourage continued support for both approaches. Although less researched and potentially higher risk than ITER and NIF, fusion alternatives may offer less expensive, faster, and more commercial pathways to net gain. Given the demonstrated progress of these alternatives and their potential viability, we believe more financial support, along with initiatives to support greater information sharing and greater exchange of human capital, is warranted. Rapid information sharing and open innovation will all lead us more rapidly to the ultimate goal: commercial fusion energy. The faster the better.

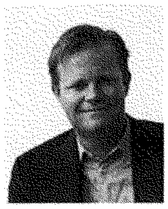
One Page Summary of Testimony before the House Committee on Science, Space and Technology

by Nathan Gilliland, Chief Executive Officer, General Fusion Inc.

May 13th, 2015

- The game-changing nature of fusion energy bears repeating: it can provide **safe, clean and widely abundant energy on a permanent basis.** The challenges of commercialization for fusion energy have been evident, but progress is demonstrable in a variety of U.S. government supported approaches as well as private companies.
- **U.S. support for fusion programs has been critical** to the progress the industry has made over the last thirty years. Research in U.S. national labs and universities have led the way.
- The research base developed by the U.S. support of ITER and NIF, and other programs has created the **foundation for innovation in fusion energy**. A wealth of historical data and expertise has driven development of alternative approaches.
- Many of these innovative, **alternative approaches have hit key milestones, and progress is evident.** There are a broad array of alternatives that may solve key challenges across fusion programs, including longstanding approaches.
- These **alternative approaches may offer a less expensive and faster pathway than the longstanding fusion programs**. But they are in general less researched, and may be higher risk.
- Examples of these alternative approaches include Z-pinch experiments, private companies General Fusion, Tri Alpha Energy and Helion Energy, as well as other private and public efforts. We believe the **pragmatism and efficiency of the private sector combined with the significant expertise in U.S. laboratories and universities will accelerate progress.**
- Just like other energy categories, solar, wind, fossil fuels, there won't be one approach that "wins." An industry with a variety of successful approaches will be the outcome.
- Going forward, **we would like to see initiatives to share information**, experimental data and simulation tools more broadly – between and among laboratories, universities and private companies. Specifically we support Ph.D exchanges between private and public programs and in general a more open innovation approach across all fusion programs. **More public-private partnerships, more open data, more open innovation.** The private sector would gladly put resources into these programs.
- We will all ultimately benefit from the decades-long foundation of research, and an acceleration of progress will become evident. The faster we can commercialize fusion the better.

Nathan Gilliland - Background



Nathan is a veteran entrepreneur in renewable energy. Nathan is currently CEO of General Fusion, a worldwide leader in developing fusion energy. General Fusion is privately funded by venture capital firms and family offices and is based in British Columbia, Canada. General Fusion was founded in 2002, and is a leader in developing Magnetized Target Fusion (MTF).

From 2008 until 2012, Nathan was President and co-founder of Harvest Power, a leading renewable energy company that creates electricity and soil products from organic waste materials.

Nathan has previously lectured at the University of California-Berkeley on entrepreneurship and how companies manage growth.

Prior to Harvest, Nathan was an investor at Bain Capital for 9 years, a consultant at Bain and Company, and is a graduate of the University of California-Berkeley.

Chairman WEBER. Thank you, Mr. Gilliland.

Dr. Parmentola, you're recognized.

TESTIMONY OF DR. JOHN PARMENTOLA, SENIOR VICE PRESIDENT, ENERGY AND ADVANCED CONCEPTS GROUP, GENERAL ATOMICS

Dr. PARMENTOLA. Good morning. Thank you, Chairman Weber, Ranking Member Grayson, and other members of the Subcommittee for holding this hearing on this important subject. I believe, as many others do, that it is important to the future of national security, energy security, and environmental quality of the United States that ample supplies of competitively priced nuclear energy are available.

Unfortunately, it appears that nuclear energy is dying in the U.S. There are few new plants being built, several have closed recently, and most of the 99 existing plants will be closed down within the next 40 years. To place this in context, last year nuclear was 20 percent of the electricity consumed by Americans, who paid 80 billion for it. We believe this death spiral can be avoided, but it'll require active involvement by the U.S. Government.

The energy market is indicating that existing nuclear power technology is not commercially viable. For nuclear power to play any future role, the U.S. will need new safer nuclear power technologies that will produce significantly cheaper electricity. However, the private sector will not be able to develop this on its own. The investments required are very large, they are risky, and, in any event, will take more than a decade before they might yield any revenue from electricity production, and even longer to yield any profit. As these new options are developed, and private firms begin to see their way to risk reduction and making profits, private investment will increase, the government will be able to withdraw, and the market will decide which would be commercially viable.

Let me now discuss GA's interest in a new advanced test reactor. We have a new reactor concept that needs a testing facility. We call it EM–2, and we designed it to address the four most prominent concerns with nuclear power, its safety, its cost, its waste, and its proliferation risk. We believe it is a potential breakthrough technology for the United States, however, research is required to realize it.

To develop EM–2, a compact gas cooled fast reactor, we looked at what physics indicates we must do. One, we must go to higher power densities through a compact reactor core using fast neutrons. Two, we must go to higher temperatures so a higher percentage of the heat produced is turned into electricity. By doing this, we can make the same amount of electricity in a smaller reactor, small enough that it could be made in a factory and shipped by truck to a site for deployment. We believe we could increase the efficiency of power production from percentages today, in the low 30s, to the lower 50s.

The bottom line is we believe that we could reduce the cost of electricity up to 40 percent below that of existing nuclear reactors, and reduce their waste by up to 80 percent. But to do this, we have to develop new materials what will be able to endure the higher temperatures, and endure the more energetic and neutron rich radiation environment inside the reactor. We need a new testing facility with high performance characteristics in which to do this research work. But there are also a number of other companies and national ads that are advocating the use of fast neutrons, and going to high temperatures, albeit with different advanced reactor designs. These also require a new testing facility that conduct tests in, say, three years that would show what happens to these materials in an actual advanced reactor during a period of 30 years.

It would not make business sense for any company, or even all interested companies together, to pay for the capital costs to construct such a facility, given the large investment, the risks, and the very long lead times involved for a return on investment. Currently there is no U.S. facility with the requisite high performance characteristics to do this type of research. The best we have are the advanced test reactor at Idaho National Laboratory, and the high flux isotope reactor at Oak Ridge, but neither of these is appropriate for a number of reasons. The best in the world is in Russia, BOR–60, but this is being shut down soon for other reasons.

In any event, it would seem odd to develop such a national security technology in Russia. Therefore, we suggest you consider building such a facility in the United States. It would be called the Versatile Advanced Test Reactor. It would be a highly neutron rich fast reactor capable also of producing thermal neutrons. We like versatile because it should be designed in such a way that it could be used to test all new reactor concepts, whether they involve molten salt, a liquid metal reactor, a liquid bismuth reactor, a gas reactor, or even light water reactor.

The Versatile Advanced Test Reactor would be a user facility in the same way that the DOE Office of Science managers other highly successful facilities. It would contribute to the public good by providing the development of future nuclear energy options. This is an excellent example of what the government should do because industry cannot, or will not, do it. The U.S. has a great opportunity to lead the world, and give nuclear power its best chance to become economically viable. This Committee could start by enacting a law calling for a study to be done, with industry participation, to determine a design for such a reactor, what its capabilities would be, and what it might cost. We believe that if the U.S. were to build such a test facility, it would be key to the development of nuclear reactors that really could spark a true renaissance of nuclear power in the United States.

Thank you for inviting me to share our views, and for your interest in finding ways to sustain an extremely important future energy source for our nation. Thank you.

[The prepared statement of Dr. Parmentola follows:]

Testimony of Dr. John A. Parmentola
Sr. Vice President, Energy and Advanced Concepts, General Atomics
Before the Subcommittee on Energy
U.S. House of Representatives Committee on Science, Space and Technology
May 13, 2015

Thank you, Chairman Weber, Ranking Member Grayson, and other Members of this Subcommittee, for holding this hearing on this important subject. I believe, as many others do, that it is important to the future national security, energy security, and environmental quality of the United States (U.S.) that ample supplies of competitively priced nuclear energy are available.

Unfortunately, it appears that nuclear energy is dying in the U.S.: there are few new plants being built, several have closed recently, and most of the 99 existing plants will be closed down within the next 40 years. To place this in context, last year nuclear energy consumed by our citizens represented 20% of U.S. electricity supply worth $80B. It also appears that the few plants being built require special regulatory arrangements because they cannot compete head-to-head on the numbers with other energy sources.

We believe this future scenario can be avoided, but it will require active involvement and investment by the U.S. Government. Why? The energy market is indicating that existing nuclear power technology (Light Water Reactors [LWRs]) is not commercially viable. For nuclear power to play any future role, the U.S. will need new nuclear power technologies that will produce significantly cheaper electricity, while ensuring public safety.

However, the private sector will not be able to develop these on its own. The investments required are very large, they are risky, and in any event will take more than a decade before they might yield any revenue from electricity production, and even longer to yield any profit. As these new technology options are developed, and private firms begin to see their way to risk reduction and making profits, private investment will increase, the government will be able to withdraw, and the market will decide which would be commercially viable.

Let me now discuss General Atomics' interest in a new advanced test reactor. We have a new reactor concept we call Energy Multiplier Module (EM^2). We specifically designed it to address the four most prominent concerns with nuclear power—its cost, its waste, its proliferation risk, and the post-Fukushima safety risk. We believe that EM^2 can significantly reduce the cost of nuclear power, and dramatically reduce the amount of waste a plant produces, while at the same time doing it safely with less proliferation risk. We believe it is a potential breakthrough technology for the U.S.; however, research is required to realize it.

To develop EM^2, a compact gas-cooled fast reactor, we looked at what physics indicates we must do: 1) go to high power densities through a compact reactor core utilizing fast neutrons; and 2) go to higher temperatures so a higher percentage of the heat produced is turned into electricity (efficiency). By doing this we can make the same amount of electricity in a much smaller reactor—small enough that it could be made in a factory and shipped by truck to a site for deployment. There are a number of prominent companies that are also advocating the use of fast neutrons and going to higher temperatures albeit with different advanced reactor designs. These also require research.

We believe we could increase the efficiency of electricity production from the lower 30s percentages in LWRs to the lower 50s – so a new reactor would only have to produce two thirds of the heat produced by a LWR to produce the same power output. We believe we could reduce the cost of electricity by up to 40% below that of existing nuclear reactors, and reduce the waste to be disposed of by up to 80%.

But to do this, we have to develop NEW materials that will be able to endure the much higher temperatures, AND endure the more energetic and neutron rich radiation environment inside the reactor. We need a new testing facility with high performance characteristics in which to do this research work.

But this is also true of all other firms and national laboratories that have other ideas and designs: all of them also need a new testing facility that could conduct tests in, say, three years that would represent what happens to these materials in an actual advanced reactor for a period of 30 years. This type of facility would dramatically increase research productivity and hence dramatically accelerate the development of new advanced nuclear technologies.

It would not make business sense for any company, or even all interested companies together, to pay for the capital costs to construct such a facility, given the large investment, the risks and the long lead times involved for return on investment.

Currently, there is no U.S. facility with the requisite high performance characteristics to do this type of research. The best we have are the Advanced Test Reactor in Idaho National Laboratory, and the High Flux Isotope Reactor in Oak Ridge National Laboratory, but neither is appropriate for a number of reasons. The best in the world is in Russia (BOR-60), but this is being shut down soon for other reasons. In any event, it would seem odd to develop such a national security technology in Russia.

Therefore, we suggest that you consider building such a facility in the U.S. It could be called the Versatile Advanced Test Reactor (VATR). It would be a highly neutron rich fast reactor capable of also providing thermal neutrons. We like "versatile" because it should be designed in a way that it could be used to test all new reactor concepts whether they involve a molten salt reactor, a liquid sodium reactor, a liquid lead bismuth reactor, a gas reactor (such as EM^2), or even LWR technology such as those reactors used in U.S. nuclear submarines. The VATR would be a user facility in the same way that the DOE Office of Science manages other highly successful user facilities. It would contribute to the public good by providing the development of future nuclear energy options. This is an excellent example of what the government should do, because industry cannot or will not do it.

The U.S. has a great opportunity to give nuclear power its best chance to become economically viable, and lead the world in this endeavor. In fact, other countries would have to seek permission from the U.S. Department of Energy to use the VATR. This Committee could start by enacting law calling for a study to be done, with industry participation, to determine a design for such a VATR, what its capabilities should be, and what it might cost.

We believe that if the U.S. were to build such a test facility, advanced reactor research and development could lead to the development of nuclear reactors that: will have much improved economics; would have improved safety through the use of high temperature materials that are also radiation resistant; will produce much less waste, and; reduce proliferation risk. This could lead to a true renaissance of nuclear power in the U.S. Thank you for inviting me to share our views, and for your interest in finding ways to sustain an extremely important future energy source for our nation.

Dr. John A. Parmentola Testimony

Appendix 1

GENERAL ATOMICS

U.S. Versatile Advanced Test Reactor (VATR) Facility

The United States (U.S.) needs a viable indigenous nuclear industry for its long-term energy security. Unfortunately, the U.S. is on a path to lose its position of world leadership in nuclear power and related technologies. And if this continues, it could present a significant national security risk to our nation. Despite the U.S.'s enviable position on fossil energy reserves, energy is a global commodity, and energy demand growth is driven by the global economy. Meeting future world energy demand will require a diverse energy mix with nuclear as a major component.

Status of the U.S. Nuclear Industry

The U.S. nuclear industry is struggling. Despite the brief stirring of a Nuclear Renaissance at the turn of the century, the industry is faced with the following bleak reality in 2015:

- Only five plants are under construction despite plans for up to 30 in 2009[i]. There are no other firm commitments for construction.
- Large nuclear plants are not economically competitive with coal and natural gas[ii]. This is due to a combination of low U.S. fossil fuel costs and the higher financing costs of nuclear plants.
- Four nuclear plants have been retired prematurely due to economic pressure and cost of repairs[iii]. Ten to 12 other plants face risk of early retirement[iv]. Five nuclear plant power upgrades have been cancelled due to economic considerations[v].
- The aging U.S. nuclear generating capacity is at the start of a steep decline based on current licenses, see Fig. 1.
- The DOE's SMR initiative is threatened by lack of market, high projected power costs and a lack of investors.

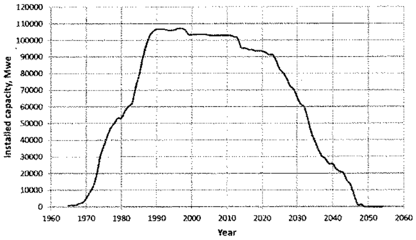


Fig. 1 U.S. licensed nuclear plant generating capacity

Global opportunities for the U.S. nuclear industry are likewise diminished due to foreign competition. With strong government support and strong indigenous markets, Asian suppliers will dominate future nuclear construction, particularly China, which has 30 LWRs under construction and plans for over 100 new LWRs by 2030. Three Chinese nuclear firms are now looking to export their nuclear plants[vi].

Many arguments can be made for preserving the U.S. nuclear industry, among the more prominent are its contribution to long-term energy security, and that it produces zero-carbon electricity. It is not likely that U.S. nuclear suppliers can compete with government supported Asian LWR vendors based on economic competitiveness. To compete, future "would-be" U.S. nuclear suppliers must rely on a unique U.S. resource -- innovation. These innovations will have to improve the new plants' safety and resource utilization while reducing the cost of electricity. These innovations will have to be bold, and will have to include new high-performance materials, higher operating temperatures for higher efficiencies, and substantially better fuel cycles to more efficiently utilize fuel resources and reduce waste production.

Nuclear R&D is Needed

Innovation requires R&D, but nuclear R&D is very expensive and its payoffs are at least a decade or more away. Countries that require nuclear power as part of their long-term energy security must be prepared to underwrite the necessary R&D efforts. Commercial companies cannot sustain a very expensive R&D effort where the payoff is likely decades in the future.

An essential nuclear R&D component is a new high-performance advanced test reactor to validate performance of fuels, materials and new high performance technologies. The U.S. has only three such reactors that can support nuclear power research: Idaho National Lab's ATR, Oak Ridge National Lab's HFIR and MIT's MITR. All three are pool-type thermal reactors. Only the ATR can support testing of larger fuel components. Only HFIR has a fast-flux region capable of testing small material samples, and only MITR can simulate LWR coolant conditions. The ages of ATR, HFIR and MITR are 57, 59 and 65 years, respectively. Due to their limited availability and capability, none is suitable for the type of innovative R&D required to stimulate and sustain a viable future U.S. nuclear industry.

The global availability of suitable test reactors is also dismal. Among fast reactors, only the Chinese 65 MWt CEFR, Russian 60 MWt BOR-60 and Indian 40MWt FBTR are operational. The CEFR is primarily a prototype reactor with limited testing capabilities. BOR-60 is scheduled to be shut down in 2015 and the FBTR is restricted to Indian military use. It is possible that no capable reactors will be available world-wide for testing fuels and materials essential to development of high-performance advanced reactors.

Among thermal test reactors, only a handful of reactors in Japan, Russia, China, Sweden and Argentina can support low-temperature nuclear fuel and materials testing. Most of these reactors are old, and some are scheduled to be shut down. An exception is the Jules Horowitz test reactor in France which went into operation in 2014 to provide fuel, materials and isotope production for the EU, but it is a thermal spectrum reactor and therefore of limited value for the necessary advanced reactor testing.

A New U.S. Test Reactor is Needed to Support Innovative R&D

To support the innovative R&D required to revive a competitive U.S. nuclear industry, a new test reactor is required **with capabilities that far exceed those of the few remaining test reactors**. This new test reactor must be an outstanding example of U.S. technical innovation. The test facility would be funded by the U.S. government and located at a national laboratory, which in turn would operate the reactor as a national user facility. Irradiation would be free to U.S. users, who would be responsible for providing test articles and support equipment. Suggested capabilities are:

Power:	500 MWt
Peak temperature:	1000°C or greater
Peak fast flux:	$1x10^{16}$ n/cm^2-s or greater
Reactivity:	Sufficient to support tests of 6 months or longer
Experimental:	Core and reflector spaces for materials and fuel testing; loops for fuel testing in different coolants; beam lines; full pre- and post-irradiation examination capability

A cooperative effort by U.S. industry, national labs and universities is required to achieve this new test reactor. A group of top U.S. nuclear experts from each sector should be convened to establish the functional requirements for this vital new test reactor. In addition to technical work, political and financial support will be needed to complete this project. A separate committee should be formed to plan and execute a strategy that would lead to a revitalized U.S. nuclear energy program.

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[i] Vogtle Units 3 & 4, V.C. Summer Units 2 & 3, Watts Bar Unit 3

[ii] DOE-EIA 2014 Annual Energy Outlook

[iii] San Onofre Units 2&3, Crystal River Unit 1, Kewaunee Unit 1

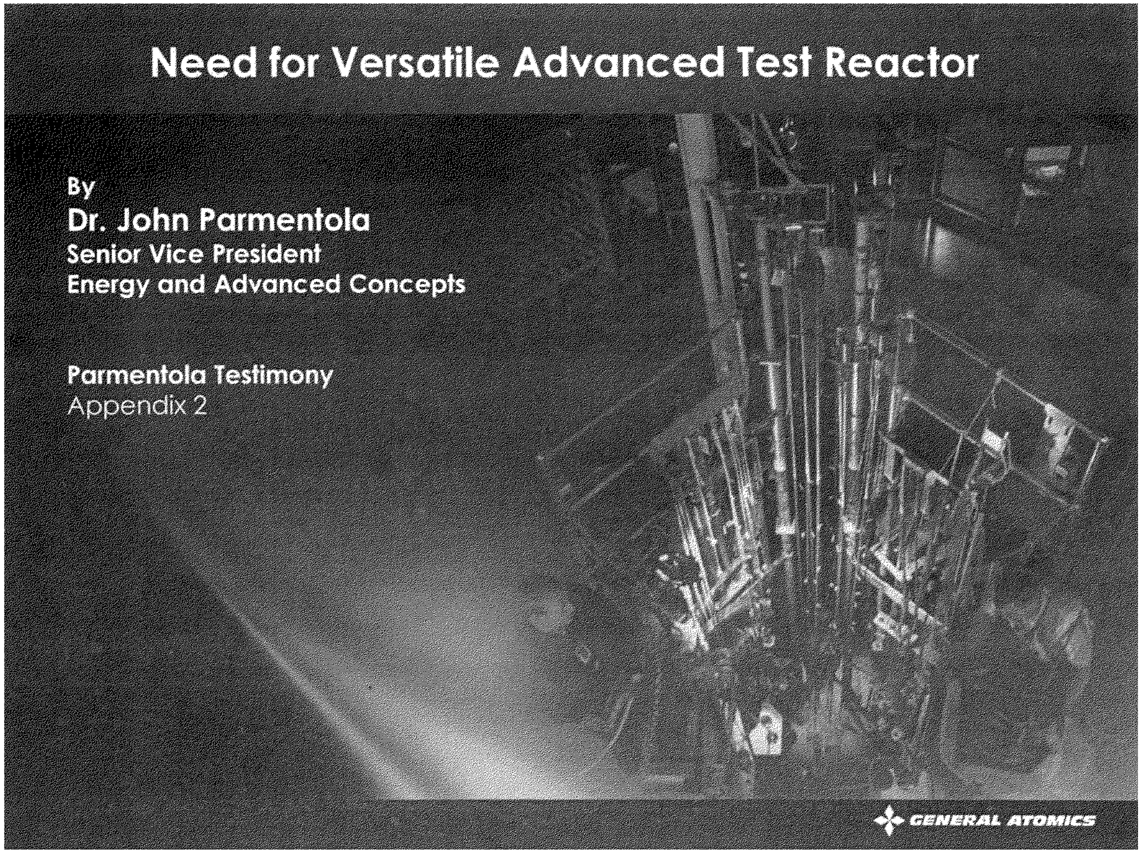
[iv] Cooper, Mark, "Renaissance in Reverse", Institute for Energy and Environment Report, July 18, 2013

[v] Prairie Island Unit 1, LaSalle units 1&2, Limerick Units 1&2.

[vi] Ng, Eric, "3 Chinese state firms looking to build nuclear plants abroad", South China Morning Post, April 2, 2014

Dr. John A. Parmentola Testimony

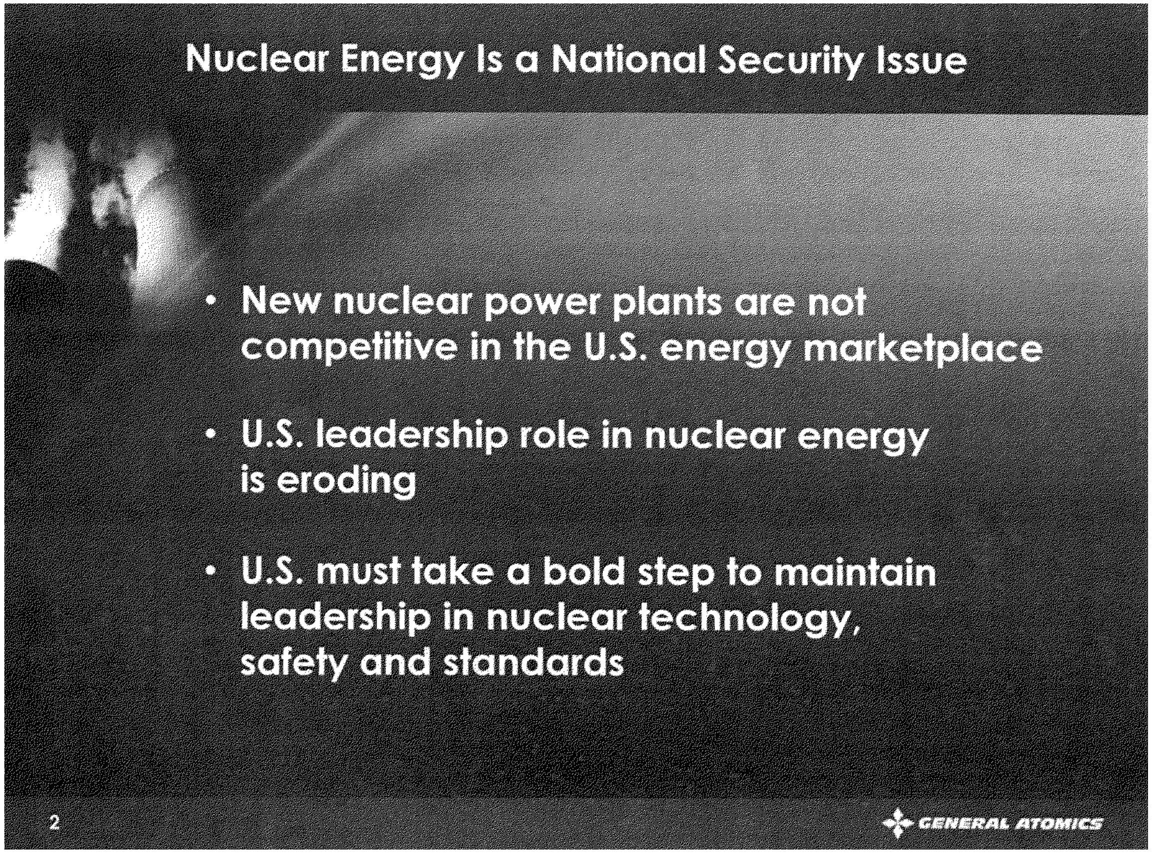
Appendix 2



Need for Versatile Advanced Test Reactor

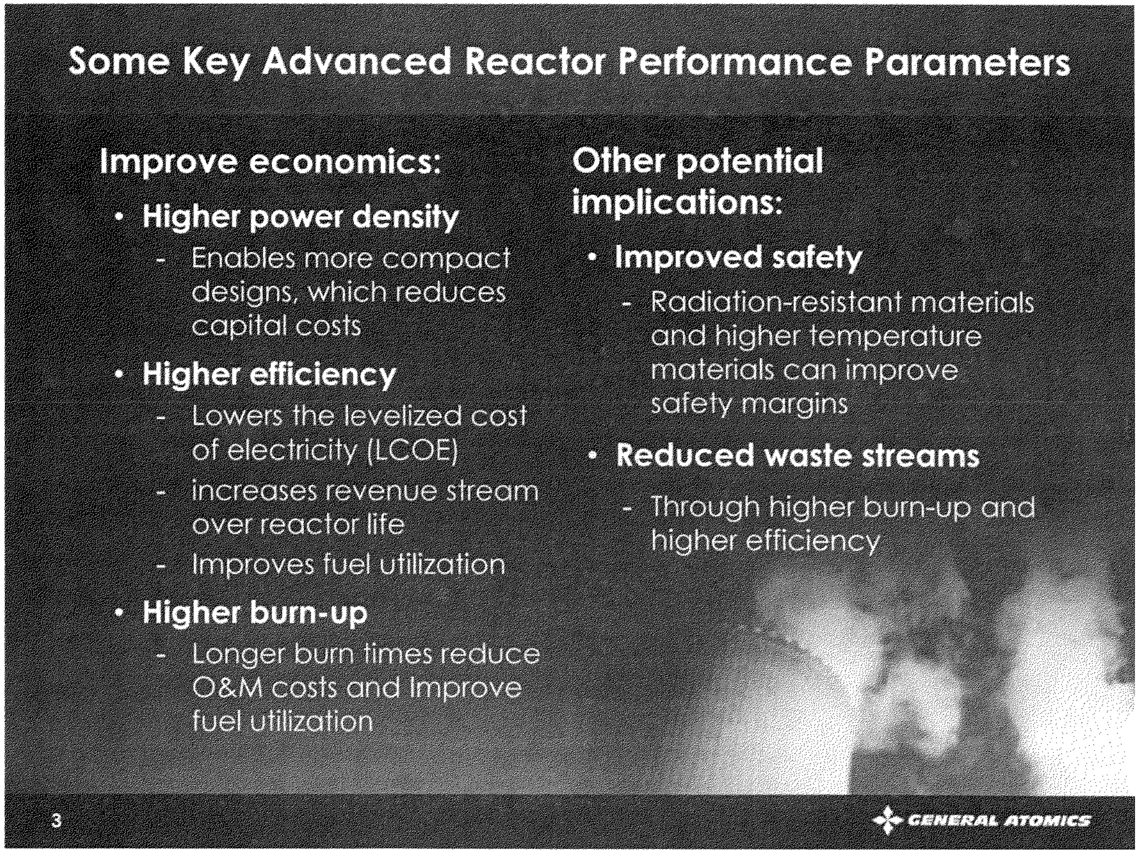
By
Dr. John Parmentola
Senior Vice President
Energy and Advanced Concepts

Parmentola Testimony
Appendix 2



Nuclear Energy Is a National Security Issue

- New nuclear power plants are not competitive in the U.S. energy marketplace
- U.S. leadership role in nuclear energy is eroding
- U.S. must take a bold step to maintain leadership in nuclear technology, safety and standards



Some Key Advanced Reactor Performance Parameters

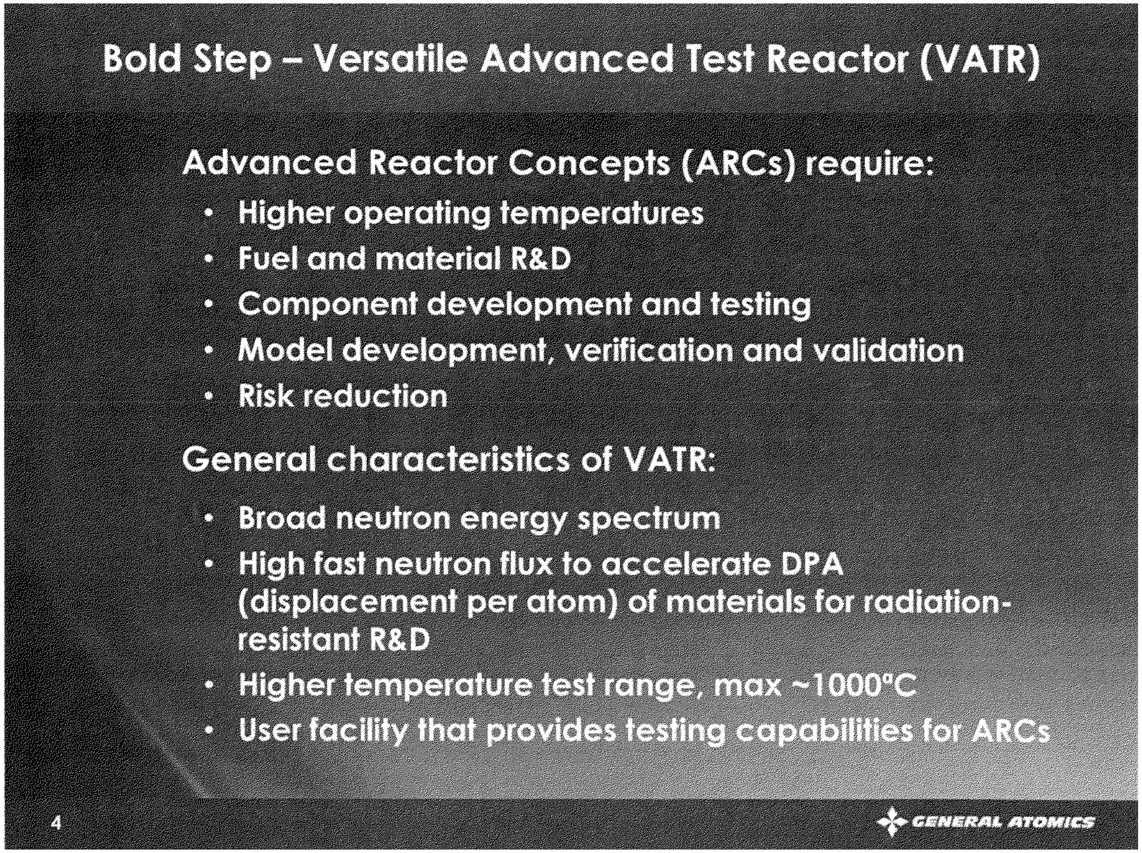
Improve economics:

- **Higher power density**
  - Enables more compact designs, which reduces capital costs
- **Higher efficiency**
  - Lowers the levelized cost of electricity (LCOE)
  - increases revenue stream over reactor life
  - Improves fuel utilization
- **Higher burn-up**
  - Longer burn times reduce O&M costs and Improve fuel utilization

Other potential implications:

- **Improved safety**
  - Radiation-resistant materials and higher temperature materials can improve safety margins
- **Reduced waste streams**
  - Through higher burn-up and higher efficiency

GENERAL ATOMICS



Bold Step – Versatile Advanced Test Reactor (VATR)

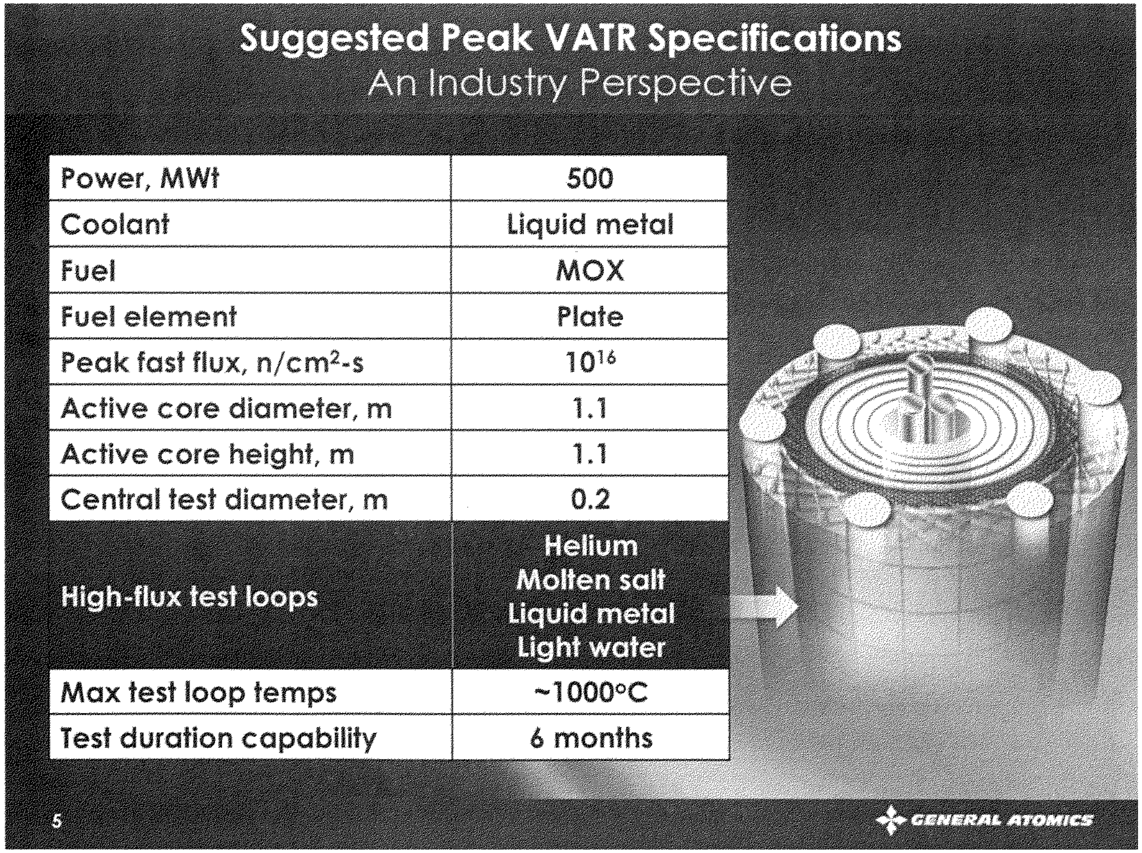
Advanced Reactor Concepts (ARCs) require:

- Higher operating temperatures
- Fuel and material R&D
- Component development and testing
- Model development, verification and validation
- Risk reduction

General characteristics of VATR:

- Broad neutron energy spectrum
- High fast neutron flux to accelerate DPA (displacement per atom) of materials for radiation-resistant R&D
- Higher temperature test range, max ~1000°C
- User facility that provides testing capabilities for ARCs

GENERAL ATOMICS

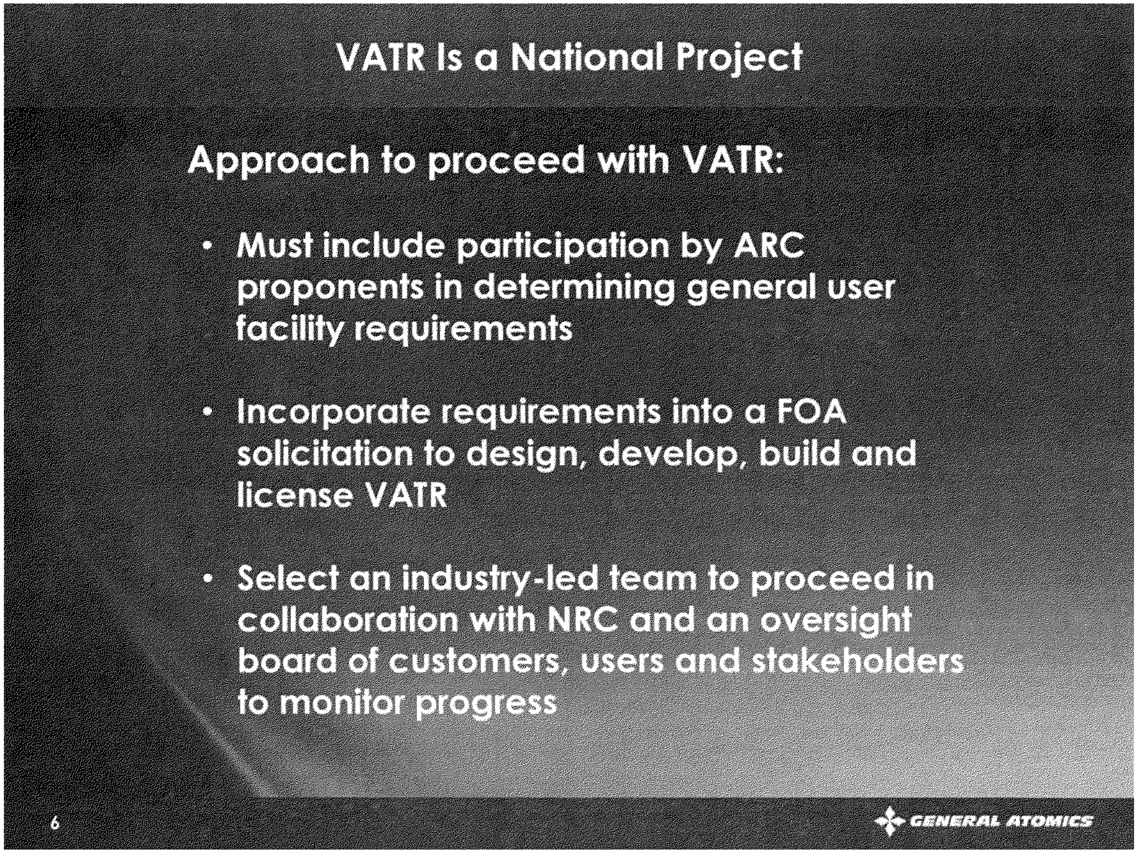


Suggested Peak VATR Specifications

An Industry Perspective

Power, MWt	500
Coolant	Liquid metal
Fuel	MOX
Fuel element	Plate
Peak fast flux, n/cm^2-s	10^{16}
Active core diameter, m	1.1
Active core height, m	1.1
Central test diameter, m	0.2
High-flux test loops	Helium Molten salt Liquid metal Light water
Max test loop temps	~1000°C
Test duration capability	6 months

GENERAL ATOMICS

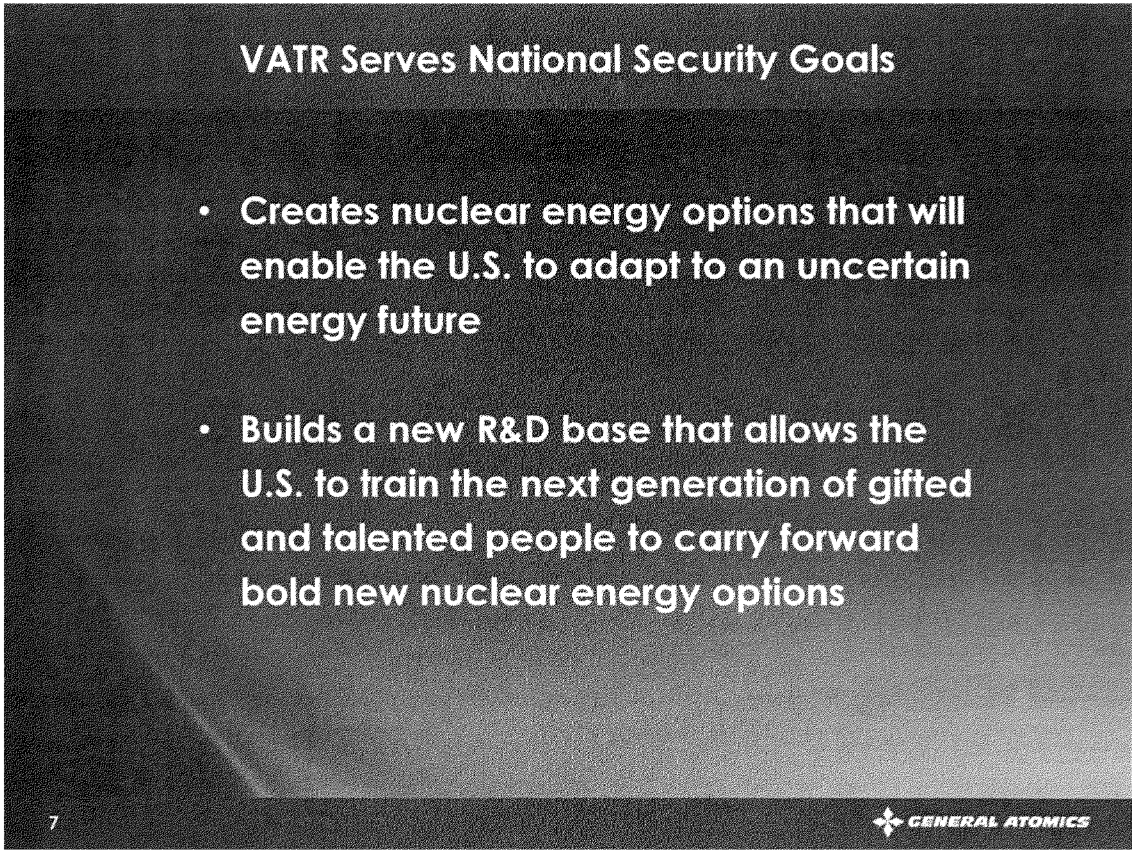


VATR Is a National Project

Approach to proceed with VATR:

- Must include participation by ARC proponents in determining general user facility requirements
- Incorporate requirements into a FOA solicitation to design, develop, build and license VATR
- Select an industry-led team to proceed in collaboration with NRC and an oversight board of customers, users and stakeholders to monitor progress

GENERAL ATOMICS



VATR Serves National Security Goals

- Creates nuclear energy options that will enable the U.S. to adapt to an uncertain energy future
- Builds a new R&D base that allows the U.S. to train the next generation of gifted and talented people to carry forward bold new nuclear energy options

Dr. John A. Parmentola Testimony

Appendix 3

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Improving the Economics and Long-Term Sustainability of Nuclear Power

John Rawls[*1], Zabrina Johal[2], John Parmentola[3]

General Atomics, P.O. Box 85608, San Diego, CA, USA 92186-5608

[*1]john.rawls@ga.com; [2]zabrina.johal@ga.com; [3]john.parmentola@ga.com

***Abstract*-The fraction of global power demand supplied by nuclear power has been decreasing steadily in recent decades, in part because the cost of electricity from Light Water Reactors (LWRs) has risen to the point that it exceeds that from available fossil fuel sources. This paper examines the economics of two alternatives to gigawatt-scale LWRs: small modular LWRs (SMRs) and the Energy Multiplier Module (EM^2), a compact, gas-cooled, direct drive, fast reactor. No economic advantage over LWRs is found for SMRs, but the capital cost of EM^2 is predicted to be significantly lower owing to improved thermal efficiency, a substantial reduction in materials required, and higher fuel utilization. The waste disposal burden is also materially reduced (by 80% without recycling, up to 97% with recycling). In addition, the economics of recycling the spent fuel are found to be the reverse of that applicable to LWRs, allowing the power cost to be further improved with recycling. The improvement in fuel utilization and the possibility of multi-pass operation also increase the sustainability of nuclear power, allowing known uranium reserves to power the world economy far longer than possible with known fossil fuel reserves.**

Keywords- Nuclear Power; Cost Optimization; Small Modular Reactors; Nuclear Fuel Recycling

I. INTRODUCTION

As shown in Figure 1, the share of global electricity production from nuclear energy has been declining since the 1990s [1]. Present plans for new construction and plant retirements indicate that this trend will persist. Energy policy decisions are complex undertakings involving many considerations, but it is interesting to note that this trend continues despite increasing concern over fossil fuel-induced climate change and the rising cost of fossil fuel, the dominant component of fossil fuel-based power cost. This is also depicted in Figure 1, using coal as a proxy for fossil fuels in general [2].

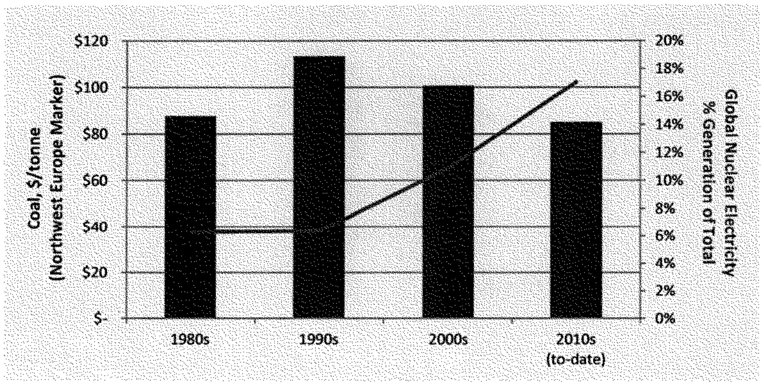

Fig. 1 Price of coal and global electricity from nuclear as a % of total electricity

Factors such as public safety and waste disposal have adversely affected the nuclear industry in some markets, but economics remains the dominant consideration in many countries and representative data in Figure 2 indicate that the capital cost of nuclear plants has been rising at a rate much greater than that of inflation[1]. These cost increases are attributable in part to increased regulatory requirements, which have had a twofold effect on costs: adding expensive safety features and extending the time required for licensing and construction. The response of regulatory bodies in the aftermath of the Fukushima event makes it clear that yet more stringent safety standards are likely to be applied to future nuclear plants. This expectation should sharpen the focus of the nuclear energy design community on developing approaches that improve the underlying economics through fundamentally new inventions and innovations. It is noted that the nuclear power industry does not have a strong tradition of making the type of R&D investments needed to maintain economic and performance competitiveness; rather, the industry has been in a largely reactive mode to regulatory mandates.

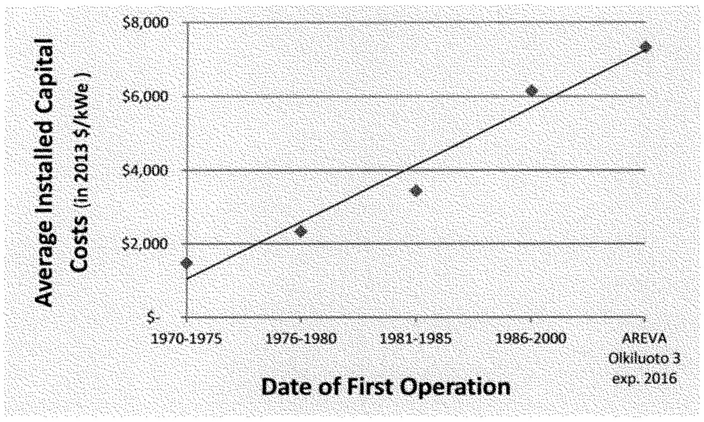

Fig. 2 Historical escalation of nuclear power capital cost; data drawn from references [3,4]

Nuclear power is unlikely to become a dominant player in the energy marketplace unless a more attractive economic model is offered. Because light water reactor (LWR) technology, which forms the basis for almost all the nuclear-based electricity generation in the world, is so mature, technical innovations that materially improve the economics are regarded as highly unlikely. This is especially true in a market where financial risk dominates investment decisions. However, in principle, a fundamental change in the approach to manufacturing and construction could make a difference to the economics. Such a change, involving a shift to smaller, lower power units, is now under serious consideration in several countries. Termed small modular reactors (SMRs), the notion is to reduce the physical size to a point that permits factory fabrication, providing economies of production and compacting the construction schedule. Such an approach clearly reduces the capital outlay required to build a power plant, but it is questionable whether the resultant cost of electricity will be lowered. Section II addresses this possibility.

Among the alternatives to LWRs under consideration are convert-and-burn reactors, which embody a number of attributes that are suggestive of a more economical price point. Two groups in the United States are developing an alternative to LWRs in the form of convert-and-burn reactors, featuring long lived reactor cores in which fertile fuel is converted to fissile fuel and then burned in-situ. One is the Traveling Wave Reactor (TWR), a gigawatt-scale sodium-cooled reactor [5] and the other is the Energy Multiplier Module (EM^2), a compact, lower power, helium-cooled reactor [6]. Such reactors offer the prospect for advances in both economics and sustainability through improved utilization of the energy stored in uranium and higher thermal conversion efficiencies. The implications for capital and operating cost are examined in the case of EM^2 in Section IV and the sustainability issue is discussed in Section V.

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[1] *The data in Figure 2 is shown for illustrative purposes only. The nature of nuclear power economics is complex with the potential for a multitude of factors to cause substantial variation. Among these factors, geographic location, regulatory environment and access to financing should be considered.*

II. ECONOMICS OF SMRS

The construction of commercial nuclear reactors in the western world is regarded apprehensively due to high initial capital costs and a legacy of cost overruns associated with uncertainty in licensing and construction delays. Apprehension drives perceived risk and increases the required rate of return for pursuing new projects. The past three decades have shown that reactors with large initial capital outlays and high required rates of return are not achieving a secure market foothold in the western world.

SMRs may be a viable option for nuclear power revival. They aim to reduce financial exposure and achieve a competitive power cost through factory fabrication, shorter construction duration and simplicity in design. However, due to scaling laws, systems are generally penalized in cost as size is reduced. SMRs will only make economic sense if the savings associated with size reduction exceed the economies of scale penalty. In addressing this issue, we follow common parlance in defining SMRs as having an electrical power output of no greater than 300 MW. In practice, the more pertinent figure of merit is physical size, with the upper bound being the largest unit whose major subsystems can be built in a factory setting and transported over land to the construction site.

The analysis begins by examining individual (single module) plants. Scaling laws can be used as an approximation for determining the relationship between the cost and power rating of systems that are otherwise identical. The cost per unit output generally decreases with increasing scale due to the economies of raw materials and spreading of fixed costs among more units of output. The economy of scale, or scaling law, used in nuclear power plants to calculate the capital cost when decreasing in unit size from P0 to P1 is

$$Cost\ (P1) = Cost(P0)\ \left(\frac{P1}{P0}\right)^{n}, \qquad (1)$$

where

Cost (P1) = Cost of power plant for unit size P1,
Cost (P0) = Cost of power plant for unit size P0, and
n = Scaling factor.

The scaling law can be used as an approximation for determining the relationship between power plants of differing sizes by using the cost data for a large nuclear plant as input and calculating the cost of an SMR. The most compelling data set comes from the French nuclear program, in which a number of replicated plants were produced over a substantial range of power levels. The scaling factor derived from plants with unit power from 300 to 1300 MWe is in the range of 0.4 to 0.7 [7]; in the analysis that follows, it is assumed that n=0.5. (It is acknowledged that extracting a scaling factor is not without controversy because building units at different times often means that different regulatory constraints were in effect.) If the cost of a large 1118 MWe reactor (the rating of an AP-1000 unit) is normalized at 1.0, the specific capital cost of varying power plant sizes (P1) are plotted in Figure 3 as "Base @ Nominal Efficiency" (the uppermost curve), which implies that electricity from a single 300 MWe power plant is expected to be 90% more expensive than that from a single 1118 MWe unit of the same general design, all other factors being equal. The unit power levels on the abscissa correspond to proposed SMR power levels and to the nominal 1118 MWe AP-1000 rating.

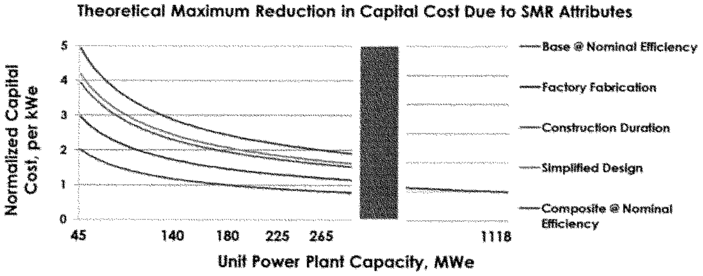

Fig. 3 Normalized capital cost when base cost is increased due to diseconomies of scale and subsequently reduced due to SMR attributes. Data points correspond to power ratings of proposed SMRs and an AP-1000

The scaling law is applicable only to plants built according to the same basic design concept. Changing to physically smaller units allows a number of options for changing the design concept in a cost advantageous fashion. Three attributes associated with SMRs that can reduce the cost of electricity have been identified and quantified by the Nuclear Energy Agency [7]. These are:

(1) Efficiencies of factory fabrication. The smaller structures and components of SMRs allow a large portion of the system to be manufactured in a factory setting. Factory fabrication allows significant cost savings in the manufacturing process through high levels of repetition, automation and quality control. The recurrent use of hard tooling, reduced weather delays, and a constant labor force also assist in achieving lower capital costs. The NEA attributes a possible 30-40% reduction in specific capital cost due to factory fabrication. Significantly larger percentage reductions have been documented in the case of very high volume production, but nuclear power plants do not fall into this category.

(2) Schedule compression. Factory fabrication also enhances parallel fabrication and reduces the construction schedule, which is a major cost driver of nuclear power. Subsystems can be fabricated in modules and then transported to the site and "plugged" in upon arrival. The NEA attributes a possible 20% reduction in specific capital cost due to reduced construction schedule.

(3) Design simplifications. SMRs may have significant design simplifications in their safety systems. Fewer safety systems and materials lead to reduced specific capital cost. The NEA attributes a possible 15% reduction due to design simplifications.

The potential individual and composite cost savings from each of these three factors as an offset to the cost disadvantage of the scaling law are shown in Figure 3. Even under the assumptions that all of these advantages can be realized simultaneously in a single SMR design concept and that these quantitative advantages will be as large at the higher end of the power range, it is concluded that the maximum composite cost savings in a standalone SMR still results in higher electricity costs than that expected from a standalone GW-class reactor unless the power rating exceeds 200 MWe. The most widely discussed water-cooled SMR designs are at lower power levels and hence can be expected to have higher cost of electricity.

The above analysis ignores several variables that could have a significant role in the economics. First, the scaling law really applies to thermal power, not electrical power, so the effect of varying power conversion efficiency must be taken into account. Second, it is applicable to stand-alone units, and the expectation is that SMRs would be built with higher multiplicity at a given site. Thirdly, the cost of capital has been assumed to be the same for all options and it has been argued that the lower total capital exposure entailed in SMRs would translate into a lower cost of capital. We examine each of these effects in the following analysis.

(1) Efficiency. All other factors being equal, the cost of electricity from a nuclear plant scales inversely with the efficiency. The AP-1000 unit that serves as the benchmark for the cost comparisons operates at 34% efficiency. A number of the water-cooled SMRs are expected to operate at 28% efficiency due to the reduced steam pressure compatible with natural cooling, which is equivalent to a factor of 1.2 increase in power cost.

(2) Multiplicity. Co-located nuclear plants will realize economies of scale by sharing operating labor, fixed systems, buildings and infrastructure. This is already the norm for the industry – two LWRs per site is standard in the U.S. and as many as six LWRs are built in a coordinated fashion in China. About a 10% power cost reduction is obtained by building two co-located plants, rather than one [7], a factor that should be essentially the same for SMRs. The level of additional cost reduction from higher multiplicity is heavily dependent on design details and the attitudes of regulators, but one reference [8] estimates a 17% savings for a six-module plant compared to a two-module plant. Regulatory insistence upon completely independent control and safety nets for each unit preclude materially larger savings at yet higher multiplicity.

(3) Cost of capital. Projects with lower total cost may be financeable at a lower cost of capital. A reduction from 9% to 6% mandated rate of return by investors and financing charges would translate into a nearly 20% project cost savings.

In cases of interest, the combined effect of these three factors leads to a negligible correction of the results presented in Figure 3 for water-cooled reactors. The efficiency factor is a 20% penalty for SMRs while multiplicity and cost of capital are mutually exclusive advantages of this same magnitude (they are mutually exclusive because the initial capital outlay of plants with many units will be comparable to that of GW-scale units).

It is concluded that diseconomies of scale are the predominant factor in the economics of water-cooled SMRs with power levels below 200 MWe. The large redundancy required for SMRs to achieve a base load rating comparable to large-scale LWR facilities is not compensated by the production and schedule advantages attendant to smaller units. This is the universal experience in the power industry and is typical of many other industries as well, including transportation. Achieving cost benefits from building multiple small unit-size modules in place of a smaller number of large unit-size modules can only occur if there is a fundamental change in the process needed to build the units.

If these conclusions are correct, the nuclear power industry faces challenging times. Aging LWRs may not be replaced with modern versions because the costs are unattractive. New versions with attributes that significantly enhance the economics are not in the offing. And the SMR route would seem on the whole to be even less attractive economically. A fundamentally new approach is needed. One such approach is addressed in the next section.

III. CONVERT-AND-BURN REACTOR DESCRIPTION

Helium is an attractive alternative to water for core cooling owing to its compatibility with higher temperature operation and to the safety advantages inherent in a chemically and neutronically inert coolant. It also provides siting flexibility and does not burden water supplies. Use of the coolant directly as a gas turbine working fluid enables the plant to take advantage of high temperature to achieve high electrical conversion efficiency. Helium-cooled thermal reactor designs have a power density in an order of magnitude lower than that of ALWRs. The associated need for large core structures and large amounts of material in the surrounding structures (per unit energy produced) has led some to conclude that helium-cooled thermal reactors will not be economical for electricity and/or process heat generation in some markets.

Because helium is effectively transparent to the neutrons produced in fission, it can also be considered as a coolant for fast reactors, viz gas-cooled fast reactors (GCFR). This concept was pursued in the 1970s but ultimately discontinued due to safety concerns associated with the low thermal inertia and corresponding low safety margins associated with metal-clad fuel, the only available clad choice at that time. However, when modern ceramic materials are employed for cladding, large thermal safety margins can be attained even at high coolant temperatures. Silicon carbide composite (SiC-SiC) is especially attractive for this purpose because it retains its structural integrity at temperatures in excess of 2000 °C, and many years of exposure in test reactors reveal that at temperatures of interest for GCFRs it experiences very little swelling or degradation of key constitutive properties even at high neutron fluence [9,10]. SiC has a very low neutron absorption cross-section at all fission energies and is likewise practically immune to transmutation in the pertinent fast neutron spectrum.

Achieving unit power levels of interest (200-300 MWe) in a volume small enough to permit factory fabrication and truck transport mandates high uranium packing density in the core. Together with the requirement of high melt temperature, uranium monocarbide (UC) emerges as the preferred fuel composition. A GCFR design based upon UC fuel and SiC-SiC, as both clad and structural material is the basis for our examination of the economics of alternatives to LWRs. This design, referred to as EM^2, is a passively safe, convert-and-burn fast reactor that is physically small enough to permit factory fabrication of the type envisioned for SMRs. By safely venting the fuel of fission product gases, the core is expected to have a lifetime exceeding 30 years during which the reactor is operated at full power without refueling or fuel shuffling. The fact that the fuel core does not need to be accessed for decades simplifies plant operations and reduces the risk of proliferation. The high packing density and large thermal safety margin combine to give rise to high thermal inertia, an additional safety consideration.

The choices of coolant and core materials facilitate high-temperature, high-efficiency operation. With a peak coolant temperature of 850°C and a power conversion design that combines a direct, closed cycle gas turbine with a Rankine bottoming cycle, the 500 MWt unit power results in 265 MWe (net efficiency of 53%) with evaporative cooling and 240 MWe (48% net efficiency) under dry cooling conditions. Dry cooling greatly expands plant-siting options, which is an important consideration for broader global adoption of nuclear power. The basic layout of a four-unit EM^2 power plant, rated at 1060 MWe (960 MWe in the case of dry cooling), is shown in Figure 4. A single reactor building houses all four reactor cores, together with their control rooms, power conversion units, and spent fuel storage areas.

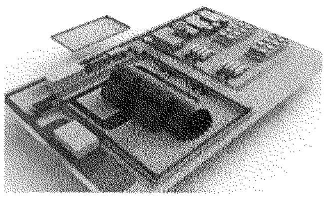

Fig. 4 Site plan for baseline, four-unit 1060 MWe plant

Data associated with this layout are strongly suggestive of improved plant economics. Drawing comparisons to typical LWR plants on a per unit electricity produced basis, an EM^2 plant requires less than 20% of the real estate and less than 20% the nuclear concrete [11], both of which are cost drivers. These reductions reflect the nature of a high efficiency, direct drive system, which simplifies and/or eliminates the need for a number of large items of equipment needed for power conversion and heat rejection. These factors supplement the advantages of the modular approach to construction, which facilitates schedule compression and hence reduces the cost of capital over the period of construction. We shall return to the economics after a brief description of the reactor and its operational features. This description provides enough information to address the economic and sustainability issues, but it is not intended to be thorough enough to permit an in-depth assessment. The reader interested in greater technical detail is referred to other papers for nuclear design [12], thermomechanical design [13], fuel cycle [14], and development status [6].

A cutaway view of the reactor building displaying one of the four individual units is presented in Figure 4. Grade level is at the floor of the maintenance hall, which services all reactors and the below-grade common spent fuel storage area (not shown). Each primary system is enclosed within a sealed below-grade containment consisting of three chambers connected by ducts. The central reactor chamber is enclosed in a concrete shield structure to enable man access to the Power Conversion Unit (PCU) and Direct Reactor Auxiliary Cooling System (DRACS) chambers. The containment structure is suspended from an approximate mid-plane support frame that also supports the primary system. Access to each chamber is through hatches from the grade-level maintenance floor. Each of the vessels depicted in Figure 5 are less than 5 m in diameter, permitting overland transport of completed vessels to the construction site.

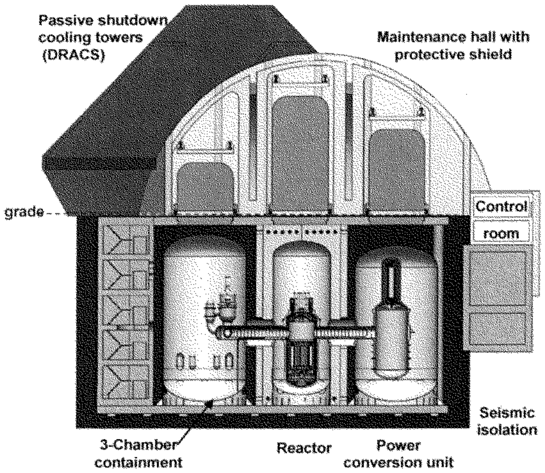

Fig. 5 Cutaway view of reactor building, showing one of four units

The active core is divided into two regions, the fissile starter and the fertile converter; the average enrichment in the core at the beginning of life (BOL) is just over 6%. Virtually all the power at BOL is in the LEU-fueled starter region, but some of the neutrons produced therein convert ^{238}U in the neighboring fertile region to ^{239}Pu, which becomes available for fissioning. Figure 6 shows the time dependence of the excess reactivity and also the relative contributions of ^{235}U and ^{239}Pu to the total fission power as a function of reactor operating time, illustrating the convert-and-burn mode of operation. The excess reactivity never exceeds 2%, which is well within the dynamic range of the control elements. Initially, most of the energy comes from the fission of ^{235}U in the starter fuel. After the first decade, the preponderance of the energy comes from the fission of ^{239}Pu. Direct fast-fission of ^{238}U produces about 20% of the energy. The average burnup is 14.6%, three times that achievable in LWRs.

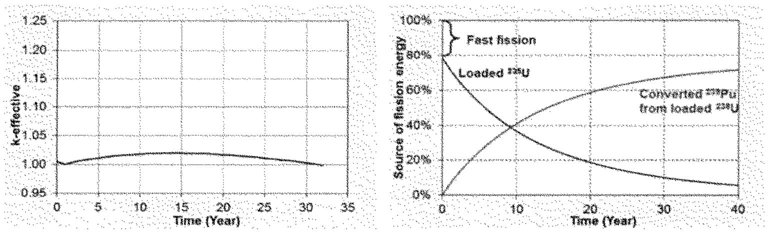

Fig. 6 Reactivity (left) and contributions to fission power (right) as a function of time

IV. ECONOMICS OF EM^2

Sensitivity analyses are useful in determining how uncertainty may affect economic outcomes in terms of net present value. The discounted free cash flow model is used as a base framework for financial modeling. Each major parameter of interest is varied by +/- 10%. The specific parameter of interest is varied with all other parameters held constant.

In the sensitivity analysis of EM^2, summarized in Figure 7, the cost of capital is the single largest factor. Cost of capital is driven by the expected rate of return to equity investors and required debt financing charges. The cost of capital used here is the weighted average cost of capital (WACC), which includes a tax shield on debt,

$$WACC = Rd(1 - Tc)\left(\frac{D}{V}\right) + Re\left(\frac{E}{V}\right), \tag{2}$$

where

Rd = cost of debt,
Tc = corporate tax rate,
D = value of debt,
Re = cost of equity,
E = value of equity, and
V = enterprise value.

The second largest driver is net efficiency. As discussed previously, the efficiency of EM^2 is improved owing to the use of a direct drive gas turbine and high operating temperature. With efficiency as the second largest economic driver, the EM^2 financial return at 53% efficiency has a marked improvement over water-cooled SMR designs at a nominal 28% efficiency.

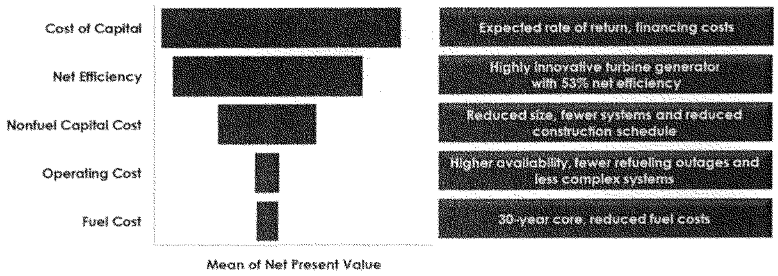

Fig. 7 Tornado chart highlighting the comparative impact of ±10% variations in the parameters that serve as the largest economic drivers for EM^2

The last three major drivers are nonfuel capital cost, operating cost and fuel cost. The Generation IV Forum's code of accounts outlines a method for arriving at overnight construction, annual operation and maintenance (O&M), and fuel costs [15]. Overnight construction cost includes capitalized preconstruction costs, direct construction costs, field indirect costs, field management costs, owner costs and supplementary costs. Interest during construction and first core fuel costs are not included in the overnight capital cost. Fuel is treated as a capitalized asset and depreciated on a modified accelerated cost recovery schedule because the fuel core life lasts 30 years. O&M costs are expensed every year and include staffing, consumables, maintenance, subcontracts, overheads and capital replacement costs.

Levelized cost of electricity (LCOE) is a common metric used to compare the competitiveness of electrical generation technologies. LCOE is equivalent to the break even sales price over the life of the plant for a required rate of return. Capital and operating costs are considered as well as financial parameters such as: cost of capital, inflation, escalation (if applicable), taxes, depreciation, and time value of money (through discounting).

As efficiency increases, the amount of product per unit cost is increased and the LCOE is reduced. The LCOE is reduced by approximately 50% when the efficiency is increased by the same factor. Figure 8 illustrates this concept.

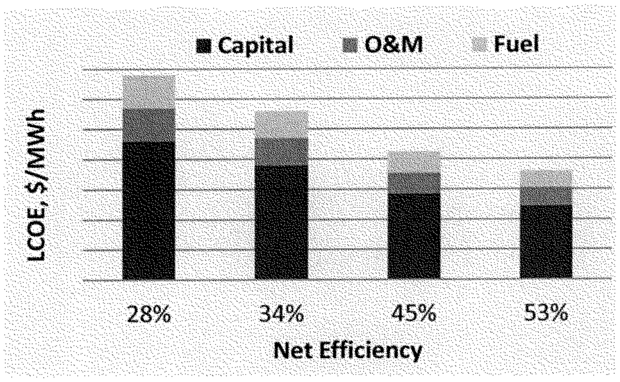

Fig 8 An illustrative example of the reduction in LCOE due to increasing efficiency

Better uranium utilization in EM^2 translates into lower life cycle fuel costs, although the threefold advantage in burnup is moderated by the increased enrichment, higher fabrication costs (see Table I) and cost of capital adjustments stemming from the need to have three decades worth of fuel available on day one.

TABLE I. ROUGH COMPARISON OF LWR AND EM^2 FUEL COST PER KG

Cost Item	LWR (\$/kg U)	EM^2 (\$/kg U)
Mining and conversion	900	1200
Enrichment	500	700
Fabrication	500	800
Waste management	1100	1300
Total	3000	4000

If EM^2 is operated not in a once-through mode, but in a multi-generation mode with end-of-cycle fuel being recycled for use in a subsequent cycle, the fuel cost advantages can be enhanced because no new uranium resources or enrichment services are needed. This would be advantageous economically if the recycled fuel can be produced less expensively than fresh fuel. In this regard, it is instructive to compare the economics of recycling convert-and-burn fuel with that applicable to LWR fuel. LWR fuel at end of life has only 25-30% of the initial fissile content and thus has a proportionately smaller energy value than fresh fuel (in practice, recycled spent LWR fuel must be upblended before reuse in a reactor). As a consequence, it is only economically sensible to reuse LWR fuel if it can be recycled at a cost of less than 25-30% of the \$3000/kg cost of fresh LWR fuel. This is not achievable with today's technology. End-of-cycle EM^2 fuel, in contrast, has about 120% of energy content of fresh fuel, owing to a conversion ratio slightly greater than unity and the fact that converted fuel is more reactive than fresh fuel. Reuse of this fuel is thus economically favorable if the recycling cost is less than 120% of the \$4000/kg cost of fresh EM^2 fuel, a much less daunting proposition (for comparison, the cost of aqueous reprocessing in France is usually estimated to be \$15,00-\$2,000/kg and this is also a remotely-operated process). This topic will be revisited in Section V.

Plant availability also plays an important role in the economics of any power source. This is an unknown in EM^2 because the plant has not yet been built and operated. However, 70% of the downtime in today's LWRs is for fueling [16], a process that is not required in EM^2. It is thus reasonable to assume that, if EM^2 is extensively deployed, it would eventually equal or surpass the already excellent availability and capacity factor standards established by the nuclear power industry.

Disposal of nuclear waste is not a very important economic consideration, but it does represent an important societal cost and has emerged as a major impediment to the broader implementation of nuclear power in some markets. In a once-through fuel cycle, EM^2 produces only one-fifth as much waste mass per unit electricity generated as today's nuclear plants. This factor is derived from combining the approximate factor of three increase in burnup, which results in that same factor decrease in the mass of waste generated per unit thermal energy generated, with the approximately 1.6 increase in thermal conversion efficiency. Mass is only one factor in determining waste disposal costs, but it is a significant one and has been used as the defining characteristic of geological repositories [16]. A similar reduction factor is applicable to waste volume (albeit there is a yet to be quantified volumetric contribution from the gases vented from the core and the resins used to store that material), while a smaller reduction pertains to waste heat. If the fuel is reused, the waste-related costs per unit electricity generated are further reduced. Decommissioning costs are also expected to be lower than existing nuclear plants because so much less material is involved in plant construction on a per unit energy produced basis.

V. SUSTAINABILITY OF CONVERT-AND-BURN REACTORS

Sustainability in this context refers to how long nuclear power can make significant contributions to global energy supply. For simplicity, we restrict attention to a uranium-based fuel cycle; thorium-based fuel cycles have comparable resource limitations, but closing the fuel cycle is more problematic. Sustainability is driven by two factors – the projected availability of economically affordable uranium and the amount of useful energy extracted per unit mass of uranium. The former is dominated by geological and mining technology considerations and the latter is governed by the specifics of the fuel cycle.

Turning first to the question of resource availability, it is noted that uranium is quite abundant in the earth's crust. One indication of this abundance is the fact that the rate at which rivers leach uranium into the world's oceans is orders of magnitude greater than the amount of uranium needed to supply 100% of the global energy demand [17]. This is in principle a perpetual supply, lasting as long as the sun continues to keep the earth in its present temperature range. But the great preponderance of this uranium is at exceedingly low concentrations, making recovery unaffordable with today's technology.

The NEA recently estimated the known and as yet unknown economically recoverable uranium reserves at 5.5 million tonnes (MT) and 10.5 million MT, respectively [18]. The threshold applied to establish "economic" was a mining cost of <$130/kg, about three times the current spot price. These reserves are large compared to the rate of uranium extraction, which peaked at 70 thousand MT in 1980 and has been in the 35-50 thousand MT annually in the last decade. Actual utilization of uranium has been steadily increasing, but a substantial fraction of the uranium consumed in recent years has come from secondary sources, primarily weapons stockpile drawdowns and depleted uranium (these are not included in the NEA resource estimates, but would not make a significant impact if they were).

The total energy that could be extracted from this resource is computed on the assumption that every uranium nucleus in the ore is fissioned, which would release about 1000 GW-days of energy per metric ton of uranium. This amounts to about 1.5×10^7 GW-yr of energy for the known economically recoverable reserves (and a factor of three higher if the projected but as yet unknown economically recoverable reserves are included). This is one order of magnitude higher than the corresponding figure for the world's total economically recoverable fossil fuel reserves (7.8 trillion barrels of oil equivalent, or 1.7×10^6 GW-yr). As an energy source three orders of magnitude larger than the current annual global energy consumption (at about 500 Quads), it is adequate to meet demand for centuries.

The nuclear fuel cycle in use today does not support the above optimistic resource outlook because only a small fraction of the uranium nuclei undergo fission. About one nucleus in every 140 is the fissionable 235 isotope but, in actual practice, the uranium utilization factor in LWRs is even smaller, less than one part in 200. This dramatically changes the sustainability conclusions: what is in principle an order of magnitude greater energy resource than fossil fuels becomes an order of magnitude lower energy resource, one that could only meet the plant's total energy need for a single decade.

Even a single pass mode of operation in a high temperature convert-and-burn reactor improves this resource picture significantly because uranium utilization is improved (a higher burnup fraction) and because the increased temperature translates into better energy conversion. But the big payoff in sustainability comes with fuel reuse. If enough (typically 50% is adequate) of each fission product is removed, the end-of-cycle fuel can be reused in a new cycle without adding any new fissionable material (fertile material is used for make-up). The effective uranium utilization increases rapidly with the number of burn cycles for two reasons: (1) comparable burnups occur in each generation, and (2) reuse as make-up fuel of the depleted uranium, which is produced as a byproduct of the initial fuel load.

If such a fraction of every fission product is removed at the end of each cycle, the reactivity reaches a steady state and can be continued indefinitely, allowing full uranium resource utilization. It is to be noted that the recycling process need not reduce the fuel to its elemental constituents and in fact need not involve any separation of actinides at all, which would be preferable from the standpoint of proliferation resistance. One promising approach to accomplishing this is the Archimedes mass filter [19], which takes advantage of the rather large gap between the mass of the actinides and that of the fission products.

VI. CONCLUSIONS

Economic considerations alone suggest that, in its present embodiment of GW-scale LWRs, nuclear power is unlikely to provide an increasing share of global energy supply. SMRs offer essentially the same technology with the potential for cost savings on several grounds, most notably factory fabrication and shortened construction schedules. However, these cost savings do not fully offset the penalty of reduced economy of scale. It is concluded that genuine innovation is required to change the economic realities of nuclear power. EM^2 is offered as an example of such innovation, embodying as it does the benefits attributable to small modular reactors but at nearly double the thermal conversion efficiency of the water-cooled units. Significantly lower power cost is forecast and the approach offers far more promise for the long-term sustainability of nuclear power.

ACKNOWLEDGMENT

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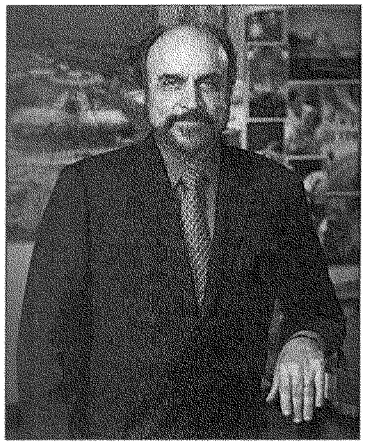
GENERAL ATOMICS

John Parmentola, Ph.D.

Senior Vice President,
Energy and Advanced Concepts



Dr. Parmentola has built a career as a pioneer, entrepreneur and innovator, with broad experience in the private sector, academia and high-level positions within the federal government and defense community.

As Senior Vice President at General Atomics, he leads the California-based technology company's Energy and Advanced Concepts Group, focusing on energy, defense, advanced computing and oversight of DIII-D National Fusion Facility, the largest in the United States (U.S.). The Group's innovations include a revolutionary waste-burning compact advanced reactor, setting new land-speed records with maglev systems and building the world's most powerful superconducting electromagnet.

Dr. Parmentola served as Director for Research and Laboratory Management for the U.S. Army, directing lab management policy, infrastructure and security for all Army laboratories, research, development and engineering centers, and base realignment and closure efforts. He also oversaw a $1-billion combined budget for basic and applied research, manufacturing technologies, small business innovative research, and high-performance computing programs.

In addition, Dr. Parmentola served as science and technology advisor to the chief financial officer of the U.S. Department of Energy (DOE), where he provided technical, budgetary, and programmatic advice to DOE leaders for more than $7B in science and technology investments.

He also co-founded the Advanced Systems and Concepts Office of the Defense Threat Reduction Agency to address major national challenges concerning the threat of weapons of mass destruction, and has served as principal scientist at MITRE Corp., where he worked in applying advanced technology associated with the $1.8-billion Cheyenne Mountain Upgrade Program.

Born in the Bronx, New York, Dr. Parmentola earned a bachelor's of science in physics cum laude from Polytechnic Institute of Brooklyn, and his doctorate in physics from MIT. He was a Professor of Physics at West Virginia University.

Dr. Parmentola received the 2007 Presidential Rank Award for Meritorious Executive. He was also an Air Intelligence Agency nominee for the R. V. Jones Central Intelligence Agency award, and a recipient of the Outstanding Civilian Service Award and the Superior Civilian Service Award for his contributions to the U.S. Army. He received the Alfred Raymond Prize and the Sigma XI Research Award, and is a Fellow of the American Association for the Advancement of Science. He has presented and published more than 400 speeches, papers, and articles in science and technology policy and is the author of an authoritative book on space defense.

EXHIBIT A - Response to Enclosure 3, Question No. 5

General Atomics - Energy and Advanced Concepts Group
Federal Grants/Subgrants/Contracts/Subcontracts
October 1, 2011 through March 31, 2015

No.	Description	GA Project	Customer
1	NSTX Fusion Device	30041	U.S. Department of Energy
2	DIII-D	30200	U.S. Department of Energy
3	ADVANCED CONCEPT EXPLORATION FC	30247	U.S. Department of Energy
4	Modeling Plasma Response	30251	University of California, San Diego
5	EDGE SIMULATION LABORATORY	30271	U.S. Department of Energy
6	NGNP Conceptual Design Studies	30302	Battelle Energy Alliance
7	BGCAPP FOAK II	30335	Parson Infrastructure & Technology Group Inc.
8	Fusion Science Center	30343	University of Rochester
9	LLNL Target Agreement	30347	Lawrence Livermore National Laboratory
10	Baseload Concentrating Solar Power Gen	30349	U.S. Department of Energy
11	BLU Demilitarization Using Cryofracture	30355	Advanced Technology International
12	LRIP Operations for Cryofracture Process	30361	Advanced Technology International
13	Hy-Tec EAFB	30363	U.S. Air Force
14	SAVIOR Unique Mobile Land/Water Survell.	30365	U.S. Army RDECOM Acquisition Center
15	ITER Central Solenoid Coil	30370	UT Battelle, LLC
16	Cellulosic Derived Biodiesal Program	30379	Eastern Kentucky University
17	HPDC MPHB RD&D	30381	Advanced Research Projects Age
18	Selective Gaseou Extraction: Research, D	30382	U.S. Department of Energy
19	Rockeye Bomblet Demil Operations	30383	Advanced Technology International
20	Project Raven	30384	Ralph Perkins Industries
21	CTAPS	30385	Naval Research Laboratory
22	Aluminum Power System	30387	Office of Naval Research
23	Characterization report for Janus12B	30388	Harvard University
24	TAPS	30389	Ralph Perkins Industries
25	ICF	30390	U.S. Department of Energy
26	SCIDAC Fusion Materials Modeling	30391	U.S. Department of Energy
27	Extreme Scale Data	30392	U.S. Department of Energy
28	Viscous Plastic Flow	30395	U.S. Department of Energy
29	Accident Tolerant Fuel Project	30396	Westinghouse Electric Company
30	Nuclear Energy University Programs - Rea	30398	Texas A&M University
31	NLUF - Laser Pulse and Plasma Investig.	30401	U.S. Department of Energy
32	BGCAPP Post FOAK Support	30402	Parson Infrastructure & Technology Group Inc.
33	Advanced SMR R&D Industry Support	30403	U.S. Department of Energy
34	TAPS II	30404	Ralph Perkins Industries
35	Scenarios and Control EAST/KSTAR	30405	U.S. Department of Energy
36	Modeling Plasma Response	30414	University of California, San Diego
37	Cryofracture Facility at MCAAP	30416	Advanced Technology International
38	ITER LFSR Diagnostic System	30417	Princeton Plasma Physics Laboratory
39	Coated Alloy Foil Targets	30420	University of Washington
40	Raven II	30422	Ralph Perkins Industries
41	NSTX Research -Plasma Boundary Interface	30423	U.S. Department of Energy
42	ITER Wide Angle Viewing System	30424	Princeton Plasma Physics Laboratory
43	Advanced Tokomak Modeling	30425	U.S. Department of Energy
44	EHT SBIR Support	30428	Eagle Harbor Technologies Inc.
45	PPPL TIP	30429	Princeton Plasma Physics Laboratory
46	DOE Education Outreach	30430	U.S. Department of Energy
47	Mod to EFIT Code	30435	Princeton Plasma Physics Laboratory
48	ONR UUV MRS Network Link	30436	Leidos
49	LLNL Task Agreement	30437	Lawrence Livermore National Laboratory
50	ARC - Complex SiC - SiC Structures	30438	U.S. Department of Energy
51	HOLLOMAN MAGLEV FOLLOW-ON	37023	U.S. AIR FORCE

EXHIBIT A - Response to Enclosure 3, Question No. 5
General Atomics - Energy and Advanced Concepts Group
Federal Grants/Subgrants/Contracts/Subcontracts
October 1, 2011 through March 31, 2015

52	New Fuel Receipt Support	39293	Battelle Energy Alliance
53	Support Reactor Relicensing Tasks	39364	Battelle Energy Alliance
54	HPPP Engineering Support Service	39387	Rock Island Contracting Center
55	SAICTead iSCWO	39406	Leidos
56	Nonlinear Evolution of the Weibel	39418	Lawrence Livermore National Laboratory
57	MIT-LL 0.8" WG Components	39419	Massachusetts Institute of Technology
58	Support to Reactor Tech Programs	39420	Shaw Environmental and Infrastructure
59	ROK SCWO Support	39421	McAlester Contracting Office
60	Fabricate Waveguide and Components	39422	UT Battelle, LLC
61	Targets for MEC Commissioning Experiment	39424	SLAC National Accelerator Laboratory
62	I&C-IPT Plasma Control Group Support	39425	UT Battelle, LLC
63	ITER Disruption Mitigation	39426	UT Battelle, LLC
64	Ion Cyclotron Heating Concept & Design	39428	UT Battelle, LLC
65	Feasibility and Safety Assessment for Ad	39430	Oregon State University
66	Tritium Autonomous Power Source	39431	Athena Energy Corp
67	ONRTS Phase II	39432	Hydro Technologies
68	SiC Joining	39433	Battelle Energy Alliance
69	LCLS MEC Targets	39439	SLAC National Accelerator Laboratory
70	SEM Lab Services	39440	Coorstek
71	SWIM Web Portal Maintenance	39441	UT Battelle, LLC
72	Supt of Uranium Processing Facility Rev.	39442	Navarro Research & Engineering
73	MTLS Phase I Test Support	39448	ARSC Research & Technology Solutions
74	SHEDS	39450	Naval Surface Warfare Center-Crane
75	MITR Feasibilility Study	39454	Battelle Energy Alliance
76	Acoustic Measurement & Connector Topology	39479	University of Texas at Dallas
77	Modified Battery Modules	39481	Naval Surface Warfare Center-Crane
78	Targets for LINAC Coherent Light Source	39482	SLAC National Accelerator Laboratory
79	Salt Waste Continuation	39485	Parson Infrastructure & Technology Group Inc.
80	LINAC Carbon Targets	39498	SLAC National Accelerator Laboratory
81	Material Processing for Energy Applications	39506	San Diego State University
82	Diamond Multi-Step Targets	39508	SLAC National Accelerator Laboratory
83	Update Control Sys & Support for SCWO	39512	McAlester Contracting Office
84	Support to BGCAPP Construction and Syste	39513	Parson Infrastructure & Technology Group Inc.
85	Targets for MEC Experiments	39515	SLAC National Accelerator Laboratory
86	Test Articles, 7P3S	39516	Naval Surface Warfare Center-Crane
87	Aluminum Microdot Targets	39518	SLAC National Accelerator Laboratory
88	Kirtland AFB Waveguide Components	39524	Leidos
89	Modeling Dynamic Fracture	39529	UT Battelle, LLC
90	Mu2e	39532	Fermilab
91	Fabrication of SiC/SiC Tubes	39533	UT Battelle, LLC
92	Test and Evaluation Battery System	39536	Ralph Perkins Industries
93	ICF OPERATING/Capital	30272/30273	U.S. Department of Energy
94	Miscellaneous Intercompany Purchase Orders	Various	Various

EXHIBIT B - Response to Enclosure 3, Question No. 8
General Atomics - Energy and Advanced Concepts Group
Major Federal Grants/Subgrants/Contracts/Subcontracts
October 1, 2011 through March 31, 2015

No.	GA Project Name	GA Project No.	Customer Name	Funding Source	Contract Number	Amount*
1	DIII-D	30200	U.S. Department of Energy	DOE	DE-FC02-04ER54698	331,327,790.00
2	BGCAPP FOAK II	30335	Parson Infrastructure & Technology Group Inc.	DOD	W52P1J-09-C-0013	15,111,398.00
3	ITER Central Solenoid Coil	30370	UT Battelle, LLC	DOE	DE-AC05-00O22725	120,857,816.86
4	ICF	30390	U.S. Department of Energy	DOE	DE-NA0001808	84,093,831.00
5	Mu2e	39532	Fermilab	DOE	618313	20,323,263.00

*Amount awarded during the period October 1, 2011 through March 31, 2015

Chairman WEBER. Thank you, Dr. Parmentola. I now recognize myself for five minutes to begin the questioning.

Mr. Batten, you've come here today with a unique story of a charitable foundation that has invested in a specific process of nuclear fuel recycling, all for the purpose of jump starting an advanced reactor technology that would reduce waste, increase resource utilization, and mitigate proliferation concerns, obviously. So how do you hope this—I think you pronounced it CRADA?

Mr. BATTEN. CRADA, yes.

Chairman WEBER. CRADA? Um-hum.

Mr. BATTEN. C–R–A–D–A.

Chairman WEBER. Right, Cooperative Research and Development Agreement, will make a difference, and what would be the benefits to the United States from successful pyroprocessing and IFR, Integral Fast Reactor, deployment? And then I've got a follow-up question about something you said. How do you hope this will make a difference?

Mr. BATTEN. Maybe I'll start with a little bit of background. I live in Norfolk, Virginia, which is only a few feet above sea level, so it's—tells how we got into this.

Chairman WEBER. How many feet?

Mr. BATTEN. A few feet.

Chairman WEBER. Okay.

Mr. BATTEN. You know, like, 2, 3, 4 feet, depending on where you are. And—so we're very concerned about the rising seas that could be caused by climate change. And so we looked around for—well, what could we do to help with that transition to a low carbon energy? And we concluded that lots of people were working on wind, and solar, and batteries, and, you know, savings of—energy savings, all of which are very important, and all of which deserve Federal research dollars. We found out that not nearly as much attention was being given to nuclear power.

So within that it seemed like there were two issues. One was nuclear waste, was there anything that could be done to reduce the nuclear waste problem, since that's such a hindrance to the expansion of nuclear power? And pyro processing seemed like a very promising technology to be able to reduce the nuclear waste problem. And, of course, advanced reactors, fast reactors, when coupled with recycling, also lets you use much more of the energy in uranium. The current, you know, light water reactors use about one percent of the energy in uranium. Fast reactors, with recycling, could use 99 percent of the energy in the uranium.

Chairman WEBER. Okay. And I applaud you for that, by the way. Just kind of a follow-up question, you said in your comments, if I was following—heard correctly that the pyroprocessing was developed in the United States?

Mr. BATTEN. It was developed at Argo National Lab by their work in Chicago, and also by their work out with the Experimental Breeder Reactor II. They have a fuel cycle facility attached to that.

Chairman WEBER. Okay.

Mr. BATTEN. So Argonne really developed that.

Chairman WEBER. But do I understand that France uses more reprocessed fuel, as it were, than we do? Do you know?

Mr. BATTEN. Yes. France—the U.S. currently is not recycling fuel. France is reprocessing, use aqueous reprocess.

Chairman WEBER. So they're not—they are not using our technology?

Mr. BATTEN. That's correct, yes.

Chairman WEBER. Okay.

Mr. BATTEN. The difference is the aqueous reprocessing produces pure plutonium, which people are obviously concerned about as a proliferation risk, whereas the pyroprocessing produces a mixture of plutonium, all sorts of different isotopes mixed together with other trans-uranics, or those other elements to the right of uranium.

Chairman WEBER. Would you compare and contrast a cost analysis to the two? Are they roughly the same, or have you—do you——

Mr. BATTEN. I do not know the answer to that.

Chairman WEBER. Okay. Dr. Parmentola, given the United States budget constraints—obviously Congress must be careful with every dollar we spend. That said, as many of you have already said, there are some activities that the private enterprise—private companies cannot undertake, but where the federal government can actually support the research and infrastructure to support that private investment.

So, Doctor, can you explain how an open access fast reactor user facility could enable private industry to deploy stranded capital that is simply waiting to be spent on research and development for new reactor designs that are more efficient, and even safer than today's technology? That's my question, but before you get there, one of the terms I heard bantered around about this process is, if we would support the development of a library where, for example, we could have the resources, and companies could come in, and kind of draw from those resources. And I think you actually had—or maybe it was Dr. Peters who called it a test reactor and a test bed. Was that the term you used?

Dr. PARMENTOLA. Yes, sir.

Chairman WEBER. Okay. And so, Dr. Parmentola, can you explain how that open access fast reactor user facility would help?

Dr. PARMENTOLA. Yes. First of all, currently there are companies that are spending R&D in trying to advance their advanced reactor designs. In the private sector, the amounts of money that go towards this, at least currently, relatively low. We focus mainly on the high risk issues that need to be reduced in order to make decisions about going forward. However, a large fraction of the issues that need to be addressed require a new test facility. Now, if such a test facility was built, this would enable the private sector to be able to go to these facilities, utilize more of its capital to be able to do the testing, and reduce the risk associated with realizing these advanced concepts.

As I said in my testimony, the type of reactor we're looking for is a high performance reactor. This would speed up testing, the productivity associated with what companies would do would go up, and it would enable us to be able to make decisions, rather significant decisions, about going forth and actually building these advanced reactors.

Chairman WEBER. Okay. Thank you. And back to Dr. Peters, you pointed out that the U.S.'s non-proliferation mission could be adversely affected by foregoing the timely development of advanced reactors for export because that void will be filled otherwise by supplier nations. Would you elaborate—I think we probably—most us understand, but would you elaborate on how exporting reactor technology is a component to the United States' security and non-proliferation mission, please, sir?

Dr. PETERS. Sure. So let me start by saying that the past shows us that, when you look at the worldwide reactors that are operating, U.S. export let to that, and the regulatory process that the U.S. established is also gold standard worldwide, so the past tells us that we can actually export our technologies and our ideas, and have a positive impact, and be a leader. Now, the matter of export's outside of a national labs purview. It's a policy and industry play, but it—past shows that it can work in the future. So I would say it definitely should be looked at very carefully, and I think it does establish international leadership.

But I do want to make the point also that there's a component of this that also is related to the R&D and the necessary infrastructure, because if you—the national labs and university system in the U.S. is world class in the nuclear space, but that—we have it now, but if we don't continue investing, we'll lose that capability, and that's an important part of getting that seat at the table. Having that world leading S&T capability is very important. So, from the labs' and universities' perspective, that continued investment—but getting on the path of research, development, demonstration, and ultimately deployment domestically can't do anything but help international leadership.

Chairman WEBER. Along those lines, you said in your prepared testimony that you provided the NRC will need to establish a new licensing structure to accommodate the next generation of more safer, efficient safe rectors. So can you explain to us further why the NRC will need to establish a new licensing framework?

Dr. PETERS. The NRC has a broader framework, but they have a set of general design criteria and detailed regulations that are focused on light water reactors, pressurized reactors, and boiling water reactors. So if we're going to move forward with licensing advanced reactors, we have to go and develop general design criteria, to license those machines.

Now, there is an effort already funded by DOE working with NRC, and the labs are supporting that, but it needs to be scaled up, let's say, in terms of budget, and also accelerated if we're going to actually license these machines.

Chairman WEBER. Got you. Thank you. And I apologize to my colleagues, I'm a little over time. The gentleman from Florida, Mr. Grayson, you're recognized for questions.

Mr. GRAYSON. Thank you, Mr. Chairman. Mr. Gilliland, some of the problems associated with using fission for power generation are meltdowns, radioactive waste, and nuclear proliferation. There are other problems as well. Can you please elaborate on your testimony on why fusion may be able to avoid some of the problems associated with fission?

Mr. GILLILAND. Yes, absolutely. Ultimately it starts with the reaction itself, so—fission is a large atom that can react spontaneously. Fusion is done with hydrogen only, and it's impossible for fusion to happen spontaneously, so—it's a difficult reaction to get started, therefore very difficult, or impossible, for it to start on its own.

So in a fusion reaction the byproducts are helium and heat, and—or high energy neutrons, so there's not—there are not long-lived radioactive waste materials produced at all. Using hydrogen it is certainly difficult to figure out how that could lead to proliferation challenges as well. So it, you know, it—we do have normal safety challenges that any power plant would have. It's not that it's without risk completely, but certainly long-lived radioactive waste is not one of them.

Mr. GRAYSON. All right. Now, your company is developing and advancing a unique fusion energy design that falls into a category of fusion energy concepts called magnetized target fusion. What is that?

Mr. GILLILAND. Magnetized target fusion, I think it's worth stepping back for a second and describing kind of the mainstream long-standing fusion programs at a high level. ITER and magnetic fusion use a low density plasma, much less dense than air, and hold it together with large superconducting magnets, and hold it together for long periods of time, even continuously. Laser fusion is sort of the other extreme, where a little fuel pellet is slammed with lasers in nanoseconds or picoseconds.

The idea behind magnetized target fusion and other what we call middle ground fusion approaches is that those extremes are extremes. They're extremes, makes them expensive. So big superconducting magnets cooled to 2 degrees Kelvin are expensive, as are, you know, using the world's largest lasers. It's not that those pathways aren't viable, they're just—they appear to be expensive. So the middle ground uses density between the two, and speed of compression—speeds of shrinking that plasma that are much slower than laser fusion. So, in our case, we compress a plasma, called a spheromak plasma, in about 80 microseconds, which is obviously much slower than the picoseconds or nanoseconds of laser fusion. So the idea is just—simply put, it's to avoid the extremes, and become much lower cost, and ultimately more practical.

Mr. GRAYSON. Now, my understanding is that your design has no permanent home in U.S. energy research, but is funded by a temporary ARPA–E program that you noted yourself in your testimony. Is there a value, in your opinion, to having such research permanently funded as a regular part of energy research by the federal government?

Mr. GILLILAND. Sure. So I would comment, you know, ARPA–E has done a great job on a fusion program. I think they are still in the middle of negotiating with the various recipients, so, you know, whether or not we are a recipient of that I don't know at this time.

However, to your question, I think it's vital that the U.S. support this middle ground, and I think the primary reason is that a lot of significant progress can be made for small dollars, so some of these middle approaches are absolutely viable, some are not. We don't know that—you don't know which is which yet, but it will not take billions of dollars to determine that.

So, you know, I think funding is one, but I think in my testimony I mentioned let's work together, labs and private companies, around simulation codes. Let's work together around exchange of Ph.D.'s and physicists. I think there's some simple things we can do to accelerate progress as well, but ultimately I do, obviously, support this middle ground of fusion.

Mr. GRAYSON. What's a rough timeframe that you could provide, allowing for, no undue optimism, for achieving that energy production?

Mr. GILLILAND. It's a difficult question, there's no question about that. I think there's an interesting graph that plots Moore's Law against fusion progress. So, fusion progress being how much energy out of a reaction are we getting in, are you—how much are we getting out for what we're putting in? And it's actually quite interesting, they parallel each other.

So I think the question is—it's, you know, we're nearly there. I think the large programs had determined that it can be done, and now it's a question of just how do we it commercially? How do we do it economically? And I think that's the question, right? So I think there's two steps involved. One is building an alpha power plant, or a prototype plant that demonstrates reliability, and then second building commercial plants.

So I'm spinning around your answer—or your question a little bit, but, you know, we're certainly several years away. I would like to think that we, as a set of alternative concepts, can get there in, you know, the next five or ten years, given the basket of options that are out there. I'm optimistic that, within that basket and that timeframe, we'll get there.

Mr. GRAYSON. Thank you.

Chairman WEBER. The gentleman from California is recognized.

Mr. ROHRABACHER. Thank you very much, Mr. Chairman. Years ago I used to believe that the environmentalist community was being, how do you say, alarmist when it came to nuclear energy. And I have seen a lot of alarmism come out of the environmental community that has not been accurate, but let me just say that in the case of nuclear energy, as time has gone on, and more information has been available, I think the environmental community over the years has been on target on this issue. The fact is that nuclear energy, as we are now using it, is very dangerous, and as now there are—there's leftover waste to deal with with the way we produce nuclear energy today.

So that's a big concession for me. In the number of debates that I had with environmental activities, they were right about that. But we are capable of technologically meeting those challenges that were brought up. And—whether it's leftover waste, or whether it's a safer way of producing nuclear energy that wouldn't have the same type of dangers associated with our current plants, we can do that.

I especially want to acknowledge our friends at General Atomics, who have been in the forefront, and spent a lot of their own money over the years trying to develop a new and next generation of nuclear energy that is safe, and won't have the massive leftover waste problem for decades, if not centuries to come.

I—but the government has to play a role in this as well. If we're going to have the benefits of nuclear energy, and—because private companies can't make this jump on their own, but once that jump is made, our private companies will be able to then, on their own, to build these next generation of nuclear power plants.

So I would like to go on the record, absolutely, saying this idea of having an open access facility is perhaps the most important thing we can do to provide America's long term energy interests, because it doesn't mean that just General Atomics, or any other company that is investing in this, and looking down this road. It will be available to all of those approaches. And, after his facility is available, we will know which is the best one to go with, which is the best way to go.

So this is a—what is not a good use of our money, however, is something that is aimed at fusion, rather than fission. And we can do these fission reactors—with all due respect to the last witness, boy, now we know it's possible. We've spent I don't know how many billions of dollars to find that it's possible? No. After spending billions of dollars, we should actually be at a point where we can—not only is it possible, but we'll have it ready within two or three years, whatever that is. But we're nowhere near that with fusion. But we do know that if we focus on this next generation of fission reactors, especially modular fission reactors, we actually can do it, and do the job, rather than just know that it's possible.

Let me note that we have spent—I would like to ask my friend from General Atomics, the—in what—the actual configuration of the next generation of nuclear reactor that you're working on, the people in Japan were sold a bill of goods that what they were given was totally safe. And now what happens, we, you know, we've seen this catastrophe in Japan. Would the model you're working on, and perhaps the other models that people are working on, would that protect us from that type of situation they have in Japan?

Dr. PARMENTOLA. Yes, thank you for the question. And, actually, I brought some results of our work with me. This is a revolutionary new cladding. It's made from ceramic materials. These materials undergo a transition from solid to gas at about 2,600 degrees. They lose their strength at about 2,000 degrees Centigrade. I point out to people that the metal that exists in current light water reactors begins to lose strength at about 700, so this increases the safety margin by a factor of almost three.

Also, these materials even benefit a light water reactor, and we've developed them for our advance reactor. So there's another version of this that we're working on to make light water reactors meltdown-proof. Because this material does not react with water at any temperature, so you can't have the kind of runaway reactions that generate huge amounts of heat inside the reactor that melt the core. It's not possible with these materials.

So if we invest in materials like this, it has multiple benefits across a number of reactor designs. Of course, the one that we're most interested in is EM–2, and EM–2 has a certain unique characteristic to it in that it utilizes these materials, but what it does is it provides a high power small reactor, so you get more bang for your buck, in terms of the capital investment, and the output of the reactor. And at the same time, one that is inherently safe because of these materials that we're developing.

But these materials require significant amounts of testing to prove them out, so this way we can convince the Nuclear Regulatory Commission that these type of materials can actually make fission reactors safe. And that's the principle reason why we're pursuing this.

Mr. ROHRABACHER. If you'd indulge me one more question, Mr. Chairman? Would that be possible to retrofit some of our current——

Dr. PARMENTOLA. Yeah.

Mr. ROHRABACHER. So some of our current light water reactors——

Dr. PARMENTOLA. Yeah.

Mr. ROHRABACHER. —which have a lot longer life on them could be refitted with that material?

Dr. PARMENTOLA. Exactly. So I have two types of cladding. This cladding here, the thin one, goes into light water reactors. The rods, these rods, are 14 feet tall. They go into the reactor, and they have fuel inside. This one is for EM–2, which is a totally different design. We pack more fuel in the core of EM–2 to increase its power density. But this material ensures safety.

Mr. ROHRABACHER. Thank you very much, and thank you, Mr. Chairman, for holding this hearing. I think it's vitally important that we not write off nuclear energy as a potential source for energy. It's—as the witnesses have stated, it's clean. It will not—it—I don't believe in global warming, but I do believe in clean air, and this will go a long way to providing energy for the world, and for the people of the United States. Thank you very much.

Chairman WEBER. I thank the gentleman, who yields back. And now, Mr. Lipinski, you're recognized.

Mr. LIPINSKI. Thank you, Mr. Chairman. Thank you for holding this hearing, and I would like to say, I do agree with Mr. Rohrabacher, except for I do believe in global climate change, but I think together we need to work to bring, you know, nuclear energy—it's something that we have to, first of all, maintain America's leadership on the innovation when it comes to nuclear energy and nuclear technologies, and we need to transition to advanced nuclear technologies, like fast reactors. And I hope to get language in the Competes bill supporting advanced nuclear reactor test facilities. So I think it's very important that we do move ahead, and research is critical, and that's what we're here to talk about.

For Dr. Peters, Illinois has been a leader in nuclear reactors since the first reactor was developed by Enrico Fermi at Met Lab, now renamed Argonne. Thank you for your leadership in keeping Argonne, and Illinois, a leader in nuclear energy innovation. Moving forward, I want to ask, what are Argonne's research and development priorities, and how do these priorities compliment work at other national labs, and fit into the DOE's strategic direction?

Dr. PETERS. Morning, Congressman, thank you for the question. So we at Argonne continue to have strong capabilities, broadly speaking, in advanced reactor design and analysis, fast reactors in particular, but also a broader set of expertise that also supports light water reactor sustainability, and also thinking extensively about potential fuel cycle options, either repositories, or closing the fuel cycle.

So we have that broad set of capabilities, where we also are working very closely with our sister laboratories, in particular Oak Ridge National Lab and Idaho National Laboratory. So we're spending a lot of time, as three labs, working with DOE, in cooperation with DOE, to ensure that the labs are working together strategically, not—and complementing each other, and so I think that's a very healthy conversation, and it's ongoing, and it's been very positive.

But our strategic interests, we really think it's important—our primary role would be to really think about what's the next set of systems that we—one would develop, demonstrate, and ultimately commercialize, both in the fuel cycle, as well as reactors for electricity. And then also, using our foundation in nuclear to also be a part of the technical basis for securing safe and secure operation worldwide as nuclear expands.

Mr. LIPINSKI. Thank you. And I also want to move on to other collaborations, specifically between the national labs and industry, because I think that's important to improve U.S. research investments by leveraging private sector expertise, and helping to bring new technology to the market. I know Argonne has been particularly effective in engaging with the private sector, for example collaborating with General Electric on the development of experimental boiling water reactors. These reactors now make up about 1/3 of the U.S. reactor fleet. So I wanted to ask you, Dr. Peters, what can we do here in Washington to support these types of collaborations?

Dr. PETERS. The lab—thank you for the question. And the history of the lab has been that we've been deeply committed to these partnerships, and that's an important part of it, but currently the Department of Energy is making it very clear that they value the labs working in cooperation with industry, so that's really, really important. So I know the work of this Committee on thinking about how we continue to enhance tech transfer, I'll call it, from the labs to industry. Those conversations are very healthy, and very important.

Again, DOE is deeply committed, but I think we can always continue to talk about it, and continue to explore ways to become more efficient. But from the labs perspective, you know, we do basic science, we do applied science and technology, but ultimately, regardless of timeframe that it takes, the research has to ultimately have an impact, and that means getting out to industry, into the market, and improving peoples' lives. So that's at the highest levels of commitment that the labs have, and I think the DOE shares that. They do share that commitment, and I know you do as well.

So continuing to just look at the detailed processes, and continuing to figure out how to become more efficient, and align the values of industry with the Federal R&D infrastructure are just vital.

Mr. LIPINSKI. Thank you. And I'll yield back.

Chairman WEBER. I thank the gentleman. Mr. Hultgren, you're recognized for five minutes.

Mr. HULTGREN. Thank you, Mr. Chairman. Thank you to all of our witnesses. Dr. Peters, it's always so good to see you. Certainly love being able to tell the great story of all the good things that are happening in Illinois. Good news for the rest of the Committee is having you here means they don't have to listen to me, and they can be much better informed hearing from you, so——

Chairman WEBER. Amen.

Mr. HULTGREN. —I'm glad you're here. Hey, watch it. Illinois is certainly the leading nuclear state in the nation, and I do appreciate the role the federal government has had in the development of nuclear technologies. Earlier this year the Committee passed legislation that I had introduced, among other things, that would require DOE to examine their capabilities to authorize, host, and oversee privately funded reactor prototypes and related demonstration facilities. It was certainly good to hear from our witnesses today about the ongoing debate that this department, the research community, and the industrial base has already been having on this topic.

Wanted to address my first question to Dr. Parmentola, and also to Dr. Peters. Some argue that open access user facilities are a more effective mechanism to enable investment and accelerate technological growth, compared to a cost-share agreement between the government and the private sector to deploy new technologies. I wonder, which type of federally funded investment do you believe is most effective to accelerate this growth, and wonder if you could explain it?

Dr. PARMENTOLA. Yes. Thank you very much for the question. So I can only tell you the way industry looks at cost sharing arrangements. Industry is very conservative. It has to do with the nature of what we do. We produce products, and we have to show a bottom line and a profit, so dollars we spend are very precious. What happens, in my experience, with cost share is that industry will look at it and take an opportunity to go with something low risk, and take advantage of the fact that the government is willing to provide a cost share for it. And what this does is it reduces innovation, in my opinion, because what we need in industry is more risk taking. Of course, the national labs undertake risk taking, but if we're going to try to advance technology, and get it into the commercial world, industry has to also undertake risk taking.

So, in my opinion, over 40 years of being involved in the research and development in this nation, what matters the most, in terms of high quality R&D, is competition, and being able to challenge the community. And by the community I just don't mean universities, I mean national labs and industry, to undertake high risk, high payoff research. The way to do that is to adopt standards, very high standards, and also goals—technical goals that challenge the community and allow industry to compete. And I think, without a cost share, you're likely to drive industry towards more risk taking than less risk taking. And it's really up to the agencies to do this. They have to take charge of this and actually meet the standards that are required.

Mr. HULTGREN. Thank you. Dr. Peters, before you answer, let me add one part to this that I would like to get your comments on just—and then I'll leave the rest of my time to you. How would you envision our national labs, such as Argonne, assisting in the process with NRC? Does the DOE need to take a more informative role with NRC? So I wonder if you could talk a little bit about, again, my first question there, but also following up a little bit on what the Chairman had started.

Dr. PETERS. Good morning, Congressman.

Mr. HULTGREN. Good morning, Dr. Peters. Continue.

Dr. PETERS. So, on the first question, in my testimony I referred to a test bed, and actually I think it's very similar to what you're referring to in the legislation. And Dr. Parmentola used the user facility model as a way to have the conversation, and I agree with him. You can set up a facility—a set of facilities that provide the ability to test and demonstrate advanced technologies, and do it in such a way that you could either do it in a pretty competitive, more open sense, or you could actually have aspects of it where industries actually bring in resources in doing proprietary work as well. We can—we do that, as you know——

Mr. HULTGREN. Um-hum.

Dr. PETERS. —at the existing scientific facilities, like the advanced photon source. There's a model for that. So, to me, I think there's a lot—I agree with Dr. Parmentola, that translates. So there's a lot to be done to define what this test bed would look like, and that would have to be something the labs, the government, universities, and industry work together to define the requirement set. But I think they would be able to push us ahead in a way that you're not necessarily picking a winning concept, but there's a test bed there for all to come test their concepts, demonstrate their concepts, and ultimately that will then lead to what makes sense in the market.

Mr. HULTGREN. Great.

Dr. PETERS. On your second question, so—specifically I had addressed the Chairman's question earlier on the NRC. Specifically, there's activity already going on between the DOE and NRC that the labs are supporting, our lab and a few other labs are supporting, to develop general—what we call general design criteria. So looking at advanced systems, like a high temperature gas reactor, or a sodium fast reactor, for example, and developing detailed general design criteria that one would use that would inform the regulatory basis going forward.

So, we know what needs to be done. It's more a question of what's the priority, because right now the NRC is, understandably, completely focused on regulating the existing fleet, and also watching the new construction of some of the Gen Three plus reactors in the southeast. But the—we know what we need to do. It's just a question of if we want to get to these advanced machines in a more timely manner, we just have to increase priority on the effort.

Mr. HULTGREN. I agree, and I do believe Argonne, and other labs, have a pivotal role, a vital role, and I want to make sure that we can have you be part of that. So, thank you, Chairman, I appreciate the time. Yield back.

Chairman WEBER. Thank you. And, in that context, very quickly, if I may, according to research, the Manhattan Project, which was '42 to '46, cost $2 billion, okay? 90 percent of that was in the production of the factories and the fissile material, and less than 10 percent was actually used in the R&D for the weapons. In today's dollars, that's $26 billion, with a B, dollars. So who's going to invest that kind of money?

Thank you for the indulgence, and the Chairman—I mean the gentleman from California is recognized.

Mr. SWALWELL. Thank you, Chair. I represent Lawrence Livermore National Laboratory and Sandia National Laboratory in Livermore, California, in the 15th District, and appreciate our witnesses here, and also Dr. Peters, what—the work you do at Argonne, is that correct?

My question is for Mr. Gilliland. And—in your testimony, you're pretty forceful on the potential power of fusion energy, and—for example, you write that the game changing nature of fusion energy bears repeating, energy production that is safe, clean, and abundant that would change the landscape of energy forever, and greatly enhance energy security.

At the two national laboratories I work—that I represent, they do a lot of work in fusion energy. For example, at Lawrence Livermore, they have the National Ignition Facility, the largest inertial fusion facility in the world, which is an amazing research tool, which has produced a wealth of information, but its primary goal right now is to assist in the maintenance of the nuclear weapon stockpile. However, we have long term hopes that it can be a sustainable energy source in the future.

So, keeping that in mind—and Representative Lofgren, who's on this Committee as well, she has worked with me on supporting fusion—but keeping that in mind, do you think, Mr. Gilliland, that the federal government is spending enough to support fusion energy research, and if not, do you have a dollar amount in mind as to how much more we should spend? And would it be helpful to have an actually dedicated funding source for research into all different types of fusion, including inertial, for energy applications?

Mr. GILLILAND. I would echo your comments on the National Ignition Facility, and their leadership in the fusion energy space. You mentioned that their primary goal is around weapons, however, they're making huge steps in fusion energy as well. I think the number is they have improved by about 100 times their fusion yield in the last three years. So I certainly believe that continued support, and even enhanced support, of National Ignition Facility is warranted. Similarly, Sandia has an alternative approach called Z Pinch, which I won't get into the details of, but they've also demonstrated a huge amount of progress. So we're certainly supportive of all of the concepts of fusion, including magnetic fusion, that General Atomics is quite involved in.

I think were funding could, you know, and—make a big difference is in some of the alternative approaches. Most of the dollars go toward magnetic fusion or inertial confinement fusion, both of which have benefits, and both of which have created really a base of research that everyone is benefitting from. I think the difference is that some of these middle ground concepts, like ours, and a number of others, do have the potential to be faster and less expensive because of the—we don't need lasers or superconducting magnets.

So I think it's a basket of alternatives, and it should be approached that way. Each have their pros and cons across the spectrum. So I can't give you a dollar amount, but certainly support, and enhanced support I think is absolutely warranted because—the final point I would make is whether it is fission, or fusion, or others, the world needs more energy, and energy is fundamental to the entire economy. So it's not one or the other, it's all.

Mr. SWALWELL. Thank you. And also, with respect to, you know, Dr. Parmentola and Mr. Peters suggested that the federal government should develop a new nuclear reactor facility to test innovative reactor ideas, now, knowing that we have, you know, few Federal dollars allocated for this type of research, and it doesn't look like the trend is going up, it's actually going down, do you have a— if you had to prioritize between fusion and nuclear reactors, any thoughts on that?

Mr. GILLILAND. How to prioritize between fission and fusion? Is that your——

Mr. SWALWELL. Yeah.

Mr. GILLILAND. —that your question? Again, I think they both have their pros and cons, right? I think fission certainly has the waste issue to deal with, proliferation and so forth, but there are certainly a number of viable pathways that fission has demonstrated, with small modular reactors and so forth. So I think that it's a little bit of an apple and orange comparison.

I think a demonstration facility could have both. I don't know why it couldn't have both. I think creating a regulatory framework is helpful for all of us, and, again, I don't—I think it would be beneficial for us all to have it at one location.

Mr. SWALWELL. Thank you. And, Mr. Chair, I yield back.

Chairman WEBER. I thank the gentleman. The gentleman from Illinois, Mr. Foster, is recognized.

Mr. FOSTER. Thank you, Mr. Chairman, and I appreciate the opportunity to attend this, despite not actually being formally on this Subcommittee. The—let's see. First question—first I would like to say that I'm a big fan of turning up research in this field. You know, the payoff if one of these comes up with a home run, and a really viable zero carbon energy source for our world, is enormous.

But ultimately, you know, the thing that I struggle with is the business of design studies that look at projected costs of electricity, which is ultimately the endpoint on this. And so the difficulty you get into there is you're comparing technologies with different levels of maturity. And, you know, ultimately we're resource constrained. You know, we've now decided to make what's—looks like a—between a $3 and $4 billion bet on tokamak fusion, you know, leveraging that to roughly 10 times that amount offshore. And, you know, we may or may not decide to do the same sort of leveraging in making a U.S. investment into offshore fission technologies that are being developed.

And so—but ultimately what we're looking for is the cheapest way of making zero carbon electricity. And—so there is certainly a role in doing design studies, just say pretend the technology works, and what would the cost of electricity be, if it all works according to your dreams? You know, there are big dangers there, because you can lose that bet, and—or find that, to make it work, you have to add a lot of costs to things.

But how do we, you know, how should Congress think about and handle that? Is this best left to separate—to committees? You know, the problem is that committees—all—knowledgeable people on committees are always composed of advocates for their technology, and you can balance the committee in different ways and get whatever answer you want, depending on how you choose to balance those committees.

And so if—so I guess my question is do you think that we're putting enough effort into the sort of design studies that I'm talking about, where you say, just pretend the technology works, does it ever have a chance of being cheaper? You know, this is something that's often talked about, for example, in terms of laser driven fusion, that if you just look at the wall power efficiency, you know, everything you'll have to do to get the compression, I guess—I—sorry I missed your presentation, Mr. Gilliland, but, from what I understand, your technology, you anticipate a higher efficiency, wall plug efficiency, in terms of getting the fusion to happen. And that's a, you know, that's a real argument when you look at the final thing.

But I—my question is, are we putting enough effort into that, and the right kind of effort, into these design—these studies of what the theoretical cost of electricity should be, or are—is—are things just so far away, and such a big spectrum in their R&D readiness to make those—to be able to make those sensible comparisons? So anyone wants to comment on—yeah, Dr. Parmentola.

Dr. PARMENTOLA. I can only talk about how General Atomics has tried to address the issue that you're raising. We've looked at basic physics to tell us what we need to do in order to be able to improve the price point of electricity. Of course, it's tied to financial models, but when you look at the financial models, the financial models tell you a story.

So, for example, the biggest driver for costs is the cost of capital, which has to do with the risk premium associated with what you're doing. And so we thought about that. What we need to do there is change the paradigm as to how we fabricate, manufacture, assemble, and deploy nuclear reactors, okay?

The next most important, which is physics-based, is efficiency. And we carefully looked at this, and we tried to look at how we could increase the efficiency of a nuclear reactor, and we've come up with a design that indicates that we could get over 50 percent efficiency, which is 20 percentage points above what we can do today. And I'll remind people that for every percentage improvement in efficiency, that adds a half a billion dollars to the bottom line over 30 years. So you're talking about $10 billion more in the pocket of a utility who's selling electricity.

Mr. FOSTER. You're also talking about turning up the peak operating——

Dr. PARMENTOLA. Correct.

Mr. FOSTER. —components, and——

Dr. PARMENTOLA. Right, and that's the reason why you have to go to new materials——

Mr. FOSTER. Yeah.

Dr. PARMENTOLA. —because the materials can't deal with it, but this is fundamental research that we have to do. And, of course, the government should be sponsoring that type of high risk research because the payoff can be tremendous.

And so the next one is capital costs, right? And, of course, what you want to do is try to reduce the capital costs. The thought is, well, if you make reactors smaller, you can reduce the material costs, but you have to have enough power output to compensate, right, for the reduction in size. So that, again, drives to a higher temperature, more—higher power density, and so on.

The physics tells you what to do, and that translates into the financial model. Then, of course, it's a matter of achieving the technical goals through research that you need to achieve in order to be able to get there. And that's really what—a facility that we're advocating, this new type of test facility, user facility. We do. In that user facility, we create competition, natural competition amongst those who are trying to achieve these advanced reactors. And, to me, that's the best way of sorting out which ones are going to survive, and which ones are not.

Mr. FOSTER. Um-hum. All right. Well, thank you.

Dr. PETERS. Could I make an—is that okay, Mr. Chairman?

Chairman WEBER. Yes, sir.

Dr. PETERS. Morning, Congressman. So I would say you're aware of the various analyses tools that are done by the various parties that are out there, as you said already in your remarks. And you have the DOEEIA does projections, and then, of course, all the various advocacy groups do their own projects, as you pointed out. And now you have a QER and a QTR that the DOE's doing that I think are important steps.

My observation would be that I think you're on the right track, because I think we haven't yet gotten to where we have an objective set of tools that can think about advanced technology, and technology insertion, into the discussion. At least I am not aware of very many robust objective tools put there.

So, to me, if we're going to sit here and talk about important things like fusion, and Generation IV fission reactors, they're at various stages in their TRL level, right? And I think we could probably model that. We could understand that and model it, but we're not really doing it in a comprehensive way, looking at the whole energy system. So I think there would be a place for that kind of analysis. I am not aware of a robust objective program that's going after it, though.

Mr. FOSTER. Yeah. Well, we'd have to spend, you know, the whole——

Dr. PETERS. Right.

Mr. FOSTER. —fission——

Dr. PETERS. Right.

Mr. FOSTER. —space, and that's difficult to assemble.

Dr. PETERS. Right. Yeah, and it would be—complex—labs, universities. It would be a—quite a big undertaking, but very informative, I think.

Mr. FOSTER. Right. Thank you, and I guess I'm well over time, and I should yield back.

Chairman WEBER. We'll just take it out of your next five minutes. But the gentleman yields back, no problem. Mr. Batten, I, you know, I said earlier that I applaud you, your collaboration and your efforts and stuff, and thank you again for being here, but I wanted to give you—and I went way over my time, Mr. Foster, by the way. What I——

Mr. FOSTER. I remember.

Chairman WEBER. What I wanted to ask was would you elaborate on your experience with working with Argonne National Lab in—and what was the best thing about it, the worst thing about it, the most frustrating thing about it? How could you—I know I'm putting you on the spot. How could we help improve the process?

Mr. BATTEN. Well, this is the first CRADA we had ever participated in, so it took us a while to just get ourselves up to speed on the process, and understand the agreement, and that sort of thing. But after we did that, we had a very good experience working with the lab, in terms of just kind of working out the cooperative agreement.

I would say by far the best thing about our experience is the technical work of the lab. For—I mean, I'm a layperson scientifically, but my impression is the—Argonne's technical work has just been superb. And, of course, it built on—that's because they have great people, but also they have all this expertise that they've built upon, all their past work.

Chairman WEBER. Okay. Dr. Peters' check is in the mail to you.

Dr. PETERS. Thank you, sir.

Mr. BATTEN. It's true——

Chairman WEBER. And——

Mr. BATTEN. —from my point of view.

Chairman WEBER. Well, we love hearing that. Any suggestions to improve—I know you were kind of on virgin territory there.

Mr. BATTEN. Right.

Chairman WEBER. Any suggestions on how we—improving that process?

Mr. BATTEN. I do not have any.

Chairman WEBER. No, yeah. So have you produced an outline, a white paper, on how the next collaborative process will work?

Mr. BATTEN. Well, I guess the question—I'll maybe answer that a little bit more broadly, sort of what would the next steps be. The—what the CRADA produced—the main thing the CRADA produced was a conceptual design which produced a cost estimate, and the CRADA report should be out in a couple months, and we'll know what that cost will be. Because—what we hope is that Congress will authorize the development of the pilot facility, but we thought you wouldn't really want to do that until you had some idea of what it would cost.

Chairman WEBER. Well, and that's why, you know, I referred to it earlier as a kind of a library facility, where, you know, we could provide the facility, and the books and stuff could be there for people to come and check out, if you will, and that would hopefully be an incentive for us to be able to take that next step you're talking about.

And the Chair now recognizes Mr. Grayson.

Mr. GRAYSON. Thank you. Uranium is fuel for nuclear reactors. If the industry were healthy, one would expect the price of uranium to be going up. In fact, the price of uranium is now 1/4 what it was eight years ago. What does that tell us about the market's assessment of the future of nuclear energy? Dr. Peters?

Dr. PETERS. I'm not an economist, but I would say that the current state of nuclear energy vis-&-vis the role of natural gas and that, the role of deregulation, et cetera, is having significant impact on the economics of nuclear reactors as they currently operate, and also as currently envisioned to be built in the next, say, decade. But I would say uranium's abundant. There's plenty of it. I mean, we don't need to mine it, because we can still use uranium that's been mined decades ago. As part of various proliferation programs, we can get uranium. So part of it is that there's hundreds of years of uranium. So one of the interesting questions would be, why recycle? It's hard to make an argument to recycle just based on uranium reserves, because there's plenty of it.

So I—you're asking a very complex question, but I would say the economics in 2050 that would drive what the energy system looks like are going to be very different than they are today.

Mr. GRAYSON. Dr. Parmentola, is the market basically trying to tell us that nuclear fission, as a market, is doomed, given the fact that uranium now costs 75 percent less than it did even seven years ago?

Dr. PARMENTOLA. Just so you understand, the—General Atomics is in the uranium mining business. We have uranium mines——

Mr. GRAYSON. Um-hum.

Dr. PARMENTOLA. —in the United States, as well as overseas, you know.

Mr. GRAYSON. Not doing too well lately, are you?

Dr. PARMENTOLA. So—and my boss is a very astute businessman, so he's in that business for a reason. And while, of course, with Fukushima, we saw a decline in the use of uranium in Japan, Germany has got out of the nuclear reactor business, Switzerland has sort of followed suit, the demand for uranium obviously has gone down, but I can tell you that there have been new deposits found, abundant ones, in Australia. With China surfacing as a major, major nuclear energy producer, they have the largest number of reactors on—in development now, 30, that'll be a lucrative business. India as well.

And I have to say, it's—with fast reactors, it's not just uranium that is a fuel. Thorium is also. And if you do an analysis of using both uranium and thorium as a source with fast reactors, that have a closed cycle, you have enough, based upon known reserves, including the waste, to last you 2,000 years. That's just known reserves. If I went and—into the ocean, there's more uranium in the ocean that there is on land.

Mr. GRAYSON. Water also. There's more water in the ocean than there is on land.

Dr. PARMENTOLA. Yeah, right, but there's a huge amount of uranium in the oceans. So the supply of uranium is—and even thorium is extremely large. I think it's great that a fuel is cheap, and that you can derive so much benefit out of it. It's great. Right now I can say to you tritium costs $100 million a kilogram. Right now, tritium, the known amount of tritium in the world, is $100 million a kilogram. So one of the challenges in fusion is to figure out a cost effective, economic way of producing it, so this way it can self-sustain itself.

Mr. GRAYSON. All right. I would like to ask Dr. Peters—Dr. Peters, you used some interesting language in your testimony. You said that the country's leadership in global nuclear energy could be further compromised, that our country runs the risk of defaulting on the return of 7 decades of investment in nuclear science. By the way, you can't actually default on a return investment. That's not possible.

Chairman WEBER. Will the gentleman yield?

Mr. GRAYSON. Sure.

Chairman WEBER. Now, this is spoken by a guy that has informed us that there's more water in the ocean on land, so you all might just take that with a grain of salt. I yield back.

Mr. GRAYSON. Chairman needs to listen more closely to my quips. That's not correct. And the—we should be careful not to forfeit the legacy of many brilliant minds, another questionable mixed metaphor. But here's the thing, what—all you're describing here is the idea that we would take a step back from our nuclear fission program, and Germany has taken two or three or four steps back from its nuclear fission program. It's planning to shut it down entirely. What does Germany know that you don't know?

Dr. PETERS. Germany buys nuclear electricity from France. That would be one point that I would make.

Mr. GRAYSON. Um-hum.

Dr. PETERS. So while Germany's made certain—I am not going to go any further than. So, from my perspective, setting aside that maybe I mixed metaphors—thanks for the feedback, I would say that we've invested, as a country, in unbelievable nuclear capabilities, and if we do not move forward with the next generation of technologies, that's going to erode. It's eroding slowly, and if we don't invest in the labs and universities, and the next generation, we're going to be sitting here a couple decades from now with no capability, and absolutely no seat at the table.

Mr. GRAYSON. But—another interesting mixed metaphor. But, Dr. Parmentola, Germany has paid the price for its decision to eliminate its nuclear program. The price is that they are now the leader in solar technology around the world. They have the healthiest solar energy market of any major country in the entire world. Is that a price that we should be willing to pay as well?

Dr. PARMENTOLA. In my opinion, what—we—no one has a crystal ball, in terms of what to expect in the future in regard to the abundance, or lack thereof, of resources that—we didn't expect natural gas to be so cheap. And, by the way, the U.S. Government invested 30 years ago, 40 years ago, in the fundamental technology that enabled fracking to produce this. So, from an energy security point of view, your best bet is to have as many energy options as possible, because we can't predict the future. And nuclear is a technology that can meet the requirements that people are asking for, in terms of the economics, the waste reduction, the proliferation risk, and the safety. There's nothing in the laws of physics that would prevent that.

What has happened, unfortunately to nuclear, it's been on the same technology for 60 years. If you look at any major technology that the U.S. has developed, and continues to develop, it's all been driven by research, and achieving performance, higher performance levels. Nuclear has not changed in 60 years. Its efficiency is back where it was, and we're using submarine technology that was designed, obviously, for submarines.

Any other major technology that I can think of has been driven by research and development and performance. Pick transportation, either ground or air. Pick communications. Look at the mobile devices we carry around with us. Look at computer technology. Computer technology has undergone five paradigm shifts in the last 100 years, all based upon an advancement in the fundamental technology to advance computing.

So nuclear stood still, and I think what Dr. Peters is talking about is the need for a research, and a research driven community. The nuclear community is not research driven, in my opinion, and I've been around research for 40 years. It's not. They want to build things. That isn't the way to develop new technology. You have to do research that drives. It's discovery first. Discovery drives invention, and invention drives innovation. That's the process. Right now, nuclear has remained stagnant because research is lacking. We haven't gone to higher performance technologies and materials to drive its performance. That's what's going to matter in the end.

Mr. GRAYSON. All right, thanks. I yield back, and thank you all for your testimony today.

Chairman WEBER. I want to thank the witnesses for coming in today, and for your testimony. It's been very, very informative, and we appreciate you all being here. With that, our hearing's adjourned.

[Whereupon, at 11:36 a.m., the Subcommittee was adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Mark Peters

U. S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
Subcommittee on Energy

Hearing Questions for the Record
The Honorable Lamar Smith

Nuclear Energy Innovation and the National Labs

Questions for Dr. Mark Peters

1. **Dr. Peters, in your prepared testimony you point out that the federal government's role in developing advanced reactors would likely be the construction of a test reactor and a demonstration test bed.**

    a. **Can you elaborate on these concepts?**

    b. **Can you explain how a versatile fast reactor in the form of an open-access user facility could advance nuclear energy technology?**

    c. **What steps could the Department of Energy, National Labs, and Nuclear Regulatory Commission take to enable the private sector to invest in Generation IV nuclear energy technology?**

Thank you for the follow up questions. It was a pleasure to appear before the committee, and I am happy to continue the discussions on this important topic.

The decision to build a test reactor and demonstration test bed to develop and demonstrate Generation IV nuclear reactors is a federal government decision. However, the national laboratories are happy to provide technical advice to policymakers on how such a set of facilities could work, and what types of characteristics would be most beneficial in enabling the next generation of advanced nuclear reactors.

a. Many concepts, materials, and designs would have to be tested and demonstrated to develop the next generation of reactors. The combination of a test reactor with a demonstration test bed would give the United States the type of flexibility needed to let all interested participants test their ideas to ensure we are pursuing the most fruitful paths toward advanced reactors. A test reactor would serve to validate many of the fundamental principles and materials that would enable advanced reactors. It could be built in such a way that multiple advanced reactor designs – and there have been many proposed – could be tested in a reactor environment. A demonstration test bed would function as a distributed set of experimental and computing facilities and support industry-lead demonstrations of advanced reactor concepts. A demonstration test bed would also allow experiments to be conducted on support and peripheral systems that are still critical to reactor function, but do not need to be conducted within an actual reactor.

b. The idea of an advanced fast test reactor as an open-access user facility is a powerful concept, and it will be an important step to enabling progress toward the next generation of nuclear reactors. As I mentioned in my testimony, our current fleet of light water reactors was developed only through combining the best efforts of government, industry, and academia. Many different ideas were explored before deciding on the concepts that were developed by industry into our current reactors. The same process will be useful in developing the next generation of reactors. By opening our facilities to many different parties, we will be able to explore multiple avenues before allowing science and the marketplace to decide which concepts make the most sense to pursue.

   Currently, there are multiple technologies that could be viable as next-generation reactors, with multiple designs spinning off the fundamental technologies. Some, such as the sodium-cooled fast reactor, are very mature, while others are more conceptual. By opening our user facility to those concepts, we can allow the early ideas to progress until they can be thoroughly evaluated, while more mature designs continue to be perfected. Eventually, scientific rigor and economics will allow us to winnow them down to successful designs, thereby ensuring that the best thinking and designs make their way into new reactors.

c. All of those entities named are currently engaged in a variety of efforts aimed at enabling Generation IV reactors. DOE and its national labs are working on many research projects that are demonstrating and proving out concepts that will be applicable to the next generation of reactors. The projects are too numerous to mention, but a few examples at Argonne include studies of thermal-hydraulic loops, passive cooling, materials testing, and component testing. By performing much of this fundamental research, DOE and its laboratories are laying the foundation on which industry will build new reactors.

   A future move forward to Generation IV reactors will likely require the type of test and demonstration facilities outlined above, but other focused and coordinated activities will be required, as well. A new type of reactor will require new licensing regulations. DOE and the laboratories are doing preliminary work with the NRC to establish requirements for this licensing. These efforts need to be ramped up. Other activities that would need to continue or be accelerated include advanced modeling and simulations, which use supercomputing to improve design and safety in a virtual space before they are incorporated in to physical designs. Safety could also be bolstered through development of computer-assisted operations and maintenance practices.

2. **Dr. Peters, does the DOE national laboratory complex have the necessary capabilities to construct and operate a fast-reactor user facility as discussed during the Energy Subcommittee's hearing on May 13th?**

The national laboratory complex does have the necessary capabilities to construct and operate the test reactor and demonstration test bed discussed during the hearing, although it is a significant undertaking that will require appropriate funding, focus, and partnerships to accomplish the goal.

The DOE complex has long experience building large user facilities that bring together the best capabilities of government, industry, and academia to address pressing national concerns. Argonne is currently operating two such facilities in the Advanced Photon Source (APS) and the Argonne Leadership Computing Facility (ALCF). Operation of these two cutting-edge facilities gives Argonne solid experience in building programs that can accommodate a variety of users working on diverse projects. Our sister labs across the country operate many similar user facilities.

As for demonstration test beds and test reactors, both Argonne and the DOE complex as a whole have great experience in constructing and operating such facilities that would be necessary to pave the way to Generation IV reactors. Many of the reactors I mentioned in my testimony were designed to demonstrate and examine the feasibility of different types of reactor technology. For example, Experimental Breeder Reactor II (EBR-II) was designed to test the concept of a sodium-cooled fast reactor, which is one of the leading designs of Generation IV reactors. This historical expertise will be key to building and operating the type of user facility needed to establish the viability of advanced reactors.

Responses by Dr. John Parmentola

1. Yes I do believe there is significant support for this from industry, the national labs and academia. All advanced reactor concepts are working toward achieving much higher performance to improve economics, safety, waste reduction and proliferation resistance. Several of these reactor concepts exploit fast neutrons and require R&D to reduce the significant technical risk that exists in accomplishing the above objectives. A fast neutron test reactor will not only support the necessary R&D associated with these concepts, but also can be designed to support other advanced reactor concepts that are not based upon fast neutrons, including existing light water reactors. Such a test reactor would be highly leveraged in terms of serving an important purpose for all advanced reactor concepts. This aspect will further encourage broader support from the nuclear energy community.

2. The financial risks associated with realizing any advanced reactor concepts, such as Generation IV reactors, is quite formidable. Recovery of the large capital investment, because of the significant costs of the R&D required, is not feasible over meaningful business time scales, if at all. Therefore, government support is the only way of overcoming this obstacle. But to increase the likelihood that the necessary R&D will lead to advanced reactor commercialization, it is essential that industry be involved in all aspects of R&D. The challenge here is the existing requirement for industry cost-share. This requirement reduces risk taking and therefore innovation, because industry will only cost-share for approaches that increase the likelihood of recovery of their investment, which essentially means proposing what they already know how to do now. To encourage risk taking, which is fundamental to achieving advanced reactor concepts with high-performance, the requirement of R&D cost-share for these reactors should be eliminated. In fact, existing law allows DOE to waive the cost-share requirement on long-range R&D for which nuclear advanced reactor concepts certainly qualify, however this waiver is never or very rarely used. The funding of promising and high-quality advanced reactor concept proposals with high-performance must be the full responsibility of the US DOE, which must also require very high source selection standards to eliminate less promising investments of taxpayer dollars.

Appendix II

ADDITIONAL MATERIAL FOR THE RECORD

PREPARED STATEMENT OF COMMITTEE RANKING MEMBER
EDDIE BERNICE JOHSNON

OPENING STATEMENT

Ranking Member Eddie Bernice Johnson (D-TX)
Committee on Science, Space, and Technology

Nuclear Energy Innovation and the National Labs
Energy Subcommittee Hearing

May 13, 2015

Thank you Mr. Chairman, and thank you to our witnesses for being here today to discuss their involvement in innovative nuclear energy research.

The more conventional form of nuclear power, known as fission, currently plays a pivotal role in providing our country with reliable energy. As a nation, it produces almost 20 percent of our total electric power, and it provides almost 9 percent of the electricity generated in the great state of Texas - all with essentially no greenhouse gas emissions.

But along with the benefits of that energy, these sources also produce radioactive waste products, and developing a permanent management solution for those waste products remains a challenge.

Historically, long-term storage has been the primary option discussed for managing that waste, but today we are going to hear about other, more innovative options that deserve serious consideration from this Committee. And we will hear about ideas for public-private partnerships to develop the next generation of these reactors, which may well be more efficient and produce less waste.

I am also excited to learn more about new, innovative approaches to fusion energy. Nuclear fusion has the potential to provide the world with a clean, safe, and practically inexhaustible source of energy. Producing reliable electric power from fusion would undoubtedly serve as one of the biggest and most important scientific achievements in the history of humankind. This is why I am so supportive of a strong research program that can help us overcome the remaining scientific and engineering challenges for this potential to become a reality.

Again, I thank each of you for joining us today and with that I yield back the balance of my time.

REPORT SUBMITTED BY MR. FRANK BATTEN, JR.

ENERGY
RESOURCES
INTERNATIONAL, INC.

ERI-2012-1401

A COST/BENEFIT ANALYSIS OF FUEL CYCLE COSTS ASSOCIATED WITH USING PYROPROCESSING AND INTEGRAL FAST REACTORS TO CONSUME SPENT NUCLEAR FUEL

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Prepared For:

The Landmark Foundation

Prepared by:

Eileen M. Supko

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1015 18th Street, NW, Suite 650
Washington, DC 20036
USA
Telephone: (202) 785-8833
Facsimile: (202) 785-8834

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EXECUTIVE SUMMARY

Background on U.S. Waste Inventories and the Waste Management Program

In the United States ("U.S."), there are a total of 100 operating commercial nuclear power plants ("NPP") that produce an estimated 2,000 metric tons of uranium ("MTU") of spent nuclear fuel ("SNF") annually. In addition to the current fleet of 100 NPPs, there are an additional 19 NPPs that have permanently ceased operation, some of which have been dismantled and others of which are awaiting final dismantling and decommissioning. All of these 19 shutdown NPPs continue to store SNF onsite. Five nuclear power reactors are under construction in the U.S. and are expected to be operational between 2015 and 2020. Including these new plants, an estimated total of 140,000 MTU of commercial SNF will be discharged over the next 70 years.[1] There is also an estimated 10,000 MTU of SNF and high-level radioactive waste ("HLW") from U.S. defense programs – bringing the total quantity of waste requiring disposal to an estimated 150,000 MTU.

The *current* nuclear fuel cycle in the U.S. is known as a "once-through" cycle, because nuclear fuel is irradiated in commercial NPPs to generate electricity, and then is slated for disposal as waste without any recycling for reuse. Under the Nuclear Waste Policy Act ("NWPA"), the capacity of the first repository is limited to 70,000 MTU, of which civilian SNF would have a 60,000 MTU share with the additional 10,000 MTU of capacity being devoted to disposal of SNF and HLW from defense programs. Due to the large quantity of commercial and defense waste anticipated to be disposed of in the U.S. over the next 70 years (150,000 MTU), more than one repository will be necessary.

Many obstacles stand in the way of developing and executing a long-term strategy for disposal of SNF in the U.S. After many years of program delays, the Yucca Mountain repository project was halted in 2010 with the suspension of the U.S. Nuclear Regulatory Commission's ("NRC") review of the Yucca Mountain License Application ("LA"). While the NRC has resumed its review of the Yucca Mountain LA, restart of the Yucca Mountain project is considered unlikely in the current political climate.

If the Yucca Mountain project is not resurrected and the repository program restarted, then a complete overhaul of the U.S. waste program will be required including new legislation; a new repository siting process; a search for one or more sites for disposal; and development, licensing, construction and operation of permanent disposal facilities. Given the history of the U.S. waste program, it could be decades before a geologic repository begins operation in the U.S. In the interim, SNF inventories at NPP sites and the federal government's liability associated with its failure to remove SNF from commercial NPP sites continue to grow.

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[1] This assumes that the majority of the existing and new plants will operate for 60-year license terms, resulting in new plants reaching the end of 60-year license terms within the next 70 years.

EXECUTIVE SUMMARY

Results of Study

Within the context of long-term waste management and sustainable nuclear fuel supply, there continue to be discussions regarding the future path that the U.S. should take in its research and development activities associated with advanced fuel cycles, including development of advanced recycling technologies. The current once-through fuel cycle used in the U.S., in which SNF is treated as waste and directly disposed of in deep geologic repositories without recycling, is not an efficient use of a valuable resource; namely, the uranium and other reusable components in SNF.

Deploying "pyroprocessing" technology and Integral Fast Reactors ("IFRs") to recycle the current inventory of commercial uranium oxide ("UO_2") SNF provides a number of significant, potential benefits, key among these are: avoiding the need for additional costs associated with a second repository by reducing the overall volume of radioactive waste requiring geologic disposal; reducing the radiotoxicity and heat load of the final commercially-generated waste form to be disposed, which would reduce the cost of the design and construction of the single geologic repository needed for nuclear waste; and the ability to pay for pyroprocessing/IFR costs by the avoided cost of a second repository. In addition, if a large-scale pyroprocessing facility and a fleet of IFRs are able to be deployed sooner than a geologic repository, then there also may be avoided costs associated with the government's liability for the Department of Energy's ("DOE") failure to begin SNF acceptance in 1998. Deployment of pyroprocessing and IFRs also will help to conserve uranium resources, thereby prolonging the use of nuclear energy if uranium supplies become scarce or the price of uranium increases significantly.

As noted above, under the NWPA, the expected 150,000 MTU inventory of commercial and defense SNF and HLW would require that at least two repositories be built. If the current U.S. inventory of commercial light-water reactor ("LWR") SNF is pyroprocessed and the plutonium and minor actinides[2] from this SNF are recycled in IFRs, the resulting HLW will have a significantly lower volume and heat load than the original SNF. The amount of repository space required for disposal of SNF and HLW is a function of the volume and heat load of the emplaced SNF or HLW. As a result of pyroprocessing the existing SNF inventory, significant reductions in the volume of material to be disposed can be realized and the need to construct a second repository *can be avoided.* Based on recent cost estimates conducted by the DOE, development and operation of a geologic repository

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[2] The minor actinides are the actinide elements in used nuclear fuel other than uranium and plutonium (which are termed the major actinides). The minor actinides include neptunium, americium, curium, as well as other elements. Plutonium and the minor actinides are the greatest contributors to SNF radiotoxicity and heat generation during the period of 300 to 20,000 years following SNF discharge.

for disposal of the projected 140,000 MTU of commercial SNF would range from $24 billion to $81 billion, and higher costs would likely be incurred to fabricate disposal canisters, repackage SNF from existing dual-purpose canisters, and provide consolidated interim storage. To put the recent DOE estimate into perspective, a 2008 cost estimate for the Yucca Mountain repository was $96.2 billion for disposal of only 70,000 MTU of SNF and HLW in a single repository – higher than the recent DOE cost estimate for disposal of 140,000 MTU of SNF. If the need for a second repository is avoided, then as a result of that alone, the cost savings attributed to pyroprocessing and IFRs could be $12 billion to $96 billion, or higher.

Recommendation

There are significant potential cost savings and technical benefits associated with recycling nuclear fuel (*i.e.*, developing pyroprocessing and IFRs), compared to the current once-through fuel cycle. Key among these is eliminating the need for a second geologic repository at a cost savings in the range of $12 to $96 billion.

However, adequate research and development funding, and deploying a pilot facility to demonstrate pyroprocessing in the U.S. is an important step in resolving remaining technical challenges prior to scaling up the technology to a commercial scale. Expanded research, development, and demonstration of pyroprocessing and IFR technology should continue in the U.S. to provide a sustainable alternative program for long-term waste management and nuclear power deployment.

1. INTRODUCTION

1.1 Background

In the United States ("U.S."), there are a total of 100 operating commercial nuclear power plants ("NPP") that produce an estimated 2,000 metric tons of uranium ("MTU") of spent nuclear fuel ("SNF") annually. In addition to the current fleet of 100 NPPs, there are an additional 19 NPPs that have permanently ceased operation, some of which have been dismantled and others of which are awaiting final dismantling and decommissioning. All of these 19 shutdown NPPs continue to store SNF onsite. Through December 2013, an estimated inventory of 72,000 MTU of SNF from these reactors has been generated. Five nuclear power reactors are under construction in the U.S. and are expected to be operational between 2015 and 2020. Including these new plants, an estimated total of 140,000 MTU of commercial SNF will be discharged over the next 70 years[3] – double the current inventory. There is also an additional estimated 10,000 MTU of SNF and high-level radioactive waste ("HLW") from U.S. defense programs – bringing the total quantity of waste to an estimated 150,000 MTU. Commercial SNF is stored in water-filled pools that are adjacent to the nuclear power reactors or, after several years of cooling, in dry cask storage facilities at NPP sites until it can be shipped off site for processing, consolidated interim storage or disposal. The current nuclear fuel cycle in the U.S. is known as a "once-through" cycle, because nuclear fuel is irradiated in commercial nuclear reactors to generate electricity, and then is slated for disposal as waste without recycling for reuse.

Due to the current debate surrounding the Yucca Mountain repository program, there is considerable uncertainty in the U.S. regarding the schedule for acceptance of SNF by the Department of Energy ("DOE") as required by the Nuclear Waste Policy Act of 1982, as amended ("NWPA").[4] While the DOE put forth a new long-term waste management strategy in early 2013, this new strategy will require Congressional action to amend the NWPA, followed by an uncertain process and schedule for siting waste management facilities. In the interim, SNF inventories at NPP sites and the federal government's liability associated with its failure to remove SNF from commercial NPP sites continue to grow. DOE anticipates spending $24 billion to $81 billion to build one or more geologic repositories for SNF.[5] The daunting task of siting and operating more than one repository

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[3] This assumes that the majority of the existing plants plus new plants will operate for 60-year license terms, resulting in new plants reaching the end of 60-year license terms within the next 70 years.

[4] The NWPA mandated the development of a first repository at Yucca Mountain with a disposal capacity of 70,000 MTU of commercial and defense SNF and high-level radioactive waste ("HLW"). The civilian SNF share of the first repository was estimated to be 60,000 MTU. Based on the projected 140,000 MTU of civilian SNF expected to be discharged from current and planned nuclear power plants in the U.S., a second repository, with a capacity of at least 80,000 MTU would be necessary to dispose of the remaining civilian SNF.

[5] As discussed in Section 3.3, this estimate was based on a January 2013 DOE cost study of repository alternatives for the disposal of 140,000 MTU of SNF with costs that ranged from approximately $24 billion to $81 billion in 2012 dollars – more than a 200% difference in costs. Even higher costs are possible if additional SNF packaging is necessary at a repository, if consolidated storage is deployed, or if SNF must be

may help to shift the U.S. focus to recycling and fuel cycle technologies that will reduce the quantities of waste requiring disposal as well as reduce the toxicity of the waste.

If a pyroprocessing facility can be deployed on an earlier schedule than permanent disposal facilities and begin accepting SNF from U.S. NPPs at an earlier date, then there may be additional avoided costs associated with DOE's liability for failure to begin SNF acceptance in 1998. One alternative to the current once-through fuel cycle is to separate the waste in UO_2 SNF requiring disposal from other materials in the SNF, such as uranium, that then could be recycled as fuel for subsequent reuse in a "fast reactor." The recycling and reactor technologies discussed in this Report are pyroprocessing and the Integral Fast Reactor ("IFR").

1.2 Purpose of Report

Within the context of long-term waste management and sustainable nuclear fuel supply, there continue to be discussions regarding the future path that the U.S. should take in its research and development activities associated with advanced fuel cycles, including development of advanced recycling technologies. The current once-through fuel cycle used in the U.S., in which SNF is treated as waste and directly disposed of in deep geologic repositories without recycling, is not an efficient use of a valuable resource; namely, the uranium and other reusable components in SNF.

This Report compares fuel cycle costs associated with the current once-through fuel cycle ("OT Cycle") for commercial light-water reactors ("LWR") which use uranium dioxide ("UO_2") fuel, with a fully-closed fuel cycle in which the SNF from the OT Cycle as well as FR SNF is recycled through pyroprocessing into new metallic fuel for use in IFRs ("FR Cycle").[6] In addition to examining fuel cycle costs for the two fuel cycles, this Report provides a comparison of key parameters associated with the two fuel cycles including: waste volumes requiring disposal, and heat load and activity of the waste requiring disposal, which affect the number of geologic repositories needed and the design and cost of those repositories.

To support continued discussions about the next phase for developing an integrated fuel cycle with pyroprocessing and IFRs, this Report also examines the benefits and costs associated with developing a 2,000 metric ton heavy metal ("MTHM") per year pyroprocessing plant for processing the existing U.S. LWR SNF inventories.

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repackaged.

[6] Calculation of fuel cycle costs are based on a model developed by the Organization for Economic Co-operation and Development (OECD) Nuclear Energy Agency ("NEA"), an international organization that is based in France and of which the U.S. is a member. The NEA model, "Steady-State Analysis Model for Advanced Fuel Cycles Schemes" ("SMAFS"), was utilized in an NEA 2006 assessment entitled "Advanced Fuel Cycles and Radioactive Waste Management." ["NEA 2006"]

Pyroprocessing allows recycling of the SNF as metallic IFR fuel, reduces the long-term toxicity of the SNF, significantly reduces the size of a first geologic repository, and could eliminate the need for a second repository.

Section 2 provides an overview of the model used to calculate fuel cycle costs in this study, including key input parameters and key output parameters. Fuel unit cost components, waste management cost components, and reactor capital costs that are used in this study are summarized in Section 2, with more detail regarding the bases for these unit costs provided in Appendix A. Unit costs include nominal costs and lower and upper bounding values for each cost component. Section 2 also provides the basis for the conclusions that pyroprocessing and IFRs can eliminate the need for a second permanent geologic repository and produce very substantial cost savings.

Section 3 provides an overview of the OT Cycle including fuel cycle, waste management, and electricity generation costs using the nominal unit cost values discussed in Section 2 and Appendix A. A summary of waste management volumes for a OT Cycle, including identification of key waste management parameters is provided. Uncertainties regarding long-term disposal costs for the OT Cycle are also identified.

Section 4 provides an overview of the FR Cycle including a high-level description of pyroprocessing and IFRs that would be used to close the existing fuel cycle. FR fuel cycle, waste management, and electricity generation costs are identified using the nominal unit cost values discussed in Section 2. In addition, a cost analysis of a 2,000-ton pyroprocessing plant is summarized including the results of a sensitivity analysis of financial parameters concerning construction and operation of such a plant.

Section 5 provides a comparison of the OT Cycle and FR Cycle waste management parameters. Conclusions regarding transition to a FR Cycle are discussed in Section 6.

Appendix A provides a summary of the unit cost assumptions used in this analysis from the SMAFS model, including the nominal, lower-bound and upper-bound unit costs. Appendix B summarizes a comparison of the OT Cycle and FR Cycle nominal costs. Appendix C provides a list of acronyms.

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2. METHODOLOGY

This section begins with an overview of the "SMAFS" model used to calculate fuel cycle costs in this study, including key input and output parameters. Assumptions associated with the fuel unit cost components, waste management cost components, and reactor capital costs that are used in this study are provided in Appendix A. Unit costs include nominal costs and lower and upper bounding values for each cost component.

This section then discusses the approach and assumptions used to develop the analysis regarding the number of permanent geologic repositories needed, and associated costs.

2.1 Description of The SMAFS Fuel Cycle Cost Model

The SMAFS model that ERI uses in this analysis was developed by NEA researchers to analyze the impact that advanced fuel cycles might have on waste management policies. It was designed to provide not only a comparison of the relative economics of different fuel cycles, but also to compare other key fuel cycle and waste management indicators. The SMAFS model has been utilized by ERI in the past to perform evaluation and comparison of multiple fuel cycles and it has been utilized by international agencies such as the Korean Atomic Energy Research Institute ("KAERI").

The key fuel cycle and waste management indicators that are used in comparing different fuel cycles, include the following:

- Fuel cycle cost – this indicator includes front-end costs (uranium, enrichment and fuel fabrication) as well as back-end waste management costs.
- Total generation cost – this indicator includes the fuel cycle and waste management costs as well as the capital, investment, and operating costs of the nuclear reactors considered.
- Uranium consumption – this is driven, in part, by the number of IFRs in the fuel cycle scheme considered.
- Activity of the SNF and HLW after 1,000 years – this indicator describes the radioactive source term after the decay of heat generating isotopes in HLW and is indicative of the long-term toxicity of the waste.[7]
- Decay heat of the SNF or HLW after various time periods (e.g., 200 years and 1,000 years) – this indicator is important in the handling, conditioning, and final disposal of SNF and HLW in geologic repositories, and also has consequences for processing and transportation.
- HLW and SNF volume to be disposed – this indicator is of key importance in the number and size of geologic repositories needed for disposal of HLW and SNF.

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[7] HLW is highly radioactive materials produced as a byproduct of reprocessing of SNF that includes fission products ("FP") from the nuclear fission reaction. HLW may contain other elements such as actinides if these elements are not separated from the FP during reprocessing operations.

2.2 SMAFS Model Input Parameters

In order to calculate the key fuel cycle and waste management indicators discussed above, the following data input parameters are utilized:

Waste generation parameters associated with:

- Front-end of the fuel cycle which includes: mining and milling of uranium, conversion of uranium to uranium hexafluoride, enrichment and fuel fabrication.
- Reactor operation (short-lived ["SL"] and long-lived ["LL"], low and intermediate level waste ["LILW"], and SNF) for LWRs and IFRs.
- Pyroprocessing of UO_2 and IFR SNF including the LILW-SL, LILW-LL, and HLW associated with pyroprocessing.

Unit cost parameters associated with:

- Front-end fuel cycle (mining and milling of natural uranium, conversion, enrichment, and fuel fabrication).
- Reactor investment and operations and maintenance ("O&M") costs.
- SNF transport and storage for UO_2 and IFR fuel types.
- Pyroprocessing of UO_2 and IFR SNF.
- On-site dry storage, packaging, and off-site long-term storage for UO_2 SNF, HLW and other waste products. Long-term storage costs are for materials such as depleted uranium ("DU") and irradiated uranium ("U_{irr}")[8].
- Waste disposal, including LILW-SL, LILW-LL, and SNF and HLW.

Unit costs include a nominal value ("NV"), lower bound ("LB") and upper bound ("UB") as summarized in more detail in Appendix A. In addition to the waste generation and cost data, the model also includes mass flows for each fuel cycle considered, and data regarding waste activity, decay heat, and neutron sources for SNF and HLW requiring long-term storage and disposal.

2.3 SMAFS Model Output

The SMAFS model was designed to calculate equilibrium fuel cycle costs assuming that all reactors in a given fuel cycle scheme operate at constant power and that all mass flows have reached an equilibrium. The model calculates the following:

For each fuel cycle scheme, the model output includes:

- SNF and HLW radioactivity measured in Terabecquerel ("TBq"), thermal output in watts ("W"), and neutron source (neutrons/second/group) at time periods of 5, 50, 200, 1000, and 10000 years. These parameters are normalized to units per Terawatt-hour electric ("TWhe") of electricity generated by NPPs.

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[8] Irradiated uranium is also referred to as "reprocessed uranium" or "RepU".

- Fuel cycle and total generation cost, including a detailed breakout of costs for front-end fuel cycle materials; pyroprocessing; reactor investment; reactor O&M; and waste management. Costs are calculated on a mill per KWh ("mill/kWh") basis as well as on a comparative basis among the fuel cycles analyzed.[9]
- Quantities of waste generated requiring disposal for each step of the fuel cycle. This includes: LILW-SL (m^3), LILW-LL (m^3), HLW (m^3), SNF (MTU or MTHM).[10]

2.4 Approach to Repository Need/Cost Analysis

The analysis of the need for permanent geologic repositor[ies], their size, and cost comparisons between the OT and FR Cycles was based on a number of factors. These included the number of commercial nuclear power plants currently operating in the U.S. and the estimated amount of SNF and its constituent products (uranium, plutonium, minor actinides, HLW) produced from those plants. The analysis also considered the number of nuclear power plants that have permanently ceased operations and the amount of SNF stored at these sites, as well as the number of nuclear power plants under construction. The analysis took into account the estimated amount of SNF and HLW from U.S. defense programs. All of these were added together to produce an estimated total quantity of waste requiring permanent geologic disposal over the next 70 years.[11] The sources for this information were based on ERI's internal projections for current installed and estimated future U.S. nuclear capacity, historical SNF and HLW from commercial plants and defense programs, and ERI's projection of SNF expected to be discharged in the future.

In addition, the repository analysis considered the statutory limit on the capacity of the first repository under the NWPA. The SMAFS model was used to produce data on the amount of permanent geologic disposal capacity needed, based upon anticipated volumes under the OT and FR Cycles, as well as heat loads and radiotoxicity, all of which contribute to the number, size and cost of permanent geologic repositor(ies) that are required. Projected costs of building repositories are based upon a January 2013 DOE assessment of the Nuclear Waste Fund ("NWF") fee, "Nuclear Waste Fund Fee Adequacy Assessment Report" as well as a 2008 Total System Life Cycle Cost Estimate for the Yucca Mountain Repository.[12]

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[9] The mill is a unit of currency used sometimes in accounting. A mill is equivalent to 1/1000 of a U.S. dollar (a tenth of a cent).

[10] The term "MTU" refers to metric tons of uranium and is generally used to quantity UO_2 SNF. Other types of SNF, such as metal IFR fuel or mixed-oxide ("MOX") fuel contain nuclear fuel elements other than uranium, such as plutonium or minor actinides. For these other types of SNF, the quantity is typically referred to as metric tons of heavy metal or "MTHM".

[11] This assumes that the majority of the existing and new plants will operate for 60-year license terms, resulting in new plants reaching the end of 60 year terms within the next 70 years.

[12] U.S. DOE, "Nuclear Waste Fund Fee Adequacy Assessment Report, January 2013. Attachment, Carter, Joe, Savannah River National Laboratory, "Back End Fuel Cycle, Cost Comparison Prepared for U.S. Department of Energy, Nuclear Fuel Storage and Transportation Planning Project, December 21, 2012.

3. THE CURRENT (ONCE-THROUGH) FUEL CYCLE WITH GEOLOGIC DISPOSAL OF SNF

The **OT Cycle** modeled for this Report assumes the use of commercial LWRs and is similar to the current fuel cycle scheme being used in the U.S. The OT Cycle relies on a fuel cycle scheme developed in NEA 2006 that includes the use of 1,450 megawatt-electric ("MWe") Pressurized Water Reactors ("PWR") operating with a 90% capacity factor, conventional UO_2 fuel, and direct disposal of SNF in a geologic repository. This fuel cycle scheme is shown in Figure 1.[13] The OT Cycle is used as the reference fuel cycle for comparison with the FR Cycle, described in Section 4. The quantities of uranium fuel and waste shown are those associated with production of 1 TWhe of electricity using the OT Cycle.

The SMAFS model assumes that UO_2 fuel will have an average enrichment of 4.90 weight percent Uranium-235 ("^{235}U") with a discharge burnup of 60 gigawatt-days per metric ton of uranium ("GWd/MTU"), which is typical of large U.S. PWRs.[14] SNF is assumed to be cooled in the spent fuel storage pool for five years prior to dry storage. The SNF is assumed to remain in dry storage for a period of 50 years prior to disposal.

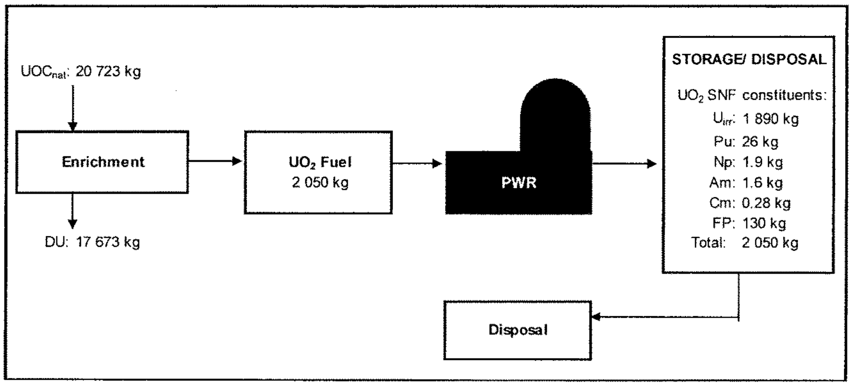

Figure 1 Once-Through Fuel Cycle

U.S. DOE, "Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007," DOE/RW-0591, July 2008.

13 Some of the abbreviations used in Figure 1 are explained in the following sections of this Report.

14 In the U.S., most large PWRs utilize fuel with enrichment levels between 4.5 and 4.95 weight percent ^{235}U. An assumed enrichment of 4.9 weight percent ^{235}U is consistent with current practice.

3.1 Overview of the Front-End of the OT Cycle

The front-end of a OT Cycle includes a number of steps that are necessary to produce fabricated UO_2 fuel for the reference PWR. These steps include production of natural uranium ore concentrates ("UOC"), conversion of UOC into uranium hexafluoride ("UF_6"), enrichment of the ^{235}U isotope in UF_6, and fuel fabrication. UOC are produced through mining and milling to convert uranium ore into U_3O_8 or through other uranium extraction processes. UOC is typically measured in either pounds or short tons of U_3O_8, kilograms uranium ("kgU"), MTU, or tonnes U. UOC is purified and converted to natural UF_6 to prepare it to be processed at uranium enrichment plants. UF_6 is usually measured in kilograms or metric tons of uranium (kgU or MTU) as UF_6.

Natural UF_6 is enriched to obtain the desired enrichment concentration for LWR fuel, usually in the range of 3 to 5 weight percent of the fissile ^{235}U isotope. Natural uranium has a concentration of 0.711 weight percent ^{235}U. The enrichment process also generates a waste stream whose concentration of ^{235}U is depleted (lower than that of natural uranium), known as the "tails" or DU. The assay of ^{235}U in the tails is variable, generally falling between 0.2 weight percent and 0.3 weight percent. The enrichment process is measured in units known as tonnes of separative work or separative work units ("SWU").

The enriched UF_6 is converted to solid UO_2 and then fabricated into fuel pellets that are contained in fuel rods. A specific number of these fuel rods are combined in a square array to form a fuel assembly suitable for use in a specific reactor. Fabricated fuel is typically measured in kgU or MTU contained in UO_2.

Once fabricated, nuclear fuel assemblies will reside in a nuclear reactor for three to four cycles until the assemblies are no longer efficient for the production of electricity. At this point in the OT Cycle, the fuel is considered to be SNF and it is stored in water-filled spent fuel storage pools or in dry cask storage at NPP sites pending permanent disposal.

3.2 Waste Streams Associated with OT Fuel Cycle in the U.S.

The OT Cycle produces DU during the enrichment process. As shown in Figure 1, the enrichment of 20,723 kg of natural UOC results in 18,673 kg of DU, which is assumed to be stored for future use or disposal. Also as shown in Figure 1, a quantity of 2,050 kgU of UO_2 SNF, which is derived from 20,723 kg of natural UOC, is comprised of a number of constituents: U_{irr}, Plutonium ("Pu"), minor actinides[15] (Neptunium ("Np"), Americium ("Am"), Curium ("Cm")), and fission products ("FP"), as shown in Table 1, below. U_{irr} makes up 92.2% of the SNF, FPs are an estimated 6.3%, and Pu and minor actinides are 1.5% as shown in Table 1.

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[15] The minor actinides are the actinide elements in used nuclear fuel other than uranium and plutonium (which are termed the major actinides). The minor actinides include neptunium, americium, curium, as well as other elements. Plutonium and the minor actinides are the greatest contributors to SNF radiotoxicity and heat generation during the period of 300 to 20,000 years following SNF discharge.

Table 1 **Composition of UO_2 SNF To Produce 1 TWhe**

UO_2 SNF Constituents	Quantity (kg)	Percent of SNF
Irradiated uranium	1,890	92.2%
Plutonium	26	1.3%
Minor Actinides	3.78	0.2%
Fission Products	130	6.3%
Total	2,050	100%

The SMAFS model includes assumptions regarding volumes of LILW, HLW, and SNF produced during the front end of the nuclear fuel cycle, during reactor operations, and during waste disposal operations. The volume of SNF of 1.5 m^3/TWhe, shown in Table 2, is based on an assumption that 1 MTHM of fuel is equivalent to 0.72 m^3, based on the dimensions of a typical PWR fuel assembly. In addition to the SNF produced, a total of 14.7 m^3 of LILW-SL and 0.3 m^3 of LILW-LL would be produced. Since SNF is disposed of directly in the OT Cycle, no HLW is produced. The parameter, "SNF repository excavation", represents the volume of earthen material that must be excavated to dispose of SNF for a given repository design. It is based on the decay heat load of the SNF, as discussed in more detail in Appendix A. To dispose of the 1.5 m^3 of SNF needed to produce 1 TWhe, 86.5 m^3 of earth would have to be excavated, based on the decay heat (kW)of the SNF.

Table 2 **Key Waste-Related Parameters Associated with the OT Cycle**

Waste-Related Parameter	Volume
LILW-SL (m^3/TWhe)	14.7
LILW-LL (m^3/TWhe)	0.3
HLW (m^3/TWhe)	0
SNF (m^3/TWhe)	1.5
SNF Repository Excavation (m^3/kW)	86.5
In addition to the above LILW, HLW, SNF and disposal excavation volume, 18,673 kg of DU require storage and/or disposal.	

3.3 U.S. Long-Term Waste Management Program Uncertainties

After many years of program delays, the Yucca Mountain repository project was halted in 2010 with the suspension of the NRC's review of the Yucca Mountain License Application ("LA") and the subsequent appointment of the Blue Ribbon Commission on America's Nuclear Future ("BRC"). In January 2010, the U.S. Secretary of Energy established the BRC to provide recommendations to DOE regarding long-term waste management alternatives for the U.S. The BRC's Final Report to the Secretary of Energy was submitted in January 2012. In that report, the BRC described eight elements that comprise its recommended strategy. While the BRC's recommendations included a number of elements to advance the U.S. waste program, no concrete action has been taken by the U.S. Congress or the Administration and the U.S. waste management program remains in limbo with U.S. NPPs facing the prospect of very long-term dry storage of SNF – possibly for decades after plants cease production of electricity. In November 2013, in response to an August 2013 decision by the U.S. Court of Appeals for the D.C. Circuit ("DC Circuit") which ordered NRC to continue its review of the Yucca Mountain LA, U.S. Nuclear Regulatory Commission ("NRC") Commissioners ordered the NRC staff to complete and publish safety evaluation reports regarding the LA for the proposed Yucca Mountain repository consistent with available resources.

In addition to the uncertainty regarding the path forward for disposal of SNF in the U.S., there is even greater uncertainty regarding the cost for disposal of SNF. In response to litigation by the nuclear industry and electric utility state regulatory agencies that prompted a Federal Court to order DOE to issue a new assessment of fees for disposal of SNF, DOE issued an updated cost estimate for development of geologic disposal in the U.S. in January 2013. DOE's updated assessment concluded that "neither insufficient nor excess revenues are being collected" to recover the federal government's waste disposal costs and therefore did not propose any adjustment to the current fee. This estimate was based on a cost study of repository alternatives for the disposal of 140,000 MTU of SNF with costs that ranged from approximately $24 billion to $81 billion in 2012 dollars – more than a 200% difference in costs. Even higher costs are possible if additional SNF packaging is necessary at a repository (a likely scenario given that the current dry storage packaging used at NPP sites hold between 9 and 15 MTU of SNF – compared with some repository concepts with waste package capacities of 2 MTU). DOE's estimate also did not include the costs associated with fabricating SNF canisters of the correct size for waste disposal, the cost of consolidated interim storage, or the costs associated with repackaging the ever-growing inventory of SNF that is stored in canisters designed for storage and transportation, but not disposal. To put the recent DOE estimate into perspective, a 2008 cost estimate for the Yucca Mountain repository was $96.2 billion for disposal of only 70,000 MTU of SNF and HLW in a single repository – higher than the recent DOE cost estimate for disposal of 140,000 MTU of SNF. In December 2013, DOE sent a proposal to the U.S. Congress to adjust the NWF fee to zero, from the current one mill per kilowatt-hour. DOE's proposed fee adjustment was mandated in November 2013 by the D.C. Circuit following litigation against the DOE by the National Association of Regulatory Utility Commissioners. At the same time, DOE also filed a motion for rehearing of the decision by the full D.C. Circuit.

As noted previously, under the NWPA, the capacity of the first repository is limited to 70,000 MTU, of which civilian SNF would have a 60,000 MTU share with the additional 10,000 MTU of capacity being devoted to disposal of SNF and HLW from defense programs. Due to the large quantity of SNF and HLW anticipated to be disposed of in the U.S. (140,000 MTU of civilian SNF plus an additional 10,000 MTU of defense-related SNF and HLW), it is likely, therefore, that more than one repository will be necessary. After more than 30 years since passage of the NWPA that authorized DOE to develop geologic disposal capacity, the U.S. is back to the starting line and it could be many decades before a first repository is developed, let alone a second repository to dispose of the entire 140,000 MTU inventory of SNF. The daunting task of siting and operating two repositories may help to shift the U.S. focus to technologies that will reduce the quantities of commercial waste requiring disposal as well as reducing the toxicity and heat load of the waste. Pyroprocessing of SNF and subsequent recycle as metal fuel for IFRs could accomplish this as discussed in more detail below.

3.4 Summary of Once-Through Fuel Cycle and Electric Generation Costs

The SMAFS model was designed to calculate equilibrium fuel cycle costs and total electric generation costs assuming that all reactors in a given fuel cycle scheme operate at constant power and that all mass flows have reached an equilibrium. Assuming the NV unit costs identified in Appendix A for all input parameters, waste management costs, total fuel cycle costs (of which waste management costs are a subset), and total electric generation costs, expressed as the cost of electricity in mills/kWhe, are summarized in Table 3 for the OT Cycle.

Assuming the NV unit costs, the OT Cycle has reactor costs of 97.5 mills/kWhe and fuel cycle costs of 7.5 mills/kWhe, for a total cost of electricity of 105 mills/kWhe. The reactor cost comprises more than 90% of the cost of electricity.

Table 3 Total Electricity Generation Costs for the OT Cycle Assuming NV Unit Costs (Mills/kWhe)

Cost Indicators	Cost Components	Percent of Total Costs
Reactor Capital & O&M Cost	97.5	92.9%
Fuel Cycle Cost		
Natural Uranium	3.2	3.0%
Conversion	0.3	0.2%
Enrichment	1.9	1.8%
Fuel Fabrication	0.7	0.7%
Waste Management	1.4	1.3%
Total Fuel Cycle Cost	**7.5**	**7.1%**
Total Generation Cost	105.0	

The SMAFS model also includes LB and UB values for all unit costs used to calculate the equilibrium generation costs for the various fuel cycles. Table 4 summarizes the results for the OT Cycle, assuming that all unit costs are either at the LB or UB values.

Assuming the LB values for all unit costs, the OT Cycle was evaluated to have a total cost of electricity of 62.1 mills/kWhe – comprised of a reactor cost of 57.3 mills/kWhe and fuel cycle costs of 4.8 mills/kWhe. Reactor costs are more than 92% of the total cost of electric generation using the LB unit costs. Assuming the UB values for all unit costs, the OT Cycle was evaluated to have a total cost of electricity of 155.3 mills/kWhe – comprised of a reactor cost of 140.4 mills/kWhe and fuel cycle costs of 14.9 mills/kWhe. Using the UB values, reactor costs comprise approximately 90% of the total cost of generation.

Table 4 Total Electricity Generation Costs for the OT Cycle Assuming NV Unit Costs (Mills/kWhe)

Cost Indicators	LB Values	UB Values
Reactor Capital & O&M Cost	57.3	140.4
Front-End Fuel Cycle Cost	3.9	12.0
Waste Management Costs	0.9	2.9
Total Fuel Cycle Cost	**4.8**	**14.9**
Total Generation Cost	**62.1**	**155.3**

4. FAST REACTOR FUEL CYCLE WITH PYROPROCESSING

The **FR Cycle** model used for this Report assumes that UO_2 SNF from 1,450-MWe PWRs (simulating U.S. commercial LWRs) and the metal fuel from 600-MWe IFR is processed using pyroprocessing and the Pu and minor actinides are recycled into new IFR metal fuel. In addition, UO_2 SNF from the existing inventory of commercially-generated UO_2 SNF can also be processed using pyroprocessing and the Pu and minor actinides can be recycled and combined with the Pu and minor actinides from recycled IFR fuel into new IFR metal fuel. The FR Cycle modeled for this Report postulates that 63% of the energy for this fuel cycle comes from PWRs using UO_2 fuel, and 37% of the energy comes from FRs using metallic FR fuel, as shown in Figure 2. The FR Cycle assumes that the SNF inventory from existing LWRs is recycled in FRs, resulting in uranium savings of 37% (equal to the fraction of energy produced by the FRs) compared to the OT Cycle generating the same amount of energy with only LWRs. There is no direct disposal of SNF in this fuel cycle scheme. Instead, plutonium and minor actinides from UO_2 SNF, along with stored DU, are recycled for use as metal IFR fuel. In addition, plutonium and minor actinides from the IFR SNF are also recycled as metal FR fuel. FPs from UO_2 and IFR SNF, along with residual heavy metal ("HM"), are disposed in a geologic repository. The quantities of uranium fuel, plutonium, minor actinides, DU, U_{irr} and waste shown in Figure 2 are those associated with production of 1 TWhe of electricity using the FR Cycle for the recycle of UO_2 and IFR SNF. Although Figure 2 assumes the use of DU as part of the IFR fuel, U_{irr} can also be recycled in IFR metal fuel along with the Pu and minor actinides. U_{irr} can also be stored and be recycled into UO_2 fuel in the future.

It should be noted that NEA 2006 did not include a scenario in which UO_2 SNF is recycled using pyroprocessing; therefore, the data used for this report employed the waste parameters in NEA 2006 associated with reprocessing using a UREX process. The resulting parameters for FP, minor actinides, plutonium, and reprocessed uranium utilized in this study are consistent with values for pyroprocessing of UO_2 SNF that are contained in recent studies, such as a 2012 study conducted by researchers from KAERI[16] and a 2010 study by multiple authors that examined the economic and business case for pyroprocessing of UO_2 SNF.[17] Material balances for the FR Cycle are discussed in more detail later in the section.

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[16] Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Economic Analysis of Different Nuclear Fuel Cycle Options, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 293467.

[17] Archambeau, Charles, Blees, Change, Hunter, Shuster, Ware and Wooley, Economic/Business Case for the Pyroprocessing of Spent Nuclear Fuel ("SNF"), 100 Ton/Yr Pyroprocessing Demonstration Plant, November 2010.

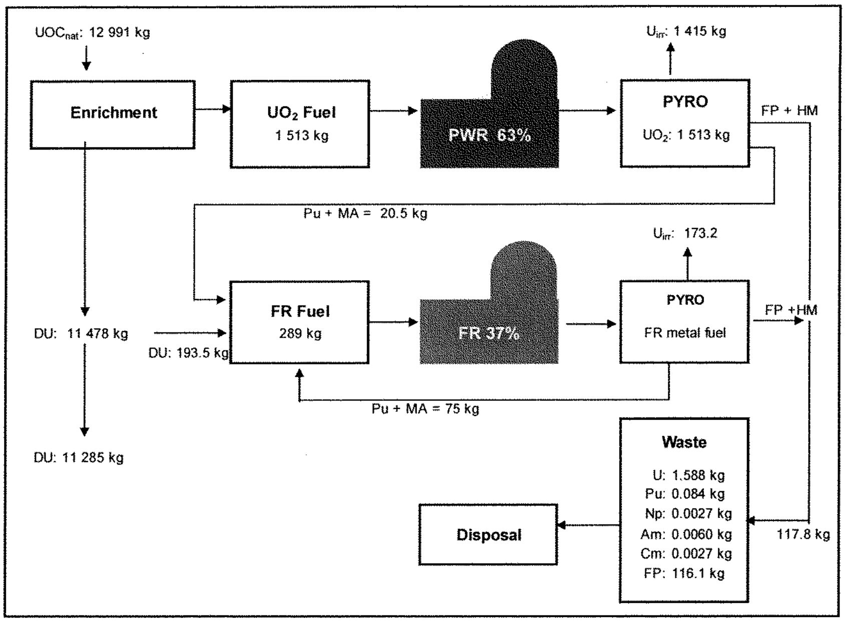

Figure 2 Fast Reactor Fuel Cycle: UO2 and IFR Fuel Pyroprocessing [18]

4.1 Overview of Integral Fast Reactors and Pyroprocessing Development

FR technology has been demonstrated on a small scale for decades and continues to be developed on larger scales in several countries. FRs were first developed in the U.S. in the 1940s with the development of the Clementine FR at Los Alamos National Laboratory and the Experimental Breeder Reactor ("EBR-I" and "EBR II") at the Idaho National Laboratory ("INL") in the 1950s and 1960s. Fermi 1 in Michigan was a prototype fast breeder reactor ("FBR") that was closed in the 1970s, and the Fast Flux Test Facility operated from 1982 to 1992 at Hanford Washington. In the U.S., Argonne National Laboratory ("ANL") developed the IFR technology (originally called the Advanced Liquid-Metal Reactor) in the 1980s. General Electric's PRISM reactor design is based on the IFR design. The PRISM reactor is an advanced fast neutron reactor that is designed to consume

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[18] Figure 2 assumes that DU is recycled as part of the IFR metal fuel along with Pu and minor actinides from UO$_2$ SNF and IFR SNF. However, Uirr can also be recycled in IFR metal fuel along with the Pu and minor actinides as assumed in several IFR concepts that are under development today. Uirr can also be stored for future recycle into UO$_2$ fuel.

the Pu and minor actinides (rather than disposing of them in SNF) as it generates electricity.[19]

There are currently several FRs in operation around the globe. Russia's BN-600, which is scheduled to cease operation in 2014 and the recently commissioned BN-800 reactor, which is expected to enter commercial operation in 2015, are both liquid metal FBRs ("LMFBR"). In Japan, the Monju LMFBR, operated by the Japan Atomic Energy Agency, was commissioned in 1994, but is currently not operating. India has a FR under construction at Kalpakkam. France operated the Phenix and Superphenix FRs - both units have ceased operation.

For the FR Cycle, the UO_2 SNF would be transported to the pyroprocessing facility where the Pu, minor actinides, FPs, and U_{irr} would be separated as shown in Figure 2. Pyroprocessing utilizes a high-temperature electrorefining process to separate the constituent materials in UO_2 SNF. While there are different variations for pyroprocessing, the process developed by ANL for the IFR program is described briefly below.[20] Research into pyroprocessing techniques is being conducted in the U.S. as part of DOE's Fuel Cycle Research and Development program, and in South Korea by KAERI, which is working to develop a closed fuel cycle that includes pyroprocessing and FRs using metallic fuel.[21] It should be noted that in pyroprocessing, no pure plutonium stream is separated during SNF processing. Instead, the plutonium remains combined with the minor actinides throughout the process. This results in the plutonium being more proliferation resistant than the pure plutonium steam that results from aqueous reprocessing (the type of reprocessing currently used in Europe), in which the minor actinides remain with the FPs and are disposed as part of the HLW.

In order for UO_2 SNF to be partitioned through pyroprocessing, it first must go through an oxide reduction step in order to convert it to a metallic form. The SNF is chopped into segments, loaded into anode baskets and the baskets are lowered into the electrorefiner. The electrorefiner performs the primary separation of the actinides from the FPs. In order to partition the constituent elements in metallic FR SNF, it is not necessary to subject IFR SNF to an oxide reduction step since the fuel is already in metallic form. The remaining processes for separation of the actinides and FPs are the same as for UO_2 SNF.[22]

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[19] Fletcher, Kelly, Sustainable Energy Advanced Technology Leader, General Electric Company, Prepared Testimony before the Energy and Water Subcommittee , U.S. Senate Appropriations Committee, September 14, 2006.

[20] Simpson, Michael F., Jack D. Law, Idaho National Laboratory, *Nuclear Fuel Reprocessing*, INL/EXT-10-1753, February 2010.

[21] Ibid.

[22] Ibid.

4.2 FR Cycle Material Balance

The front-end of the portion of the FR Cycle that uses the reference PWR is identical to the front-end of the OT Cycle. As in the OT Cycle, the production of UO_2 fuel for the reference PWR includes uranium mining and milling, conversion and enrichment services and fuel fabrication as previously described in Section 3.1. However, in the FR Cycle, the reference PWR contributes only 63% of 1 TWhe of electricity generated.

The resulting separation products from pyroprocessing 1,513 kg of UO_2 SNF from the reference PWR is summarized in Table 5: 1415 kg of U_{irr}, 20.5 kg Pu and minor actinides, and 77 kg of FPs including traces of uranium and other elements in the FP waste stream.[23] Plutonium plus minor actinides are recycled into FR metal fuel as previously shown in Figure 2.

The resulting separation products from pyroprocessing 289 kg of metallic FR SNF are summarized in Table 5: 173.2 kg of U_{irr}, 75 kg of Pu and minor actinides, and 40.3 kg of FPs. In total, 95.5 kg of Pu and minor actinides are recycled in the equilibrium FR shown in Figure 2 along with 193.5 kg of DU (or U_{irr}). Total FPs requiring disposal in the FR Cycle are an estimated 118 kg.

Table 5
Composition of UO_2 and FR SNF Resulting per TWhe

SNF Constituents	UO_2 SNF (kg)	FR Metal SNF (kg)	Total SNF Constituents (kg)
Irradiated uranium	1415	173.2	1588
Plutonium	18.2	66.0	84.2
Minor Actinides	2.3	9.0	11.3
Fission Products, plus trace quantities of HM	77.4	40.3	117.7
Total	1513	289	1802

Note: Numbers may not add exactly due to rounding.

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[23] Simpson, Michael F., Jack D. Law, Idaho National Laboratory, Nuclear Fuel Reprocessing, INL/EXT-10-1753, February 2010. The various waste streams may be treated using different processes – FPs can be processed into a HLW ceramic waste form, while SNF cladding and noble metals can be processed in a metal waste furnace into a HLW metal form.

4.3 Recycling SNF

As noted in Section 1, through December 2013, an estimated 72,000 MTU of UO_2 SNF had been discharged from U.S. NPPs and was in storage at NPP sites in the U.S, an amount that is already in excess of the NWPA's statutory capacity of 70,000 MTU for a first repository. By 2040, an estimated 127,000 MTU of SNF will have been discharged, growing to an estimated 140,000 by 2070.

As previously shown in Figure 2, the FR generates 37% of the electricity necessary to produce 1 TWhe in the FR Cycle. This represents an estimated 47 MWe and the PWR portion of electricity represents an estimated 80 MWe. The 47 MWe represented by FR generation in the FR Cycle requires metallic FR fuel containing 0.095 MT of Pu and minor actinides plus an additional 0.194 MT of DU. To refuel a 600 MWe IFR, an estimated 1.2 MT of Pu and minor actinides, and 2.5 MT of DU are necessary, as shown in Table 6. It is envisioned that IFRs will be deployed in multiple units at one site. To refuel two 600 MWe IFRs (1,200 MWe total), 2.4 MT of Pu and minor actinides, and 5.0 MT of DU are needed.

Table 6 Estimate of Pu and Minor Actinides and DU to Supply Metallic FR Fuel

Reload Fuel Component	47 MWe	600 MWe	1200 MWe
Pu & MA (MT)	0.095	1.2	2.4
Depleted Uranium (MT)	0.194	2.5	5.0
Total Fuel (MT)	0.29	3.7	7.4

As was shown in Table 1, the constituent elements in UO_2 SNF include an estimated 1.5% of Pu and minor actinides. Thus, in order to separate 2.4 MT of Pu and minor actinides needed to refuel two 600 MWe FRs (1,200 MWE total), 160 MTU of UO_2 SNF would need to be pyroprocessed (2.4 MT / 0.015). Table 7 summarizes the estimated inventory of Pu and minor actinides that is contained in current and projected inventories of UO_2 SNF. Hypothetically, if the reload fuel for two 600 MWe FRs consumes 2.4 MT of Pu and minor actinides from processing 160 MTU of UO_2 SNF, then the current inventory of 72,000 MTU of UO_2 SNF, consumed at a rate of 160 MTU per FR per year, would require an estimated 22,600 MWe IFRs (or 11 sites, each with 2 IFRs) to consume the current inventory of Pu and minor actinides contained in UO_2 SNF.[24] In order to consume the Pu

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[24] An estimated 11 Fast Reactor Sites is derived from dividing the current inventory of 72,000 MTU of UO_2 SNF by 160 MTU consumed per 1,200 MWE per year, assuming 40 years of FR operation, assuming 2,600 MWE FRs ([72,000 ÷ 160 ÷ 40] * 2 = 22)

and minor actinides from 127,000 MTU of UO_2 SNF, a fleet of 40 600 MWe IFRs operating for 40 years would be necessary.

Table 7 Estimate of Pu and Minor Actinides, U_{irr} and FP Produced in Current and Projected UO_2 Inventory (MT)

Constituents of UO_2 SNF	2013	2020	2040
Quantity of UO_2 SNF	72,000	86,700	127,000
Irradiated Uranium – 93%	66,960	80,631	118,110
Pu + Minor Actinides – 1.5%	1,080	1,300	1,905
Fission Products – 5.5%	3,960	4,769	6,985
DU (or U_{irr}) Consumed Over 40 years (MTU)	2,200	2,700	4,000
# 600 MWe FRs, Operating 40 Years	22	27	40

As shown in Table 6, 2.5 MT of DU is needed to fuel a 600 MWe IFR each year. Therefore, over a 40-year period, a 600 MWe IFR will consume 100 MT of DU. As shown in Table 7, the 22 IFRs needed to recycle the existing 72,000 MT of UO_2 SNF, would consume 2,200 MTU of DU (or alternatively U_{irr}) and 40 IFRs needed to recycle 127,000 MTU that will exist by 2040 will consume 4,000 MTU of DU. There are 686,500 MTU of DU in storage at three former gaseous diffusion enrichment plants in Kentucky, Ohio and Tennessee.[25] While DU with higher uranium tails assay can be re-enriched to create natural uranium equivalent, significant quantities of DU will require continued storage and eventual disposal unless this material can be recycled. Alternatively, U_{irr} may also be recycled instead of DU.

It should also be noted that while two 600 MWe IFRs (1,200 MWe total) are consuming Pu and minor actinides from UO_2 SNF, the IFRs are also producing additional Pu and minor actinides as summarized in Table 8. Two 600 MWe IFRs (1,200 MWe total) will produce an additional 1.9 MT of Pu and minor actinides, while consuming 2.4 MT of Pu and minor actinides. This is a net reduction of 0.5 MT of Pu and minor actinide elements for each year of IFR operation. The estimated number of IFRs needed to consume inventories of Pu and minor actinides from the current inventory of UO_2 SNF shown in Table 7 does not include the further recycle of IFR SNF as a fuel source for continued operation of this IFR fleet. This is because the focus of this report is on the use of pyroprocessing and IFRs to recycle the current inventory of commercial UO_2 SNF. However, the recycle of Pu and minor actinides from IFR SNF would provide a fuel for IFRs going forward once existing

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[25] Depleted UF6 Management Information Network, http://web.ead.anl.gov/uranium/faq/storage/faq16.cfm

inventories of LWR SNF are consumed. The Pu and minor actinides recycled from IFR SNF also could be combined with Pu and minor actinides recycled from existing UO_2 SNF. However, this would result in either (1) a longer time period to recycle existing UO_2 inventories in the IFR fleets identified in Table 7 or (2) construction of a larger number of IFRs to consume Pu and minor actinides from both UO_2 inventories and IFR SNF processing. Whether Pu and minor actinides from IFR SNF are recycled along with UO_2 SNF or recycled at a later date into additional IFR metal fuel, the Pu would not be separated from the minor actinides, providing proliferation resistance and reducing concerns regarding proliferation.

Table 8 Estimate of Pu and Minor Actinides, U_{irr} and FP Produced in IFR Fuel (MT)

Reload Fuel Component	47 MWe	600 MWe (1 IFR)	1200 MWe (2 IFRs)
Quantity of FR SNF	0.289	3.7	7.4
Irradiated Uranium – 60%	0.173	2.2	4.4
Pu + Minor Actinides – 26%	0.075	0.96	1.9
Fission Products – 14%	0.040	0.5	1.0

4.4 Waste Volumes for FR Cycle

The SMAFS model includes assumptions regarding volumes of LILW, HLW, and SNF produced during the front end of the nuclear fuel cycle, during reactor operations, and as a result of reprocessing operations. Under a FR Cycle, a total volume of 11.9 m^3/TWhe of LILW-SL is produced including waste from the front-end of the fuel cycle and from reactor operation and a volume of 2.3 m^3/TWhe of LILW-LL is produced, as shown in Table 9. The volume of HLW requiring disposal is estimated to be 0.4 m^3. The volume of earthen material that must be excavated to dispose of SNF for a given repository design, is based on the decay heat load of the HLW, as discussed in more detail in Appendix A. Since the Pu and minor actinides have been removed from the constituent elements of the HLW, the overall decay heat of the HLW waste is lower than for direct disposal of SNF, reducing the amount of earth that would have to be excavated to dispose of HLW from pyroprocessing of UO_2 SNF compared to direct disposal. To dispose of the 0.4 m^3 of HLW, 38.3 m^3 of earth would have to be excavated, based on the decay heat (kW) of the SNF.

Table 9 Key Waste Parameters Associated with the FR Cycle

Waste Parameter	Volume
LILW-SL	11.9
LILW-LL	2.3
HLW	0.4
SNF	0
HLW Repository Excavation	38.3

In addition to the above LILW, HLW, SNF and disposal excavation volume, 11,478 kg DU require storage or can be recycled in metallic FR fuel.

4.5 Pyroprocessing Plant Financing

In order to close the nuclear fuel cycle in the U.S., it will be necessary to construct and operate facilities for recycling of SNF; both recycling of UO_2 SNF from PWRs and recycling of metallic IFR SNF. A summary of a cost analysis conducted by ERI for a 2,000 MTHM per year pyroprocessing plant is provided below, including the results of a sensitivity analysis of financial parameters concerning construction and operation of this plant. Initial cost parameters used in the base case analysis are based on a November 2010 study performed by multiple individuals regarding the development of a 100 MTHM pyroprocessing *demonstration* facility in the U.S. ("2010 Archambeau study.")[26] The 2010 Archambeau study also examined the costs associated with development of a 2,000 MTHM pyroprocessing facility. Sensitivity analyses performed by ERI examine a range of debt positions, return on investment, debt interest rates, financing periods, and total overnight costs.

The financial assumptions and operating parameters utilized in the 2010 Archambeau study were used to form the base case assumptions in ERI's analysis of the financing alternatives for a 2,000 MTHM pyroprocessing plant, as summarized in Table 10. ERI developed a MSExcel spreadsheet to calculate the unit costs for a base case analysis that models a pyroprocessing plant with a 2,000-ton capacity for processing UO_2 SNF from the current U.S. nuclear power plants, partitioning U_{irr}, Pu, minor actinides, and FPs, and future

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[26] Archambeau, Charles, Blees, Chang, Hunter, Shuster, Ware and Wooley, Economic/Business Case for the Pyroprocessing of Spent Nuclear Fuel (SNF), 100 Ton/Yr Pyroprocessing Demonstration Plant, November 2010

recycling of Pu and minor actinides in an IFR.[27] The facility is assumed to operate for a period of 25 years. Initial overnight capital costs are assumed to be $7 billion with annual O&M costs of $500/kgHM processed. A depreciation period of 25 years is assumed. The ratio of debt to equity is 60:40, with a debt interest rate of 6% and a loan payback period of 15 years. ERI utilized its own assumptions for the return on investment ("ROI") of 15% and a Federal corporate income tax rate of 35%, as these factors were not explicitly identified in the 2010 Archambeau study.

The levelized reprocessing unit cost that results from the base case assumptions shown in Table 10 is an estimated $1,218/kgHM reprocessed in the plant. In an addendum to the 2010 Archambeau study, a $1,200 processing fee for UO_2 SNF was assumed, which is the same order of magnitude as the unit cost calculated by ERI.

Table 10 2,000 MTHM Pyroprocessing Plant Financial and Operating Assumptions

Base Case Parameters	Base Case Assumptions
Plant Capacity	2,000 MTHM/year
Operating Period	25 years
Overnight Cost	$7 Billion
Operating and Maintenance Cost	$500/kgHM
Debt Ratio	60%
Debt Interest Rate	6%
Equity Ratio	40%
Return on Investment	15%
Federal Taxes	35%
Depreciation Period	25 years
Loan Payback Period	15 years

In addition to calculating unit costs for a pyroprocessing plant using the above base case assumptions, ERI performed sensitivity analyses to determine the impact of changes to the financial and operating assumptions. As summarized in Table 11, values that are ±50% of the capital cost, and ±25% of the other parameters were varied one-at-a-time in order to determine the sensitivity of the unit cost of pyroprocessing at a 2,000-ton pyroprocessing plant to changes in the various parameters.

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[27] While Pu and minor actinides are recycled in FRs and FPs are disposed of as HLW, the U_{irr} is assumed to be stored for future recycle as UO_2 fuel for LWRs. U_{irr} from aqueous reprocessing in Europe has been recycled as LWR fuel in European reactors.

Table 11 Sensitivity Analysis Parameters for Financial and Operating Assumptions

	Lower Bound Sensitivity	Upper Bound Sensitivity
Plant Capacity (MTHM/year)	2,000	2,000
Overnight Cost	$10.5 Billion	$3.5 Billion
Operating and Maintenance Cost	$375/kgHM	$625/kgHM
Debt Ratio	45%	75%
Loan Payback Period	11.25 years	18.75 years
Debt Interest Rate	4.5%	7.5%
Equity Ratio	55%	25%
Return on Investment	11.25%	18.75%
Federal Taxes	35%	

By varying the above financial parameters one-at-a-time, ERI was able to determine which of the financial parameters have the greatest impact on the cost of pyroprocessing per MTHM processed. Figure 3 summarizes the results of the sensitivity analysis using the lower bound and upper bound parameters identified in Table 11 and compares the results to the base case unit cost of $1,218/kgHM for pyroprocessing of UO_2 SNF at the 2,000-ton facility.

- The base case overnight capital cost of $7 billion was varied from $3.5 billion to $10.5 billion, resulting in unit costs of $860 to $1,579 per kgHM, respectively.
- Annual O&M costs were varied from $375/kgHM to $625/kgHM, resulting in unit costs of $1,091 to $1,345 per kgHM, respectively.
- The ROI was varied from 11.25% to 18.75%, resulting in unit costs of $1,060 to $1,395 per kgHM.
- Debt ratio was varied from 45% to 75%, resulting in unit costs of $1,299 to $1,139 per kgHM, respectively.
- The debt rate was varied separately from 4.5% to 7.5%, resulting in unit costs of $1,188 to $1,253 per kgHM, respectively.
- The loan repayment period was varied from 11.25 years to 18.75 years resulting in unit costs of $1,264/kgHM to $1,181/kgHM, respectively.

The overnight capital cost of a pyroprocessing plant will have the greatest impact on the unit costs for pyroprocessing UO_2 SNF, as shown in Figure 3. Other financial parameters that will be important to the unit costs for a pyroprocessing plant are the required ROI, the annual O&M costs, and the ratio of debt to equity.

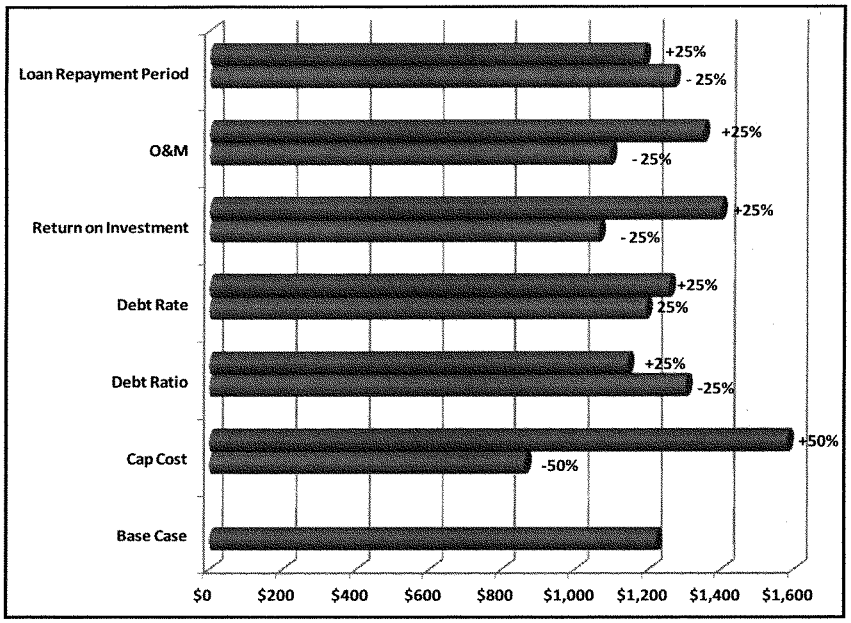

Figure 3 **Comparison of Unit Costs for Pyroprocessing of UO$_2$ SNF In a 2,000-Ton Plant Over a Range of Financial Parameters**

4.6 Summary of FR Cycle and Electric Generation Costs

The SMAFS model was designed to calculate equilibrium fuel cycle costs and total electric generation costs assuming that all reactors in a given fuel cycle scheme operate at constant power and that all mass flows have reached an equilibrium. Assuming the NV unit costs identified in Appendix A for all input parameters, waste management costs, total fuel cycle costs (of which waste management costs are subset), and total electric generation costs, expressed as the cost of electricity in mills/kWhe, are summarized in Table 12 for the FR Cycle.

Assuming the NV unit costs, the FR Cycle, in which UO$_2$ SNF from operating PWRs is pyroprocessed along with IFR SNF to provide feed for IFR metal fuel, has equilibrium reactor costs of 96.2 mills/kWhe and fuel cycle costs of 7.8 mills/kWhe, for a total cost of electricity of 104 mills/kWhe. The reactor cost comprises an estimated 93% of the cost of electricity.

Table 12 Total Electricity Generation Costs for the FR Cycle Assuming NV Unit Costs (Mills/kWhe)

Cost Indicators	Cost Components	Percent of Total Costs
Reactor Capital & O&M Cost	**96.2**	**93%**
Fuel Cycle Cost		
Natural Uranium	2.0	2%
Conversion	0.2	0%
Enrichment	1.1	1%
Fuel Fabrication	1.3	1%
UO_2 & IFR Reprocessing	2.9	3%
Waste Management	0.3	0%
Total Fuel Cycle Cost	**7.8**	**7%**
Total Generation Cost	**104**	**100%**

The SMAFS model also includes LB and UB values for all unit costs utilized to calculate the equilibrium generation costs for the various fuel cycles. Table 13 summarizes the results for the FR Cycle, assuming that all unit costs are either at the LB or UB values. Assuming the LB values for all unit costs, the FR Cycle was evaluated to have a total cost of electricity of 54.7 mills/kWhe, with a reactor cost of 50.2 mills/kWhe and fuel cycle costs of 4.5 mills/kWhe. Reactor costs are more than 91% of the total cost of electric generation using the LB unit costs. Assuming the UB values for all unit costs, the FR Cycle was evaluated to have a total cost of electricity of 151.5 mills/kWhe, with a reactor cost of 136.4 mills/kWhe and fuel cycle costs of 15.1 mills/kWhe. Using the UB values, reactor costs comprise 90% of the total cost of generation.

Table 13 Total Electricity Generation Costs for the FR Cycle Assuming NV Unit Costs (Mills/kWhe)

Cost Indicators	LB Values	UB Values
Reactor Capital & O&M Cost	50.2	136.4
Front-End Fuel Cycle Cost	2.9	9.0
UO_2 & IFR Reprocessing	1.4	5.2
Waste Management Costs	0.2	0.9
Total Fuel Cycle Cost	**4.5**	**15.1**
Total Generation Cost	**54.7**	**151.5**

5. COMPARISON OF WASTE VOLUME, RADIOTOXICITY AND THERMAL OUTPUT FOR OT CYCLE AND FR CYCLE

Table 14 compares the volumes of LILW, HLW, and SNF produced during the front end of the nuclear fuel cycle, reactor operations, and as a result of reprocessing operations for the OT Cycle and FR Cycle. Under the OT Cycle, a total volume of 14.7 m^3/TWhe of LILW-SL (including waste from the front-end of the fuel cycle and during reactor operation) and 0.3 m^3/TWhe of LILW-LL are produced. Under the FR Cycle, LILW-SL volumes are lower than in the OT Cycle – 11.9 m^3/TWhe of LILW-SL. However, LILW-SL volumes are higher in the FR Cycle – 2.3 m^3/TWhe. The volume of SNF in the OT Cycle requiring direct disposal is estimated to be 1.5 m^3/TWhe compared to 0.4 m^3/TWhe of HLW for the FR Cycle.

Disposal costs will be a function not only of the volume of waste being disposed but also of the heat load of the waste requiring disposal. This is due to the fact that repository designs typically assume that a certain amount of repository space is needed for SNF/HLW of a specific heat load in order to have a uniform heat load throughout the repository. SNF/HLW with lower heat loads per unit volume of waste can be emplaced at closer distances than waste with higher heat loads. In the SMAFS model, this is accounted for with the SNF Repository Excavation parameter as shown in Table 14. Disposal of SNF in the OT Cycle requires 86.5 m^3/kW of waste disposed. Disposal of HLW resulting from the FR Cycle requires 38.3 m^3/kW of waste disposed, less than half of the repository volume required to disposal of SNF in the OT Cycle

Table 14 Comparison of Waste-Related Volumes Produced in the OT Cycle and FR Cycle

Waste-Related Parameter	OT Cycle Waste Volume	FR Cycle Waste Volumes
LILW-SL (m^3/TWhe)	14.7	11.9
LILW-LL (m^3/TWhe)	0.3	2.3
HLW (m^3/TWhe)	0	0.4
SNF (m^3/TWhe)	1.5	0
SNF Repository Excavation (m^3/kW)	86.5	38.3

Table 15 compares the radioactivity and thermal output of waste volumes for the OT and FR Cycles in Terabecquerel/TWhe ("TBq/TWhe") at time periods of 200 years after discharge from the NPP and 1,000 years after discharge. UO_2 SNF from the OT Cycle has an activity of 1,070 TBq/TWhe at 200 years and this is reduced to 201 TBq/TWhe at the 1,000 year mark – 18% of the original activity. The HLW volumes from the FR Cycle (387 TBq/TWhe) at 200 years are only 36% of those for the OT Cycle and at 1,000 years (2.4 TBq/TWhe) are 1% of the activity for the OT Cycle. Similarly, the heat load of the waste to be disposed decreases significantly in the FR Cycle. At 200 years, the OT Cycle waste has a heat load of 591 watts/TWhe compared to 30 watts/TWhe for the FR Cycle, 5% of the OT Cycle heat load. At 1,000 years, the FR Cycle waste heat load (0.5 watts/TWhe) are <1% of the OT Cycle heat load (171 watts/TWhe).

Table 15 Comparison of Radiotoxicity and Thermal Output of Waste Produced in the OT Cycle and FR Cycle (m3/TWhe)

	OT Cycle Waste Parameters	FR Cycle
Activity – 200 years (TBq/TWhe)	1,070	387
Activity – 1,000 years (TBq/TWhe)	201	2.4
Thermal Output – 200 Years (Watts/TWhe)	591	30
Thermal Output –1,000 Years (Watts/TWhe)	171	0.5

As shown in Table 15, pyroprocessing of UO_2 SNF for recycle of Pu and minor actinides in metallic FR fuel removes the majority of the long-lived isotopes from the waste stream and reduces long-term radioactivity or radiotoxicity. Developing a repository for disposal of commercial waste with a lower radiotoxicity and without the long-lived isotopes should result in simplified repository design, including avoidance of the need for some engineering barriers, ultimately reducing cost. As an example, the Yucca Mountain repository project was designed with a complex engineered barrier system that utilizes drip shields made of titanium (an expensive metal) and specialty metals in the waste disposal package in order to protect the waste packages from corrosion for thousands of years after emplacement. The cost to fabricate and install the drip shields was estimated to cost several billion dollars - costs that would not be necessary for disposal of wastes with lower activity and without the inventory of long-lived radioisotopes.

The thermal load of the FR Cycle waste is also significantly lower than the waste for the OT Cycle – 0.5 watts/TWhe for the FR Cycle compared to 171 watts/TWhe for the OT Cycle – less than 1% of the heat load of OT Cycle waste at 1,000 years. As noted above, the distance between each disposal canister and between rows of disposal canisters in a geologic repository can be reduced if the heat load of the emplaced waste is reduced due to the fact that repository designs typically assume that a certain amount of repository space is needed for disposal of a SNF/HLW with a specific thermal output. Therefore, the size of the required repository excavation is a function of the heat load of the waste being emplaced. Accordingly, a significant reduction in heat load will also reduce the cost of repository development since less material will have to be excavated. The repository size needed to dispose of the HLW that results from pyroprocessing existing inventories of UO_2 SNF could be halved compared to that needed to directly dispose of UO_2 SNF – that is, there would not be the need for a second repository to be constructed in the U.S.

6. CONCLUSIONS

Deploying "pyroprocessing" technology and IFRs to recycle the current inventory of commercial UO_2 SNF provides a number of significant, potential benefits, key among these are: avoiding the need for additional costs associated with a second repository by reducing the overall volume of radioactive waste requiring geologic disposal; reducing the radiotoxicity and heat load of the final waste form to be disposed, which would reduce the cost of the design and construction of the single geologic repository needed for nuclear waste; and the ability to pay for pyroprocessing/IFR costs by the avoided cost of a second repository. In addition, if a large-scale pyroprocessing facility and a fleet of IFRs are able to be deployed sooner than a geologic repository, then there also may be avoided costs associated with the government's liability for the DOE's failure to begin SNF acceptance in 1998. Deployment of pyroprocessing and IFRs also will help to conserve uranium resources, thereby prolonging the use of nuclear energy if uranium supplies become scarce or the price of uranium increases significantly.

6.1 Reduction in Waste Volume, Radiotoxicity, and Heat Load of Waste Requiring Disposal

Assuming the NWPA statutory capacity for a first repository of 70,000 MTU of SNF, the projected 140,000 inventory of commercial UO_2 SNF, plus an estimated 10,000 MTU of SNF and HLW from U.S. defense programs, would require that at least two repositories be built in the U.S. As shown in Table 14, the volume of HLW resulting from the FR Cycle that requires disposal (0.4 m^3/TWhe) is 27% of the same volume of UO_2 SNF (2,050 kg) requiring disposal (1.5 m^3/TWhe) in the OT Cycle. While the entire inventory of UO_2 SNF may not be suitable for pyroprocessing and recycle of TRU elements in metallic IFR fuel, clearly, significant reductions in the volume of material to be disposed can be realized to avoid building a second repository.

In addition to the reduced volume of waste, as shown in Table 14, the HLW resulting from pyroprocessing that requires disposal in the FR Cycle has a lower radiotoxicity at 1,000 years after discharge from the reactor due to the recycle of Pu and minor actinides in FR metal fuel – FR Cycle HLW contains only 1% of the activity found in OT Cycle waste at 1000 years after discharge as summarized in Table 15. The thermal load of the FR Cycle waste is also significantly lower than the waste for the OT Cycle – it is less than 1% of the heat load of OT Cycle waste at 1,000 years. The distance between each disposal canister and between rows of disposal canisters in a geologic repository can be reduced if the heat load of the emplaced waste is reduced. This is due to the fact that repository designs typically assume that a certain amount of repository space is needed for disposal of SNF/HLW with a specific thermal output (watts/m^3). Therefore, the size of the required repository excavation is a function of the heat load of the waste being emplaced. Accordingly, a significant reduction in heat load will reduce the cost of repository development since less material will be excavated. Due to the reduction in the thermal load of HLW from the FR Cycle, as shown in Table 15, the amount of material required to be excavated to emplace that waste in a repository in the FR cycle is also reduced - from

86.5 m^3 for the OT Cycle to 38.3 m^3 for the FR Cycle. This results in 44% of the required repository volume for disposal of SNF being needed to dispose of HLW from processing UO_2 SNF, which could lead to the need to develop only one repository and substantially reduce the cost to dispose of HLW.

In addition, recycling SNF in metallic IFR fuel removes the majority of the long-lived isotopes from the waste stream and reduces long-term radioactivity or radiotoxicity. Developing a repository for disposal of commercial waste with a lower radiotoxicity and without the long-lived isotopes should result in simplified repository design, including avoidance of the need for some engineering barriers, ultimately reducing cost. As an example, the Yucca Mountain repository project was designed with a complex engineered barrier system that utilizes drip shields made of titanium (an expensive metal) and specialty metals in the waste disposal package in order to protect the waste packages from corrosion for thousands of years after emplacement. The cost to fabricate and install the drip shields was estimated to cost several billion dollars - costs that would not be necessary for disposal of wastes with lower activity and without the inventory of long-lived radioisotopes.

As discussed in Section 3.3, a recent cost estimate by DOE regarding the costs of various geologic repository alternatives ranged from $24 billion to $81 billion for disposal of 140,000 MTU of SNF. In addition, higher costs would likely be in order to fabricate disposal canisters, repackage SNF from existing dual-purpose canisters, and provide consolidated interim storage. While ERI has not performed a detailed cost analysis of these additional costs, a 2008 DOE cost estimate assumed that disposal canisters would cost an estimated $12.6 billion,[28] bringing the upper level of the cost estimate to $94 billion, a 16% increase. Repackaging and consolidated interim storage would raise the ultimate price tag even higher. To put the recent DOE estimate into perspective, a 2008 cost estimate for the Yucca Mountain repository was $96.2 billion for disposal of only 70,000 MTU of SNF and HLW in a single repository – higher than the recent DOE cost estimate for disposal of 140,000 MTU of SNF. Thus, the opportunity to develop only one repository and avoid the costs for developing, licensing, constructing, and operating a second repository could be realized by using pyroprocessing and IFRs to recycle SNF. If a second repository is avoided, then the cost savings attributed to pyroprocessing and IFRs could be $12 billion (half the lower range of the recent DOE cost estimate) to $96 billion (the 2008 estimate for a 70,000 MTU repository at Yucca Mountain), or higher.

6.2 Uncertainties in Schedule of U.S. Repository Program

As discussed in Section 3.3, many obstacles stand in the way of developing and executing a long-term strategy for disposal of SNF in the U.S. While the NRC has resumed its review of the Yucca Mountain LA , restart of the Yucca Mountain project is considered unlikely in the current political climate. If the Yucca Mountain project is not resurrected and the

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[28] U.S. DOE, Office of Civilian Radioactive Waste Management, Analysis of the Total System Life Cycle Cost of the Civilian Radioactive Waste Management Program, Fiscal Year 2007, DOE/RW-0591,July 2008

repository program restarted, then a complete overhaul of the U.S. waste program will require the NWPA to be amended by Congress; a search for one or more sites for disposal of SNF; and development, licensing, construction and operation of disposal facilities. Given the history of the U.S. waste program, it could be decades before a geologic repository begins operation in the U.S.

Siting, licensing and construction of fuel cycle facilities, such as a pyroprocessing facility can be accomplished under more predictable schedules than siting, licensing and construction of a permanent geologic disposal facility. During the past decade, four new uranium enrichment plants have been sited and licensed and one plant has been constructed and operated. In addition, the construction of a specialty fuel fabrication facility was authorized during the same time period. In addition, U.S. regulations for siting and licensing NPPs have been successfully used for construction of four new NPPs expected to begin operation between 2015 and 2020.

If a large-scale pyroprocessing facility can be deployed earlier than a repository and begin accepting SNF from U.S. NPP sites sooner than a geologic repository, then there may be additional avoided costs associated with continued payments to nuclear operating companies associated with DOE's failure to begin SNF acceptance in 1998 in accordance with the Standard Contract for Disposal of SNF and/or HLW. DOE has estimated that its annual liability is on the order of $0.5 billion per year – resulting in the potential for significant avoided costs for the government.

6.3 Prolonged Supply of Uranium Resources

IFRs do not consume natural uranium and therefore help to prolong the use of nuclear energy if uranium supplies become scarce or the price of uranium increases significantly.

APPENDIX A STEADY-STATE SMAFS MODEL INPUT ASSUMPTIONS

Unit costs in the SMAFS model were updated for this study in order to reflect cost assumptions that are indicative of current and expected future UO_2 fuel unit costs (uranium, enrichment, conversion and fuel fabrication), waste management costs that are indicative of U.S.-specific costs, and recent experience with costs for investment in new LWRs. Unit costs associated with the FR Cycle are based on recent published studies of FR metal fuel fabrication and UO_2 and FR pyroprocessing costs. The LB and UB unit costs for the FR Cycle reflect the current uncertainty associated with fuel cycle costs and FR capital costs for this fuel cycle.

A.1 Front-End Unit Costs

The unit costs that comprise the front-end of the nuclear fuel cycle include natural uranium ore concentrates ("UOC" or "U_3O_8"); conversion of UOC to natural uranium hexafluoride ("UF_6"), enrichment of natural UF_6 to enriched UF_6, and fabrication of uranium-oxide ("UO_2") nuclear fuel assemblies. Both fuel cycles considered in this report assume the use of PWRs that utilize UO_2 fuel as one of the steps in the fuel cycle.

A.1.1 Uranium Ore Concentrates

This study assumes the NV unit cost for natural UOC is \$60/lb U_3O_8 (\$156/kgU); a LB of \$35/lb U_3O_8 (\$90/kgU), and a UB of \$150/lb U_3O_8 (\$390/kgU). While the NEA Study assumed that the unit cost of depleted uranium was the same as the unit cost for UOC, this study assumes that depleted uranium has a value that is 50% of the unit cost for UOC since there are ample stores of depleted uranium in both government and private inventories.

A.1.2 Conversion Services

Unit costs for conversion services assume a NV of \$15/kgU as UF6, a LB of \$7/kgU as UF6, and an UB of \$20/kgU as UF6.

A.1.3 Enrichment Services

Unit costs for enrichment services assume a NV of \$120 per Separative Work Unit ("SWU"), a LB value of \$80/SWU and an UB of \$175/SWU.

A.1.4 Fuel Fabrication

The NV unit costs for UO_2 fuel fabrication are based on current market prices for PWR fuel – a NV of $320 per kilogram heavy metal ("kgHM"), a LB of $280/kgHM and an UB of $365/kgHM.

NEA 2006 assumed that FR metal fuel fabrication would have a NV of $2,600/kgHM, $1,400/kgHM for the LB, and $5,000/kgHM for the UB. A recent study from researchers at KAERI identified a single cost for pyroprocessing and FR metal fuel fabrication (NV: $5,000/kgHM, LB:$2,500/kgHM, UB: $7,500/kgHM), but did not identify the portion of these costs attributable to fabrication.[29] Since the overall values in NEA 2006 and the KAERI study for pyroprocessing and FR metal fuel fabrication are similar, the ratio between the cost for fabrication and pyroprocessing in NEA 2006 was applied to the KAERI value of $5,000/kgHM. This resulted in FR metal fuel fabrication costs of $2,900/kgHM, LB of $1,400/kgHM, and UB of $5,000/kgHM.

A.2 Reactor Investment Unit Costs

The SMAFS model includes assumptions for the unit cost of installed power and the load factors for a PWR and FR. The unit costs for a PWR assume a NV of $5,600/kWe, a LB of $4,500/kWe, and an UB of $6,500/kWe. The unit costs for a FR include a NV of 5,400/kWe, a LB of $3,000/kWe; and an UB of $6,400/kWe. The NVs for the PWR are based on recently published estimates of overnight capital costs by the U.S. Department of Energy's Energy Information Agency, escalated to 2013 dollars.[30] The NV for a FR is based on recently published reactor costs from a study by researchers from KAERI, escalated to 2013 dollars.[31]

A.3 Spent fuel pool storage onsite

The costs for interim storage of SNF include a fixed component and a component that is time dependent. For interim storage of UO_2 SNF, the fixed interim storage cost to store SNF in reactor pools (not dry storage) assumes a NV of $50/kgHM and a variable value of $5/kgHM per year stored. The LB values are $40/kgHM and $5/kgHM stored per year and the UB values are $60/kgHM and $5/kgHM stored per year. The NV for storage of FR

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[29] Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Economic Analysis of Different Nuclear Fuel Cycle Options, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 293467.

[30] U.S. DOE, Energy Information Agency, Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants, April 2013.

[31] Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Dynamic Analysis of a Pyroprocessing Coupled SFR Fuel Recycling, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 390758.

metal SNF are \$90/kgHM and \$7.5/kgHM per year. LB values are \$60/kgHM and \$5/kgHM per year and UB values are \$240/kgHM and \$20/kgHM per year. These values are based on those provided as input to the SMAFS model and summarized in NEA 2006.

A.4 Spent Fuel Dry Storage Unit Costs

This study assumes a unit dry storage cost for UO_2 SNF with a NV of \$150/kgHM; a LB unit cost of \$100/kgHM, and an UB unit cost of \$250/kgHM. For dry storage of HLW resulting from pyroprocessing of UO_2 SNF and FR metal SNF, a NV of \$120,000/kgHM is assumed along with a LB value of \$80,000/kgHM and UB of \$200,000/kgHM. These unit costs are consistent with the values identified in NEA 2006.

A.5 Reprocessing Unit Costs

Based on the analysis of the cost for pyroprocessing LWR SNF in Section 4.5, this study assumes a NV for pyroprocessing UO_2 SNF of \$1,218/kgHM. The LB value is assumed to be \$500/kgHM and the UB - \$2,500/kgHM.

A recent study from researchers at KAERI identified a single cost for pyroprocessing and FR metal fuel fabrication (NV: \$5,000/kgHM, LB: \$2,500/kgHM, UB: \$7,500/kgHM), but did not identify the portion of these costs attributable to fabrication.[32] As noted above, using the ratio of fabrication costs to pyroprocessing costs in NEA 2006, the NV for FR metal pyroprocessing is \$2,100/kgHM, with a LB of \$1,100 kg/HM and UB of \$2,500/kgHM.

A.6 Disposal Packaging Unit Costs

The SMAFS model includes assumptions for the unit costs for packaging of UO_2 SNF and HLW for disposal. Based on a comparison of the unit costs in the NEA study to the costs projected by the U.S. DOE for SNF packaging for the Yucca Mountain repository, it appears that the packaging costs in the SMAFS model include the cost of the disposal package as well as the costs associated with loading the waste package (repository surface facilities and loading operations). Based on a study conducted by researchers for the Electric Power Research Institute ("EPRI") in 2007, this study utilizes NV for UO_2 SNF disposal packaging of \$200/kgHM, a LB value of \$150/kgHM, and an UB value of \$350/kgHM.[33]

The unit costs for packaging HLW from UO_2 and FR SNF from pyroprocessing are based on assumptions in NEA 2006. The unit costs for UO_2 HLW and FR HLW disposal

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[32] Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Economic Analysis of Different Nuclear Fuel Cycle Options, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 293467.

[33] Electric Power Research Institute, An Economic Analysis of Select Fuel Cycles Using the Steady-State Analysis Model for Advanced Fuel Cycle Schemes, Report 1015387, December 2007.

packaging assumes a LB of $100,000/m3 of HLW; a NV of $200,000/m3 of HLW; and a UB of $400,000/m3 of HLW.

A.7 Waste Disposal Unit Costs

Waste disposal costs include unit costs for disposal of low and intermediate level radioactive waste ("LILW"), short-lived ("SL") isotopes requiring near-surface disposal, LILW long-lived ("LL") isotopes requiring geological disposal, and SNF and HLW assuming deep geologic disposal. The SNF and HLW unit costs are captured using two separate parameters: one for the unit cost of disposal in $\$/m^{3,}$ and a second for the unit volume of earthen material that must be excavated for heat generating waste, expressed in m^3/kW.

The values for disposal of LILW-SL and LILW-LL wastes are consistent with those from NEA 2006. The LILW-SL unit costs assumed a LB of $\$1,200/m^3$, a NV of $\$2,000/m^3$, and a UB of $\$3,000/m^3$. These LILW-SL disposal costs appear to be reasonable estimates that bound the range of disposal costs for near-surface disposal in the U.S.

The LILW-LL unit costs for cavern-based disposal assumed a LB of $\$4,000/m^3$, a NV of $\$6,000/m^3$, and a UB of $8,000/m^3$. These values are consistent with estimates from other countries.

In a 2007 study conducted by EPRI researchers, SNF and HLW disposal costs and parameters for the SMAFS model were developed based on information for the Yucca Mountain repository. The Yucca Mountain Final Environmental Impact Statement (FEIS) estimated the total excavated repository volume to be 4.4 million m^3. This study utilized the EPRI LB and NV for unit cost for SNF and HLW disposal galleries of $\$600/m^3$ (LB) and $\$2,500/m^3$ (NV). An UB value of $\$5,000/m^3$ is used, double the NV. Regarding the unit volume of disposal galleries that must be excavated for heat generating waste, this study uses the LB and NV from the 2007 EPRI study which assumed a NV of 41 m^3/kW of SNF or HLW and a LB of $10 m^3/kW. The NV is based on a waste package thermal limit for Yucca Mountain, the estimated repository excavated volume and the amount of SNF to be disposed. This study assumes a UB of 100 m^3/kW (more than twice the NV).

A.8 Other Parameters

In addition to the unit cost parameters described above, the SMAFS model also includes the waste generation parameters described in Section 2. This includes LILW generated during the conversion, enrichment and fuel fabrication processes, during reactor operation, and during reprocessing operations. In addition, the SMAFS includes volumes of SNF and HLW resulting from the fuel cycle schemes considered. This study utilizes the waste management parameters from NEA 2006. Since NEA 2006 did not include a scenario in which UO_2 SNF is reprocessing using pyroprocessing, this study utilizes the waste parameters associated with reprocessing using a UREX process. The resulting parameters for FP, minor actinides, plutonium and reprocessed uranium utilized in this study are consistent with values for pyroprocessing of UO_2 SNF that are contained in recent studies such as a 2012 study conducted by researchers from KAERI[34] and a 2010 study by multiple authors that examined the economic and business case for pyroprocessing of UO^2 SNF.[35]

The SMAFS model includes an estimate of the activity, thermal output and neutron source for SNF and HLW associated with each fuel cycle. The SMAFS model includes values for the amount of time that SNF and HLW remains in interim storage and dry storage. There is an interim storage parameter that is tied to the amount of time SNF and HLW remain in interim storage prior to dry storage or further processing.

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34 Gao, Fanxing and Won Il Ko, Korea Atomic Energy Research Institute, Economic Analysis of Different Nuclear Fuel Cycle Options, Science and Technology of Nuclear Installations, Hindawi Publishing Corporation, Volume 2012, Article ID 293467.

35 Archambeau, Charles, Blees, Change, Hunter, Shuster, Ware and Wooley, Economic/Business Case for the Pyroprocessing of Spent Nuclear Fuel (SNF), 100 Ton/Yr Pyroprocessing Demonstration Plant, November 2010.

Table A- 1 General Fuel Cycle, Reactor, Fuel Fabrication, and Reprocessing Unit Costs

Parameter Description	*Lower Bound (1)*	*Nominal Value (2)*	*Upper Bound (3)*	*Unit*
General				
Unit cost of natural uranium	90	156	390	$/kgU
Unit cost of depleted uranium	45	78	195	$/kgU
Unit cost of conversion	7	15	20	$/kgU
Unit cost of enrichment	80	120	175	$/SWU
Unit cost of storing depleted uranium	2.6	3.6	4.6	$/kgU
Unit cost of storing reprocessed uranium	2.6	3.6	40.0	$/kgU
Fixed charge rate for investment	6%	9%	12%	%/year
Fixed charge rate for D&D	8%	8%	8%	%/year
Annual Rx O&M costs (as fraction of capital cost)	3%	4%	5%	%/year
Reactors				
Unit cost of installed power PWR	4,500	5,600	6,500	$/kWe
Unit cost of installed power FR	3,000	5,400	6,400	$/kWe
Load Factor for PWR	85%	90%	95%	%
Load Factor for FR	80%	85%	95%	%
Fuel Fabrication				
Unit cost of UO$_2$-fuel fabrication	280	320	365	$/kgHM
Unit cost of FR-Metal fuel fabrication	1,400	2,900	5,000	$/kgHM
Reprocessing				
Unit cost of UO$_2$ Pyroprocessing	500	1,218	2,500	$/kgHM
Unit cost of FR-Metal fuel Pyroprocessing	1,100	2,100	2,500	$/kgHM

Table A- 2 SNF and HLW Transportation, Interim Storage and Dry Storage Unit Costs

Parameter Description	*Lower Bound (1)*	*Nominal Value (2)*	*Upper Bound (3)*	*Unit*
SNF And HLW Transportation				
Unit cost of UO_2 SNF Transportation	75	100	125	$/kgHM
Unit cost of FR Metal SNF Transportation	125	250	500	$/kgHM
Interim SNF Storage				
Unit cost of UO_2 SNF interim storage (fixed)	40	50	60	$/kgHM
Unit cost of UO_2 SNF interim storage (var. with time)	5	5	5	$/kgHM
Unit cost of FR-Metal SNF interim storage (fixed)	60	90	240	$/kgHM
Unit cost of FR-Metal SNF interim storage (var. with time)	5	7.5	20	$/kgHM
Dry Storage				
Unit cost of UO_2 SNF dry storage	100	150	250	$/kgHM
Unit cost of UO_2 Pyroprocessing HLW Dry Storage	80,000	120,000	200,000	$\$/m^3$
Unit cost of FR PYRO HLW Dry Storage	80,000	120,000	200,000	$\$/m^3$

Table A- 3 SNF and HLW Packaging and Disposal Unit Costs

Parameter Description	*Lower Bound (1)*	*Nominal Value (2)*	*Upper Bound (3)*	*Unit*
Packaging				
Unit cost of UO_2 SNF Packaging	150	200	350	\$/kgHM
Unit cost of UO_2 PYRO HLW Packaging	100,000	200,000	400,000	\$/m^3
Unit cost of FR PYRO HLW Packaging	100,000	200,000	400,000	\$/m^3
Disposal				
Unit cost of LILW (short lived) near-surface disposal	1,200	2,000	3,000	\$/m^3
Unit cost of LILW (long lived) cavern-based and geological disposal	4,000	6,000	8,000	\$/m^3
Unit cost of disposal galleries for spent fuel (underground cost)	600	2,500	5,000	\$/m^3
Unit cost of disposal galleries for HLW (underground cost)	600	2,500	5,000	\$/m^3
Unit volume of disposal galleries that have to be excavated for heat generating waste	10	41	100	m^3/kW

APPENDIX B COMPARISON OF FUEL CYCLE COSTS FOR AN OT CYCLE AND FR CYCLE

Using the nominal unit costs for the fuel cycle parameters that are summarized in Appendix A, nominal total generation costs for an OT Cycle and FR Cycle are summarized in Table 3 and Table 12, respectively. The nominal equilibrium fuel cycle costs for these two fuel cycles are compared in Table B-1.

Table B- 1 Comparison of Fuel Cycle Costs for the OT Cycle and FR Cycle Using Nominal Front-End Unit Costs

Cost Component	Nominal Unit Cost	OT Cycle (mills/kWhe)	FR Cycle (mills/kWhe)
Uranium	$156/kgU	3.2	2.0
Conversion	$15/kgU	0.3	0.2
Enrichment	$120/SWU	1.9	1.1
UO_2 Fuel Fabrication	$320/kgU	0.7	0.5
Metal IFR Fuel Fabrication	$2,900/kgHM		0.8
UO_2 Pyroprocessing	$1,218/kgHM		2.2
IFR Pyroprocessing	$2,100/kgHM		0.7
Waste Management	Appendix A	1.4	0.3
Total		7.5	7.8

The total calculated fuel cycle costs for the OT Cycle are 7.5 mills/kWhe compared to 7.8 mills/kWhe for the FR Cycle. In the OT Cycle, front-end fuel cycle costs account for 81% of the overall fuel cycle costs, with the remaining costs 19% attributed to waste management costs. In contrast, in the FR Cycle, which includes operation of LWRs and IFRs that supply Pu and minor actinides as feed for metallic IFR fuel, front-end fuel cycle costs (uranium, conversion, enrichment, UO_2 fuel fabrication) account for 49% of overall fuel cycle costs, metal IFR fabrication represents 10%, costs for pyroprocessing account for 37% and the remaining 4% of costs are attributed to waste management.

While not quantified as a potential cost savings in Table 14, the FR Cycle also consumes 194 kg of DU in the FR metal fuel used to produce 1 TWhe of electricity and the consumed DU will no longer require continued storage and eventual disposal.

Importantly, however, the total NV, LB and UB costs of producing electricity by way of the OT and FR Cycles are quite comparable. While the NV cost for the OT Cycle is 105 mills/KWhe compared to 104 mills/KWhe for the FR cycle.

APPENDIX C LIST OF ACRONYMS

Am	Americium
ANL	Argonne National Laboratory
BRC	Blue Ribbon Commission on America's Nuclear Future
Cm	Curium
DOE	U.S. Department of Energy
DU	Depleted uranium
EBR I, EBR II	Experimental Breeder Reactor I, II
EPRI	Electric Power Research Institute
FBR	Fast breeder reactor
FEIS	Final Environmental Impact Statement
FP	Fission products
FR	Fast reactor
FR Cycle	Fast reactor cycle
GWd/MTU	Gigawatt-days/metric ton of uranium
HLW	High-level radioactive waste
HM	Heavy metal
IFR	Integral fast reactor
INL	Idaho National Laboratory
KAERI	Korean Atomic Energy Research Institute
kgU	Kilogram of uranium
kgHM	Kilogram of heavy metal
kW	Kilowatt
kWhe	Kilowatt-hour electric
LA	License application
LB	Lower bound
LILW-LL	Low- and intermediate-level waste – long-lived
LILW-SL	Low- and intermediate-level waste – short lived

LMFBR	Liquid metal fast breeder reactor
LWR	Light water reactor
m^3	Cubic meters
MOX	Mixed oxide
MTHM	Metric tons heavy metal
MTU	Metric tons of uranium
MWe	Megawatt-electric
Np	Neptunium
NPP	Nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NV	Nominal value
NWF	Nuclear Waste Fund
NWPA	Nuclear Waste Policy Act, as amended
O&M	Operation and maintenance
OT Cycle	Once-through cycle
Pu	Plutonium
PWR	Pressurized water reactor
ROI	Return on investment
SMAFS	Steady-State Analysis Model for Advanced Fuel Cycles Schemes
SNF	Spent nuclear fuel
SWU	Separative work unit
TBq	Terabecquerel

TWhe	Terawatt-hours electric
UB	Upper bound
U_{irr}	Irradiated uranium
UF_6	Uranium hexafluoride
UO_2	Uranium dioxide
UOC	Uranium ore concentrates
U.S.	United States
W	Watts