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NUCLEAR ENERGY TECHNOLOGY

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The rapid increase in world energy prices since 2003, combined with concerns about the environmental impacts of greenhouse gas emissions, has led to renewed interest in alternatives to fossil fuels—particularly, nuclear power and renewable resources[1]. This growing interest offers opportunities for significant economic expansion but is accompanied by uncertainties with respect to global economic conditions, environmental regulation, and energy policy direction. The nuclear power industry has not been exempt from these pressures.

While uncertainty in energy markets will continue to dominate the theme in this decade, many countries have concluded that nuclear energy needs to expand for three key reasons: (1) the more favorable economics of nuclear energy, (2) concerns about security of supply, and (3) climate change. As discussed below, the United States is taking a fresh look at all aspects of the fuel cycle to take advantage of technological developments that have occurred over the last 30 years, which could generate game-changing solutions to the management and disposition of nuclear waste. That said, it is not technical challenges per se that affect viability of nuclear energy, but economics of the first wave of new builds and capital availability. In response, a number of countries (including the United States) are pursuing policies to stimulate new nuclear plants and reinvigorate the manufacturing base for global competitiveness, recognizing that the benefits of nuclear energy extend beyond electricity and ancillary benefits (i.e., water desalination and petrochemical applications) to serving as an engine for high quality jobs.

1. ECONOMICS

Moving toward a low-carbon economy will require a fundamental change in the way countries obtain and use energy. Because there are differences in magnitude and types of investment in low-carbon technologies, each country (i.e., Japan, Republic of Korea, China, and the United States) pursues energy policies and approaches that reflect its status with respect to resource availability, abundance, and utilization, as well as economic, political, and societal considerations. There are also many similarities and, thus, opportunities for international cooperation. There is no single answer for base load generation – all technologies will be needed, including nuclear energy, as the papers submitted for this conference affirm.

The economics of nuclear energy have improved over the last two decades because the marginal costs of nuclear are competitive with other options. As output increases due to higher capacity factors and power up-rates, operating costs have decreased. Nuclear plant capacity factors exceed 70% world-wide, and exceed 90% (2009) in the United States. Operating costs themselves have decreased with the price of uranium and the use of higher burn-up fuels. Unlike fossil fuels, fuel costs are a small component of the overall cost to operate the plant. Finally, the United States and other countries have successfully demonstrated that current generation reactors can operate well beyond their initial licenses, perhaps even in excess of 60 years, increasing their profitability.

Capital cost is the single-most important factor in determining the economic competitiveness of energy technologies today, but the price of carbon will also be a major determining factor in the future. Other factors include fossil fuel prices (including implicit prices reflecting energy security considerations), declining nuclear plant construction costs and construction time periods, and an efficient licensing and regulatory framework[2]. Each technology has strengths and weaknesses, depending on circumstances. Nuclear energy delivers significant amounts of low-carbon base load electricity at stable costs over time. However, nuclear plants are capital intensive and may face public opposition because of safety and proliferation concerns associated with the nuclear fuel cycle (enrichment on the front-end and reprocessing on the back-end).

The recent joint study by the International Energy Agency (IEA) and the Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency (NEA) found that with a price placed on coal ($30 per ton of carbon dioxide) when financing costs are low (5%), more capital-intensive, low-carbon technologies (e.g., nuclear energy and coal with capture and storage) are the most competitive solution for base load generation compared with coal without carbon capture and natural gas combined-cycle plants. For higher financing costs (10%), coal, coal with carbon capture (without storage), and gas combined-cycle turbines are the cheapest sources of electricity. The study also found that generation costs for renewables depend on local resources and rapid deployment of technological improvements; new hydropower, which is not an option in the US, and wind, are competitive when local circumstances are favorable[3]. The reality is that nuclear energy is competitive against base load options except for conventional coal fired without carbon capture and low-cost gas, again without carbon capture.

The biggest challenge facing new nuclear plants is still financing, and for that reason, federal policies (e.g., loan guarantees, accelerated depreciation, investment tax credit, and production tax credit) are needed that reduce investor risk and financing costs associated with first new nuclear plants built over the next decade[4]. For investors, these sources of risk are the possibilities that construction delays will escalate plant costs and that plant estimates will exceed estimates for other reasons. With loan guarantees, the levelized cost of nuclear-generated electricity decreases from $47 to $71 per Megawatt hours (MWh) to $32 to $50 MWh and is on par with coal and gas-fired electricity. However, if carbon is constrained and coal and natural gas do not incorporate carbon capture, nuclear energy has a significant competitive advantage over coal and gas.

World electricity generation from nuclear power is expected to increase from approximately 2.6 trillion kilowatt-hours in 2007 to a projected 4.5 trillion kilowatt-hours in 2035. Higher future prices for fossil fuels will make nuclear power economically competitive with generation from coal, natural gas, and liquid fuels, despite the relatively high capital costs of nuclear power plants[1].

Overall, access to favorable financing and the stability of environmental policy frameworks will be crucial to reducing carbon emissions from the power sector[3].

2. REGULATORY, POLICY, AND STRATEGY DEVELOPMENTS

The Obama Administration has halted work on the Yucca Mountain geologic repository and formed a Blue Ribbon Commission to address the future direction of nuclear waste disposition. Updated, modern policies that take advantage of new technologies and fuel cycle strategies and acknowledge the necessity of a long-term role for nuclear energy are becoming increasingly important. The Blue Ribbon Commission is considering a broad range of technological, policy, and statutory alternatives related to management of used nuclear fuel and nuclear waste and will submit a final report by January 2012. Waste can be safely stored for many years, which provides time to explore these alternatives, including those that can perhaps reduce the volume and/or toxicity of used fuel. It is an opportunity to restructure the back end of the fuel cycle and create a more sustainable fuel cycle.

This is just one of several recent changes in direction for U.S. nuclear energy policy. Reiterating the Administration's position that nuclear energy is an important part of the U.S. energy mix, Energy Secretary Steven Chu has affirmed the importance of nuclear energy in ensuring access to affordable and environmentally sustainable energy. In 2009, the U.S. Department of Energy (DOE) Office of Nuclear Energy shifted its focus from developing fuel cycle facilities in the near term to building a science-based nuclear energy research and development program to address technical, cost, safety, security, and proliferation resistance barriers to nuclear energy expansion. The Office subsequently issued the *Nuclear Energy Research and Development Roadmap*[5], which identified specific research and development objectives aimed at achieving Administration environmental goals, including a reduction in greenhouse gas emissions, with a quantitative goal of 83% reduction below 2005 emissions levels by 2050[6].

To accomplish these objectives, the Administration's Fiscal Year 2011 budget request for the DOE gave special emphasis to funding for development of a clean energy economy. It requested funding for investments in advanced science, research, and innovation; cross-disciplinary scientific approaches, including innovative and transformative research at DOE's national laboratories; and significant investments in fuel cycle research ($200 million), advanced reactor concepts ($200 million), long-term operation of existing light water reactors ($25 million). Also included were $36 billion in expanded loan-guarantee volume for nuclear energy, increasing the authority to $50 billion. A nuclear energy research budget approaching $1 billion, including infrastructure investments, will likely be passed by Congress this year. The Fiscal Year 2011 House and Senate appropriation bills have both recommended additional authority for loan guarantees, the amount of which could be as high as $25 billion depending on the agreement reached at the conference between the two chambers on the bill.

In February 2010, DOE awarded the first loan guarantees for new nuclear plants, as stipulated under the Energy Policy Act of 2005 – $8.33 billion in loan guarantees for construction and operation of two new nuclear reactors at Southern Company's Votgle plant in Burke, Georgia. These reactors would be the first to break ground in the United States in almost 30 years.

The Energy Policy Act also included production tax credits for the first 6,000 megawatts of electrical capacity (MWe) of newly installed capacity and standby support in the event that actions outside the control of the licensee delay the issuance of the license. An 8-year effort to demonstrate key regulatory processes through cost-shared development of combined operating and construction licenses and design certifications will conclude this year.

In May 2010, DOE awarded a loan guarantee for the AREVA Eagle Rock Enrichment Facility in Idaho; that facility and a new enrichment plant in New Mexico are the first new uranium enrichment plants built in the United States in more than 50 years. USEC, Inc., which operates the Paducah gaseous diffusion plant in Kentucky, is also seeking a loan guarantee to build its advanced gas centrifuge technology, and a General Electric-Hitachi consortium is pursuing development of laser-based enrichment technology.

Two manufacturing projects were awarded investment tax credits provided by the American Recovery and Reinvestment Act (2009). A nuclear steam generator supplier provided $63 million for its manufacturing plant, and another company received $10.8 million for its plant that fabricates modules for the Westinghouse AP 1000 reactor design. The Administration has proposed another $5 billion for this program to stimulate the manufacturing base.

Also in May, DOE awarded $122 million over 5 years to a consortium that includes Oak Ridge National Laboratory, Idaho National Laboratory, Los Alamos National Laboratory, Massachusetts Institute of Technology, the Tennessee Valley Authority, and others for a new Nuclear Energy Modeling and Simulation Energy Innovation Hub for advanced nuclear reactor design and engineering. This consortium's first goal is to develop a virtual reactor model for predictive simulation of light water reactors.

In addition to economic incentives, the United States has streamlined the federal safety review and licensing process. The U.S. Nuclear Regulatory Commission (NRC) had received combined license applications for 28 new plants as of July 2010, and additional applications are likely. That said, the speed at which the utility industry is proceeding toward construction of a new reactor has slowed under the current economic conditions. Most energy analysts do not believe the United States will return to 2008 levels of electricity demand for several years, and for that reason, electricity markets will be over-supplied and soft; therefore, there will not be a rush to build new plants. Industry believes that four new reactors will be in commercial operation in the 2016 - 2017 timeframe. Loan guarantees that bring down the cost of money remain a high priority for the industry.

The path toward a comprehensive energy bill in the United States, or combined energy/climate change bill, is uncertain, and Congress is not expected to move forward with legislation before the November elections. However, U.S. climate policy has progressed over the past 2 years at the state and local level. In addition, the U.S. Environmental Protection Agency has been making steady progress toward establishing a regulatory cap on greenhouse gas emissions since the U.S. Supreme Court's 2007 ruling that greenhouse gasses could be regulated as an air pollutant under the Clean Air Act (42 USC § 85).

Japan and the Republic of Korea (ROK) are 96-97% dependent on outside sources of energy for their supply. As island or peninsula nations, their national strategies rely on nuclear energy as a major component of electricity supply. Over the last decade, the Japanese government reached a consensus about its nuclear energy strategy, with the issuance of a Nuclear Energy National Plan (August 2006). Japan’s strategy is to continue depending on light-water reactor (LWR) technology for 30-40% of electricity supply beyond 2030, with plans to begin commercializing fast reactor technology for electricity, resource utilization, and actinide management around 2050.

Concerns about energy security are driving more aggressive energy efficiency policies and affecting nuclear fuel cycle and technology selection decisions as well. With 54 operating units and two under construction, Japan has the world’s third largest nuclear power capacity, next to the United States and France, and a full fuel cycle set up, including enrichment and reprocessing of used fuel for recycle[7]. Japan estimates that recovering uranium and plutonium contained in used fuel represents 23% of nuclear energy output from its reactors – a semi-indigenous resource for a country that has limited options with respect to natural resources.

China, the world's most populous nation, largest consumer of energy, and largest producer of carbon dioxide, shares with the United States similar patterns of demand, supply, growth, and sustainability. To fuel its rapid growth, China is proposing to respond with a diverse energy portfolio, including increased use of low-emission technologies. The United States faced a similar situation when cheap, rapid growth trumped environmental considerations and resulted in heavy reliance on coal for electricity and heat – an issue we still face to some extent.

Coal will continue to dominate China's energy mix for the next several decades (70% of electricity generation) as renewable energy and nuclear energy increase in importance[8]. China is investing in carbon sequestration technology and encouraging the construction of large, more efficient plants, preferring to decommission thousands of small, inefficient, older coal-and oil-fueled power plants and replace them with supercritical or ultra-supercritical plants that are more efficient. Its ambitious goals for growing renewable energy include providing 16% of energy needs by 2020, with heavy reliance on hydroelectric power, and growth in wind-, biomass-, ethanol-, and biodiesel-generated power. In addition to the 12 reactors currently operating, China has 23 under construction – more than any other country.

In its 11th Five-Year Economic Plan, the Chinese government set an aggressive goal of reducing energy intensity by 20% between 2005 and 2010, which the U.S. Energy Information Agency (EIA) projects it will surpass, achieving a 23% reduction in energy intensity[1]. China has employed a complete toolbox of incentives and mechanisms (i.e., levies, taxes, rebates, subsidies, and access to credit and direct funding) targeted at nearly every sector of the economy. These policy tools are aimed at changing China's "currently energy inefficient and environmentally unfriendly pattern of industrial growth"[8] by encouraging conservation, discouraging exports that are heavily dependent on energy and resources, and moving to a low carbon economy while supporting continued economic growth.

The ROK is the fifth largest civilian nuclear power program in the world, with 20 operating reactors representing 40% of the country's electricity and six under construction, and is actively engaged in the development of advanced reactor and fuel cycle technologies. The ROK strategy is to depend on nuclear energy for 40% of its electricity, while embarking on an aggressive nuclear energy build program that will double its capacity by 2030 (bringing it up to 27.3 gigawatt-electric [GWe]). Estimates are that nuclear power generation will increase from 36% (presently) to 59% in 2030.

Within the last several years, the ROK committed $100 billion to nuclear power development, expecting to enable construction of an additional 10 or 11 new nuclear power plants. After importing U.S. pressurized water reactor (PWR) technology (Westinghouse) in the early 1970s, and Framatome (AREVA) technology for its first eight

PWR units, the ROK imported two Combustion Engineering PWRs[9]. The acquisition of Combustion Engineering's technology became the basis for its own 1,000-MWe and 1,400-MWe Optimized Power Reactor, a technology that the ROK is marketing globally. Currently, six OPR-1000s are operating and four more are under construction. Furthermore, ROK industry recently signed contracts with Westinghouse to supply major nuclear components for the AP 1000 reactors in China and in the United States.

The ROK is conducting research on advanced reactors, fuels, and fuel-cycle technologies, and has an indigenous design for a fast reactor derived from the U.S. Experimental Breeder Reactor (EBR)-II test reactor. Developments include a design for both metal and oxide fuels, construction of a research reactor and modern hot cell facilities, and research on re-using PWR fuel in Candu (heavy water) reactors imported from Canada. The ROK industry has also shown interest in supplying reactor technology to countries interested in establishing civilian nuclear power capabilities.

3. EXPECTED DOMESTIC AND INTERNATIONAL EXPANSION

As of July 2010, there were 439 commercial nuclear power reactors in operation and 61 under construction globally[10]. The renewed interest in fossil-fuel alternatives, supported by government incentives and by higher fossil fuel prices, continues to improve the long-term prospects for both nuclear and renewable energy sources. Nuclear energy is a major component of emissions-free energy for the United States, Japan, and the ROK, and all are actively building new plants and/or in the licensing and planning stage for new plants. These nations seek to export nuclear technologies to countries with civil nuclear programs or to countries interested in establishing programs.

The United States has more nuclear power plants in operation than any other country; 104 plants provide almost 20% of the country's electricity generation. These plants are among the safest, most secure industrial facilities in the country because of their consistently high performance, a diligent regulator, and multiple layers of physical security that protect workers, the public, and the environment.

With growing electricity demand and the potential retirement of 45 GW of existing capacity, the United States will need 250 GW of new generating capacity between 2009 and 2035. The EIA projects that natural-gas-fired plants will account for 46% of capacity additions, compared with 37% for renewables, 12% for coal-fired plants, and 3% for nuclear. Although U.S. nuclear generation is expected to increase by 11%, the share of total generation falls from 20% in 2008 to 17% in 2035[11].

There has been a resurgence of interest by the U.S. electricity industry in building new nuclear plants; however, the central challenge is economic: the expense of these plants ranges from $6 to $8 billion or more in today's economy. Some utility executives, particularly those in unregulated markets, maintain that they cannot build new plants without loan guarantees. On the other hand, industry believes that the economics of the new advanced LWRs will become competitive in this decade as costs fall and as construction durations decline.

Along with renewed U.S. interest in new builds, as evidenced by the 28 combined license applications submitted to NRC, industry expects to operate the existing fleet well beyond their original 40-year licenses – through 60 years and perhaps longer. To date, the NRC has received 32 completed license renewal applications for 55 existing plants. Another 14 applications for 20 plants are under review, and 14 more applications are expected by 2017[12].

The EIA's 2010 projection for world nuclear electricity generation in 2030 is 9% higher than last year's projection. The World Nuclear Association (WNA) Nuclear Century Outlook projects a global total for 2030 that ranges from a low estimate of 602 GWe to a high estimate of 1,350 GWe, and includes countries that have, are planning, or are potential entrants to nuclear programs[13]. Nearly 72% of the world expansion in installed nuclear power capacity is expected in non-OECD countries, with China, India, and Russia accounting for the largest net increase between 2007 and 2035[1].

On a regional basis, the reference case projects the strongest growth in nuclear power for the countries of non-OECD Asia, where nuclear power generation is projected to grow at an average rate of 7.7% per year from 2007 to 2035, including projected increases averaging 8.4% per year in China and 9.5% per year in India.

Outside Asia, the largest projected increase in installed nuclear capacity is in Central and South America, with increases in nuclear power generation averaging 4.3% per year. Prospects for nuclear generation in OECD Europe have undergone a significant revision from last year's outlook because a number of countries in the region are reversing policies that require the retirement of nuclear power plants and moratoria on new construction. In the reference case, nuclear generation in OECD Europe increases on average by 0.8% per year, as compared with the small decline previously projected.

In addition to its 54 reactors (and two under construction), Japan plans to start construction on 12 more reactors by 2018. China is building new low-carbon capacity through renewable energy projects and its nuclear energy program, which is expected to grow at an average rate of 8.9% per year from 2006 to 2030[14]. It has 56 reactors under construction and planned, with another 150 proposed. In addition to 20 reactors and six under construction, ROK has six reactors on order or planned[15].

Nevertheless, the average annual projected rate of growth for nuclear generation globally is 2.0%, well below that of renewables (3.0%) and slightly less than coal (2.3%) and natural gas (2.1%). With government policies and incentives throughout the world supporting the rapid construction of renewable generation facilities, the renewable share of world generation increases from 18% in 2007 to 23% in 2035[1].

A potential new area of growth is development of designs for small modular reactors with a range of generating capacities, often through cooperation between government and industry. (The IAEA defines 'small' as less than 300 MWe; however, 500 MWe might be considered an upper limit to 'small'.) Countries involved include Argentina, China, Japan, the ROK, Russia, South Africa, and the United States. These reactors could operate as single or double units in remote areas or provide incremental capacity on multi-unit sites on larger grids. With simplified designs and factory fabrication, they could be less expensive and faster to produce, which should make financing easier. They could also have proliferation resistance advantages, depending on design and refueling requirements, as well advanced fuel cycles that burn recycled materials[16].

In China, Chinergy is preparing to build an advanced small modular reactor, the 210-MWe high-temperature-reactor pebble-bed module (HTR-PM). Pebble Bed Modular Reactor Limited and Eskom have been developing the 80-MWe pebble bed modular reactor for South Africa. A U.S. consortium led by General Atomics is developing the gas turbine modular helium-cooled reactor with 285 MWe modules driving a gas turbine and operating at very high temperatures[17].

In the United States, B&W Nuclear Energy recently announced a partnership with Bechtel Power Corporation to design, license, and deploy its 125-MWe mPower modular, integral pressurized water reactor and to open a testing facility for that purpose in the United States. NuScale Power, which has developed a small, scalable nuclear power system based on LWR technology, expects to file for design certification in 2012[18]. The 64-MW TRIGA Power System is a PWR concept based on a General Atomics proven research reactor design. More advanced technologies are also on the drawing board, such as the traveling wave reactor concept proposed by Terra Power.

The United States has also been pursuing a much higher temperature gas-cooled reactor capable of delivering high temperature process heat (at temperatures from 700 to 950°C) for industrial applications via a high temperature electrolysis system. DOE has supported research on this system over the last 8 years, building on several innovative reactors built in the 1970s and 1980s. DOE has also supported development of particle fuel and has demonstrated burn-ups at higher levels than ever achieved in the past. In 2005, the Energy Policy Act established the Next Generation Nuclear Plant (NGNP) Project as a public-private demonstration project. Intended to demonstrate the commercial viability of the concept, this project has not yet broken ground because of challenges associated with fulfilling the federal statutes regarding the 50-50 cost share for large-scale demonstration projects. This is an issue that affects not just the ability for large-scale demonstration of nuclear systems but other technologies, including carbon capture and storage demonstrations.

While small and medium size reactors (as well as more advanced reactor concepts such as the NGNP) show great promise as far as meeting electricity and process heat needs of smaller and potentially even larger markets, at present, little is known about what will be required to license these technologies. This makes it difficult to complete a credible business case analysis of the economics of designing, licensing, and building them.

4. MANUFACTURING CAPABILITY

Nations committed to constructing next-generation nuclear facilities that leverage the latest technology will depend on manufacturers to provide high-quality products that foster a safe, secure, and enduring environment for nuclear energy production. The United States, France, and Japan supply more than half of the global value of nuclear energy technology manufacturing. By 2013, market value for U.S. nuclear manufacturing is expected to reach $61.1 billion, with $34.8 billion for France, and $23.7 billion for Japan. The top three manufacturing nations will maintain their leadership positions, although they will lose shares to other nations that are accelerating their manufacturing efforts. Japan and China operate heavy forging capacity, and new capacity is being established in China and the ROK. The policy decisions made by these countries over the next several years with respect to nuclear fuel cycle technologies will also influence the magnitude of this shift[19].

In the last several years, manufacturing in the United States has begun to rebound, focusing first on the external market where new reactors are currently under construction and subsequently on the United States. An increasing number of N-stamps have been issued by the American Society of Mechanical Engineers to manufacture nuclear grade equipment and components. While there are no plans to launch a large forge capable of handling a 400-ton pressure vessel, the United States plans to make everything else. A joint venture between AREVA and Northrop Grumman to build a $300-million factory in Virginia and another one by Shaw Group in Louisiana will supply reactor components to build AREVA and Westinghouse reactors. GE-Hitachi is proposing to set up a nuclear components manufacturing center in India to serve markets there and in other regions.

Japan has the broad industrial base needed to manufacture, build, and export reactor technology, as well as extensive nuclear energy research infrastructure, materials test reactors (the Japan Materials Test Reactor), fast test reactors (Monju and Joyo), and other specialized capabilities necessary to develop and test materials, fuels, and new technologies[20].

China followed a nuclear program model that imports proven technology and builds upon it to develop its own reactor designs as well as other aspects of the fuel cycle. Its 2007 agreement with U.S. vendor Westinghouse to build four AP 1000 units in China, and for Westinghouse to transfer the technology to China, enables China to build the subsequent units on its own. Westinghouse is currently setting up factories in the United States and China to produce modules for the AP 1000 reactors[21]. In addition, China has constructed the heavy industry necessary to produce vessels, forgings, and other large components for the reactors currently under development.

5. INTERNATIONAL DIALOGUE AND COOPERATION

The nuclear industry is a global enterprise that is changing rapidly. Cooperation and collaboration are taking place more openly, and in more areas (e.g., technical, political, and cultural), than ever before. We are already sharing, and in many ways competing for, limited global nuclear manufacturing and new plant construction resources. We are sharing knowledge and expertise in emerging nuclear technologies (i.e., fast reactors). There is also a history of dialogue and cooperation among the United States and ROK, Japan, and China individually (since 1998) regarding civilian nuclear power.

As we go forward, it will be in the interest of all of these countries to cooperate even further on low-carbon energy technologies, including nuclear technologies, which can help break our dependence on foreign oil and reduce greenhouse gas emissions. We must continue to work together to make renewable energy sources like wind and solar even more efficient, reliable, and cost effective. To be truly successful in addressing global energy and economic and climate challenges, we must apply the same level of global cooperation and collaboration to bring about these same improvements in the nuclear energy industry.

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