Nuclear Outlook: Above and Beyond the Fukushima Tragedy

Kune Y. Suh, PhD

Professor, Department of Nuclear Engineering, Seoul National University, CEO, PHILOSOPHIA, 4+D Systems Engineering Enterprise
Director, PRINCIPIA, Engineering Super Simulation Emulation Workspace

Over the past decade, there has been escalating worldwide debate pertaining to the impact of human activities on the global climate due to emission of greenhouse gases. The industrialized, or Annex I countries, are now responsible for much of the worldwide release of greenhouse gases. All but two-thirds of greenhouse gas emissions can be traced to activities related with power production and the transport sector. Compliance with the Kyoto Protocol by Annex I countries thus will require a strong commitment to developing and exploiting those sources of energy that are low emitters of CO$_2$. Along with renewable energy sources as well as conservation, nuclear power appears to provide us with a viable path forward.

Nuclear power is any technology designed to extract usable energy from atomic nuclei via controlled nuclear reactions. The only method in use today is through nuclear fission, though other methods might one day include nuclear fusion and radioactive decay.

The United States (US) generates the most nuclear energy, with nuclear power providing 19% of the electricity it consumes, while France produces the highest percentage of its electrical energy from nuclear reactors. In the European Union (EU) en bloc, nuclear energy provides 30% of the electricity. Nuclear energy policy differs between EU countries, and some, such as Austria, Estonia, and Ireland, have no active nuclear power plants (NPPs). In comparison, France has a large number of NPPs, with 16 multi-unit stations in current use.

A Korean consortium led by the Korea Electric Power Corporation (KEPCO) has won a USD 20 billion contract to develop civilian NPP for the United Arab Emirates (UAE), beating French, US and Japanese rivals to grab one of the world’s largest nuclear tenders on offer. The global NPP technology was previously vested in five countries: the US, France, Japan, Russia and Canada. The UAE deal is worth USD 40 billion, inclusive of future operating costs.

Indeed, nuclear power is having a renewed start due to a confluence of factors including global warming, the cost and supply reliability of oil, issues involving coal and greenhouse gases, and the safety record and excellent operational performance of NPPs. Those factors and the improved political climate have resulted in many utilities filing applications for construction permits and operating licenses for new NPPs.

The current state of the art is reviewed of nuclear power both home and abroad. Also addressed are the events and forces that have influenced, and continue to influence, commercial nuclear power. All the participants are expected to understand how we got to where we are today, including the reasons for the long period of dormancy in the nuclear power industry. Significant industry events will be discussed including the Three Mile Island (TMI), Chernobyl and the most recent Fukushima accidents. Pressurized water reactors (PWRs) and boiling water reactors (BWRs) will briefly be reviewed. The changes in both the
political and environmental landscapes and the Energy Policy Act of 2005, which are all critical to the nuclear resurgence, will be addressed.

Additional topics include the small modular reactors (SMRs), the nuclear fuel cycle, the uranium enrichment and reprocessing controversies, radioactive waste including spent nuclear fuel storage, spent fuel transportation as well as the US Nuclear Regulatory Commission (NRC) set of performance indicators signifying excellent operations. This article aims to provide you with a clear understanding of nuclear power and the challenges at the forefront.

Topics of our mutual interests include the issues concerning the resurgence of nuclear energy, the history of nuclear power and its development, nuclear events that impacted the nuclear industry, the Energy Policy Act of 2005, designs and functions of PWRs and BWRs, panorama of Generation III and IV reactors, SMRs, the nuclear fuel cycle, the Fukushima accident and the future for nuclear power.

More specifically we are going to review the historical events, technical issues, and industry challenges that have shaped the nuclear power industry to where it is today. We describe why the nuclear power industry has been dormant for the past 20 years. We then scan the impact of the confluence of global warming and energy security on the future of nuclear power. We talk about the pivotal topics critical to the nuclear power renaissance, and identify factors impacting the nuclear power industry today, including the changing political and environmental perspectives on nuclear power.

The NRC regulates the nuclear power industry through the reactor oversight process and seven safety performance indicators. We recognize that the safety standards required by the NRC and the safety culture transformation of the industry were heavily influenced by TMI.

We next analyze the changes in the nuclear power regulatory environment that are important to the success of the nuclear power renaissance. We walk through the PWR and BWR technologies. We examine the safety performance record of the nuclear power industry. We look at the design and benefits of SMRs. We describe the Fukushima NPPs accident and the emerging lessons learned. We identify and discuss the components that make up the nuclear fuel cycle. We recognize the critical issues of enrichment, radioactive wastes, spent nuclear fuel transportation, and proliferation concerns.

Let us first turn our attention to the nuclear power renaissance. The confluence of factors creating the renaissance has to do with rising and volatile gas and oil prices, foreign dependence on fuels, unknown future mandated CO₂ regulation, climate change concerns, energy autonomy, environmentalists’ changing view of nuclear power, outstanding safety record of nuclear power, changes in the licensing and regulatory climates, more receptive public and political support, and incentives in the Energy Policy Act of 2005.

On the other hand, the obstacles to the rebirth come from unresolved challenges of highly radioactive spent fuel, potential security risks from proliferation, perceived adverse safety, environmental as well as health effects, high relative costs, needed engineering personnel to design and operate NPPs, necessary nuclear component manufacturing capability, alternatives including wind, solar, biomass, fuel cell, and conservation, the anti-nuclear movements, and change in administrations home and abroad. The potential fatal flaws that could impact the renaissance may arise from a major accident as well as a terrorism event at a NPP.
Let us now consider electricity consumption and demand. We first need to account for standard of living and its correlation to electricity consumption, projected world electricity demand growth, electric generating capability, and generating capability by fuel type of coal, nuclear, gas, renewable and others. We then turn to current and future nuclear power status worldwide. There are now 439 NPPs worldwide, and 34 NPPs under construction. Korea, China, India and Russia have plans to push forward. NPPs are even beginning to call the oil-rich Middle East home. The US is home to differing plants in different states, viz. 104 reactors at 64 sites in 31 states. While the US suffers from their aging nuclear fleet, 17 companies have submitted applications for 26 new NPPs. Korea hosts 21 reactors in operation plus 7 under construction, and look forward to generating 59% of its electricity from nuclear by 2050.

Let us next take a quick look back at nuclear power history, and what to learn from the past. The nuclear power timeline indicates that the legendary Einstein formula $E = mc^2$ had regrettably materialized itself in nuclear weapons first. There are by now too many of them in too many places. Then came the nuclear ice age, during which nuclear power went dormant with 97 NPPs being cancelled in the US alone. The early NPPs in the US include Dresden and Oyster Creek built in four years. The 1960s-1970s have witnessed the rush to build more and more NPPs, 168 units being boosted by the Clean Air Act of 1970, the Arab Oil Embargo of 1973, and natural gas restrictions. The industry responded with reactor vendors scaling up their designs. The nuclear regulator changed in the meantime. They were no longer the promoter of nuclear power. Then happened the Browns Ferry fire, whence changes continued for over 10 years including, but not restricted to, cable separation, and alternate shutdown.

Let us now delve into the TMI accident and its impact. Highlighting equipment and operator and human errors, the accident called for massive changes impacting equipment, personnel training, safety culture, human performance, and emergency preparedness. TMI gave birth to the Institute of Nuclear Power Operations (INPO) at the end of the day. The industry also took seismic design seriously. The NRC looked to meticulous compliance and safety conservatism culminating into the Systematic Assessment of Licensee Performance (SALP) program. The challenges faced by the nuclear industry around the globe included the changing regulatory environment, and anti-nuclear and environmental movements. Shoreham in the US turned out to be the poster child for the anti-nuclear movement. The plant was undermined by delays, mistakes and timing, and devastated by the construction spanning 20 years and the cost snowballing from then USD 70 million to USD 3.2 billion. In Ukraine of the former USSR, Chernobyl suffered badly from human error on top of fundamental design flaws.

With the rising standard and the new culture, excellence became a moving target, and safety trumped cost. That is, a safe plant was an economic plant. The corrective action had to be prompt, complete and effective. Prudence and reasonableness by themselves were not acceptable. Then the nuclear industry retreated. NPPs became a resource draining burden. The public, press, and politicians turned against nuclear power. Trifling operating events and licensee errors resulted in fines. Wall Street became disenchanted. The NRC turned to be a hardened regulator. The industry could not respond effectively or convincingly.

The nuclear industry soon after changed its methods and means by consolidating. Plants were up for sale, and most single-unit NPPs got sold. At the same time the industry went with operating license extensions. More than half of the NPPs added 20 years to their license. The NPP capacity factors went from 65% to over 90%. NPPs were uprated at the same time. The design margins were translated into more megawatts.
The regulatory and licensing changes also began to shape. Most notably, the 1992 NRC changes featured streamlining of the conventional two-step licensing to one-step licensing – the Combined Construction and Operating License. The Early Site Permits allowed banking the site for 20 years. Design certifications were granted to bank the design for 15 years for the AP1000, ESBWR, USEPR, and APWR. The Energy Policy Act of 2005, heir to the Price-Anderson Nuclear Industries Indemnity Act first passed in 1957, provided standby support of the construction and licensing delay insurance, production tax credits, and loan guarantees.

Let us now go over the existing and next generation reactor designs. First and foremost, PWRs and BWRs are both designed resorting to defense in depth. PWRs comprise the reactor coolant system, reactor pressure vessel, steam generators, and nuclear fuel and fuel handling system. BWRs consist of the reactor pressure vessel, and nuclear fuel and refueling system. Generation III design features evolutionary improvements and passive safety systems. Generation IV design showcases yet enhanced safety, less waste generation, higher proliferation resistance, and better economics. SMRs come with their own advantages and expectations in terms of project costs, and licensing issues. SMRs are prone to such versatile applications as desalination and propulsion other than electricity generation. SMR designs include mPower, NuScale, Hyperion, and SMART.

With regard to costs and economics, we need to compare the production cost of nuclear vs. fossil-fired plants. Other ingredients embrace fuel costs comparison of nuclear vs. fossil-fired plants. We have to study the life cycle nuclear power costs and evaluate the capital cost of nuclear vs. fossil-fired plant.

The nuclear fuel cycle envelops the uranium ore, uranium conversion, uranium enrichment by gaseous diffusion, gas centrifuge and laser application, and fuel fabrication. Korea makes sure of abiding by the Nonproliferation Treaty (NPT). The US is going ahead with the megatons-to-megawatts program to demote the weapons grade fissile material for use in civilian reactors. The fuel costs are one of the driving factors in considering nuclear power generation.

The radioactive waste is handled according to the principle of “as low as reasonably achievable (ALARA).” The high level radioactive waste involves spent nuclear fuel storage. The back end of the nuclear fuel cycle is concerned with reprocessing. The Yucca Mountain nuclear waste repository, the US deep geological repository storage facility for spent nuclear reactor fuel and other high level radioactive waste, was stopped from being funded under pressure from the Obama Administration. They stated that the closure was for policy not technical or safety reasons. This leaves the US civilians without any long-term storage site for high level radioactive waste, currently stored on site at various nuclear facilities around the country. The same is more or less true of Korea.

A near-term task force was established in response to Commission direction to conduct a systematic and methodical review of US NRC processes and regulations to determine whether the agency should make additional improvements to its regulatory system and to make recommendations to the Commission for its policy direction in light of the accident at the Fukushima Daiichi NPPs. The Task Force appreciated that an accident involving core damage and uncontrolled release of radioactive material to the environment is inherently unacceptable. The Task Force also recognized that there likely will be more than 100 NPPs operating throughout the US for decades to come. The Task Force developed its recommendations in full recognition of this environment. In examining the Fukushima Daiichi accident for insights for reactors in the US, the Task Force addressed protecting against the accidents resulting from natural phenomena, mitigating the consequences of such accidents, and ensuring emergency preparedness.
The Fukushima accident was caused by a natural event which was far more severe than the design basis for the NPP. The Task Force studied the manner in which the NRC has historically required protection from natural phenomena and how the NRC has addressed events that exceed the current design basis for NPPs in the US. The Task Force found that the current NRC regulatory approach includes requirements for design-basis events with protection and mitigation features controlled through specific regulations or the general design criteria, requirements for some beyond-design-basis events through specific regulations, and voluntary industry initiatives to address severe accident features, strategies, and guidelines for operating reactors.

The future for nuclear power hangs in the balance. There are the Fukushima factor, the political environment, the new licensing approach, rebuilding the nuclear industry infrastructure, favorable state Public Utilities Commission actions, the oil addiction, global security, national security, hybrid and electric cars, just to name a few. Despite the high risks of nuclear power, we have yet to come up with adequate global security mechanisms sooner rather than later. How, when, where and by whom will this be done? Will this be done at all? Last, but unquestionably not least, will utilities commit? Will the public accept nuclear as part of their living? That is the question.