While the crisis at the Fukushima Daiichi nuclear power plant may slow the pace of the nuclear renaissance, several countries—including Egypt, Indonesia, Malaysia, the United Arab Emirates (UAE), Saudi Arabia, Vietnam, and China—are proceeding with plans to build nuclear reactors. Many countries are taking part in the continued interest in nuclear energy; South Korea is playing a larger role in plant construction, and Russia seeks to be the leader in supplying nuclear fuel. Meanwhile, the United States' nuclear energy industry is facing increased regulation, tighter fiscal constraints, and serious competition from natural gas-based energy generation. In addition, the question of how to best deal with used nuclear fuel remains. The expansion of civilian nuclear power worldwide and the increase in global competition among the nuclear industry, underscores the urgency of minimizing the risks associated with the global spread of nuclear energy

For over three years, the American Academy of Arts and Sciences' Global Nuclear Future Initiative has examined the safety, security, and nonproliferation implications of the global spread of nuclear energy. The Initiative continues to explore these implications, incorporating the lessons learned from recent events, and developing pragmatic recommendations for managing the emerging nuclear order.

As part of this effort, in June 2011 the American Academy joined with the University of Chicago Harris School Energy Policy Institute; the Bulletin of the Atomic Scientists; and Argonne National Laboratory, with the Chicago Council on Science and Technology (C^2ST), to bring together leaders from industry, government, policy, and academic circles, to discuss gaps in knowledge and practice, and propose agendas for further research and dialogue to increase nuclear safety and security in a global market-based expansion of nuclear power.

Four underlying questions motivate the meeting, questions that build upon the work carried out by both the American Academy's Global Nuclear Future Initiative and the Bulletin of Atomic Scientists:

(1) How can exemplary safety and security practices be institutionalized and implemented worldwide?

(2) What programs might the United States, Russia, France, China, and others undertake that would improve the nuclear safety and security environment both domestically and internationally?

(3) What role should they play in setting standards and implementing regulations to ensure the safety and security of future nuclear power internationally?

(4) Does the absence of a U.S.-based nuclear revival or renaissance matter in defining or constraining the U.S. role in building a safe and secure international nuclear energy regime?

What follows is the report from the two-day meeting. We would like to thank the Bulletin, the Energy Policy Institute at Chicago, Argonne, and C^2ST for helping to organize this meeting and to the participants for their thoughtful contributions. We are grateful to the John D. and Catherine T. MacArthur Foundation for supporting this meeting and to the Carnegie Corporation of New York; the William and Flora Hewlett Foundation, the Alfred P. Sloan Foundation the Flora Family Foundation; and Fred Kavli and the Kavli Foundation for supporting the work of the Global Nuclear Future Initiative.

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Leadership and the Future of Nuclear Energy

Workshop Report

June 9-10th, 2011
Chicago, Illinois

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{A workshop organized by *the Bulletin of the Atomic Scientists*, The University of Chicago's Energy Policy Institute, and Argonne National Laboratory, in cooperation with the American Academy of Arts and Sciences and the Chicago Council on Science and Technology. The MacArthur Foundation provided funding for the workshop with a grant to the *Bulletin*.**}**[1]

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Purpose

The nuclear industry sees opportunities to expand civilian nuclear power worldwide in the coming decades. The purpose of the workshop was to consider how the needs for nuclear power safety and security will be met as new facilities are built to meet the growing demand for base-load electricity in developing and industrialized countries. China and India, for example, are making plans to expand substantially their nuclear power generation. South Korea is playing a larger role in plant construction. Russia seeks to be the leader in supplying nuclear fuel. And countries such as Vietnam and the United Arab Emirates are among the eager customers for this source of large-scale power generation. At the same time, the United States' nuclear energy industry is coming up against financial and regulatory constraints, as well as the absence of a clear roadmap to address the storage and disposal of commercial used fuel. These and other issues, including competition from potentially low-cost natural gas, have slowed planning for vigorous domestic nuclear power development in the United States.

In light of these trends, four underlying questions motivated the meeting:

1. How can exemplary safety and security practices be institutionalized and implemented worldwide?

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[1]NOTE: Planning for the workshop began in the fall 2010. The organizers could not have foreseen the terrible events at Japan's Fukushima Dai-ichi nuclear power plant in the wake of an unprecedented earthquake and tsunami. The nuclear disaster provided a sobering context for discussions at the June 2011 meeting. With 80,000 people evacuated from the communities surrounding the power plant, and the situation not yet resolved, we recognize the suffering and hardship of the people of Japan in the aftermath of this disaster.

2. What programs might the United States, Russia, France, China, and others undertake that would improve the nuclear safety and security environment both domestically and internationally?

3. What role should they play in setting standards and implementing regulations to ensure the safety and security of future nuclear power internationally?

4. Does the absence of a U.S.-based nuclear power revival constrain the U.S. role in building a safe and secure international nuclear energy regime?

Executive Summary

The Fukushima nuclear power plant disaster of March 11, 2011, provided a sobering reminder of how dangerous nuclear technology can be and underscored the seriousness of the challenges faced by the nuclear industry. The context of disaster lent urgency to the discussion and prompted unusually candid and direct conversations. Exchanges were nuanced, as well as honest, and covered a full range of safety and security issues. The major points follow in summary format:

- New reactor designs could provide for better safety and security of nuclear technology and materials—several may be promising.
    - But the "old technologies" that provide for cooling operations of the reactor core also need to be examined.
    - Expense of new designs and of finding the best among several alternatives may be high and may not meet market tests, at least in the U.S. context.
    - If the US chooses not to invest in new designs that potentially provide better safety based on cost, will it continue to be a leader in the industry? Will it continue to influence worldwide safety and security regulations, both by example and by participation in international organizations?
- Increased transparency is required to ensure safety and to build public trust in the nuclear industry.
    - BUT such transparency may be at odds with security needs to keep operations secret from possible terrorist groups.
- Safety and security standards are difficult to enforce internationally without central enforcement body.
    - Need to identify incentives for compliance.
    - Beware of political uses of regulation that make compliance requirements appear unfair (as for example in the case of Iran).
- Multilateral fuel-cycle arrangements might adequately address transparency and compliance issues in both the safety and security areas.
    - They would also help in the financing of nuclear power projects, i.e., if a country does not have the capacity to enrich its own fuel.
    - Reprocessing may address short-term spent fuel storage issues, but continues to be costly and risky for proliferation in view of inadequate final storage facilities.
    - IAEA's IUEC will provide multinational fuel arrangements, and the international community can learn from that practical experience

- Needs for energy security provide strong incentive for nuclear power development and may trump market economics (as in South Korea for example)
- United States no longer seems as influential as it once was—despite still having the greatest number of nuclear reactors (104) of any country
- Many other candidates exist for leadership in the new nuclear power era
    - China, France, India, South Korea, Russia, Brazil and Argentina, and Southeast Asia are all interested in expanding nuclear power
    - Southeast Asia is a region of porous borders and high-volume trade, making it more difficult to enforce controls over shipment of nuclear technologies and materials
    - Industry could take the lead on implementing safety and security standards with facilitation from government
    - IAEA has demonstrated capability, but is not adequately funded by member countries (and sometimes hampered by politics) to play the strongest leadership role, especially in the area of operational safety

Summary of panel discussions

Discussion of the major issues was organized into six panels. The first two panels provided an opportunity to hear the latest information about the Fukushima disaster and to learn about initial responses of other governments around the world.

Panel 1: Fukushima Dai-ichi Nuclear Crisis

The full effects of the nuclear power plant disaster are not yet known. Current estimates suggest that it will take six to nine months to stabilize the power station. The Fukushima disaster, so far, has released 1/10 of the radiation of the Chernobyl accident. The full long-term effects have yet to be seen. All possible efforts are being taken to limit the radiation exposure locally and internationally. Unfortunately, because of mistakes and of misinformation provided early on, there is extensive mistrust of the Japanese government's and the utility's reports. The Japanese authorities, however, are committed to full disclosure and transparency as new information develops.

While the designs for these GE Mark I reactors were not meant to withstand the force of a 9.0 earthquake, it appears they actually survived the earthquake and that the backup generators were only disabled after the tsunami hit. In each of the units a similar cascade of events occurred: scrammed reactors, loss of core cooling, buildup of hydrogen gas from exposed cores in pressure vessels, meltdown of cores (and, in some cases cracking of pressure vessels), hydrogen-fed explosions and radioactive leaks.

There were organizational and design-basis issues that led to a worsening of the situation. First, no disaster of this magnitude had been conceived of previously by the authorities, who therefore had no emergency protocol in place for this event. The nuclear plant, including the seawater-cooling pumps, was originally designed to withstand a tsunami of 3.1m—TEPCO had increased its standards just recently in 2002, raising the height by 2.6m to 5.7m. The tsunami that disabled the seawater pump and backup generators for cooling was between 14 and 15 meters in height.

The cores within units #1, #2 and #3 all experienced a loss of coolant when the auxiliary pumps were disabled by a lack of power. As a result, Unit #1 was without coolant for 14 hours and 9 minutes. During this time, extensive damage was done to the reactor pressure vessel as the core melted down and in turn damaged the primary containment vessel. Hydrogen gas built up and, as it was not vented immediately, caused an explosion. Similar events took place in units #2 and #3. Unit #4 also experienced a hydrogen explosion, even though the reactor was shut down for inspection at the time. This lag time for venting is cited as a major mistake that significantly worsened the situation.

The electricity supplies were inadequate for a number of reasons. The Japanese authorities relied heavily on power resources that were inter-connected. The backup batteries were intended to keep the coolant circulating in the cores in the case of a power loss, but they did not have large enough storage capacity to prevent the core meltdown following the external power outage and before external power was restored; the failure of on-site backup power meant that recharging of these batteries could not take place.

The international nature of this accident was underscored; many people beyond Japan will be affected. Panel participants called for continued openness regarding all aspects of safety and security as the Fukushima disaster unfolds.

Japan will be reexamining all its plans to install new reactors. The government has now shut down – at least temporarily – 35 of their 54 reactors. While some were shut down for safety reasons, others were shut down for political reasons, that is, some of the reactors in question were not viewed as posing a danger, but were closed to reassure the public, which is viewed as a first priority. Indeed, despite the growing power shortages in Japan, and potential prolonged economic disruption associated with even temporary closures of plants, there is substantial public support for this pause in deploying nuclear power.

Panel Two: Implications of Fukushima Dai-ichi Nuclear Crisis

Panelists touched on the varying responses globally to the accident. In Germany, the government has renounced nuclear power altogether; its use will be completely phased out by 2022 Seven older reactors had been shut down and one had been temporarily shut before the Fukushima disaster; the remaining nine plants will be closed down by 2022. As the nuclear debate in Germany evolved over the past thirty years, the government developed several alternative energy infrastructure plans, and as a result, Chancellor Angela Merkel had policy paths available to her even before the accident in Japan. This allowed Germany to respond based on energy transition policy options already in place. Comparable transitions to abandon nuclear power in other nations will likely be more difficult. Even Germany's exit from nuclear power will be challenging given the implications of considerable reliance on natural gas imports from Russia, a substantially enhanced reliance on renewable energy sources that have yet to be built, and a strongly enhanced focus on energy efficiency.

Other speakers revisited design-basis assumptions from Fukushima. Compared to Three Mile Island and Chernobyl, the failures at Fukushima were not so much technical as operational and managerial. These processes are not uniform from country to country. As such, a central plan for the industry worldwide is not going to be appropriate or implemented in the same way across the globe. Each set of problems requires a unique approach, even though there exists a temptation to standardize approaches to these problems. Some participants insisted that “the best of the best” must work on these problems, no matter where. The final message was one of perseverance—the industry will learn, improve and overcome this experience as it did with Chernobyl and Three Mile Island.

Reflecting a different perspective, however, another participant suggested that the issue was indeed a technical one. Not only was the accident outside of the design-basis guidelines and regulatory scope but it was also the result of technical limitations. Present reactor designs fail to ensure safety when long-term power outages occur. Calling for the expansion of regulatory requirements, mitigation strategies and safety margins, this expert gave a sobering account of the present situation in the United States and suggested that many of the observed failures in Japan have counterparts in the United States. As with the voluntary safety standards in Japan, the United States also has voluntary guidelines (e.g., the Severe Accident Mitigation Guidelines [SAMGs]).

With multiple system failures having caused such a serious event at Fukushima, it is important to consider the vulnerabilities of reactors with the same design. The vulnerabilities of these Mark I designs include the ability to disable multiple systems by force as well as susceptibility to loss of coolant accidents (LOCA) and hydrogen leakages. These limitations are not simply managerial or operational. They are technical problems that will need to be addressed in proposed new designs.

Expanding the design-basis assumptions and safety margins, however, add to the cost of reactor operations. Some firms already have built in expanded assumptions and safety margins to their reactor designs. Others continue to ask how safety and costs can effectively and realistically be balanced? **And** even with increased financial commitments, how can plants be designed to meet the challenges of low probability/high consequence events?

Finally, safety is an international problem, so weakness in one regulatory location means weakness for the industry as a whole. To address the issues of nuclear safety internationally nuclear leadership must foster trust and transparency. Leadership must also weigh the costs of innovation with the opportunity costs of failing to innovate. More importantly, the failure to innovate now and be engaged in the process of finding solutions internationally may have serious consequences for safety and security in the future.

Panel Three: New Designs to Mitigate the Risks of Nuclear Technology

In light of the risks and benefits of nuclear energy, new designs to mitigate the risks and are being considered in several countries to keep their nuclear sectors competitive and to minimize technical problems. The designs include Generation III, III+ and IV as well as Small Modular Reactors (SMRs).

One panelist put the economic expenditures in perspective. While there is no doubt that a lot of money is spent to support the nuclear industry, when compared to other industries, subsidies for nuclear power do not break any records. The amount of money given to the oil industry in tax breaks alone is approximately the same amount spent on research and development in the nuclear industry. Existing interests are often favored, but a redirection of resources would transform the nuclear industry. If the United States were to set expectations and goals for nuclear as high as it does for other technologies, the industry as a whole would look completely different and be much safer—not only because of new reactor designs but also because of the development of new front-end and back-end facilities.

The new design possibilities presented by the panelists focused on the mitigation of technical problems, with discussions of passive designs, different fuel options, and reduced enrichment and refueling needs. The concepts behind passive models of reactors hinge on three major simplifications to improve safety: 1) minimize the reliance on active back-up systems; 2) reduce the reliance on operators; and, 3) implement fundamental safety features based on simple physical properties that hold true anywhere, regardless of operators or location. These designs would incorporate features such as below grade reactor vessels that rely on gravity and thermal heat convection instead of on pumps to cool reactor cores, fuels that expand, separate and go subcritical when reaching unsafe temperatures, and the use of liquid metal coolants. Some participants suggested that many of the problems that occurred at Fukushima could have been avoided had safety features been less reliant on human judgment and operations.

Shifting from traditional fuel configurations may also improve safety and efficiency. For example, the way the fuel rods in some new technologies are designed improves up-rate and coolant distribution and cooling efficiency. The introduction of thorium-based fuels was also discussed as a possibility, relevant especially to concerns regarding nuclear proliferation. Finally, the benefits of metallic fuel options were explored, especially in the context of recycling 'spent' LWR fuel; these are compatible with the current pressurized water reactor (PWRs) designs. In contrast, thorium-based fuels would require some significant changes to infrastructure, and many thorium cycles are being abandoned.

The traveling wave reactor is a new design that reduces the amount of fuel enrichment needed. This proposed technology allows for sealing the reactor vessel as refueling and removal of used fuel only needs to occur every few decades. The higher burn rate also substantially increases the fuel cycle lifetime. Additionally, some of the safety concerns, such as loss-of-coolant accidents, are mitigated because no pumps are needed to cool the core. This technology could also use existing used fuel.

Considering these newer designs to improve safety, security, and efficiency, the question of financial burden inevitably arises. Current estimated economic costs including construction costs, safety and security costs are prohibitive in the United States. Can the U.S. nuclear industry compete, and if so, at what price?

Some suggested that small nuclear reactors (SMRs) could address the construction costs head-on. Building reactors in a factory environment (rather than 'stick-building' them on site) the market could be changed substantially. Smaller utilities or companies would bear less risk investing in a small plant that could be expanded rather than erecting a full gigawatt-scale plant. The United States already has the capability to manufacture SMRs, based on its naval reactor program and industry.

The benefits of new technologies, however, are limited by the present infrastructure. Concerns were raised about how to retrofit old designs and make the transition to newer designs. What should the priority be? Should more time and money be spent on retrofitting than on new models? While discussing issues of relicensing older reactors, one participant mentioned that more effort should be directed at addressing non-nuclear based failures that occur within power plants such as the mechanics (pumps and generators), operations (management and training), and the security of electricity supplies even when power sources for cooling are disrupted. The international community needs to develop shared goals, and, as stressed in other panels, leadership is necessary to achieve this.

Panel Four: Standards for Safety and Security

Perhaps the most compelling need for leadership is in the area of safety and security. While many participants argue that regulation must be specifically suited to the technology, it is unclear who decides the level of security and the most reliable and economic safety measures to be used. Speakers also focused on the frightening possibilities of terrorist attacks and other man-made disasters, such as a forced entry into a plant by knowledgeable assailants, as happened in South Africa four years ago.

As with unexpected natural disasters, "Everything is unprecedented until it happens." The global standards now in place to prevent nuclear disasters, to respond to security threats, and to provide for safe energy infrastructure appear insufficient. Most notably, these standards lack binding features and enforcement mechanisms to which all nations must conform. While there is international agreement on the need for increased standards for safe and secure facilities, what is meant by a safe or secure facility? The two major components of a safety and security plan are the compliance checklist and the design-basis threat. To maximize the effectiveness of these two components, three issues need to be addressed: threats from insider sabotage; keeping security personnel motivated and always on high alert even when risk may appear low; and insuring that redundant safety layers are in place and in operating condition.

Other participants spoke candidly about their main concerns: proliferation and security. How do nations in areas of violent conflict safeguard their nuclear materials and sites? Some locate facilities underground, but concerns about safety tradeoffs are certainly present.

Though public scrutiny can serve safety goals, transparency may not be desirable in all situations. There is a fine line that many noted between transparency for diplomatic reasons and the need to limit transparency for security reasons. Some governments allow for more transparency as a matter of course than others. There are also special cases, in the face of terrorist threats, for example, when increased transparency may not be desirable.

Panel Five: Fuel Cycle Issues

There is increased interest in and need for a multilateral fuel cycle, but what are the prospects of putting it in place? Two versions of the future of the fuel cycle were discussed— the implementable and the optimal. A realistic approach recognizes the need to keep the fuel market relatively undisturbed, and thus the need for a slow multilateralization process. Furthermore, any proposal must incorporate flexibility to make it attractive for a variety of countries to join. The optimal plan—but more difficult to implement— is to retroactively put all operating fuel processing sites under multilateral control, build new plants under the same mechanism, and ensure that all participants have access to fuel.

There are both benefits and liabilities to multilateralization. The benefits are ensured fuel supply, shared financial responsibility for a repository, and security of technology use. The disadvantages lie in implementing and enforcing the relationships among participating parties, and the potential unequal influence of participating parties due to the differences in financial contributions and investment shares in the shared fuel facility.

We turned to the issue of reprocessing spent fuel, where significant differences were expressed. Several experts observed that reprocessing is prohibitively expensive, and questioned the peaceful intentions, given the dangers of weapons proliferation that attend reprocessing. Historically, most nations pursued reprocessing to obtain the capacity to create nuclear weapons rather than to reduce the costs of fuel production and storage. To highlight the disparity in cost, one panelist suggested that the costs of reprocessing in Japan could increase the cost of disposal by a factor of 1.5. Others on the panel observed that the costs and benefits of reprocessing are comparable when considered in terms of the overall cost of electricity to the consumer. In addition, reprocessing reduces plutonium stockpiles—another clear advantage. The panel closed with the reminder that ultimately, all countries will serve their own individual needs. Economic advantage may not always be the driver, but using it as leverage may increase the prospects for cooperation and participation in cooperative fuel cycle plans.

Panel Six: Safeguarding Dual Use Technology

There are two paths to weapons development in the nuclear energy cycle as the panel pointed out: enrichment and reprocessing. What then is needed to safeguard this dual use technology? Bundled fuel packages seem to be a realistic possibility that is made appealing by fuel take-back programs. But panelists asserted that leadership is necessary to safeguard these dangerous technologies and foster successful multilateral fuel cycle cooperation. Where will this leadership come from? Could industry take it on? In order to convince countries such as North Korea and Iran to participate in international fuel cycle programs, hearts and minds must be changed. Furthermore, a monitoring system must be put in place that utilizes objective methods to assess proliferation dangers.

Conclusion

The Fukushima nuclear plant disaster provided an unusually somber context for the workshop discussions on international nuclear safety and security. Participants were reminded anew of the catastrophic consequences of nuclear accidents, however unlikely they may be, and of the responsibility of industry, government, and independent science and technology to manage nuclear technology safely and well. Although the disaster unfolded at one power station, participants understood that no firm or country was immune from such a calamity.

Beyond the immediate issues surrounding the incident at Fukushima, four major questions require more study to develop satisfactory policy solutions.

1. Multilateral fuel banks offer a potential solution to the problems of guaranteeing nuclear fuel supply and of the proliferation of enriched uranium and plutonium for weapons fabrication. Several such banks have been put in place, including the most recent approved by the IAEA, the Russia-based International Uranium Enrichment Center (IUEC) at Angarsk. Yet these banks remain relatively unattractive to consumers of new nuclear reactors and technology, and are not being used as intended. How do countries move from the ideal to the practical? How do we create a road map that moves more countries along the path of using multilateral fuel banks? What kinds of mechanisms will provide the necessary guarantees and incentives for participating in fuel banks?

2. Global standards for safety and security are only as useful as the enforcement measures to implement them. Without a legitimate central authority to impose sanctions, what mechanisms and incentives will ensure compliance with safety and security standards? Is it possible to generate "self-enforcing contracts" among firms and regulatory agencies that would ensure safety, security, and accountability to the public?

3. The question of US relevance and leadership in the global future of nuclear energy remains. Participants acknowledged the increasing role being played by South Korea, France, and Russia in building nuclear reactors and supplying fuel. They also noted the great energy needs of the largest developing countries, China and India, and their ambition to meet those needs with additional nuclear power. In this context, how important is the US as a leader in the field, and what would be the consequences if its role were diminished?

4. New reactor designs are heralded as the answers to safety questions, yet skepticism about the claims continues to surface. Small nuclear reactors (SMRs), for instance, might solve the problems of the high cost of construction, at the same time that they would address safety concerns raised by large reactors. But, because they are easier and quicker to build, and could be made more easily available to new entrants to the field, they raise concerns about nuclear weapons proliferation. No matter how small the plants, their export to new entrants may raise concerns about whether these countries have the necessary expertise to ensure safety and security even at these smaller plants.

We heard a range of perspectives on these and other questions at this workshop. To formulate sound policy recommendations, it will be useful to reach consensus based on proposals for practical measures. That consensus is likely to come only with further policy study and discussion—work that the organizers plan to continue.