

## Making nuclear energy work

How shifting research goals and improving collaboration with industry will help U.S. national labs spur new nuclear energy development.

BY ROBERT ROSNER

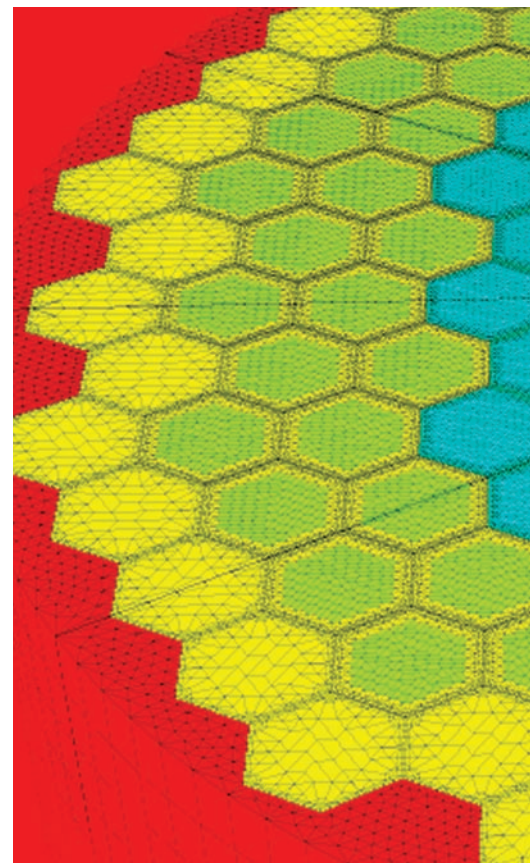
**T**HE SEARCH FOR SOLUTIONS TO two growing crises—human-induced climate change and the loss of cheap oil—places nuclear energy front and center. Many see the expansion of nuclear power in the United States as a way to mitigate concerns over energy as well as national and environmental security brought on by the two global problems. Looking at the U.S. nuclear scene’s past, present, and future, and focusing on a twenty-first century approach to the underlying technical issues, one can see the potential for an expanded nuclear energy future.<sup>1</sup>

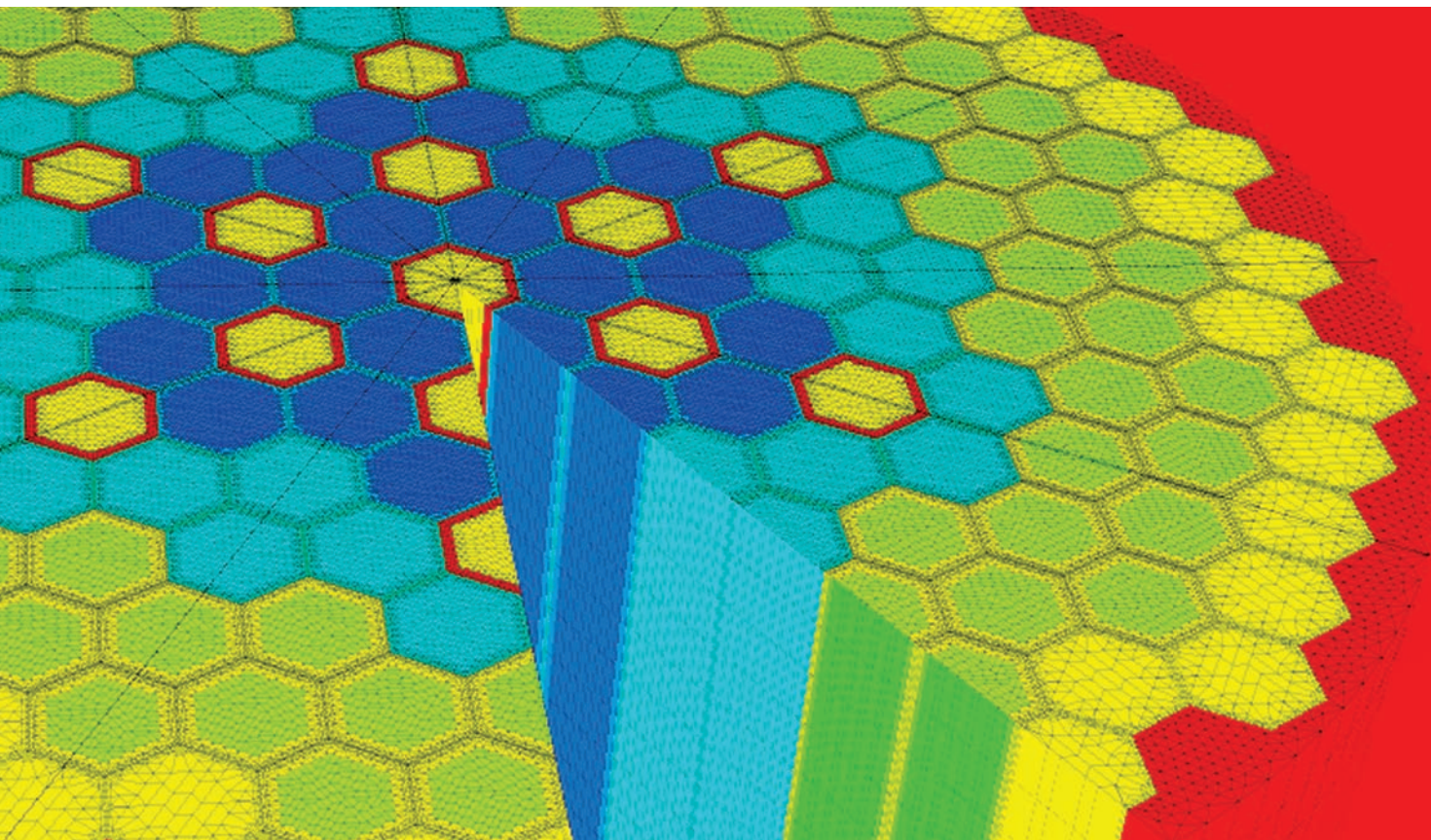
There is little question but that the United States rushed into the nuclear age, driven by an enthusiasm sparked in part by the technical success of the Manhattan Project. Adm. Lewis L. Strauss, then chairman of the U.S. Atomic Energy Commission, in an address to the National Association of Science Writers in September 1954, made the memorable statement: “It is not too much to expect that our children will enjoy in their homes electrical energy too cheap to meter.” Aside from whether it ever made any sense in the context of energy production via fission

or fusion, Strauss’ statement revealed a state of mind that saw any remaining technical challenges confronting nuclear energy production as readily overcome by infusions of government funds and talents, as was the World War II weapons program. The possibility that safety, proliferation, environmental, or public acceptance issues might enter the picture and complicate the regulatory environment, and thus the economics of nuclear energy, was simply not understood. Quite the opposite—recall that Walt Disney released a film in 1956 titled *Our Friend the Atom*, which painted a rosy (and not entirely accurate) picture of the history of physics and the future of atomic energy.

It must also be said that the hubris associated with the success of the Manhattan Project clouded the vision of scientists and engineers who might otherwise have been more cautious about the predictive capabilities of the engineering sciences of the day. Nuclear engineering, as all other applied science/engineering disciplines, started out as a phenomenology-dominated, interdisciplinary approach that merged atomic science with the

conventional engineering disciplines to harness the atom for peaceful purposes. It is useful to recall that even as late as the 1940s, disciplines as established as structural and civil engineering were not yet in a position to predict and prevent disasters such as the 1940 collapse of the Tacoma Narrows suspension bridge. Traditionally, the engineering professions have tended to adopt a “design-in-depth” philosophy, that is, a series of redundant systems to mitigate the lack of transparency or, at times, lack of understanding of the basic phenomenological processes. These engineers have understood extremely well that designs that depart significantly from point designs (known to be effective and safe in the absence of detailed experimental verification and validation) were highly suspect. Thus, Leon Moisseiff’s design for the Tacoma Narrows Bridge had not been vetted aerodynamically, largely because it was not well understood that the design could suffer from wind-induced destructive instabilities. In the absence of an understanding of complex, time-dependent processes, experimentation is the only way to verify and validate a new





design—and such experimentation tends to be very time-consuming and expensive. As a consequence, engineering designs tend to be rather “approximate.”

Given this perspective, I think we should, in hindsight, not be overly surprised that nuclear plants designed and built before the 1970s were subject to the very same conceptual limitation, so that accidents such as that at Chernobyl’s Reactor 4 in 1986 might well have been anticipated. Reactor 4 featured a very large, very low-enrichment, “over-moderated” core design, which actually operated on the wrong side of a reactivity curve for stable operation—that is, loss of coolant (moderator) could actually increase reactivity (hence power), and because of its large size (hence cost), the Soviets had decided to forgo a containment building, leading to lethal consequences and widespread radioactive contamination of the environment. This contrasts starkly with the standard U.S. practice of designing light water reactors for operation in an under-moderated, stable regime—one that loses reactivity with a loss of coolant and is therefore inherently safer.

In the 1979 Three Mile Island (TMI) incident in Pennsylvania, a combination of suboptimal design choices led to a loss-of-coolant accident (LOCA). Operators could neither determine the level of coolant in the core (they did not have a direct probe) nor whether the pressurizer relief valve was operating properly. With insufficient training in such conditions, the operators were slow to recognize the seriousness of the problem, the extent of which was determined by indirect measurements. The seriousness of a LOCA had in fact been appreciated in advance (and extensive experimental tests carried out), and TMI’s containment building prevented the lethal exposures and dispersal of radioactivity experienced at Chernobyl. Nonetheless, the core was destroyed and the power plant lost. The experience at TMI not only led to regulatory reform and considerable improvements in training and operations across the nuclear utilities, but also underlined the importance of fail-safe design approaches for next-generation reactor designs (such as passively safe systems, which are inherently resistant

Broader use of computer simulations, such as this simplified mock-up of the core region of a proposed Advanced Burner Test Reactor (ABTR), could help reduce the need for costly nuclear energy experiments.

to mechanical failure). The TMI accident also led to extensive and costly retrofits at nuclear plants under construction and in operation at the time.

The consequences of these incidents were powerful. The regulatory climate within the United States became much more formidable, with Nuclear Regulatory Commission (NRC) regulation becoming highly conservative and, it has been argued, the single largest cost driver for new nuclear energy facilities. Requiring operators to perform detailed and costly experimental mock-ups in order to obtain a license or permit resulted in a lengthier, more expensive regulatory process—a lose-lose situation for project engineers as well as for the NRC.

Furthermore, public confidence and acceptance of nuclear power plummeted, and the nuclear construction industry froze in place. The last U.S. reactor

completed was the Tennessee Valley Authority's Watts Bar 1, which was ordered in 1970 and became operational in 1996; the last utility order for a nuclear plant came in 1978 but was ultimately canceled. To complete this tale, we recall that in 1977, due largely to nuclear

can only advance as the pace of the design process advances, resulting in a convoluted licensing process that is time-consuming and costly. Regulators are more or less restricted to diagnose what the real design margins are, even after extensive mock-ups are completed. This is

The question I would like to pose is: What needs to change so that we can accomplish this?

For the United States to build new nuclear power plants, several conditions must change. To make the point most cleanly, I will focus solely on the problem of replacing the existing nuclear power plants as they age and are decommissioned, and ask what the current challenges to accomplishing this goal might be.

The first major issue is public perception and acceptance. This issue is intimately tied to reactor safety—that is, demonstrated capabilities for assuring safety during operations.

The second issue revolves around nuclear proliferation. It is a peculiar feature of U.S. political thinking to believe that U.S. views on matters of consequence are universal, despite evidence to the contrary. For example, Japan, undoubtedly the nation most negatively affected by the dawning of the atomic age, has vigorously pursued nuclear reprocessing—despite President Carter's view (shared at the time by a large sector of the U.S. policy community) that since the United States abandoned reprocessing, all other nations would follow suit. Indeed, there is not much evidence that U.S. domestic policies have much influence on the internal behavior of other nations, and it is for this reason that I strongly doubt that U.S. domestic reprocessing has any effect on international nuclear proliferation. However, appropriate international steps to place barriers to countries seeking their own reprocessing and enrichment capabilities, coupled with economic incentives, can result in constraining and even eliminating proliferation risks.<sup>3</sup>

Economics is the third issue. There is broad agreement that under current circumstances, new nuclear power is not competitive with fossil fuel power. The key financial issues for nuclear power are the costs related to the uncertainties of the plant licensing process and the construction costs related to the very imprecise plant design and highly compliance-driven operating climate. Delays in nuclear construction can be quite costly. A two-year delay can add as much as \$1 billion in interest costs for a 3,000-megawatt (two-unit) facility.<sup>4</sup> Given that nuclear's main

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proliferation fears driven in part by India's success in developing nuclear weapons, President Jimmy Carter ended commercial U.S. spent fuel reprocessing.

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GIVEN THIS HISTORY, IT SHOULD NOT come as a surprise that funding for nuclear energy research and development nose-dived in the 1980s and has only within the past year or two seen a mild turnaround. Without a healthy funding climate, and with a few key disciplinary exceptions (such as neutronics, which has applications in other technical areas), nuclear engineering has remained primarily phenomenology-driven and did not participate in the science-based engineering revolution of the 1980s and 1990s. Coping with approximation and imprecision is still the undercurrent of the design process—designs cannot be easily optimized without science-based predictive tools. In addition, the regulatory process

basically why NRC licensing of new plant designs, new fuels, and new waste forms is so slow and unpredictable. It is therefore entirely unsurprising that nuclear energy is seen today as both inherently expensive and problematic. Economic studies of nuclear energy show that construction/licensing costs—and financial risk management—dominate the economic competitiveness of nuclear technology relative to other energy options.

In this context, it is important to realize that even if one were to discount the possibility of a significant expansion in new nuclear plants as a major new carbonless power source (displacing some large fraction of the existing fossil fuel-based power plants, or those to be built in response to continued growth in U.S. energy needs), one must take into account the fact that roughly 20 percent of the current U.S. base electricity production comes from nuclear plants. These plants have finite operating lives, and failure to replace them will make mitigating global climate change via energy conservation, renewable energy sources, and carbon sequestration that much harder. The required replacement rate is formidable: It has been estimated, based on the expected lifetimes of the existing plants, that one new plant will have to be built every four to six months for the next 40 years.<sup>2</sup>

economic competitor is fossil fuels (coal in particular), one can calculate that nuclear power can become realistically competitive if the economic disincentives for nuclear power—principally those related to the delays involved in plant licensing—are relieved, and if the external costs of fossil fuels, particularly the costs of mitigating greenhouse gases, are included in their electricity generation costs.

The fourth major issue, spent fuel management, is stuck on the horns of many seemingly irreconcilable dilemmas and tradeoffs. Apart from ecological and safety concerns, there are challenging technical questions about the role of future innovations, such as technologies that would transmute the transuranic elements and thereby have the potential to make spent fuel less harmful as well as reduce the volume of nuclear waste. I believe that the technical community would be much better informed by using more advanced analytic tools to assess the various nuclear waste-disposition strategies in a way that would provide more reliability and predictability regarding the environmental, safety, and technical issues related to recycling and detoxifying nuclear waste.

So how can we optimize new reactor designs—and indeed, the entire fuel cycle—while keeping operational safety the uppermost goal? To answer this question, we need only look at other engineering disciplines, such as the aeronautics industry, in which issues have arisen within a similarly constrained and sensitive regulatory and public environment.

Before the advent of large-scale, computer-based simulations, designing new airplanes involved building a succession of prototypes, starting with small-scale models of the entire airplane, whose performance was established experimentally. New designs required extensive testing of these complex prototypes in large, subsonic wind tunnels; correspondingly large laboratory installations, such as at the NASA Ames Research Center, were required to provide the necessary experimental infrastructure.

But the subsonic wind tunnels at Ames are largely silent these days. Advances in computational simulations, especially in fluid dynamics,

## TECHNICAL PRIORITIES

The nuclear industry has asked the national labs for help addressing several technological challenges, and we consider such assistance a top priority. An informal straw poll of my colleagues at the national laboratories indicated several issues that the industry would like to better understand, including the scaling of thermal hydraulics; design optimizations for improving the economics of fuel reprocessing; the consequences of severe impacts, such as plane crashes, on reactors and other facilities; and the dispersion of fission products during a meltdown in water-cooled systems versus sodium-cooled ones, to cite just a few examples.

At Argonne, we have identified three major areas in which specific questions that industry is asking overlap with our lab's considerable expertise: separation and reprocessing for both aqueous and pyroprocessing regimes; waste management; and reactor design, including both thermal water-cooled reactors and fast spectrum (neutron) flux sodium-cooled reactors.

In an effort to answer industry questions, our modeling efforts have progressed notably and are most advanced in the reactor area. During the past two years, we have been developing simulation-based high-efficiency advanced reactor prototyping and neutronics codes. During the next five years, our objectives are to use the Energy Department's high-end computing facilities and state-of-the-art simulation capabilities to better understand predictive capabilities at the design level; provide validated predictive capabilities, based on a fidelity hierarchy; allow for distinct modeling capabilities, such as direct numerical simulation and large-scale eddy simulation, based on the level of detail required; and allow for systems-level optimization by providing coupled simulation capability.

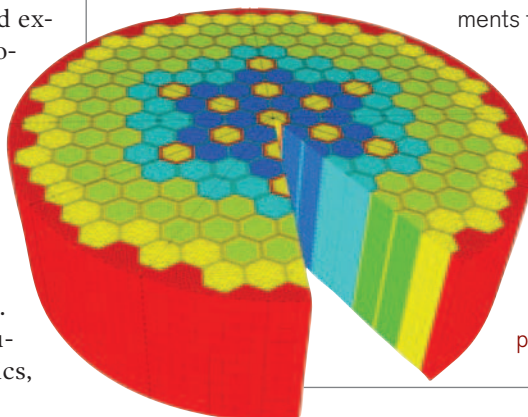
Ultimately, over the next 10 years, we plan to cover all aspects of reactor issues in order to answer all of industry's questions. While the simulation tools we are developing can be used for different reactor types (from high-temperature gas-cooled to fast spectrum liquid metal-cooled), our short-term objectives over the next year are focused on advanced fast liquid metal-cooled reactors.

The immediate goal is to understand and optimize the current design of such reactors. We are also interested in computing the interchannel mixing factors, as well as the heat transfer and cross-assembly dispersion from isolated hot pins; these calculations should give us a fairly complete first-principles picture of thermal transport within the pin assembly for realistic geometries and flow conditions. Naturally we have a few additional aims, namely to examine alternative designs, incorporate LES results into a coarser thermal hydraulics model, and establish a direct numerical simulation database for fast-reactor-relevant geometry.

These capabilities will allow us to explore undesired temperature fluctuations within the reactor core and to study bypass flow in side channels, and will allow systematic optimization of structural geometry within the core. In other words, we will be able, to a limited extent, to do rapid prototyping to answer industry questions. These tools will also allow us to apply the same methodology to the design not only of the next generation of advanced light water reactors, but also to replacements for the existing fleet of reactors.

In terms of collaboration, the labs must look beyond industry. We must be mindful of workforce development and partner with universities in order to ensure that the next generation of nuclear engineers and designers will be in place in the coming decades.

The ABTR, if built, would demonstrate the performance of newly recycled fuel.



material science, and structural mechanics, combined with remarkable advances in hardware computational capabilities associated with massively parallel computers, have allowed aeronautical engineers to build simulation tools that are far more predictive and no longer

were torn off the plane bodies, leading to immediate fatal crashes.

In these cases, public confidence in the safety of flying was severely compromised. The key response was a high-profile government-industry partnership to identify the problems rapidly

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require the same intensity of experimental verification and validation. New airplanes such as the Boeing 777 (in service) and 787 (in production) have been designed and built with no need for full-scale prototypes; experiments have been limited to validating portions of the overall design. Even the mock-ups for plane assembly, and the ergonomic analyses of both building and servicing the planes, are now entirely digital.<sup>5</sup>

Today, the commercial airline industry faces regulatory and public perception hurdles similar to those faced by the nuclear industry. New airplane designs must be certified by the Federal Aviation Administration (a very costly process), and commercial operators (the airlines) must maintain the public perception that flying is safe.

Few today remember the problems of the first commercial jet airliner, de Havilland's Comet, or of Lockheed's Electra. The early versions of the Comet suffered from poorly designed wing profiles and metal fatigue, which resulted in several serious accidents in 1954, including two in which the airplane disintegrated in flight, killing all onboard. Similar design issues led to major accidents involving the Electra, a turboprop introduced to commercial aviation in 1958. In two Electra incidents (in 1959 and 1960), wings

and fix them definitively. As a result, fear of flying is now almost an anomaly. The lessons here for nuclear are twofold: First, public perception of safety within an industry is closely connected to the degree to which industry and government focus effectively and transparently on safe operations. Second, the costs of meeting performance, safety, and regulatory benchmarks in today's highly competitive environment make it imperative to optimize designs and minimize expensive experimentation without loss of performance.

THE TRANSFORMATION OF DESIGN AND manufacturing has spread well beyond the aeronautics industry but has unfortunately hardly touched the nuclear engineering discipline or the nuclear industry. What is needed is evident: verified and validated simulation tools for rapid prototyping of components and systems; analysis tools for performance optimization at both the systems and component levels; and reliable safety assessments of components and systems. We would like, for example, to understand how one could optimize the transmutation of transuranics to less toxic elements within defined risk margins without resorting to large mock-up experiments.

To focus our argument, let's consider goals less ambitious than changing the entire nuclear industry—modest goals such as sharply increased reliability of risk assessments and sharply decreased costs. To achieve these two worthy goals, we will need first-rate scientists and engineers familiar with nuclear engineering, as well as the cohort of scientists and engineers who have been involved in transformations of other disciplines.

The Energy Department's national laboratories remain the principal U.S. reservoir of top nuclear designers (in areas as diverse as reactors, fuels, recycling/reprocessing, and waste management); this is a field that Energy has managed to preserve, despite the vagaries of fortune of nuclear power outside the protective confines of the department. Furthermore, beginning with the Manhattan Project and in collaboration with the computation community, the national labs have always led the United States in high-performance computing. And through the Advanced Simulation and Computing program and the Scientific Discovery Through Advanced Computing program, Energy has demonstrated that large collaborations between physicists, chemists, applied mathematicians, and computer scientists can effectively produce world-leading simulations for complex systems, ranging from fusion plasma tokomaks to nuclear weapons. In these projects, it was realized early on that three highly interconnected methodologies would lead to results—experiment/phenomenology, theory, and simulations. Modern technical inquiry entails these three critical axes of investigation, which together provide as complete a picture as possible of the relevant physics and engineering phenomena.<sup>6</sup>

To improve the nuclear engineering discipline, and hence boost the nuclear industry, the ultimate aim is to do fewer, cheaper, and smarter experiments; we want to augment our theories and guide our judgment. So, one might ask, why have we not simply gone forth and done the needed work? What has been holding us back? There are, in my opinion, several reasons for this lack of progress. (For an overview of technology issues that need to be addressed, see "Technical Priorities," p. 31.)

The first is a serious lack of funds. Nuclear fission programs within the Energy Department remain on life support. The lab infrastructure is in poor shape because of a lack of investment in it over the last 20 years, and the “free energy” to collaborate with industry (as opposed to continuing to be supported by existing meager Energy funds) is weak.

Bad habits at national laboratories also stymie progress. National laboratories tend to drive industry toward solutions to problems that the labs themselves have defined, and they tend to avoid determining industry needs prior to offering those solutions. This is an attitudinal problem and is alterable, with the appropriate incentives. For example, Argonne National Laboratory (where I serve as director) has been collaborating with industry on reaching technical solutions and establishing institutional solutions to address the proliferation concerns of expanded nuclear energy.<sup>7</sup> However, we have been doing so in an ad hoc fashion; this type of collaboration needs to be regularized and further encouraged.

Lastly, the nuclear industry’s own bad habits inhibit headway. If nuclear power is ever going to become commercially viable, industry needs to take charge. The nuclear industry knows its problems, though it may not have the personnel or the facilities to solve them. However, the U.S. nuclear industry funds very little government research and development, whereas in France, for example, the Atomic Energy Commission receives more than half its simulation funding from energy conglomerate Areva. This kind of industry-government relationship is typical of the French approach to nuclear projects, but it has traditionally not been found in the United States.

WHEN DISCUSSING NUCLEAR POWER IN the United States, the same arguments against building new plants repeatedly surface. It is useful to review these arguments and consider responses to them.

Some maintain that there is no need to rush ahead with plans for new nuclear power. But time is a luxury the nuclear industry does not have. Existing plants must be replaced as they are decommissioned

or as they need refurbishing, and given the industry’s poor condition, this will have to begin in the near future. Indeed, *not* moving ahead very soon will guarantee mediocrity of the U.S. nuclear engineering community, ensure that the United States is technically disadvantaged compared to foreign technology leaders, and assure that U.S. industry will be unable to compete in the ongoing worldwide nuclear revival.

Others contend that new plants would be too expensive. But expensive compared to what? We do not know enough about the impact of new technologies to reliably predict costs out to 2050, especially given the likely transformational effects of computing and material science advances. Are the cost comparisons truly comparable—do we know the ultimate costs associated with carbon sequestration as well as we know the costs of handling nuclear waste? Having looked at existing economic comparisons, my view is that basing far-reaching policy decisions on such comparison is unwise, and that serious work in this regard still remains to be done.

I have also heard people claim that industry would not be able to get the job done, or that the labs only want to get their hands on new funds. The presumptions here—that the nuclear industry is damaged beyond saving, and that the national labs are more interested in building (or protecting) their existing research programs without seriously engaging industry—are false. The nuclear industry can renew itself, and the national labs can help. I cannot speak for the past behavior of industry and the labs, but I can speak to what has happened within the past few years, certainly since I’ve been director at Argonne. We have seen very clearly that U.S. industry knows exactly what it wants and that it needs to partner with those who have the required expertise and who truly want to collaborate in order to reach industry’s goals—and this is broadly recognized within the industry. At the same time, I have seen laboratories such as Argonne start to focus on specific, industry-defined goals, instead of simply focusing on basic research topics disconnected from industry needs.

In order to get to the point where we can replace nuclear power plants as needed, several things must happen, both

technologically and culturally. Nuclear engineering must adapt twenty-first century analytic tools that are based on a scientific dialectic, that is, on a transformational approach that connects advanced simulations and basic scientific understanding with engineering design decisions. In this way, the exchange of design proposals and counterproposals can result in a transparent transformation in the course of the design process. High-fidelity (science-based) integrated simulations must form the core of design efforts, allowing for rapid prototyping that minimizes the need to experiment. And science-based, validated modeling at both the small-scale and systems-level must be part of the core capabilities, so that scientists can achieve realistic design optimizations.

To make significant progress, the field must somehow generate internal technical excitement to attract the best and the brightest minds. And the national labs need to establish long-term partnerships with industry in order to translate present and future advances in science-based simulations into industrial practice. This will work only if we achieve mutual trust.

We need a cultural shift in both the private and public sectors so that a real science/engineering synthesis can take place. What I have learned in my 30-plus years of science is that nature is full of surprises, and we need all the scientific tools at our disposal to understand nature and how technology intersects with it.

To move nuclear power to a more publicly acceptable position to meet future U.S. energy needs, it is absolutely necessary to use all the instruments in our scientific toolbox to buttress the engineering decisions for a future nuclear energy economy. We know we can do it—after all, this would be a transition from phenomenology-based to science-based research and development, which has been done before. Our national labs hold the necessary expertise right now. What is needed, above all, is the will to proceed. ■

FOR NOTES, PLEASE SEE P. 57.

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“Mechanism, Regulation, and Ecological Role of Bacterial Cyanide Biosynthesis,” *Archives of Microbiology*, vol. 173, no. 3, pp. 170–177.

27. Eckard Wimmer of the State University of New York at Stony Brook has argued that viruses are more akin to nonliving chemicals than to living organisms and proved the point by synthesizing infectious poliovirus in the laboratory from off-the-shelf chemicals. In principle, it would be possible to include synthetic viruses under the General Purpose Criterion of the CWC. At the same time, it would be politically and practically unrealistic to incorporate synthetic viruses into the treaty’s routine verification regime.

28. OPCW, Conference of the States Parties, First Review Conference, “Note by the Director-General: Report of the Scientific Advisory Board on Developments in Science and Technology,” RC-1/DG.2, April 23, 2003, p. 4.

29. Neil Davison, “‘Off the Rocker’ and ‘On the Floor’: The Continued Development of Biochemical Incapacitating Weapons,” Bradford Science and Technology Report No. 8 (Bradford Disarmament Research Center, University of Bradford, United Kingdom, August 2007), p. 24.

30. See “The Danger of ‘Nonlethal’ Weapons,” sidebar in Wheelis, “Will the New Biology Lead to New Weapons?” pp. 8–9.

31. Julian Perry Robinson, “Categories of Challenge Now Facing the Chemical Weapons Convention,” discussion paper, 52nd Pugwash CBW Workshop, Noordwijk, The Netherlands, 17–18 March 2007, p. 18.

32. Alan Pearson, “Incapacitating Biochemical Weapons: Science, Technology and Policy for the Twenty-First Century,” *Nonproliferation Review*, vol. 13, no. 2, p. 170.

33. Kerry Boyd, “Rumsfeld Wants to Use Riot Control Agents in Combat,” *Arms Control Today*, vol. 33, no. 2, p. 32; Kerry Boyd, “U.S. Grapples with Use of Nonlethal Agents,” *Arms Control Today*, vol. 33, no. 3, p. 44.

34. For a discussion of possible oversight mechanisms for dual-use research in the life sciences, see National Science Advisory Board for Biosecurity, “Proposed Framework for the Oversight of Dual Use Life Sciences Research: Strategies for Minimizing the Potential Misuse of Research Information,” available at [www.biosecurityboard.gov/FrameWork%20for%20transmittal%200807\\_Septo7.pdf](http://www.biosecurityboard.gov/FrameWork%20for%20transmittal%200807_Septo7.pdf).

## Making nuclear energy work

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1. I would like to thank my colleagues at Argonne for tutoring me in the intricacies of the nuclear power industry; these include Yoon Chang, Phillip Finck, Steve Goldberg, Bob Hill, Hussein Khalil, Walt Kirchner, Pino Palmiotti, Mark Peters, and Andrew Siegel. I would like particularly to thank Steve Goldberg and Walt Kirchner for their critical readings of this paper.

2. Charles D. Ferguson, “Nuclear Energy: Balancing Benefits and Risks,” Council on Foreign

Relations Special Report, CSR No. 28, April 2007, p. 9. Note, however, that this estimate is very conservative, as the study assumed no efforts at life extension. A better assumption might be that by 2050, the majority of the existing 104 reactors in the United States will have to be replaced, which still leads to a construction schedule of one to two new reactors per year through this period.

3. This informal conclusion is supported by recent detailed studies, including “Poland Becoming a Member of the Global Nuclear Energy Partnership,” pp. 1, 18–19, ANL-0710 vol. 1, V. Koritarov, March 2007; and “TRUST, an Innovative Nuclear Fuel Leasing Arrangement,” J. Malone, Exelon Corporation, presentation to the NEI-WNA International Fuel Cycle Conference, April 2007. The studies were conducted in collaboration with the University of Chicago, Northwestern University, and staff from Exelon Corporation. Results from the Poland study indicate that a trans-Baltic solution—that is, a regional nuclear energy facility—would be economically attractive, as would a robust fuel supplier system and take-back regime. In the second study, we developed an innovative fuel-leasing strategy that meets the objectives of the International Atomic Energy Agency and other entities, is market-based, facilitates additional nonproliferation agreements, and is compatible with various back-end strategies.

4. Moray Dewhurst, FPL Group, presentation to the 3rd Annual Platt’s Nuclear Energy Conference, February 8–9, 2007.

5. See, for example, Committee on Bridging Design and Manufacturing, National Research Council, *Retooling Manufacturing: Bridging Design, Materials, and Production* (Washington, D.C.: National Academies Press, 2004).

6. We must recognize that experiment, theory, and simulation do not compete, and that none is without its pros and cons. The “cons” are clear: *Experiment* is expensive, sometimes dangerous, and very difficult to get precise answers with; *theory* is limited to very idealized cases and does not work well for highly nonlinear phenomena, detailed geometries, etc.; *simulation* relies heavily on competently executed (but often neglected) validation and verification, and has a very limited application domain extent when relying solely on a first-principles (“direct”) simulation approach. However, when applied in concert, these three research modalities have shown repeatedly that highly complex systems can be designed and built efficiently and operated effectively and safely—recall again the commercial aeronautics industry.

7. “TRUST, an Innovative Nuclear Fuel Leasing Arrangement,” J. Malone, Exelon Corporation.

## Disarmament redux

CONTINUED FROM P. 39

1. Lawrence Wittner, *Resisting the Bomb* (Stanford: Stanford University Press, 1997), p. 447.

2. Daryl G. Kimball, “Looking Back: The Nuclear Arms Control Legacy of Ronald Reagan,” *Arms Control Today*, July/August 2004.

3. Lawrence Wittner, *Toward Nuclear Abolition*

(Stanford: Stanford University Press, 2003), p. 167.

4. *Ibid.*, p. 406.

5. Committee on International Security and Arms Control, National Academy of Sciences, *The Future of U.S. Nuclear Weapons Policy* (Washington, D.C.: National Academy Press, 1997). The study was chaired by retired Maj. Gen. William Burns, who served as the director of the Arms Control and Disarmament Agency during the Reagan administration.

6. Gaffney’s comment on Gottemoeller’s nomination to the Energy Department appears at [www.centerforsecuritypolicy.org/modules/newsmanager/ShowSectionNews.aspx?CategoryID=66&SubCategoryID=189&NewsID=1451](http://www.centerforsecuritypolicy.org/modules/newsmanager/ShowSectionNews.aspx?CategoryID=66&SubCategoryID=189&NewsID=1451). It cites his earlier opposition to her Defense Department appointment.

7. R. Jeffrey Smith, “Aides Question Elimination of Pentagon Job; Arms Control at Issue for Would-Be Appointee,” *Washington Post*, September 23, 1997, p. A1. Interview with Clinton administration official.

8. See Stephen Rademaker, “Blame America First,” *Wall Street Journal*, May 7, 2007.

9. Keith B. Payne, “Nuclear Weapons: Theirs and Ours,” National Institute for Public Policy, May 7, 1999.

10. “Epiphanies: Hans Blix,” *Foreign Policy*, March/April 2007.

11. Walter Pincus, “Bush Urged to Develop Overall Nuclear Arms Policy,” *Washington Post*, March 18, 2007, p. A5; Walter Pincus, “Bipartisan Panel Will Review Nuclear Posture,” *Washington Post*, May 3, 2007, p. A3.

12. Statement by Sen. Dianne Feinstein introducing S. 1914, August 1, 2007.

13. U.S. Congress, “National Defense Authorization Act for Fiscal year 2008,” S. 1547, Sec. 3122.

14. U.S. Congress, “Nuclear Weapons Threat Reduction Act of 2007,” S. 1977.

15. Center for International Security Studies and WorldPublicOpinion.org, “Americans and Russians on the Future of Disarmament,” November 9, 2007.

16. American Envionics, “American Values Survey for the Peace & Security Community,” Summer 2007.

17. Christopher Wills, “Obama Urges Eliminating Nuclear Weapons,” Associated Press, October 2, 2007.

18. Harold Brown and John Deutch, “The Nuclear Disarmament Fantasy,” *Wall Street Journal*, November 19, 2007, p. A19.

## The bureaucracy of deterrence

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1. See Janne E. Nolan, *Guardians of the Arsenal* (New York: Basic Books, 1989).

2. Max Weber, *Economy and Society: An Outline of Interpretive Sociology*, Guenther Roth and Claus Wittich, eds., translated by Ephraim Fischoff and others (New York: Bedminster Press, 1968), pp. 215–223, 961–962, 973, 987–993.

3. National Defense Panel, *Transforming Defense: National Security in the 21st Century* (Washington,