Overcoming Obstacles to Advanced Reactor Technologies

Edward Geist

Whither the Nuclear Renaissance?

A decade ago, it appeared that the United States might be on the verge of a so-called nuclear renaissance. Bolstered by high natural gas prices, new standardized reactor designs, a streamlined regulatory framework, and the prospect of stronger greenhouse gas regulations, U.S. utilities began ordering new nuclear power plants for the first time since the 1970s. Proponents asserted that the new reactors would not merely provide a massive improvement in safety over existing designs but also produce electricity at a cost competitive with conventional alternatives. Nuclear fission would finally become a viable business proposition, offering a profitable avenue to wean the American economy off of fossil fuels.

An unanticipated confluence of economic and political factors smothered the nuclear renaissance. The economic case for new nuclear power plants had been premised on the notion that the high natural gas prices experienced prior to the 2008 financial crisis would continue indefinitely. Instead, the economic downturn and the increasing supply of shale gas transformed methane from an increasingly unaffordable commodity into the most cost-effective fuel for new generating capacity, including baseload applications. Second, the predicted capital costs for new nuclear plants increased markedly, from as little as $1,100 per kilowatt a decade ago to more than three times that for the units now under construction, even as the economic crisis tamped down demand for new generating capacity. The U.S. government’s failure to put a price on carbon

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1 The U.S. Energy Information Administration’s Annual Energy Outlook 2004 with Projections to 2025 predicted that Westinghouse’s AP1000 reactors would cost $1,580 per kilowatt for first-of-a-kind units, dropping to $1,081 in 2019 (U.S. Energy Information Administration, 2004, p. 58). As of early 2015, the projected completion costs of the two AP1000s under construction by Georgia Power are
emissions deprived nuclear fission of a critical economic advantage over fossil fuels. The accident at Japan’s Fukushima Daiichi nuclear plant and waning enthusiasm for nuclear power in Congress and state governments coincided with U.S. Nuclear Regulatory Commission (NRC) decisions to increase the licensing requirements for new nuclear plants, imposing costly delays on the plants under construction. As a consequence, all but two of the new reactor projects in the United States were either canceled or put on hold.

These economic and political factors were merely proximate causes for the failure of the nuclear renaissance. The fundamental reason for the economic uncompetitiveness of the current generation of nuclear plants lies in the imperfect safety characteristics of the large light-water reactors (LWRs) that have historically formed the basis of U.S. civilian nuclear technology. Although these LWRs are more affordable and less dangerous than reactor designs commercialized in some other nations, the physics of these large LWRs and the zirconium-clad uranium oxide fuel they employ requires the inclusion of costly engineered safety systems to protect the public from the consequences of severe accidents. The nuclear renaissance hinged on the assumption that standardized design and modular construction would reduce the expense of these systems to manageable levels, but experience has not borne out this hope.

If nuclear power is to play a greater role in the U.S. energy supply in coming years, it must move beyond the current paradigm of large LWRs. Numerous candidates for alternative nuclear technologies, ranging from miniature, mass-produced versions of existing LWRs to exotic possibilities, such as reactors utilizing liquid fuels, hold out the possibility of being both cheaper and safer than current nuclear plants. Unfortunately, the NRC is ill-equipped to assess the safety of these novel nuclear plants, in large part because the institutions charged with encouraging the development of these technologies and demonstrating their operational characteristics have failed to do so effectively. Therefore, institutional reforms are needed if nuclear fission is to play a greater role in ensuring U.S. energy security and forestalling climate change. This paper aims to outline the policy challenges that must be met in order to establish the commercial viability of advanced nuclear technologies while developing a regulatory framework that can ensure the safety of the public without imposing prohibitive costs on new reactors.2

The Physical Underpinnings of Nuclear Safety

The unfavorability of the economics of current nuclear power plants ultimately stems from the potential consequences of extreme accidents. The core of a typical nuclear power reactor contains an immense radiological inventory, equivalent to that released by a large thermonuclear explosion. The release of merely a small fraction of these radioactive isotopes to the environment can result in radiation exposures demanding the evacuation of local populations and billions of dollars in economic losses. Therefore, the goal of nuclear safety is to forestall this outcome both by reducing the likelihood of accidents as much as possible and by attempting to prevent the release of radioactive material even in the event of a severe accident.

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2 We use the term advanced nuclear reactor to refer to a reactor using technologies other than those used in the large LWRs that are currently operating in the United States.

$7.4$ billion, or about $3,300 per kilowatt, the increase being caused by mounting construction delays (Overton, 2015).
Current LWRs achieve these goals through the use of a defense-in-depth strategy that aims to provide multiple barriers between the radiological inventory in the fuel and the environment. The first, and most important, of these barriers consists of the fuel assemblies themselves. All nuclear power plants currently operating in the United States utilize fuel that consists of uranium dioxide pellets jacketed in a zirconium-alloy cladding (the best-known brand being Zircaloy). These are assembled into carefully engineered fuel bundles with the geometric, chemical, and nuclear characteristics essential to survive within the punishing environment of a nuclear reactor core. So long as the fuel assemblies remain intact, little or no radioactive material will escape. The second layer of defense is found in the massive steel reactor vessel that surrounds the fuel assemblies. Designed to operate at high pressure and temperature, the reactor vessel places several inches of steel between the fuel and the third layer, the containment building. This ferroconcrete structure, which varies considerably in design between power plants, aims to prevent the release of radioactive material even in case of an accident compromising the integrity of one of the reactor’s primary coolant loops.

Typical LWR fuel assemblies have problematic physical and chemical properties that pose serious challenges in the case of an accident. Although the uranium oxide fuel pellets have a high heat resistance, their poor thermal conductivity allows their interior to approach the material’s melting point of 2,865 degrees Celsius even under ordinary operating conditions. The zirconium-alloy fuel cladding fails at a much lower temperature and experiences a catalytic reaction with heated steam producing large amounts of potentially explosive hydrogen, as the Fukushima Daiichi accident dramatically illustrated. To avoid these pitfalls, the fuel must be adequately cooled at all times, including when the reactor is shut down. Although LWRs are essentially immune to the kind of runaway power excursion that caused the explosion of Chernobyl Nuclear Power Plant unit 4 in April 1986, the decay of short-lived radioisotopes in the core produces so much heat that, in the absence of cooling water, it can cause the fuel assemblies to lose integrity within minutes, resulting in a nuclear meltdown. Unfortunately, the use of highly pressurized water as coolant makes maintaining cooling under accident conditions particularly challenging. A break in the reactor loop can allow the water to flash into steam, potentially exposing the fuel assemblies, and introducing additional cooling water requires either substantial energy, the depressurization of the reactor vessel, or both.

LWRs therefore need engineered safety systems to avoid a nuclear meltdown, but these do not come cheap. Having multiple redundant emergency cooling arrangements designed to address different accident conditions increases the construction and operational complexity of LWRs, swelling their costs. Furthermore, in older plant designs, these systems require considerable amounts of electrical power to function, but the Fukushima Daiichi accident proved the naïveté of assuming the availability of emergency power. Plant designers have sought to overcome these challenges by pursuing economies of scale, but increasing the size of LWRs compounds some of their safety problems. The larger the reactor core, the lower the ratio of the surface area of the reactor vessel to the core volume, increasing the difficulty of passive cooling. Furthermore,
large nuclear plants demand precision, high-quality construction on a scale that severely taxes the contractors tasked with building them, often increasing costs because of the need to redo work first performed incorrectly. Finally, larger plants have longer construction times, and those help inflate financing costs to prohibitive levels.

Despite these challenges, the general technical consensus is that current LWR designs, such as Westinghouse’s AP1000 and Areva’s EPR, are safe enough to offer an extremely high assurance that even an extreme accident would pose negligible danger to the public.\(^4\) Sixty years of experience designing and operating LWRs, thousands of reactor-years of cumulative operation, and the best efforts of thousands of nuclear engineers, however, have not produced a design for a large LWR that is both safe and affordable enough to compete with conventional sources of electricity. If nuclear power is to play a major role in America’s energy

\(^4\) The cancellation of Constellation Energy’s plans to build an EPR in Maryland leaves the AP1000 as the only new nuclear plant design under construction in the United States. For an assessment of the safety characteristics of the AP1000 produced by the UK government, see UK Health and Safety Executive, undated.
future, new reactor designs with intrinsically better safety characteristics must be found.

Thankfully, large LWRs are far from the only way to exploit the potential of fission. Historically, pressurized-water reactors and boiling-water reactors were merely two of a wide range of power reactor designs investigated by the Atomic Energy Commission (AEC), and, arguably, they came to predominate for circumstantial reasons. Today, a variety of alternative nuclear power paradigms are under investigation both in the United States and abroad.

All but the least exotic of these proposals take a very different technical approach to nuclear safety from that of current LWRs. Aiming to eliminate the reliance on costly engineered safety systems that crippled the economic viability of present-day designs, these reactors posit combinations of fuel and coolant that promise high safety margins even in the absence of emergency power or operator intervention. In short, they seek safety in physics rather than in engineering. But without experience operating pilot plants, the NRC is ill-equipped to evaluate power reactors that deviate substantially from light-water designs, and the current regulatory framework makes assumptions that might not be appropriate for novel nuclear concepts. For reasons explained below, both practical experience with alternative nuclear technologies and institutional reforms are necessary before the United States can contemplate deploying these new reactors.

Regulating Beyond Light Water

Unfortunately, because of the historical predominance of LWRs in the United States, the NRC is poorly equipped to evaluate the safety of alternative technologies. Practical experience with a type of reactor is essential to develop appropriate regulations, and all but a handful of early U.S. nuclear power plants utilized LWRs. The NRC’s institutional procedures evolved over time on the basis of growing experience constructing and operating nuclear power plants, on several occasions as a reaction to near misses that called its regulatory assumptions into question. These events, including the 1975 Browns Ferry fire and the 1979 meltdown of Three Mile Island unit 2, stemmed from the dismissive attitude toward safety risks that the NRC’s institutional predecessor, the AEC, demonstrated. Determined to spur the widespread commercial adoption of nuclear fission, the AEC discounted its own employees’ warnings that the technical assumptions undergirding its safety regulations remained untested and might be egregiously in error (Walker, 2004, pp. 54–62). Most critically, AEC regulators focused on a narrow range of possible accidents—in particular, a so-called design-basis accident involving the sudden breakage of the largest pipe in the primary coolant loop—and convinced themselves that safety measures designed for this extreme scenario would prevent severe core damage in any likely accident. Because the design-basis accident did not incorporate external initiating events, such as earthquakes, and the possibility of operator error, nuclear engineers sought to combat it largely by means of redundant engineered safety systems.

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5 An influential 1990 article by economist Robin Cowan argues that, although “light water is considered inferior to other technologies,” the heavy investment of the U.S. Navy in LWRs for naval propulsion allowed it to become entrenched before alternatives could enter the market (Cowan, 1990).

6 For a discussion of the AEC’s philosophy regarding the design-basis accident, see Thompson and McCullough, 1973.
Although the AEC’s overconfidence in this area later caused considerable grief for the U.S. nuclear industry, the organization was actually overly conservative in other areas of nuclear safety. Uncertain how melting fuel would interact with reactor vessels and containment buildings and unwilling to undertake expensive and politically risky physical experiments in this field, the AEC assumed that substantial fuel damage would likely cause unacceptable radioactivity releases to the environment (Geist, 2014). This belief compounded the emphasis on engineered safety systems because LWR fuel would require some sort of cooling during an accident.

A public scandal resulting from the AEC’s attempt to squelch concerns about the potential inadequacy of the emergency core-cooling systems in plants then under construction helped impel the establishment of the independent NRC in 1975 (Walker, 2004, p. 62). Shortly after the NRC’s formation, the new agency began exploring alternatives to the deterministic approach to nuclear safety embodied in the perspective of the design-basis accident. The influential Reactor Safety Study adapted the probabilistic risk assessment (PRA), a technique first pioneered in the aerospace industry, to estimate the probability that a large LWR would experience an accident resulting in severe core damage. The PRA assigns probabilities to a large number of events that might occur during the course of a nuclear accident, then utilizes these figures to calculate probabilities of sequences threatening core integrity. The PRA represented an immense improvement over the older, deterministic technique because it can account for a much broader array of possible accidents, but it had two associated pitfalls: It addressed only those risks considered by the analysts, and its estimates could never be any more accurate than the probabilities the analysts employed, even though, in many cases, these values were no more than semi-educated guesses.

As a consequence, the PRA initially received a mixed response from both the nuclear industry and skeptics of nuclear power. Producers of nuclear energy found it much less straightforward to design and operate plants to account for the many accident sequences envisioned by the PRA than to address a single design-basis accident (Guibert, 1983). Opponents of nuclear power, meanwhile, dismissed the PRA as a cynical attempt to silence criticism by using dodgy statistics to assert that nuclear reactors were “safe enough.”8 As a consequence, the NRC only gradually integrated the PRA into its regulatory activities over the subsequent decades; even today, it continues to employ a combination of empirical and risk-based techniques.9

The NRC did not apply its shifting regulatory requirements equally to all plants. In accordance with the so-called backfit rule, modified regulations apply differently to facilities depending on the date on which their construction or operating licenses were issued.10 In practice, the logic of the backfit rule has led to absurd

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7 On the history of the PRA for civilian nuclear facilities, see Keller and Modarres, 2005.

8 For an important early example of this, see Union of Concerned Scientists, 1977.

9 For the NRC’s account of the increasing use of risk-based techniques in its regulatory activities between the 1970s and the 1990s, see NRC, 2013. In recent years, the NRC has increasingly explored the possibility of making a full transition to what it calls a Risk Management Regulatory Framework that would complete the transition to risk-informed approaches. See Risk Management Task Force, 2012.

10 For the NRC’s regulatory definition of the backfit rule, see NRC, 2014a.
results, which are illustrated by the handful of nuclear power plants currently under construction in the United States. Although the four AP1000s being built in Georgia and South Carolina are the only nuclear power plants that have begun construction in the United States since the 1970s, another plant is currently nearing completion—the Tennessee Valley Authority’s (TVA’s) Watts Bar unit 2 in Tennessee. Although the AP1000s experienced costly construction delays when the NRC imposed new regulations for resistance to aircraft impact, Watts Bar was exempt from these measures—because it has an active construction license that the AEC approved during the Nixon administration.11

The NRC’s current regulatory regime is a source of intense dissatisfaction for all stakeholders, including the nuclear industry, its critics, and the NRC itself. The builders and operators of nuclear power plants consider themselves to be subject to arbitrary and inconsistent regulations, capriciously applied by an overbearing bureaucracy.12 Antinuclear activists, meanwhile, regularly assert that the NRC too often bows to industry demands and is the victim of “regulatory capture.”13 These positions are not mutually exclusive—it is entirely possible for the nuclear industry to be simultaneously overregulated in some respects and underregulated in others. Finally, the NRC is underfunded and understaffed to carry out all parts of its mandate, despite the small number of facilities under construction and the shrinking number of older plants that remain in service.14 It struggles to compete for qualified personnel with private industry and other sectors of the government, and it is torn between a fee-for-service funding model that makes it dependent on the industry it regulates and politicians who meddle in its decisions (U.S. Government Accountability Office [GAO], 2012, p. 30).

In short, the history of civilian nuclear regulation in the United States offers relatively few positive lessons for how to craft a regulatory foundation for a qualitatively different type of civil-

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11 For these regulations regarding aircraft impact, see NRC, 2014b. Watts Bar units 1 and 2 began construction in 1973, but work ceased in 1988. In 1996, TVA completed unit 1, which is the most recent nuclear plant to enter service in the United States. Because of a peculiarity of its charter, which forbade it from writing off its partially completed nuclear plants like all private utilities ultimately did, TVA is the only utility with outstanding construction licenses predating the NRC. In addition to building Watts Bar, TVA also has construction licenses for Bellefonte units 1 and 2 in Alabama, and it has seriously considered completing these units as well.

12 Congressional nuclear energy proponents grilled Allison Macfarlane on NRC “overregulation” at her 2013 confirmation hearings (Nuclear Energy Institute, 2013).


14 Although NRC staffing increased considerably in the 2000s in response to increasing retirements and anticipation of a nuclear renaissance, these personnel lacked the experience of those departing and did not necessarily have the particular esoteric skills that the regulator needed. At present, the NRC is proposing to reduce its staff from 3,677 today to about 3,400 in 2020 (“US NRC Could Shrink by 10% in Five Years,” 2011).
ian nuclear technology. It does, however, provide several important lessons:

• Because of its hybrid of deterministic and risk-informed approaches, the NRC’s current regulatory regime might be too closely tailored to the large LWRs currently in use to evaluate other reactor technologies fairly.
• The risks of any new technology need to be assessed prior to the design of the regulatory framework, rather than following commercialization, as occurred with LWRs.
• This assessment should include an analysis of off-site consequences of the maximum credible accident whose assumptions have been verified by empirical data.15

The Neglected Department of Energy Role in New Reactor Development

In theory, the NRC is supposed to work in concert with the Department of Energy and industry interests to develop, license, and commercialize new nuclear power reactor technologies, but this arrangement has never worked as intended. Prior to its dissolution in the mid-1970s, the AEC aggressively sought the commercialization of nuclear reactors for civilian power generation. In addition to evaluating the LWRs that ultimately saw widespread adoption, which were originally developed for military applications, the AEC investigated a wide array of reactor technologies envisioned solely for civilian roles. In some cases, such as the aqueous homogenous reactor at Oak Ridge National Laboratory, the AEC constructed an experimental reactor on the territory of its own facilities (Rosenthal, 2010, pp. 14–23). In others, such as that of the short-lived Hallam Nuclear Generating Station in Nebraska, the AEC partnered with private industry to construct and operate pilot commercial plants (U.S. Department of Energy Office of Legacy Management, 2008, pp. 2–4). These experiments provided the operational experience essential both to develop commercially viable reactors and to establish necessary regulatory norms. The AEC’s role as both promoter and regulator of civilian nuclear power, however, created a serious conflict of interest. An increasing perception that the AEC had pressed for the aggressive adoption of large nuclear reactors for power generation without establishing their safety characteristics first helped impel the breakup of the AEC into the NRC and the Energy Research and Development Administration (ERDA) in 1975. As implied by its moniker, ERDA inherited the AEC’s mission to develop and promote new civilian nuclear technologies (Walker, 2004, pp. 31–34).

Although ERDA—and, from 1977, its successor, the Department of Energy—aimed to continue the AEC’s earlier precedent of maintaining effective partnerships between government and industry to bring new reactor technologies into commercial use, both political and market pressures conspired to prevent this. Private industry invested heavily in nuclear energy during the 1960s and 1970s for two reasons. Firstly, strong growth in electric power consumption throughout the postwar period established a perception that electricity demand would continue to increase rapidly for the foreseeable future. With so much future demand, it seemed that new forms of electricity generation would be essential to meet it all—and utilities invested in nuclear fission accordingly. Secondly,
form of new generation.\textsuperscript{16} Thanks to these assumptions, during the AEC era, both utilities and plant vendors had been willing to fund the construction and operation of commercially unviable prototype nuclear plants in the belief that the experience they gained would pay handsome dividends down the road. By the end of the 1970s, changing economic conditions exploded both of these rationales for commercial interests to risk investment in untried nuclear technologies. The 1973 energy crisis and its 1979 reprise, along with a stagnant economy, slowed growth in electricity demand to a fraction of what had been expected a few years before. Furthermore, massive cost overruns and indifferent operational performance made the large LWRs under construction much less economically attractive than projected. Where the AEC had coaxed utilities to invest in nuclear power with visions of ample future profits, they found themselves struggling to recoup their multidecade investment in the technology (Walker, 2004, pp. 7–9). Understandably feeling burned by this experience, utilities showed little subsequent interest in taking chances on exotic nuclear reactors.

Nor did the Department of Energy prove a particularly enthusiastic advocate for the development of new types of nuclear power plants. Charged with activities ranging from maintaining the nation’s nuclear arsenal to conducting basic scientific research, the Department of Energy found itself overburdened with more pressing responsibilities. Increasing awareness of the lamentable environmental legacy produced by careless practices during the early years of U.S. nuclear weapon development both consumed an ever-increasing fraction of the department’s budget and helped inspire intense scrutiny of the department’s research programs, particularly in controversial areas, such as nuclear power. The department could legally construct and operate exotic research reactors on its own territory without being subject to NRC regulations because it inherited from the AEC the right to self-regulate its own nuclear facilities, but there has been little budgetary or political support to exercise this privilege.\textsuperscript{17}

Given these unfavorable conditions, it is of little surprise that the Department of Energy’s activities developing new types of power reactors have largely been continuations of research efforts that were particularly advanced at the time of the AEC’s dissolution. These programs have emphasized two types of reactors: liquid sodium–cooled fast reactors and high-temperature gas-cooled reactors (HTGRs). During the AEC era, many in the technical community believed that future energy demand would ultimately

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\textsuperscript{17} Given the Department of Energy’s imperfect safety and environmental record, there have been several proposals that an agency, such as the NRC, should have oversight of the department’s nuclear facilities. For instance, see Haughney et al., 1999.

\textsuperscript{16} For a contemporary assertion of these views, see Atlantic Council of the United States, 1976.
demand the widespread deployment of nuclear breeder reactors, which produce more usable nuclear fuel than they consume, and fast reactors utilizing molten sodium as coolant appeared to offer the most promising gateway to a future so-called plutonium economy. As a consequence, the AEC lavished a disproportionate share of its attention and resources on these reactors, including test reactors on its own territory (such as the Experimental Breeder Reactor), and pilot commercial plants (such as the Enrico Fermi Nuclear Generating Station on Lake Erie) (Waltar and Reynolds, 1981, pp. 24–25).

At the time the AEC broke up, the centerpiece of this program was the Clinch River Breeder Reactor project, which aimed to build a 350-megawatt prototype fast reactor plant in Oak Ridge, Tennessee. Although safety and proliferation concerns stoked increasing political opposition to this effort in the late 1970s, runaway cost inflation sounded the project’s ultimate death knell. Where the AEC had expected costs to be split evenly between government and industry investors, as the budget swelled, commercial interests refused to increase their pledged contributions. As a result, this single project cannibalized most of the Department of Energy’s budget for advanced nuclear development in its early years, and more than $1 billion in government money was expended by 1981 even though construction never progressed beyond the preliminary phase (Boudreau, 1981, p. 119). By the time Congress canceled the project in 1983, the General Accounting Office predicted that the reactor would require a total of $3.6 billion to complete (Bowsher, 1982, p. i).

Following the cancellation of the Clinch River Breeder Reactor project, the Department of Energy pursued the integral fast reactor, an alternative sodium-cooled reactor development program that made more-efficient use of resources inherited from the AEC. Instead of attempting to construct an astronomically expensive pilot plant from scratch, which the French and Soviets were doing on a grander scale anyway, the integral-fast-reactor program aimed to demonstrate critical new technologies in facilities originally built in the 1960s. Modifications to the Experimental Breeder Reactor II aimed to demonstrate both the reactor’s passive safety characteristics and on-site reprocessing of metallic fuel using electrolysis (Chang, 1989). Opposition to the project in Congress, however, resulted in its cancellation in 1994 before some of these goals had been met (Westfall, 2004, pp. 25–27).

In addition to the stillborn dream of fast reactors, the Department of Energy pursued a second advanced reactor technology—HTGRs. Like research on the breeder, research into this concept was already well advanced when the department was established. The AEC had worked with the Philadelphia Electric Company to build a pilot HTGR that went online in 1966, and a powerful industrial player, Gulf General Atomic, was aggressively promoting a standardized HTGR of its own design (International Atomic Energy Agency [IAEA], 2001, p. 6). Most orders for these plants were canceled, but a single unit, Fort St. Vrain, operated in Colorado from 1979 until 1989 (Copinger and Moses, 2004). Whereas growing concerns about safety and proliferation, as well as low uranium prices, made fast metal-cooled reactors an increasingly dubious proposition in the 1980s, they increased the appeal of HTGRs. Bolstered by the coalition of commercial interests dubbed Gas Cooled Reactor Associates, the Department of Energy sponsored a research program to develop what it called a Modular High-Temperature Gas-Cooled Reactor (MHTGR) that built on earlier experience. Thanks to this industry interest, a preliminary safety
information document about a 350-megawatt-thermal MHTGR was submitted to the NRC in 1986. The NRC issued a generally favorable draft safety evaluation report on the proposed design in 1989, but regulatory progress then stalled because of what briefly seemed like a fortuitous development for the MHTGR program (IAEA, 2001, p. 9).

Although it initially envisioned the MHTGR as a useful source of process heat for industrial applications, at the end of the 1980s, the Department of Energy became interested in the possibility of building a highly modified MHTGR on the territory of one of its own research facilities to produce the tritium needed to maintain the U.S. nuclear arsenal. Dubbed the New Production MHTGR, the design changes necessary for tritium production inspired doubt within the NRC as to the applicability of the earlier safety review; in any case, the predicted final cost of $3.6 billion made the project a political nonstarter. The New Production MHTGR program was canceled in 1992, followed by the interruption of the Department of Energy’s other HTGR development efforts in 1994 (IAEA, 2001; Lartonoix, 2014, p. 158).

Near the end of the Clinton administration, the Department of Energy revived its HTGR research efforts, which led to the still-ongoing Next Generation Nuclear Plant (NGNP) program. In 1999, the department launched the Nuclear Energy Research Initiative, which aimed to develop nuclear reactors with better safety, proliferation resistance, and economic characteristics than LWRs (World Nuclear Association, 2015). Because HTGRs operating on a once-through fuel cycle appeared to meet these goals and looked comparatively technologically mature, the department soon chose to emphasize this particular technology. The Energy Policy Act of 2005 (Pub. L. 109-58) formally established the NGNP program, with the ultimate aim “to demonstrate the generation of electricity and/or hydrogen with a high-temperature nuclear energy source”—in this case, by completing a prototype HTGR at Idaho National Laboratory by 2021. Between fiscal years 2006 and 2010, the Department of Energy expended $528.4 million on the NGNP program, but, in 2011, plans to move forward with what it called phase 2 and build the pilot plant were put on hold for budgetary reasons (U.S. Department of Energy Office of Nuclear Energy, 2010, pp. i, iii; GAO, 2014). Despite this impasse, in 2012, the department selected an Areva HTGR design utilizing prismatic block fuel and a steam cycle for the prototype facility, although it did not provide Congress with initial design parameters as required under the Energy Policy Act (“Areva Modular Reactor Selected for NGNP Development,” 2012).

In 2014, GAO reported that progress toward constructing the NGNP had effectively stalled. The inability to formulate a cost-sharing agreement acceptable to both government and industry poses an imposing obstacle to the NGNP, but the Department of Energy’s unwillingness to specify exactly what it aims to build makes both budgetary and regulatory challenges impossible to resolve. Wary of the department’s well-established reputation for cost inflation and missed deadlines, industry players are loath to invest in the project without a clear guarantee that their contributions will both remain predictable and result in an operational facility. Meanwhile, the NRC “has reassigned staff from its NGNP work and engages with [the Department of Energy’s Office of Nuclear Energy] on a minimal basis” because NRC officials believe “that they cannot proceed substantively further in developing a licensing framework until [the Office of Nuclear Energy] has developed a specific design for an advanced reactor technology” (GAO,
In light of these circumstances, GAO reached the sensible conclusion that “it is not clear if or when” the Department of Energy will actually build the NGNP (GAO, 2014, p. 32).

The institutional procedures of both the Department of Energy and the NRC contribute to a vicious cycle that impedes the development of new types of nuclear reactors in the United States. During its four decades of existence, the Department of Energy has spent billions of dollars on research into non-LWR technologies, without many tangible results. Technologically, the selected design for the NGNP is not all that different from the stillborn 1980s MHTGR. Without experience operating new types of reactors, it is difficult to learn enough about their operational and safety characteristics to ascertain their commercial viability. Government investment in experimental reactors is acceptable only with substantial investment from private sources, but these interests fear a repeat of the Clinch River Breeder Reactor scenario, in which the project consumed far more than the original budget despite never coming anywhere near completion. Furthermore, private industry is obviously interested in contributing only to projects with clear commercial potential, yet costly pilot facilities must be built before the marketability of new reactors can be confirmed. As a consequence, the Department of Energy and industry have concentrated their resources on technologies that are already comparatively mature, particularly HTGRs. Yet, even after decades of intense interest from both the department and industry, the NRC has yet to specify what the safety requirements for HTGRs should be; without substantial guidance on this issue, it is impossible to design the pilot plant and predict how much it will cost. Without institutional reforms of some kind, this pattern is likely to repeat itself ad infinitum, preventing the construction and licensing of non-LWR nuclear plants in the United States.

Such reforms could take a variety of forms, but only a few of them are politically or economically realistic. One possibility would be to recreate the conditions under which nuclear power was originally developed by significantly relaxing regulatory requirements for prototype plants, but this seems highly implausible, as does the prospect of vastly increased federal research and development funding for the development of new types of nuclear reactors. For the foreseeable future, the likeliest means of licensing non-LWR plants in the United States might be to draw more effectively on the experience of other countries that are aggressively pursuing such technologies. By forging effective partnerships with these nations, the United States could influence their research priorities toward issues of particular interest to U.S. regulators and industry. Foreign partners would benefit from this arrangement because the NRC has a reputation of being particularly thorough compared with its counterparts elsewhere, so a plant approved by the NRC would probably benefit from greatly improved international marketability. The downside of emphasizing such partnerships is that they would betray the longstanding goal of the Department of Energy’s research efforts to maintain U.S. industry leadership in civilian nuclear energy. Without operational experience, however, there is
little chance that the United States will be able to attain leadership in the field of advanced reactor technologies.

Envisioning Alternative Nuclear Futures

The Chernobyl and Fukushima Daiichi disasters established that the primary hazard that nuclear power plant accidents pose to the public results from the escape of cesium and iodine radioisotopes (United Nations General Assembly, 2013, p. 8). Although these two elements make up only a limited fraction of the radiological inventory of a power reactor, their volatility allows them to escape and disperse in the surrounding environment much more readily than other isotopes. To represent a meaningful improvement over current LWR technology, new nuclear reactor designs, such as those listed in the table, need to provide a significantly more cost-effective strategy for preventing the escape of such radioactive materials during an accident. Although proposed new reactor concepts pursue this end with means ranging from minor variations on well-established technologies to highly exotic deviations from past practice, all of them sit uncomfortably in the present regulatory paradigm.

The most mundane of the current contenders for the future of nuclear power is a small, modular variant on current LWRs. The comparatively small size of these reactors—ranging from tens to a few hundred megawatts of generating capacity, in contrast to more than a gigawatt for a typical LWR—offers a variety of safety advantages. It is much more straightforward to design passive emergency cooling systems requiring no electrical power to operate for a small LWR, and the reactors can be made compact enough to site underground, obviating the NRC’s concerns about resistance to aircraft impact. The reactors can also be assembled in a factory rather than on site, leading to higher quality assurances and shorter construction times. Small LWRs also benefit from decades of naval experience and utilize the same fuel and materials as existing plants. Yet this attribute is a mixed blessing because it also means that small, modular LWRs can achieve only a limited improvement in their cost and safety performance over their larger brethren, particularly because they cannot take advantage of the same economies of scale. Furthermore, despite their relatively conventional designs, even these reactors are hamstrung by the fact that the NRC currently licenses nuclear plants on a per-reactor basis, with no discount for smaller capacities.

Some Possible Future Reactor Types

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<td></td>
<td>Lead-cooled fast reactor (BREST [Bystry Reaktor so Svintsoy Teplonositelem, or fast reactor with lead coolant])</td>
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<tr>
<td>Molten salt</td>
<td>Advanced high-temperature reactor</td>
<td>Liquid-fluoride MSR</td>
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The most—technologically mature alternatives to LWRs at present are fast reactors utilizing molten metal as coolant. Historically, these reactors were the subject of much enthusiasm in both the United States and abroad because of the possibility that they could be constructed to breed more usable nuclear fuel than they consumed, but lower-than-envisioned uranium prices and proliferation concerns have caused most nations to abandon this pursuit. Fast reactors present a set of hazards that differs from that of LWRs because, without careful core design, they could be subject to the kind of positive void and thermal coefficients of reactivity that caused the Chernobyl disaster. The use of molten metal as coolant is arguably preferable to using water because of the former’s high thermal capacity and high boiling point. This allows the reactor to operate at high temperature and low pressure. Unlike an LWR, in which a pipe break can allow the cooling water to flash to steam as it depressurizes, potentially exposing the fuel, the coolant in a metal-cooled fast reactor can be at atmospheric pressure, and it can absorb substantial amounts of decay heat during an accident before emergency cooling is needed to prevent damage to the fuel.

The particular safety characteristics of such a reactor, however, depend on the exact choice of fuel and coolant. The combination used in Russia’s BN-600 and BN-800 reactors—uranium oxide fuel with molten-sodium coolant—is both familiar and relatively inexpensive, but, although the sodium interacts well with reactor materials, its violent reaction to water has caused serious operational problems. Another option, employed by the Soviet Union in its Alpha attack submarine, is the use of lead-bismuth eutectic as coolant. This offers a low melting point and extraordinary thermal capacity, which allows lead-bismuth fast reactors to be extremely compact relative to their power output—with the potential for considerable associated cost savings. A miniature fast reactor could easily be sited underground, alleviating concerns about terrorist attack and some kinds of natural disasters. The thermal properties of lead bismuth also mean that such reactors could be highly resilient against operator error and the loss of external power. Unfortunately, lead bismuth suffers from economic and operational disadvantages as well. Enormous quantities of bismuth are required relative to current uses of that element, and the lead-bismuth eutectic is much harder on reactor materials than either sodium or water, despite being free of elemental sodium’s violent chemical reactivity with water. Russia has declared its intention to build a prototype of a small, modular lead-bismuth fast reactor in the next few years, and an American start-up, Gen4 Energy, is also attempting to commercialize the technology.

Although metal-cooled reactors aim to make nuclear power safer by using a coolant that is difficult to boil away, HTGRs pursue this end by using fuel assemblies that are extremely difficult to melt. In theory, ceramic fuel assemblies could retain their integrity without emergency cooling even in case of a severe accident. Like liquid metal–cooled fast reactors, this concept has a long history both inside and outside of the United States. As noted above, the only non-LWR power reactor that ever operated in the United States under NRC auspices, the Fort St. Vrain Generating Station, was an HTGR, and Department of Energy research efforts have disproportionately focused on these reactors.

In more-recent decades, much attention has been paid to a variety of HTGR known as the pebble-bed modular reactor, in which the ceramic fuel and graphite moderator are combined into spherical pebbles. These were pioneered in Germany between the 1960s and 1980s; today, the Chinese are constructing a two-unit
prototype at Shidaowan in Shandong province of their own variation of the pebble-bed concept, dubbed the High Temperature Reactor—Pebble Module (HTR-PM). This plant’s designers assert that it will be so safe as to “practically exclude the need for [an] off-site emergency plan.” This safety depends heavily on the expected high performance of the reactor’s tristructural-isotropic fuel. Although the fuel pebbles are intended to withstand temperatures in excess of 1,600 degrees Celsius during an accident, further heating could cause them to fail and release dangerous radioisotopes. As a result, to withstand a lengthy period without active cooling, the pebbles need to be able to eject heat to the environment—but the sort of steel and concrete containment structures normally used in LWRs would prevent this. The HTR-PM therefore features a “low-pressure vented containment” (which probably does not meet the NRC’s definition of containment as an “essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment” [NRC, 2014c, criterion 16]). It would therefore be difficult to license such reactors under the NRC’s current defense-in-depth paradigm, even if a risk-based assessment found that the HTGR posed smaller hazards to the public than present-day LWR designs.

A still more exotic type of reactor aims to overcome the challenges of meltdowns by starting with molten fuel. Although, at first glance, such an approach appears highly counterintuitive, reactors employing molten salt as fuel could provide substantial safety advantages over solid-fuel designs. Like liquid metal–cooled fast reactors, MSRs can operate at high temperature and low pressure and can be extremely compact relative to water- or gas-cooled reactors with the same power output. Employing the fuel itself as a heat-transfer medium, as well as the ability to use simple passive measures, such as freeze plugs, to automatically drain the fuel into a passively cooled noncritical configuration in case of an emerg-
emergency, could substantially or totally eliminate the need for the kind of complicated safety systems that make LWRs so expensive. In contrast to the reactors described above, however, practical experience with MSRs is too limited at present to ascertain how easily they could realize these promises. Oak Ridge National Laboratory operated two experimental MSRs during the 1960s and early 1970s, and, although the results showed considerable potential, they could not clarify many of the practical issues that must be understood before MSRs can be commercialized (Haubenreich and Engel, 1970). A mind-boggling diversity of MSR designs is theoretically possible, with some of them incorporating online reprocessing capabilities that might pose serious safety and proliferation concerns. Furthermore, their safety and operational characteristics are likely to be linked strongly to their exact fuel chemistries and core designs, which could take many forms.

MSRs are so alien to the current NRC regulatory paradigms that it is difficult to see a path to licensing them in the United States, particularly given the Department of Energy’s historical struggles to construct a prototype of the vastly more-conventional HTGR. The chief executive officer of a start-up developing an MSR complained in congressional testimony in December 2014 that, “right now, there is no viable pathway for bringing advanced nuclear reactor designs beyond laboratory-scale development” and that, as a result, the current system incentivizes reactor designers to develop their first products outside of the US. In fact, this has already happened: some existing nuclear reactor design companies are planning on building their first power plants overseas . . . because they do not think it will be possible to build an advanced reactor in the US under the current regulatory system. (Dewan, 2014, p. 2)

NRC chair Stephen G. Burns essentially admitted the inability of his agency to formulate a regulatory framework for advanced reactors at the NRC’s 27th annual Regulatory Information Conference in March 2015. Noting the interest of firms, such as Trans-

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20 Although MSR technology has never matured to the point of being a serious proliferation risk, these reactors could produce weapon-usable fissile materials, such as U-233. Theoretical investigations of proliferation-resistant MSR variants date back to the 1970s and continue today (Ahmad, McClamrock, and Glaser, 2015).
atomic and Gen4, in receiving NRC feedback on exotic reactor designs, Burns insisted that the commission was “willing and able” to work on this problem but that, “without a specific applicant, and with intense pressure on resources and budget, it is challenging for the NRC to be too forward-leaning and expend significant resources on the development of a new regulatory framework” (“No Mid-Life Crisis for NRC,” 2015). Therefore, next-generation reactors face a potentially insurmountable chicken-and-egg problem: Investors will fund the development of the technology only with a viable path to commercialization, but the NRC will develop the requisite regulatory framework only in response to a serious applicant.

**Nuclear Safety from the Outside In**

If fission is to play a larger role in America’s energy future, fundamental reforms are needed in the U.S. nuclear regulatory regime. The current regulatory paradigm is questionable even for the large LWRs in use today, as the NRC’s decades-long attempt to transition to a consistent risk-informed approach attests, and it is not at all adapted to significantly different reactor designs. Although such reforms pose a massive challenge, they also present an opportunity to escape some of the dubious assumptions and preoccupations that have bedeviled the U.S. nuclear industry since the AEC era.

Although the NRC has failed to articulate an appropriate regulatory framework for advanced reactors, the Department of Energy and industry share the blame for the United States’ difficulties developing these technologies. Sensibly, the NRC feels that, without substantial hands-on experience with new types of reactors, it cannot determine how to regulate them appropriately. In theory, the Department of Energy is supposed to work with industry to develop new nuclear reactor technologies and demonstrate their commercial viability, but this arrangement has never worked as intended. Planned prototype plants, such as the Clinch River Breeder Reactor and the MHTGR, consumed vast sums without ever coming to fruition. Scarred by these experiences, industry is skeptical of cost-sharing arrangements with the Department of Energy to build pilot facilities, but, without these, building the prototype reactors needed to understand exotic nuclear technologies well enough to draft commercial designs is politically infeasible. Meanwhile, the NRC is unwilling to issue a clear judgment on the safety requirements for advanced nuclear reactors without a fully specified design requiring years of effort and a massive investment to produce. This expectation is tantamount to a demand that companies invest tens of millions of dollars developing advanced plant designs based on no more than an educated guess about what the ultimate regulatory requirements will be. Given this mutually reinforcing tangle of institutional dysfunction, it is little wonder that advanced nuclear reactor technologies are little closer to commercialization in the United States today than they were a quarter-century ago.

Since the 1950s, the United States has conceptualized the problem of nuclear power plant safety “from the inside out.” Safety regulations emphasized preventing or limiting damage to reactors themselves on the assumption that this approach would protect the public most effectively. This monomania for preventing, rather than
managing, accidents led to embarrassing failures, such as the Three Mile Island accident, and the same attitude catalyzed the catastrophes at Chernobyl and Fukushima Daiichi. In each of these cases, the belief that serious accidents would never occur encouraged a neglect of emergency planning that crippled authorities’ ability to take effective action to protect the public (Geist, 2014).

The objective of nuclear safety regulation should be to minimize the health and economic impacts of large-scale accidents, rather than to minimize the theoretical incidence of damage to reactors. Rather than focus on saving the reactor, the goal should be to protect the public from the outside in. New nuclear technologies, such as liquid-fuel reactors, could enable formerly inconceivable means of achieving this end. Reactors designed to sacrifice themselves in an accident in order to minimize the chance of radiological releases might prove not only feasible but vastly more cost-effective than present-day LWR designs. Plants might be designed so that, in the worst-case scenario, they fail elegantly so as to create an accident with characteristics more favorable to effective emergency management. Instead of perpetuating the hubristic, and infeasible, ambition to somehow prevent all accidents, the aim should be to prevent accidents from becoming catastrophes.

To encourage the development of new civilian nuclear technologies, the United States should forge relationships with other nations to develop the operational experience and technical data necessary to commercialize non-LWR nuclear plants. Much of these data can be acquired only through the construction and operation of pilot facilities, but, even with substantially increased funding and political support, it seems unlikely that the Department of Energy will construct more than one type of prototype reactor. To face the possible energy challenges of the 21st century, the department has a responsibility to explore all potentially promising energy technologies, and this is feasible only by partnering with nuclear research programs in states that are aggressively developing advanced reactors. Although a nuclear energy policy emphasizing international cooperation is contrary to the past goal of maintaining U.S. industry leadership, if present conditions continue, the United States risks having little influence over the future of nuclear power at all. Working with international partners, instead of competing with them, will help ensure that U.S. values regarding safety and proliferation resistance will be reflected in future nuclear plants wherever they are built and potentially produce the knowledge base needed to commercialize advanced nuclear reactors in the United States.

21 For instance, NRC review of the NGNP still set goals in terms of core damage frequency, rather than assessments of offsite consequences (NRC, undated).

22 A liquid-fuel format offers the intriguing possibility of radically altering the fuel chemistry during an accident to reduce the volatility of radioisotopes, such as I-131 and Cs-137. For instance, an MSR could incorporate a passive safety arrangement utilizing blocks of salt designed to melt if the reactor exceeds a certain temperature to effect such a change in the fuel. Even though the resulting fuel mixture might cause irreparable damage to the reactor, the simplicity of the arrangement might make the reactor so cheap as to be essentially disposable—achieving a far better combination of economics and safety than that of current LWRs.
References


IAEA—See International Atomic Energy Agency.


NRC—See U.S. Nuclear Regulatory Commission.


### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AEC</td>
<td>Atomic Energy Commission</td>
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<tr>
<td>ERDA</td>
<td>Energy Research and Development Administration</td>
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<tr>
<td>GAO</td>
<td>U.S. Government Accountability Office</td>
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<td>HTGR</td>
<td>high-temperature gas-cooled reactor</td>
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<tr>
<td>HTR-PM</td>
<td>High Temperature Reactor—Pebble Module</td>
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<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
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<td>LWR</td>
<td>light-water reactor</td>
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<tr>
<td>μ</td>
<td>micron</td>
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<td>MHTGR</td>
<td>Modular High-Temperature Gas-Cooled Reactor</td>
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<td>MSR</td>
<td>molten-salt reactor</td>
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<tr>
<td>NGNP</td>
<td>Next Generation Nuclear Plant</td>
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<tr>
<td>NRC</td>
<td>U.S. Nuclear Regulatory Commission</td>
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<tr>
<td>PRA</td>
<td>probabilistic risk assessment</td>
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<tr>
<td>TVA</td>
<td>Tennessee Valley Authority</td>
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About the Author

Edward Geist has a Ph.D. and M.A. in history from the University of North Carolina at Chapel Hill and a B.A. in history from the College of William and Mary. He is a MacArthur Foundation Nuclear Security Fellow with the Center for International Security and Cooperation at Stanford University.
About This Perspective

This perspective examines the institutional and technical obstacles to the commercialization of advanced nuclear reactors for electrical power generation in the United States. The so-called nuclear renaissance that seemed imminent ten years ago has failed to materialize, in considerable part because of the failure of large light-water reactors (LWRs) to achieve the envisioned improvement in capital costs. If nuclear fission is to play a substantial role in the future of the U.S. energy supply, a more cost-effective type of nuclear power plant must be commercialized. This piece examines the underlying technical reasons LWRs require expensive engineered safety systems to protect the public. It then explores the institutional barriers that make it difficult for the U.S. Nuclear Regulatory Commission (NRC) to evaluate non-LWR nuclear plants and discourage the U.S. Department of Energy and industry from investing the time and resources needed to establish the operational and safety characteristics of these technologies. Finally, it provides an overview of several candidate reactor designs that might offer alternatives to the current technological paradigm and outlines steps policymakers can take to overcome the barriers to the commercialization of next-generation nuclear reactors.

Thoughtful feedback from former NRC commissioner Victor Gilinsky and Tom LaTourrette of RAND was instrumental in the development of this perspective. I would also like to thank Brian A. Jackson, Andrew R. Hoehn, and Sarah Harting of RAND, and the Stanton Foundation for helping make this piece possible.

The research reported here was conducted as part of the Stanton Nuclear Security Fellows Program at the RAND Corporation. The Stanton Nuclear Security Fellows Program was created to stimulate the development of the next generation of leaders on nuclear security by supporting interdisciplinary research that will advance policy-relevant understanding of the issues. Each fellow carries out a yearlong period of independent research, collectively producing studies that contribute to the general body of knowledge on nuclear security.

The Stanton Foundation, a creation of Frank Stanton, former president of CBS and a pioneering executive who led the television network for 25 years, supports Stanton fellows. In 1954, President Dwight D. Eisenhower appointed Stanton to a committee convened to develop the first comprehensive plan for the survival of the United States following a nuclear attack. Stanton led the effort to develop plans for national and international communication in the aftermath of a nuclear incident. Stanton also served as chair (1961–1967) and member (1957–1978) of the RAND Corporation Board of Trustees. The Stanton Foundation aims, through its support of the Stanton Nuclear Security Fellows Program, to perpetuate his efforts to meet these challenges. For more information about the Stanton Fellowship at RAND, visit www.rand.org/about/edu_op/fellowships/stanton-nuclear.

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