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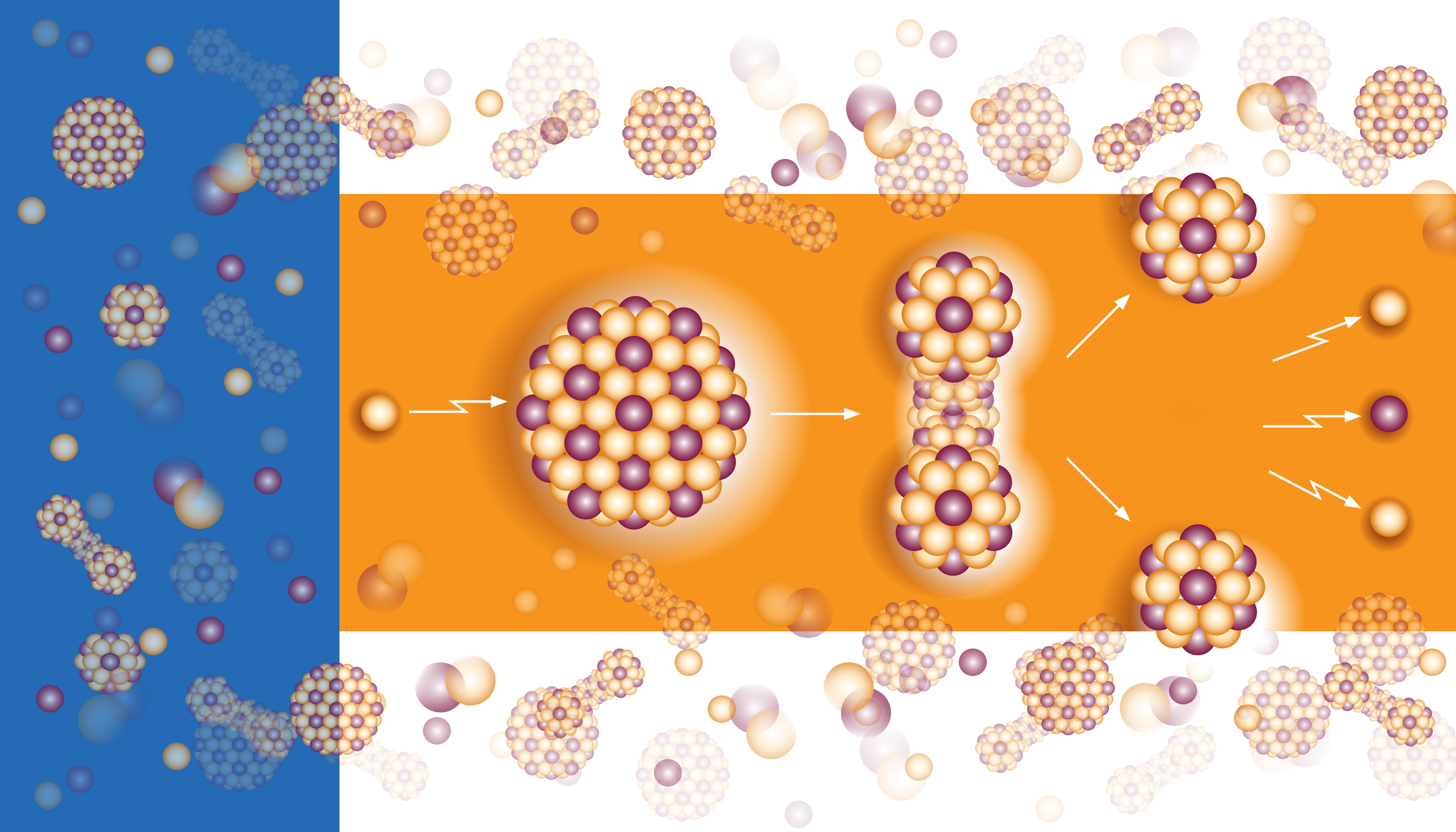
July 2015

TECHNOLOGY ASSESSMENT

Nuclear Reactors

Status and challenges in development and deployment of new commercial concepts

Accessible Version



GAO-15-652

Cover image is GAO's rendition of a nuclear fission reaction. A neutron collides with a large atom, such as uranium-235, causing it to split, or fission. This results in heat, fission fragments, and additional neutrons that may then initiate another fission reaction, creating a chain reaction. A nuclear reactor uses a controlled fission chain reaction to produce heat for electricity generation.

Highlights of GAO-15-652, a report to the Ranking Member, Subcommittee on Energy and Water Development, Committee on Appropriations, U.S. Senate

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Why GAO did this study

Energy demand in the United States is expected to continue to grow over the coming decades, and DOE considers nuclear energy to be one way to help meet this increased demand without producing air pollution. However, the current domestic commercial nuclear reactor fleet, consisting of 99 large LWRs that provide about 20 percent of U.S. electricity, is aging, and some reactors have shut down in recent years. LWRs use light, or ordinary, water to cool the reactor. New reactor concepts are under development as alternative energy options. Light water SMRs have some similarities, including the coolant used, to the existing large LWRs, and advanced reactors differ more from the large LWRs. Both new reactor concepts differ from the existing large LWRs in potential applications.

GAO was asked to conduct a technology assessment of these new reactor concepts in the United States. This report discusses (1) the status of light water SMR and advanced reactor concepts under development; (2) the intended benefits of these new reactor concepts; and (3) the challenges associated with developing and deploying these new types of reactors. GAO reviewed documents from DOE and NRC, and interviewed DOE and NRC staff as well as industry representatives involved in developing reactors. GAO, with the assistance of the National Academies, convened a meeting with a group of 20 experts on nuclear reactor development and related issues to provide additional information.

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What GAO found

In the United States, four light water small modular reactors (SMRs)—nuclear power reactors with a generating capacity of less than 300 MW of electricity—have been developed to the point that the reactor designers have begun discussing design certification and license applications with the Nuclear Regulatory Commission (NRC), and one SMR designer has established time frames for applications to NRC and construction of a power plant. The Department of Energy (DOE) has provided financial support to the designers of two SMRs for reactor certification and licensing work. DOE supports the SMR design by NuScale through a cost-sharing agreement in which DOE will pay as much as half of NuScale's costs—up to $217 million over 5 years—for certifying the design. The SMR design by mPower has a similar cost-sharing agreement with DOE, but DOE is no longer providing funds because mPower has scaled back its efforts while it looks for additional investors. NuScale expects to submit a design certification application to NRC in late 2016, with its first power plant beginning operation as early as 2023. Other SMR designers do not yet have established time frames for such applications. DOE also supports research and development (R&D) activities on advanced reactor concepts that focus on the high temperature gas reactor and the sodium fast reactor. DOE provides this support in areas such as fuels and material qualification and reactor safety studies. DOE and NRC officials do not expect applications for advanced reactors for at least 5 years.

According to DOE officials and reactor designers, both SMRs and advanced reactors are intended to provide benefits that could facilitate the use of nuclear reactors in new markets or commercial applications. SMR designers plan to decrease the overall cost and time for reactor construction, compared with existing large light water reactors (LWRs), without significantly increasing ongoing operational costs. They told GAO they expect that the smaller size of SMRs may expand the locations where a nuclear power plant could be constructed. For example, they may be used in remote or rural areas that have lower electricity demands or smaller distribution systems. DOE officials and reactor designers expect advanced reactors to operate at higher temperatures and therefore they could generate electricity more efficiently. Furthermore, they told GAO heat from these higher temperature reactors could be used directly in certain industrial processes that currently depend on fossil fuels. Some advanced reactors may also allow for improved spent nuclear fuel recycling and management.

DOE officials and SMR and advanced reactor designers told GAO they face challenges in developing and deploying these reactors. SMR designers face technical challenges in demonstrating economic feasibility and safety without increasing reactor complexity, and advanced reactor designers face greater technical challenges because advanced reactors differ more from current reactors than SMRs. Reactor designers told GAO they face challenges associated with the up to $1 billion to $2 billion cost of developing and certifying a design. Even with a reactor design ready to submit to NRC, the licensing and construction can take nearly a decade or more before a reactor is operational. DOE officials, members of GAO's expert group, and reactor designers said that the cost and time needed to certify or license a reactor design and construct it, along with uncertainty about the energy market in the future and potential customer interest, create obstacles to the development and deployment of new reactors.

Contents

Abbreviations

AEO2015	Annual Energy Outlook 2015
CFR	Code of Federal Regulations
COL	Combined License
DC	Design Certification
DOE	Department of Energy
EIA	Energy Information Administration
FHR	Fluoride Salt Cooled High Temperature Reactor
FOAK	First-of-a-Kind
GIF	Generation IV International Forum
HTGR	High Temperature Gas Cooled Reactor
MSR	Molten Salt Reactor
LWR	Light Water Reactor
MWe	Megawatt-Electric
MWth	Megawatt-Thermal
NGCC	Natural Gas-Fired Combined Cycle
NGNP	Next Generation Nuclear Plant
NOAK	Nth-of-a-Kind
NRC	Nuclear Regulatory Commission
O&M	Operations and Maintenance
R&D	Research and Development
SFR	Sodium Cooled Fast Reactor
SMR	Small Modular Reactor
TVA	Tennessee Valley Authority

July 28, 2015

The Honorable Senator Dianne Feinstein
Ranking Member
Subcommittee on Energy and Water Development
Committee on Appropriations
United States Senate

Dear Senator Feinstein:

Over the coming decades, energy demand in the United States is expected to continue to grow, and energy security, scalability, reliability, and the mitigation of greenhouse gas emissions from the burning of fossil fuels, such as coal, will remain key elements of national interest. The Department of Energy (DOE) considers nuclear energy to be a proven technology that can reliably generate large amounts of electricity without producing air pollution or greenhouse gases. The U.S. agency that regulates commercial nuclear reactors, the Nuclear Regulatory Commission (NRC), has been granting license renewals for the continued operation of the current commercial fleet of large light water nuclear reactors to extend their operating lifetimes to 60 years, and may grant another license renewal to allow operation for 80 years if a reactor operator applies for one and NRC determines through a review of the application that the additional license renewal is acceptable. However, the industry faces several challenges. Commercial nuclear reactors in the United States are aging, and some have shut down before their license expirations because of economic pressures in certain markets. In addition, the accident at Japan's Fukushima Daiichi commercial nuclear power plant, which was damaged by the March 2011 earthquake and tsunami, has increased concerns about nuclear safety and resulted in modifications to some reactors that have affected their economic competitiveness. There are also concerns and uncertainties surrounding long-term disposal options for spent nuclear fuel as well as concerns over nuclear proliferation and terrorism.[1]

Government agencies and industry sponsor and conduct research on new nuclear reactor concepts, which are intended to provide additional capabilities and improvements, such as improved efficiency or simpler reactor design, over the existing fleet of large commercial

[1] Nuclear proliferation is the spread of nuclear weapons, fissile materials, and weapons-applicable nuclear technology and information to nations not recognized by the Treaty on the Nonproliferation of Nuclear Weapons.

light water nuclear reactors (LWRs).[2] In the United States, these large LWRs have an average generating capacity over 1,000 megawatt-electric (MWe).[3] From funds appropriated to DOE for nuclear energy in fiscal year 2015, DOE used $152.5 million to support small modular reactors (SMRs) and advanced reactor concepts. Of that amount, DOE allocated $54.5 million to support the industry's reactor designers with their licensing work on light water SMRs, which are small reactors under 300 MWe that are designed for modular production and assembly with components transportable by road, rail, or barge.[4] DOE's support of light water SMRs, which are a type of LWR that are less than about a third the size of average-sized large LWRs, is in the form of industry cost-sharing agreements, by which DOE provides funds to match those expended by its industry partners to support the certification and licensing of specific light water SMR designs. According to DOE documents and reactor designers, the goal for SMR designs is to provide a more commercially flexible reactor option with lower investment cost. DOE also allocated $98 million to support research and development (R&D) on advanced reactors, which use coolant technologies significantly different from LWRs. As we previously found, DOE supports research on advanced reactor concepts with the goal of improving the economic competitiveness of nuclear technology relative to other energy options, ensuring that nuclear energy continues to play a role in meeting our nation's energy needs, minimizing the risks of nuclear proliferation, and addressing environmental challenges such as greenhouse gas emissions.[5]

You asked us to conduct a technology assessment of new reactor concepts under development in the United States. This report discusses (1) the status of light water SMR and advanced reactor concepts under development; (2) the intended benefits of these new reactor concepts; and (3) the challenges associated with developing and deploying these new types of reactors.

To address these objectives, we reviewed relevant NRC regulations as well as our past work. We reviewed reports and technical literature from DOE, international nuclear technology organizations, and reactor designers that describe DOE's and industry's efforts to develop light water SMRs and advanced reactor concepts, and we attended six conferences on SMR or advanced reactor concepts. In addition, to understand the status of light water SMRs and advanced reactor concepts under development, their applications, and challenges they face, during this and related work we reviewed reports and economic studies and interviewed DOE officials, NRC officials, and industry and reactor operator representatives, including designers of light water

[2] A light water reactor refers to a reactor of any size that uses light water (ordinary water) to cool the reactor, as opposed to heavy water which contains deuterium, an isotope of hydrogen. Throughout this report, large LWR refers to the existing fleet of large light water commercial nuclear reactors.

[3] A power plant's electricity generating capacity is measured in megawatts of electricity, or MWe. A power plant also can be measured by the thermal energy (heat) it produces, megawatt-thermal (MWth). The ratio of MWe to MWth is the thermal efficiency of the reactor, a measure of how well it converts heat to electricity.

[4] Throughout this report, we refer to light water SMRs, but advanced reactor technologies using other coolants are also being developed as SMRs.

[5] GAO, *Advanced Reactor Research: DOE Supports Multiple Technologies, but Actions Needed to Ensure a Prototype is Built*, **GAO-14-545** (Washington, D.C.: June 23, 2014). Advanced reactors, also sometimes referred to as Generation IV reactors, generally use coolant other than ordinary water. While some advanced reactors have been studied and operated in the past, current DOE work on advanced reactors seeks to support commercialization of these new reactors.

SMRs and advanced reactors that receive DOE support or have been in pre-licensing discussions with NRC. We also visited a DOE national laboratory—Idaho National Laboratory—to better understand the R&D activities DOE has undertaken with regard to light water SMRs and advanced reactor concepts. With the assistance of the National Academies, we convened a meeting of 20 experts on nuclear reactor technology and related issues to obtain additional information and advice for this review. These experts were selected from academia, government, and industry, with expertise ranging from reactor and electricity economics to reactor development and licensing. We have limited the scope of our review to specific domestic light water SMR designs and the advanced reactor concepts that DOE has focused on for domestic R&D because these are the new reactor technologies closest to being certified, licensed, and built in the United States.

We conducted our work from June 2014 to July 2015 in accordance with all sections of GAO's quality assurance framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for our findings and conclusions in this product.

1 Background

Nuclear reactors, along with other types of power plants, provide electricity to consumers in the United States, but nuclear power plants can face economic pressures that lead to their shutting down before the expiration of their operating licenses, and other large power plants can face similar economic pressures. Designing and certifying a new type of nuclear reactor design can cost up to $1 billion to $2 billion, with much of the cost going to R&D and reactor design work, and around $50 million to $75 million paying for NRC's fees for design certification.[6] The design work and design certification is dependent on funding and can take several years, including up to 10 years or more for design work before submitting an application to NRC and nearly 3.5 years, as a best-case scenario, for certifying a LWR design.[7] With a certified design in place, the decision by a customer[8] to build a new nuclear reactor of any type is ultimately an economic one, requiring consideration of a number of factors, including reactor license approval times of at least 4 to 6 years, reactor construction costs, large LWR construction times of 6 years or more, and ongoing operation and maintenance costs. While some of these time frames can have overlapping schedules, it is still a multi-decade process to design, license, and build a reactor using a new design.

6 The two most recent design certifications—for the Westinghouse AP1000 and the GE Hitachi ESBWR—cost about $45 million and $69 million, respectively, for NRC fees related to pre-application, application, and revision reviews.

7 NRC estimates design certification for a new LWR design will take 41 months, including a 60 day acceptance period, as a best-case scenario.

8 In this report, we use the term "customer" to refer to any electricity generator that would use a nuclear reactor to produce electricity, such as an investor or municipal owned utility, or to generate process heat, such as an industrial plant.

1.1 Nuclear reactors are one component of the larger electric grid

Nuclear power plants and other electricity production facilities generate electricity using fuels such as uranium, coal, natural gas, and renewable energy sources. This electricity is sent through the electric grid, which consists of high-voltage, high-capacity transmission systems, to areas where it is transformed to a lower voltage and sent through the local distribution system for use by business and residential consumers. During this process, a grid operator must constantly balance the generation and consumption of electricity. To do so, grid operators monitor electricity consumption from a centralized location using computerized systems and send minute-by-minute signals to power plants to adjust their output—to the extent possible for each type of plant—to match changes in the demand for electricity. Electricity demand can vary throughout a day, as well as seasonally, so grid operators use baseload plants and peaker plants.[9] Historically, baseload plants, typically nuclear or coal powered, generally cost more to build but supply electricity at a lower hourly cost. Peaker plants, such as natural gas facilities, can be built relatively cheaply and generally operate at a higher hourly cost, and they can rapidly be brought on or offline in response to changes in electricity demand.[10] Some renewable energy sources, such as solar and wind power, are intermittent and are prioritized as electricity sources by grid operators because of green energy usage requirements and their near-zero operating costs when that energy source is available. The intermittent nature of electricity generated by these renewable energy sources can be a challenge for baseload plant operators—including nuclear power plants operators—because the operators cannot increase and decrease their power production to balance it with that of intermittent electricity sources without additional wear on their equipment or less economic power generation. Another difference between intermittent renewables, like wind and solar, and nuclear power or fossil fuel plants is that they are not generally dispatchable without battery storage, meaning that they are either producing power or not without respect to demand.

In the last several years, five commercial nuclear reactors have shut down before their operating licenses expired, and additional reactors currently face economic pressures that may lead to early shutdowns. These economic pressures vary by market, but include competition from renewable energy sources, or less expensive natural gas, coupled with increased reactor operating costs.[11] As of April 2015, the commercial nuclear reactor fleet in the United States consisted of 99 operating nuclear reactors, which provided nearly 20 percent of total U.S. electricity generation. Even if these reactors operate for their full license durations, assuming all the reactors receive license extensions allowing operational lifetimes of 60 years, those licenses will begin expiring in 2029 unless reactor operators apply for, and NRC determines through a review of the applications to allow an additional 20-year renewal period to extend allowed reactor operational lifetimes to

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9 There are also intermediate load plants that are used during the transition between baseload and peak load needs.

10 Some power plants using natural gas have been used as baseload plants. For additional information, see GAO, *Electricity: Generation Mix Has Shifted, and Growth in Consumption Has Slowed, Affecting System Operations and Prices*, GAO-15-524 (Washington, D.C.: May 29, 2015).

11 For additional information, see GAO-15-524 and GAO, *Energy Policy: Information on Federal and Other Factors Influencing U.S. Energy Production and Consumption from 2000 through 2013*, GAO-14-836 (Washington, D.C.: September 30, 2014).

80 years. Additional reactor shutdowns would require increased electricity generation from other sources, including fossil fuels and renewable energy sources, or would require improvements in energy efficiency. As shown in figure 1, U.S. electricity demand over the next several decades is forecast to increase, so additional sources of electricity generation, such as nuclear power, would be needed to meet that demand, according to the U.S. Energy Information Administration (EIA) Annual Energy Outlook 2015 (AEO2015) Reference Case.[12]

1.2 Designing and certifying or licensing a new reactor

In the United States, both DOE and industry play major roles in R&D for new reactor concepts, and NRC certifies the resulting designs and licenses the construction and operation of the reactors built to those designs. The overall process of developing and certifying a specific reactor design can take 10 years or more for design work and nearly 3.5 years, as a best case, for certification, and includes the following elements:

- the R&D by reactor designers to support their claims about reactor safety and economic competitiveness, including construction costs and ongoing operations and maintenance costs;
- engineering design work by reactor designers including any needed fuel and materials development and qualification; and
- reactor design certification efforts by the designers and the NRC.

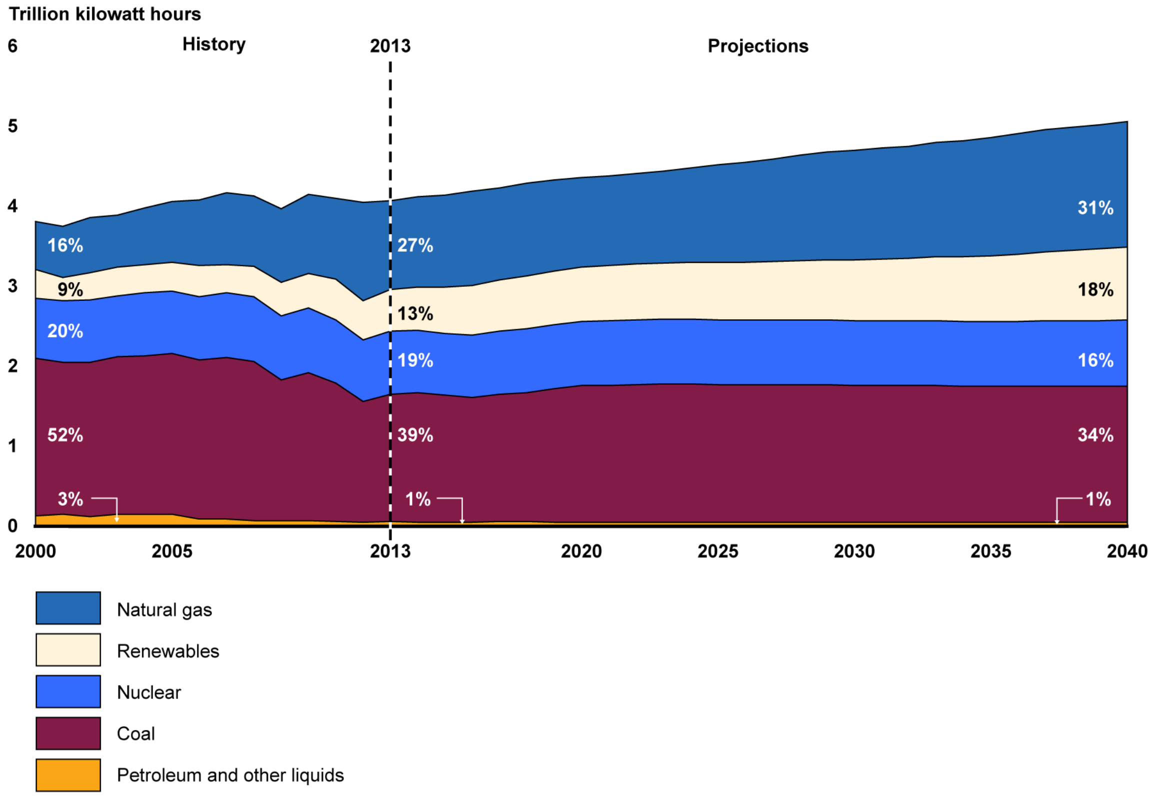
While the R&D and engineering work can vary based on the specific design, the NRC certification and licensing process is defined through federal regulations. However, according to NRC documents, this process is focused on LWR designs and may require adjustments, such as exemptions from the current process, when applied to advanced reactors.

NRC has two licensing paths for constructing and operating nuclear power plants defined in the Code of Federal Regulations (CFR). The first follows 10 CFR Part 50 (Part 50). Under Part 50, a license for a proposed power plant is issued in two parts—a construction permit allowing the plant construction to begin, and an operating license. This licensing process requires several items in the application to be reviewed by NRC and its independent advisory committee before a reactor is built and operational. These items include the plant design and operations, environmental and site studies, and emergency response plans. Once the review is complete, the NRC prepares a Safety Evaluation Report, which summarizes the potential effects on public health, safety, and the environment based on the final design and location of the reactor. During construction of the reactor, NRC verifies that construction meets acceptance criteria to provide reasonable assurance the reactor will operate in conformance with the license and regulations. In

[12] EIA is the statistical agency within DOE that collects, analyzes, and disseminates independent information on energy issues. EIA notes that the AEO2015 projections are based generally on federal, state, and local laws and regulations in effect at the end of October 2014. The projections generally do not reflect the potential impacts of pending or proposed legislation, regulations, and standards—or of sections of existing legislation that require implementing regulations or funds that have not been appropriated. In certain situations, however, where it is clear that a law or a regulation will take effect shortly after AEO2015 is completed, that law or regulation may be considered in the projection.

The AEO2015 Reference case projection is a business-as-usual trend estimate, given known technology and technological and demographic trends. Energy market projections are subject to much uncertainty. Many of the events that shape energy markets are random and cannot be anticipated, such as the effect that heavy rainfall can have on hydroelectric power and the resulting reduction in electricity prices. In addition, future developments in technologies, demographics, and resources cannot be foreseen with certainty.

Figure 1 U.S. Energy Information Administration Annual Energy Outlook 2015 Reference Case historical data and forecast of electricity generation by fuel type (trillion kilowatt hours)



Source: GAO, adapted from U.S. Energy Information Administration Annual Energy Outlook 2015 Reference Case. | GAO-15-652

Note: This energy forecast, by fuel type, incorporates a number of assumptions, including the effects of planned and unplanned builds and retirements of nuclear reactors. It also assumes that most existing reactor operators will apply for and receive approval from the Nuclear Regulatory Commission for a second 20-year license renewal.

addition, NRC provides opportunities for public hearings or comments at specified points.

The second path, following 10 CFR Part 52 (Part 52), requires the same types of studies and reports as the Part 50 process, but Part 52 allows for a single combined license (COL) to be granted that authorizes the construction and operation of a specific reactor design at a specific site, subject to post-construction verification that the plant meets the acceptance criteria defined in the COL. Light water reactor designers we interviewed may use Part 52 because it also allows for two options that can be exercised independent of a construction permit or license: (1) an early site permit for NRC approval of a site for a future reactor, and (2) a design certification (DC) for NRC approval of a standardized nuclear reactor design. According to NRC documents, a Part 52 COL application can reference an approved early site permit or DC to increase regulatory efficiency and predictability in the review process. Using this process, reactor designers may apply for a DC for their specific design so that it may be incorporated into the COL applications that potential customers would submit, reducing the timeframes for the COL application review. This use of a single DC for multiple reactor COL applications is in contrast with the Part 50 process, where the reactor design would need to be submitted and approved by NRC for each proposed construction site. However, members of our expert group noted that the Part 50 process may be more advantageous for a reactor customer who is constructing and licensing a new reactor for the first time, because fewer design details need to be complete when construction begins and design changes can be easier to make than amending designs certified through Part 52. For these reasons, advanced reactor designers and their customers may be particularly interested in Part 50, according to members of our expert group. Regardless of whether a reactor designer or its customer pursues Part 50 or Part 52, the NRC regulatory process for a reactor can take at least 4-6 years before a reactor is licensed to be built and operated. NRC estimates the DC process for an LWR design will take nearly 3.5 years as a best-case scenario, assuming the submission of a high-quality application and that NRC's requests for additional information from the reactor designers are received and responded to in a timely manner and meet NRC needs. Recent LWR design certifications—for the Westinghouse AP1000 and the GE Hitachi ESBWR—have taken about 15 and 11 years, including revisions.[13]

NRC encourages reactor designers and license applicants to engage in pre-application discussions with NRC to help identify potential certification or licensing issues the designers may wish to address before submitting DC or COL applications, according to NRC documents and officials and reactor designers. NRC officials told us identifying such issues is important for new light water SMR and advanced reactor concepts because these concepts incorporate design features that differ from those of existing large LWRs—for example, the new reactor concepts may approach reactor safety differently from the large LWRs that NRC has experience in licensing. If a designer intends to submit a DC application, these pre-application discussions may also lead to NRC drafting a Design Specific Review Standard, an NRC document that can be used to guide NRC's review of the application. According to NRC documents, before submitting DC applications, reactor designers may also request NRC to conduct pre-application readiness reviews to provide general feedback on the readiness of the applications for submission. During the review process, reactor designers told us they must expend resources to conduct studies and provide responses to NRC inquiries to support DC application claims about the reactor design. According to NRC regulations, reactor designers must also reimburse NRC for the agency's staff time during pre-application discussions, pre-application readiness reviews, and application reviews.[14]

In this report, most references to the licensing process describe the Part 52 process because the reactor designers with the earliest planned license approval activities told us they intend to submit DC applications. As noted above, the first step in this process may consist of reactor designers working with NRC in optional pre-application discussions. According to NRC documents, as the designers get closer to submitting a DC application to NRC, a potential customer for

[13] The DC applications were originally approved by the NRC in about 4 years for the AP1000 and 9 years for the ESBWR. Subsequent revisions to the reactor designs have increased the review period.

[14] The NRC is required to recover approximately 90 percent of its annual budget authority through fees charged to applicants and licensees. Under 10 CFR Part 170, applicants for a construction permit or operating license under 10 CFR Part 50; an early site permit, standard design certification, standard design approval, manufacturing license, or combined license under 10 CFR Part 52; and requests related to pre-application consultations and reviews from the NRC will be assessed a fee to recover NRC's costs for providing those services.

the reactor may begin conducting early site characterization, with designer assistance, to prepare for a COL application for a specific reactor design and site. Alternatively, a potential reactor customer may plan to submit an early site permit application independent of a specific reactor design, which would support a later COL application for any reactor design meeting the parameters of the permit at that site. According to NRC documents, a DC application and COL application may then be processed in parallel by the NRC. If the applications are successful, the end result would be a reactor design that is certified by the NRC independent of any specific site along with a COL that permits that reactor design to be built and operated at a specific site. See figure 2 for the notional best-case time frames associated with this process which, according to NRC documents, assume well-prepared applications, timely review, and timely responses to NRC requests for additional information. The time frames shown in figure 2 are based on NRC best-case estimates for a light water reactor design. Because of the need for more adjustments and exemptions to apply these processes to an advanced reactor design, time frames for an advanced reactor design would be longer, according to DOE and NRC officials and members of our expert group.

1.3 Reactor economics

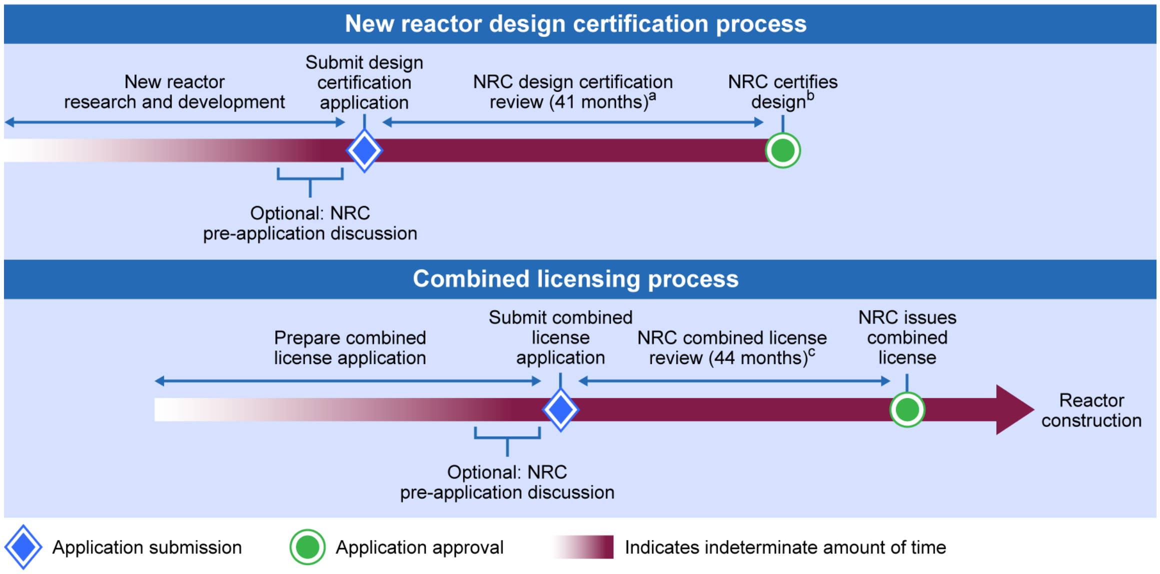
There are several considerations for a customer, such as a utility, planning to construct and operate a nuclear power plant. Besides considering atmospheric emissions, electricity reliability, and source diversification (that is, having a portfolio of electricity production methods), a customer will also consider whether the power plant will be cost-competitive with other sources of electricity.[15]

For example, one type of customer, traditionally called a utility, has a guaranteed rate of return set by a public authority to meet a baseload demand so that the utility can fully recover its prudently incurred costs, including the cost of its debt, plus an established return on its equity. These customers may have an easier path to nuclear power plant construction because, once the plant is approved by the public authority, the customer may be guaranteed a certain return on its investment. On the other hand, a customer that is not guaranteed a rate by a public authority—a merchant generator—will have to pay for the plant by competing with other electricity generators or through prior purchase agreements, which are guaranteed rates over a contracted time from an electricity purchaser.

As an example of a way to determine if a nuclear power plant will be competitive, the per MWe cost of generating capacity from the plant is estimated and compared with the cost of alternative energy sources available to meet the demand in the same market. To estimate the costs several metrics are considered. First is the overnight capital cost of a plant—that is, the cost of engineering, procuring, constructing, and licensing the plant, and its associated

[15] During the last two decades, some state governments and the federal government have taken steps to restructure the wholesale electricity markets with the goal of increasing competition and prices are now largely determined by the interaction of supply and demand rather than regulatory bodies. The electricity industry has historically been characterized by utilities that were integrated and provided the four functions of electricity service—generation, transmission, distribution, and system operations—to all retail consumers in a specified area. In much of the Western, Central, and Southeastern United States, retail electricity delivery continues to operate under this regulatory approach, and these regions are referred to as traditionally regulated regions. In parts of the country where states have taken steps to restructure retail electricity markets, utilities compete with other qualified providers who may not own generation, transmission, or distribution assets to provide electricity to retail consumers by offering electricity plans with differing prices, terms, and incentives.

Figure 2 Overview of Nuclear Regulatory Commission's (NRC) Part 52 licensing process with notional time frames



Source: GAO, based on Nuclear Regulatory Commission documentation. | GAO-15-652

[a] The 41-month review includes a 60 day acceptance review followed by a 39-month design certification application review. The Nuclear Regulatory Commission (NRC) estimates the design certification application review will take 41 months based on the assumption that NRC's requests for additional information from the reactor designers are received and responded to in a timely manner and meet NRC needs.

[b] The certified design may be amended during construction.

[c] The 44-month review includes a 60 day acceptance review followed by a 30-month review for a combined license application that references a certified design and a 12-month period to complete the hearing process. The 30-month review period is increased to 48-60 months for combined license applications that do not reference a certified design. These NRC estimates for the review duration are based on the assumption that NRC's requests for additional information from applicants are received and responded to in a timely manner and meet NRC needs.

infrastructure, as if it were paid for instantly and the plant were to be built overnight such that no interest would accrue during its construction. For example, the existing LWRs are generally large and expensive, with a generating capacity around 1000-1600 MWe per reactor at an overnight capital cost of $6 billion or more with construction times of 6 years or more. Second is the financing cost, which includes the investments made by the plant owners and the costs of financing the construction with a loan, which can be significant given the billions of dollars and the long construction time—including potential delays, for example because of licensing uncertainty—associated with building a nuclear power plant. Third are the ongoing operations and maintenance costs for a nuclear power plant, including security and operations staffing and fuel purchasing costs.

A number of issues can affect the costs and competitiveness of the nuclear power plant operations and maintenance. For example, the thermal efficiency of a reactor—how well it converts the heat it generates to electricity—and the simplicity or complexity of the reactor can affect how expensive it is to operate a reactor relative to the electricity it can produce. All other things being equal, a more efficient reactor will generate more electricity for the same operations and maintenance cost, while a simpler reactor can be both less expensive to build and less expensive to maintain, and members of our expert group noted reactors with passive safety systems could provide such simplification. The analysis of whether a reactor will be competitive is complicated by long time frames—besides the multi-decade process to design, license and build a reactor, there is uncertainty in the energy market over the expected 40 to 80 year operational lifetime of the reactor. Therefore, the decision on whether or not to build may not be based solely on profitability, but also on other factors such as the reliability or diversification of power production.

1.4 Nuclear reactor operation

Nuclear reactors generate heat by sustaining a fission chain reaction in nuclear fuel. Nuclear fission reactions can occur when a neutron strikes the nucleus of a large atom, causing that nucleus to split, or fission. The result of a fission reaction is typically two fission fragments, or smaller nuclei; two or more new fast-moving neutrons; and significant heat. In a nuclear reactor, the large atoms used for fission are typically the fissile isotopes uranium-235 or plutonium-239.[16] The new neutrons produced by a fission reaction are used to initiate new fission reactions, resulting in a sustained fission chain reaction. The heat generated by this fission reaction is typically used to create steam and drive a steam turbine to generate electricity.

While there are a large number of reactor technologies that can differ significantly, reactor designs generally incorporate certain common components. For example, the fission reaction occurs in the central region of a reactor called the reactor core. The reactor core typically contains the following components:

- **Nuclear fuel.** Nuclear reactors need fissile isotopes, such as uranium-235 and plutonium-239, to sustain chain reactions. Commercial reactors often use uranium that has been slightly enriched in the isotope uranium-235 as their fissile fuel; the rest of the fuel consists of the non-fissile uranium-238, some of which can be converted to plutonium-239 during reactor operation. Some reactors can also utilize thorium-232 to produce uranium-233 for fuel. Uranium-233 is an isotope that, like plutonium-239, raises proliferation concerns because it may be used in nuclear weapons.

- **Fuel Cladding.** In order to hold and contain the nuclear fuel, as well as the fission products that are created during reactor operation, most reactors use fuel cladding to encase the fuel pellets. This cladding may be a zirconium alloy, as it often is in LWRs; stainless steel; silicon carbide; or other materials designed to withstand the extreme conditions of a reactor. Some advanced reactor concepts use liquid fuel, in which case there is no fuel cladding.

- **Moderator.** Thermal reactors use a moderator material to slow down the fission neutrons in order to sustain the fission reaction. In LWRs, the moderator is water, and a certain type of

[16] Isotopes are varieties of a given chemical element with the same number of protons but different numbers of neutrons. For example, the helium-3 isotope, which is used in research and in radiation detection equipment, has one less neutron than the helium-4 isotope, which is the helium isotope commonly used in party balloons.

advanced reactor—a high temperature gas cooled reactor—uses graphite as a moderator. Fast reactors are designed to utilize fast neutrons for the fission reactions and fuel breeding or fuel burning and, accordingly, do not use a moderator.

- **Coolant.** To remove heat from the core, a coolant—typically water, a gas, liquid metal, or liquid salt—is circulated through the core. The coolant both prevents the core from overheating (which could damage or melt the fuel, as in the case of the Fukushima accident) and it carries energy, in the form of heat, outside the core. In some reactor types, such as LWRs, the coolant can also function as the reactor's moderator.

- **Reaction control.** Reactors can use different techniques to maintain the fission chain reaction at appropriate rates. For example, control rods, incorporating materials like boron that absorb neutrons to reduce or stop the nuclear chain reaction, may be inserted into reactor cores to provide control over the reaction rate. Neutron-absorbing materials, such as boric acid, may be introduced to the coolant system to achieve a similar effect.

Reactors also have components outside of the reactor core that help transfer heat from the core and create electricity. Certain types of LWRs—pressurized water reactors—contain a pressurizer to help maintain the correct coolant pressure.[17] The reactor coolant is circulated through the core and is used to generate steam, which then powers a turbine to generate electricity. Some reactor designs may utilize the energy of the coolant in other ways, such as by directly using the heat as process heat in chemical reactions.

Reactors may be classified by size. LWRs that use the same basic technology for the nuclear reactor core can be classified as small, for example the light water SMRs, with an electricity generating capacity of less than 300 MWe, or as large, with capacities of around 1000 MWe or more. See figure 3 for an example large LWR and figure 4 for an example light water SMR. In figure 3, the primary coolant loop uses pumps (not shown) to circulate heated water from the core to the steam generator and back, while in figure 4 this circulation is achieved entirely within the pressure vessel using natural, temperature-driven flow of the water between the reactor elements. An advanced reactor will often utilize similar design concepts with fuel, fuel cladding, coolant, moderators, and reaction control systems, but with modifications due to differences in the types of coolants, fuels, and materials used in the reactor.

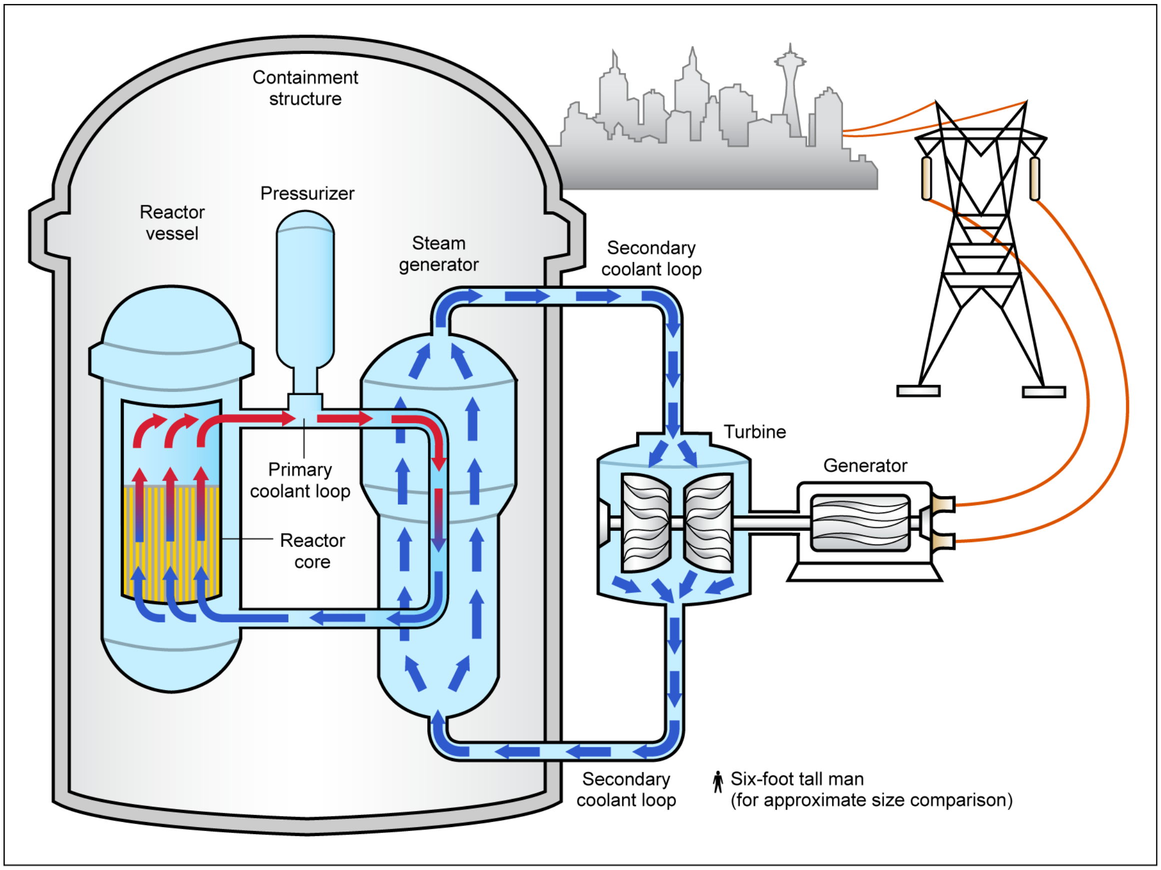
Nuclear reactors typically fall into one of two types, based on the neutron spectrum, or neutron energies at which the fission reactions occur:

- **Thermal reactors** optimize the fission reaction rate in their fuel by slowing down, or moderating, the high-energy fast neutrons that are the products of fission reactions, resulting in thermal neutrons. This moderation of the fast neutrons increases the likelihood that a neutron will initiate a fission reaction. Existing large LWRs are thermal reactors.

- **Fast reactors** do not moderate the fission neutrons, instead leaving them fast. Fast

[17] Another type of LWR—the boiling water reactor—is also used in the United States. Approximately one-third of the operating commercial nuclear reactors in the United States are boiling water reactors.

Figure 3 Illustration of a pressurized large light water nuclear reactor (LWR)



Source: GAO, based on Nuclear Regulatory Commission documentation. | GAO-15-652

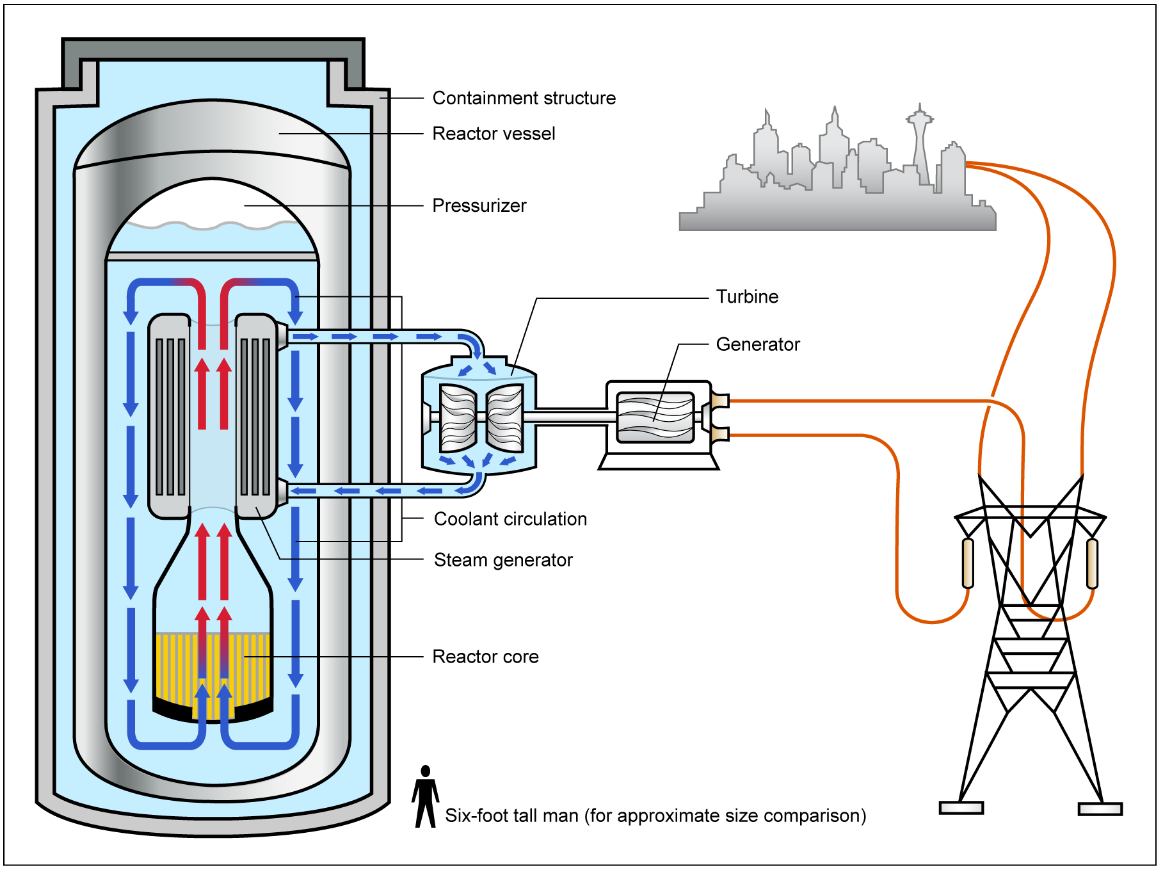
neutrons allow these reactors to be more effective than thermal reactors at creating, or breeding, new fuel through neutron bombardment of uranium-238, creating plutonium-239, an isotope that can be used in nuclear weapons.[18]

Reactors may therefore also be classified by their neutron energies as either thermal or fast reactors, or they may be classified by the materials used in the reactor.[19] For example, an LWR is a thermal reactor using water as both a coolant and moderator, and a gas-cooled fast reactor is a fast reactor using gas (helium) as a coolant with no moderator.

[18] Although thermal reactors produce plutonium-239, because fast reactors can be particularly effective at fissioning plutonium-239 and changing some isotopes into fissionable isotopes, fast reactors are more likely to raise proliferation concerns. This is because their fuel cycle, using plutonium-239, can involve fuel reprocessing facilities that may pose proliferation risks. Fast reactors optimized for fuel production are called fast breeder reactors and can produce more fuel through breeding than they consume. Because fast reactors may use reprocessed spent fuel from other nuclear reactors as fuel they may reduce the need for long-term disposal of spent fuel.

[19] Some reactor technologies are "epithermal" and fall in between thermal and fast reactors.

Figure 4 Illustration of a light water small modular nuclear reactor (SMR)



Source: GAO, based on Department of Energy documentation. | GAO-15-652

2 Four light water SMR designers have discussed certification and licensing with the NRC, and DOE has also focused on two advanced reactor concepts

In the United States, four domestic light water SMR designs have been developed to the point that pre-application discussions with NRC have begun, with DOE providing financial support for some of these efforts. Of the four light water SMR designs by reactor designers NuScale, Generation mPower (mPower), Holtec, and Westinghouse, one is developed to the point that a DC application may be submitted to NRC in late 2016, and applications for others may follow, according to the light water SMR designers and DOE officials. DOE has also supported R&D activities on advanced reactor concepts. Specifically, DOE focused support on two advanced reactor concepts that use coolants other than light water—the high temperature gas cooled reactor and the sodium cooled fast reactor—and a third advanced reactor concept using liquid salt receives some support, but these concepts are generally further from certification or licensing and construction than the light water SMR designs. Designs based on these two advanced reactor concepts will likely not have applications submitted to NRC for at least 5 more years, according to DOE and NRC officials.

2.1 One light water SMR design receiving DOE support is scheduled to be submitted for NRC certification in late 2016, and others may follow

One application for design certification of the light water SMR design under development by NuScale is currently on schedule to be submitted to NRC in late 2016. Time frames have not been set for submission of DC applications for the other light water SMR designs that have been discussed with NRC in pre-application discussions—those by mPower, Holtec, and Westinghouse.

In 2014, DOE entered into a cost-sharing cooperative agreement with NuScale to support certification and licensing efforts, including the DC application, for the NuScale light water SMR design.[20] According to both NuScale representatives and DOE officials we interviewed, as of March 2015 the NuScale design certification application was on track to be submitted to NRC in late 2016. NRC officials estimate that the DC process for this light water SMR will take nearly 3.5 years as a best-case scenario. According to NuScale representatives, this submission schedule could allow their first light water SMR power plant to be operational by 2023 or 2024. NuScale

[20] This cost share agreement provides matching support from DOE for NuScale costs associated with licensing the NuScale design with NRC. The DOE support can be up to $217 million over 5 years.

representatives told us they are working with a potential customer and operator for that plant to conduct a site evaluation supporting the COL application that will be needed to license the plant's construction and operation.

In 2013, DOE entered into a similar cost-sharing agreement with mPower, a subsidiary of Babcock & Wilcox, to support the designer's light water SMR certification and licensing efforts. Pre-application discussions between mPower and NRC had resulted in a Design Specific Review Standard, with draft sections issued for public comment through the Federal Register in May 2013. However, mPower decided to scale back efforts on its SMR in mid-2014 because of a lack of committed customers and the need to find additional investors to provide financial support for their certification effort, according to mPower representatives and DOE documentation. DOE continued to provide reduced financial support, in the form of cost-sharing, under this agreement to mPower through November 2014 while mPower attempted to find another investor for the project. When that effort was unsuccessful, DOE suspended further funding and continued the agreement as a no-cost agreement—that is, the agreement is still in place in the event mPower finds an investor, but until that occurs, DOE is not providing funds. As part of the mPower cost-sharing agreement, the Tennessee Valley Authority (TVA) was also receiving funding to support site planning and licensing for an mPower light water SMR power plant at Clinch River, Tennessee. With mPower's reduced licensing effort, TVA representatives told us they have shifted to working on an early site permit application which, if approved by NRC, could allow TVA to build any light water SMR facility that meets the parameters of the permit at that location. As of June 2015, DOE officials told us they were working to finalize an interagency agreement to allow TVA to continue receiving financial support for permitting activity independent of support for mPower.

Holtec and Westinghouse held some pre-application discussions with NRC on their light water SMR designs until 2014. However, while Holtec continues its development work, representatives told us they do not have a detailed schedule for completion of this work, and Westinghouse has suspended its efforts to certify its SMR design. According to Westinghouse representatives, moving forward with significant investments to submit a DC application to NRC was not justified, because they do not have a sufficient number of committed customers in the United States or a DOE cost-sharing agreement. Westinghouse representatives said they may resume efforts to certify their light water SMR design if market conditions change—that is, if they identify a sufficient committed customer base—or if financial risks are otherwise reduced.

In addition to the four light water SMR designs that have been the topics of pre-application discussions with NRC, other SMR designs have been proposed and developed to varying degrees. For example, light water SMR designs are under development or construction internationally, including Argentina, China, France, Russia, and South Korea.

2.2 DOE has also focused R&D support on two advanced reactor concepts

DOE has supported R&D for cross-cutting advanced reactor work—work that could be applied to multiple concepts, such as materials studies—as well as development focused on specific advanced reactor concepts. The two specific advanced reactor concepts on which

DOE has focused for domestic R&D are the high temperature gas cooled reactor (HTGR) and the sodium cooled fast reactor (SFR). DOE has also supported, to a lesser degree, work on the molten salt reactor (MSR)—specifically, a sub-type of this reactor known as the fluoride salt cooled high temperature reactor (FHR). DOE supports development of these advanced reactor concepts through awards to universities and national laboratories and through cost-sharing arrangements with several reactor designers. All three of these reactor concepts are also being developed internationally, and DOE participates in multi-national efforts, such as the Generation IV International Forum (GIF), an international cooperative endeavor with 13 partners established to carry out R&D for new nuclear energy systems. According to GIF documentation and NRC officials, no advanced reactor is likely to be ready for an application to NRC for at least 5 years.

The HTGR is a high-temperature thermal (graphite-moderated) helium-cooled gas reactor that has a core outlet temperature of 700° to 950° C.[21] The concept is based on commercial gas reactors that have been already built and operated.[22] According to DOE, the high outlet temperature allows the reactor to be used to produce high temperature process heat for use in oil refineries, chemical plants, and the production of hydrogen. This process heat can potentially expand the role that nuclear energy has in energy sectors beyond electricity production by providing an alternative for processes currently using fossil fuels to supply process heat. The outlet temperature also allows for electricity production with thermal efficiencies of 40 to 50 percent, which are high compared with the typical thermal efficiencies for large LWRs of approximately 32 to 34 percent. While HTGR designs would still need safety reviews for licensing or design certification, according to GIF documentation, gas reactors, including HTGRs, are expected to have good safety performance.[23]

The HTGR is regarded by DOE and its international partners as one of the more mature advanced reactor concepts because it is based on gas reactor technology with significant operating experience as well as research progress made over the last 10 years, including work done as part of the Next Generation Nuclear Plant (NGNP) Project.[24] According to GIF documentation, a reactor in China—the 200 MWe HTR-PM—will further demonstrate aspects of the concept's safety and operational feasibility and may be operational in 2017. Additional work on the HTGR continues in areas such as demonstrating the safety features, including passive decay heat

21 HTGRs designed for the higher end of these temperatures may also sometimes be referred to as VHTRs – very high temperature reactors.

22 These gas reactors include the Fort Saint Vrain and Peach Bottom 1 reactors, commercially operating 1979-1989 and 1967-1974, respectively, in the United States.

23 The expected HTGR safety performance is based on a number of factors, described below, that together make it difficult for an accident to cause the HTGR core to increase in temperature to a sufficient degree that fuel and fission products can be released from the reactor. HTGRs have a strong negative temperature coefficient of reactivity, meaning that as temperatures increase the nuclear reaction slows down. In addition, the graphite moderator has a high heat capacity, meaning it will heat up relatively slowly, and the core has a low power density, meaning the reactor is better able to passively remove decay heat. Moreover, the nuclear fuel currently in development for use in the HTGR consists of many small spherical kernels of fuel, each individually coated with materials that allow very high temperatures to be reached before the fuel and its fission products will be released, and the reactor vessel relies on natural heat transfer to ensure fuel temperatures remain well below potential fuel failure points in the event coolant is lost.

24 NGNP was established by the Energy Policy Act of 2005. Under the act, DOE is to deploy a prototype NGNP reactor using advanced technology to generate electricity, produce hydrogen, or both, by the end of fiscal year 2021. However, in 2011, DOE decided not to proceed with the deployment phase of the project, citing several barriers. For additional information see **GAO-14-545**.

removal systems that can prevent the reactor from overheating without external intervention; fuels and materials qualification, including testing of the fuel coatings under postulated accident conditions and the pressure vessel materials for high temperature use; and developing and testing the process heat application concepts.

The SFR uses liquid sodium as a coolant and operates as a fast reactor and thus does not have a moderator. It is a moderately high temperature reactor with an outlet temperature of 500-550° C. While SFR designs would still need safety reviews for licensing or design certification, according to GIF documentation, SFRs are generally expected to have good safety performance; however, the liquid sodium coolant is reactive and may burn if exposed to water or air, requiring that the system be sealed.[25]

DOE and GIF documentation states that the SFR, like the HTGR, is one of the more mature of the advanced reactor concepts, in large part because of experience with similar reactors that operated in the past and with current reactors, such as the operational Chinese Experimental Fast Reactor and Russian BN-600.[26] Additional work is being done to look at safety and severe accident prevention and mitigation, fuel development, and certain component development.

The MSR uses liquid fluoride salt as a coolant. There are generally two types of MSR concepts. The first dissolves the fissile fuel in the salt coolant itself. The second circulates the salt coolant around the solid fuel pebbles without dissolving the fuel. This second type is sometimes also referred to as a fluoride salt-cooled high-temperature reactor (FHR), and much of the DOE support for MSR development in the United States is focused on the FHR. These reactors operate at atmospheric pressure and high temperature (700° C).

According to members of our expert group and GIF documentation, the MSR/FHR is considered to be a less mature advanced reactor concept than the HTGR or SFR. While two test MSR reactors were operated several decades ago in the United States, there is less experience with operating FHRs.[27] According to GIF documentation, additional work is needed on current commercial MSR concepts, including further studies of the salt chemistry and thermodynamics, as well as the salt interaction with air and water in the event of a severe accident. Components and materials need to be developed and tested for compatibility with the salt, including through corrosion studies. The salt under study for the FHR requires highly enriched lithium-7, which we previously found may face a potential future shortage.[28]

According to GIF documentation, a number of countries, including the United States, have agreed to coordinate on development of six advanced

25 The expected SFR safety performance is based on a number of factors. The coolant has a high thermal inertia, meaning it is harder to increase the temperature of the coolant, and it has a good temperature margin before boiling—that is, the reactor operates at coolant temperatures well below where the coolant might begin to boil. The coolant can be held at atmospheric pressure, reducing the likelihood of a loss of coolant accident.

26 Other examples of SFRs are, among others, the Fast Flux Test Facility, operated in the United States from 1980 to 1992; the Experimental Breeder Reactor-II, operated in the United States from 1964 to 1994; the Fermi reactor, operated in the United States from 1963 to 1975; and the Phénix reactor, operated in France from 1973 to 2009.

27 These two salt-cooled reactors operated in the United States were the Aircraft Reactor Experiment in 1954 and the Molten-Salt Reactor Experiment from 1965 to 1969.

28 GAO, *Managing Critical Isotopes: Stewardship of Lithium-7 Is Needed to Ensure a Stable Supply*, **GAO-13-716** (Washington, D.C.: September 19, 2013).

reactor concepts—the three discussed above, on which DOE coordinates work on HTGRs and SFRs through the GIF, as well as the lead-cooled fast reactor, the supercritical water reactor, and the gas fast reactor. According to these documents, DOE has been observing the international efforts on the MSR and lead-cooled fast reactor concepts but has not been participating in those R&D efforts. The lead-cooled fast reactor is primarily under development by Russia, where some small reactors using this technology are under construction, and the work has been informed by lead reactor experiences with the former Soviet naval program. The major source of interest in the supercritical water reactor is in Canada, where it is viewed as a potential successor to their heavy water reactors. However, the supercritical water reactor concept still requires significant R&D with respect to materials and water chemistry. According to documents we reviewed, the gas fast reactor is related to the HTGR but is designed without a moderator to allow it to operate as a fast reactor. This concept requires significant materials and fuel work as well as safety studies, and no gas fast reactor has yet been operated.

3 New reactor concepts could provide benefits that may allow expansion of potential commercial applications for nuclear reactors

Key benefits that light water SMRs or advanced reactors under development are intended to provide include lower construction and financing cost, greater flexibility, and greater operational efficiency. Light water SMR designers intend for their designs to reduce the cost and time of reactor construction and to allow for greater flexibility in the application of nuclear power by providing reactors that can be located in more places than large LWRs and that can be more flexible for meeting various electric grid needs. Advanced reactor designers intend for their designs to provide improved safety, efficiencies, and fuel utilization, as well as increased flexibility to use nuclear reactors for non-electric applications such as supplying process heat or managing spent fuel. However, both light water SMRs and advanced reactor concepts face challenges in development and deployment.

3.1 Light water SMR designers intend for their designs to reduce cost and time of reactor construction and to provide flexibility in nuclear power options

Light water SMRs can provide benefits such as increased flexibility and options for potential reactor operators. Light water SMRs, as their name implies, have two important design features, each of which leads to certain reactor characteristics. First, they are designed to be small compared to large LWRs—both in physical size and in power output. Second, they are designed modularly—that is, components can be manufactured in a factory environment, where standardization and learning of production techniques can help reduce costs, and the components can then be assembled later on-site. Furthermore, light water SMRs are generally designed around the idea that there are trade-offs between the economy of scale that large LWRs provide (by lowering the cost per MWe with very large facilities) and the potential economy of mass production that modular construction of larger numbers of smaller-sized reactors can provide. In February 2015, NuScale announced that their expected overnight construction cost of a light water SMR power plant consisting of twelve reactor modules, with total electric generating capacity of about 570 MWe, would be about $2.9 billion, and that future plants could potentially drop in cost to $2.5 billion—about half of what a single large LWR would cost, and at a similar cost per MWe.[29] However, the operations and maintenance cost estimates for light water SMRs have yet to be fully developed, and while they may be similar to those for existing reactors, several issues related to these costs have yet to be resolved.

[29] According to NuScale representatives, the plant cost estimate for the first plant assumes a generic location in the southeast region of the United States, does not include owner costs such as licensing or transmission interconnect, and has an expected accuracy of +35%/-10%. According to NuScale representatives, the future plant cost estimate is less firmly supported than the estimate for the first plant.

Light water SMR characteristics that could provide benefits that increase their flexibility for potential operators include the following:

- **Lower construction cost:** The smaller size of light water SMRs decreases the component costs for the reactor, and the lower cost allows for easier financing. While there is a reduction in power output for a light water SMR as compared to a large LWR, the smaller overall construction cost may make nuclear power, in the form of SMRs, a more viable option for smaller customers—although joint ownership of a large power plant remains an option for them. According to reactor designers, one part of reducing construction costs is simplification of the safety systems, which may also increase overall safety. For example, existing large LWRs require external power or backup generators to run coolant pumps to remove the residual decay heat that is in the reactor core after the reactor is shut down.[30] Light water SMRs can remove heat using fewer pumps and motors or by using passive processes, such as natural circulation of coolant. According to reactor designers, passive safety measures, whether in light water SMRs or in other large LWR designs under construction, can increase the time period that reactors can remain safe—even without external electricity—to several days or longer, possibly indefinitely.[31]

- **Shorter construction times:** While a light water SMR power plant is expected to still require 3 or 4 years to build, large LWRs can take 6 years or more. The shorter construction times for SMRs could allow for easier planning as well as reduced financing costs, and because an SMR power plant may consist of multiple reactor modules, the modules installed first may become operational earlier than the project completion date.

- **Siting flexibility:** Light water SMRs are intended to have a smaller facility footprint, allowing more locations to be considered for a reactor. In addition, due to their smaller fuel loads and design features, according to DOE officials and reactor designers, these light water SMRs may further increase siting flexibility if NRC grants regulatory exceptions to allow them to have smaller exclusion area and emergency planning zones than existing large LWRs. Exclusion areas are based on potential releases of radioactive material and specify maximum population densities around planned reactor sites. The emergency planning zone is the area within about 10 miles of the reactor site for which the operator and state and local entities must prepare predetermined emergency response plans. There is a second emergency planning zone at about 50 miles from a reactor site that requires predetermined plans for monitoring water and food sources.

- **Grid flexibility:** The smaller size of light water SMRs provides potential benefits with respect to the electric grid or distribution systems. First, some markets may not need the 1000 MWe or more that a large LWR provides, so a light water SMR may be better suited for that locality's electricity distribution needs. For example, SMRs may be suitable for replacing coal-fired power plants of similar size. Second, some rural or remote areas can have electricity distribution systems that do not have the

[30] The failure of backup power supplies was a contributing factor to the Fukushima accident in 2011.

[31] The Westinghouse AP1000, a large LWR, has a design certified by NRC and uses some of these passive safety measures. Four AP1000 reactors are under construction in Georgia and South Carolina.

capacity to handle the power output from a large LWR.

- **Remote locations:** Some customers in rural or remote areas with high costs associated with shipping fossil fuel to them—and subsequently with high electricity generation costs—may find light water SMRs to be economically competitive. Light water SMRs can provide additional flexibility with electricity generation options for customers in such areas. For example, remote mining operations or isolated villages may find SMRs competitive compared to continuously importing diesel.

3.2 Advanced reactor designers intend for their concepts to provide higher efficiencies and opportunities for additional industrial applications

Advanced reactor designers, including those receiving support from DOE, intend for their concepts to result in reactors that have higher thermal efficiency than either light water SMRs or large LWRs. The thermal efficiency is related to the outlet temperature of the reactor. Large LWRs (as well as light water SMRs) have outlet temperatures around 300° C and a resulting thermal efficiency of around 32 to 34 percent. However, advanced reactors have significantly higher outlet temperatures—500-550° C for SFRs and 700° C or higher for HTGRs and FHRs—allowing them to operate with significantly higher efficiencies of 40 to 50 percent. The higher thermal efficiencies can translate to more economical and competitive reactors. They also have the potential for reducing water consumption requirements for the reactors, according to members of our expert group.

Advanced fast reactors can provide another type of efficiency—they can be designed to consume more of their fuel before needing to be refueled. They can also be operated as breeder reactors, whereby they can create more fuel than they consume, or they can be operated as burners, in which case they can lessen the need for spent fuel storage by consuming some of the spent fuel from LWRs. While uranium prices and reprocessing costs may not change significantly, these options could become increasingly important if uranium fuel costs increase significantly or while uncertainty remains about a permanent spent fuel repository. However, some of these options would require additional R&D and investment in spent fuel reprocessing capabilities. There are also potential nonproliferation considerations. For example, reprocessing facilities are sometimes viewed as proliferation risks because they can provide a means to separate out materials from spent fuel that can be used to make nuclear weapons and would therefore require safeguards and security that could affect the reprocessing operations or economics. Furthermore, the reprocessing facilities still generate waste that must be stored and disposed. According to a reactor designer, one of the advanced reactor concepts—the FHR—may also efficiently store energy in the form of heat, making it a potential option for integration with intermittent renewable energy sources.

According to DOE and reactor designers, advanced reactors—as well as light water SMRs to a lesser degree—are intended to provide a benefit that could potentially allow a new commercial application for nuclear reactors if they were located with industrial processes that could directly use the heat they produce. The relatively high temperatures of advanced reactors could supply process heat for use in oil refineries, chemical plants, and the production of hydrogen—potentially expanding the role that nuclear energy can have in energy sectors beyond electricity production by providing an alternative for processes currently using fossil fuels to supply process heat. For example, at the lower temperature range of water-cooled reactors, including large LWRs and light water SMRs, desalination plants could use heat to distill water for drinking water or agricultural purposes. Some of these industrial applications may also allow the reactors to be used for the industrial application intermittently when electricity demands on the grid are reduced, rather than decreasing the reactors' energy production to match electricity demand. However, according to members of our expert group and NRC documentation, co-locating a nuclear reactor with a potentially hazardous industrial facility will require the license to include the potential impacts of an industrial accident on reactor safety—which is already considered for reactors near other facilities—and it could raise industry concerns that a potentially expensive industrial facility could be forced offline if the reactor shut down or had an accident. DOE explored some of these commercial applications for nuclear-generated process heat as part of its NGNP Project. In 2011, DOE decided not to proceed with the deployment phase of the project, citing several barriers, including being unable to reach an agreement on a cost-share arrangement with industry partners to fund the deployment phase.[32]

Several members of our expert group agreed with the idea that advanced reactors will likely initially be developed with small, modular designs. In this case, in addition to the advanced reactor capabilities described in this section, advanced reactors may also offer the flexibilities of SMRs, as previously discussed.

[32] See **GAO-14-545**.

4 Development and deployment efforts for new reactor concepts face several challenges

While new reactor concepts may provide some benefits, light water SMRs face some development challenges even though they are similar to existing large LWRs. Advanced reactors, which differ significantly from the existing large LWRs, face more development challenges. Both types of new reactor concepts face some common challenges such as long time frames and high costs associated with the shift from development to deployment—that is, in the construction of the first commercial reactors of a particular type.

4.1 Light water SMR development faces some technical, certification, and licensing challenges, and advanced reactor development faces more substantial challenges

While both light water SMRs and advanced reactor concepts are built on knowledge gained over decades of industry and government work in nuclear power, both types of reactors still face some technical, certification, and licensing challenges. Because they use the same coolant and operate under similar temperatures and pressures as the existing large LWRs, as well as recently certified large LWR designs, the four light water SMR designs discussed above share many operational similarities with such reactors, according to DOE and NRC officials. The light water SMRs generally use the same types of reactor concepts as large LWRs, but with the goal of reducing the size and complexity of the reactor. The result is a reactor with similar components and similar operational characteristics, such as water chemistry and temperature, but with a different geometry and, in some cases, components that have been integrated into a single pressure vessel. The light water SMR designs are evolutionary changes to existing large LWRs and, as such, have reduced technical risk. Because of their similarities to reactors widely used in the United States, reactor designers and DOE officials told us they have greater confidence in the performance of the light water SMR designs than in designs using advanced reactor concepts.

According to reactor designers, the work remaining for light water SMRs largely involves the SMR designers finishing the detailed design of the power plants and completing the demonstration of their economics and safety claims, as well as providing support to the NRC during the certification or licensing processes to address claims specific to their intended operation, such as claims that operations and security staff regulatory requirements could be reduced as compared to existing large LWR requirements. If the light water SMR designers are unable to demonstrate that their designs can operate safely without adding to the complexity of the design, their construction and maintenance costs may increase and thus weaken their economic competitiveness. Similarly, if the light water SMR designers are unable to demonstrate that the numbers of per-reactor operations and security staff may be safely reduced from those required for an existing large LWR, the estimated ongoing operations costs may increase and weaken

SMR economic competitiveness. According to members of our expert group, light water SMR designers will also need to address some technical challenges related to the manufacturing and assembly of these reactors. Because the light water SMRs rely on standardization of the design of a reactor and producing large numbers of that reactor to lower construction costs, the individual components need to be highly standardized so that they can be assembled properly at the reactor sites. Members of our expert group told us this component standardization has proven challenging for the construction of the Westinghouse AP1000, which is a large LWR that has some modular components, but they also noted light water SMRs have smaller components than the AP1000, so component standardization may be more easily accomplished for SMRs. Despite these remaining challenges, members of our expert group were in nearly unanimous agreement that there were no "show-stoppers" for the NuScale light water SMR design, with one dissenting expert noting that the passive safety features still need to be fully demonstrated.

According to DOE officials, in contrast to the light water SMRs, which are similar to existing large LWRs, advanced reactors face more challenges, in part because the reactor industry has less operating experience with advanced reactors. Advanced reactors also operate at higher temperatures and, for the fast reactors, in a more severe neutron environment. Therefore, according to DOE officials, before advanced reactors can be commercially viable, designers have significantly more R&D issues to resolve, including in areas such as materials studies and fuel certification, coolant chemistry studies, and safety analysis. Some members of our expert group also noted a potential need for new test facilities to support this work. Furthermore, the current NRC certification or licensing processes were described to us by former and current NRC staff as being focused on the reactors that have been built—that is, large LWRs. According to reactor designers, certifying or licensing an advanced reactor may be particularly time-consuming and difficult, and the need for exemptions to and interpretation of the current processes if applied to advanced reactors could introduce economic uncertainty for the applicants.

4.2 New reactor development and deployment may be affected by long time frames, high cost, and uncertainties

The development of new nuclear reactor designs through the Part 52 process is time consuming, with up to 10 or more years of design work leading to a DC process that NRC projects to take nearly 3.5 years as a best-case scenario, COL applications that can take at least about 4 years if referencing the DC, and construction that can take at least another 3 to 4 years. Members of our expert group, reactor designers, and DOE officials told us that the cost of this process rapidly escalates—early R&D can be done for tens of millions of dollars, while the cost to complete the R&D and to obtain a design certification from the NRC could reach $1 billion to $2 billion. Of this amount, based on the two most recent design certifications NRC has granted, about $50 million to $75 million is for NRC fees related to DC pre-application, application, and revisions, and the rest is spent on reactor R&D and design work. Some reactor designers told us that they have been challenged to find investors for such a costly process when some uncertainties remain about the NRC certification or licensing processes for light water SMRs, and particularly for advanced reactors. Reactor designers seeking customers for their reactors also face challenges arising from uncertainties related to the scale of investment needed to build a new reactor, with general hesitancy among potential customers to commit to a several billion dollar construction project without a demonstration of the technology. According to members of our expert group and reactor designers we spoke with, reactor designers may also have difficulties arising from uncertainties related to the future competitiveness of reactors relative to other forms of electricity production or because of future changes in public perceptions about nuclear power, including concerns about reactor safety and spent fuel disposition. Finally, according to members of our expert group, reactor designers may see a reduced customer market for their new reactor designs if they perceive difficulties or uncertainties with exporting their designs.

New reactors can be certified or licensed with existing regulations, but uncertainties could increase the time needed

According to the NRC, any new reactor technology can be certified or licensed using existing 10 CFR Part 50 or 52 regulations. However, these deterministic regulations were developed for existing large LWRs,[33] so exemptions would be needed for reactor designs differing significantly from existing large LWRs, or the regulations would otherwise need to be adapted, according to reactor designers and NRC officials. According to NRC officials, these exemptions must be specifically applied for by reactor designers or license applicants before the NRC will actively pursue them, and the pre-application discussions between reactor designers and NRC are intended to help identify these exemption items. Several reactor designers told us that they would like regulations changed in order to lessen the uncertainty introduced by relying on exemptions during the DC or licensing process. According to reactor designers, the uncertainty associated with the need for exemptions increases their development risk by potentially increasing the length of the multiple-year DC or license application process. Reducing that uncertainty could help reactor designers find customers—such as utilities—and obtain financing to build plants. A reactor designer representative told us that they were waiting until after the first light water SMR has completed a DC application in order to benefit from a better understanding of the process and potentially updated regulations or exemptions before they would apply for a DC.

Advanced reactors will require more exemptions from current regulations than light water SMRs and thus face greater licensing uncertainties, according to members of our expert group and officials from NRC and DOE. Furthermore, advanced reactors that are designed to produce process heat will need additional scrutiny from NRC because of the need for them to operate safely in proximity to an industrial facility that could affect operations at the reactor site—this NRC requirement applies to any reactors operating near external facilities that may impact safety at the reactor site. For reactors that create process heat for direct use in other applications, such as industrial chemical processes, additional design analysis and regulatory reviews are needed of the interface between the nuclear and non-nuclear process and

[33] Deterministic regulations are not based on numerical estimates of risk, but rather on experience, test results, expert judgment, engineering margins, and the concept of defense-in-depth; for example, current NRC regulations require that no more than two reactor units may be operated from a single control room, although at least one light water SMR designer hopes to operate more than two units from a common control room. NRC regulations have been shifting from a deterministic to "risk-informed" and/or "performance-based" approach for certain topics, but deterministic regulations are still present and are largely based on the experiences with existing large LWRs.

the degree to which failure of the non-nuclear process could affect safety.

To identify and resolve some of the open policy issues related to advanced reactors and to reduce the licensing uncertainties faced by advanced reactors as a result of the exemptions they would currently need, in July 2013, DOE and NRC established a joint initiative to address portions of the licensing framework they determined to be essential to advanced reactor technologies. In December 2014, the Argonne, Idaho, and Oak Ridge National Laboratories, under a DOE contract, completed the first phase of this work with the production of guidance for developing principal design criteria for advanced, non-light water reactors.[34] NRC officials told us they are evaluating this guidance and anticipate issuing updated regulatory guidance for licensing advanced reactors by December 2016.

First-of-a-kind nuclear plant costs increase construction challenges

As previously described, nuclear power plant economics involve considerable costs, such as capital costs and plant operating costs. Included in capital costs are site preparation, construction, manufacturing, commissioning and financing a nuclear power plant. Plant operating costs include the costs of fuel, operations and maintenance (O&M), and a contribution to funding the decommissioning of the plant and treating, storing, and disposing of used nuclear fuel and wastes. For newly built nuclear power plants, capital cost recovery is a major driver of the cost of power.[35]

Based, in part, on our review of economic studies for SMRs, the first-of-a-kind (FOAK) plants generally cost more than nth-of-a-kind (NOAK) plants, because FOAK plants are designed to show that a plant is commercially viable and to facilitate the optimization of the construction of a manufacturing plant and supply chain dedicated to NOAK plant production. The overnight capital cost of the FOAK plants would therefore be higher than those of NOAK plants of the same type, which benefit from major design costs having already been expended, a more mature manufacturing and supply chain, and lessons learned from the FOAK plants, so their overnight capital costs decrease. For example, according to members of our expert group, if a new nuclear reactor design is certified by NRC, the cost for the FOAK plant's COL essentially bears the total cost of the DC application, assuming that no further changes to the design are made and no provisions are made to spread out the cost over later NOAK plants. This increased cost for a FOAK plant particularly applies to light water SMRs, and to a greater extent advanced reactors, because they are different enough from existing LWRs that NRC officials told us they will need to certify or license them with exemptions, assuming current regulations remain in place. In fact, some reactor designers told us that the U.S. government should take the risk to certify or license, and build, the first light water SMR, because of the difficulty in getting financing for an unproven design. While SMR designers seek to decrease their NOAK plant costs over time, some studies suggest that existing, large LWRs have not greatly benefitted from industry-wide standardization or learning to date for reasons including intermittent development and production.

[34] Idaho National Laboratory, *Guidance for Developing Principal Design Criteria for Advanced (Non-Light Water) Reactors* (Idaho Falls, Idaho: December 2014).

[35] Once capital costs are paid off, plant operating costs become the major components of the cost of power.

In fact, some studies have found that "reverse or negative learning" occurs when increased complexity or operation experience leads to newer safety standards. On a related point, another reactor designer said that the cost and schedule difficulties associated with building the first new design that has been certified by the NRC and started construction in the United States in three decades—the Westinghouse AP1000, a recently designed large LWR—have made it harder for light water SMRs to obtain financing because high-profile problems have made nuclear reactors in general less attractive.[36] However, if costs of the AP1000 units decrease over time through their certified design and modular design, it may show that the nuclear industry could benefit from lessons learned and simplified, modular designs.

In addition to financing the design and certification if Part 52 is used, reactor designers must be able to find a customer to buy, license, and operate the plant. One reactor designer representative told us they would be able to move forward with their design if they had a signed contract with a customer. However, reactor designers also told us customers want a certified design with fewer uncertainties regarding cost before they will commit to buying a plant.

Changes in alternative electricity generation create uncertainty for nuclear reactor profitability

The studies and reports we reviewed and members of our expert group that we spoke with indicated that recent decreases in U.S. nuclear energy production may be due to a number of factors, including a decline in natural gas prices and increases in renewable energy generation. Potential changes in future natural gas prices and renewable energy generation capacity create uncertainty in the profitability of nuclear reactors that compete with these energy sources. Regarding natural gas prices, some nuclear plant operators cited price reductions as an important factor in their decisions regarding nuclear power reactor operations. Utilities appear to have increased baseload generation primarily by stepping up production at natural gas-fired combined cycle (NGCC) plants, with the exception of the construction of five additional large LWRs.[37] Utilities may prefer new natural gas power plants as a source of additional baseload and peak capacity because when natural gas prices are relatively low, high-efficiency NGCC power plants can supply electricity at a lower cost than coal-fired generators, and they are faster and less costly to build than nuclear plants.

The declining price of natural gas was a major contributor to the rise in NGCC electricity generation and the decline in coal-fired generation in recent years, and more stringent clean air standards also contributed to the decline in coal generation. NGCC generation capacity can be added to meet forecasted changes in electricity demand by better matching short-term changes in electricity demand, compared to less-flexible, coal-fired generators and large nuclear reactors. In recent years, the number of nuclear plant retirements has increased, in part

36 The AP1000 was the first new design that has been certified by the NRC and started construction in the United States in three decades. However, construction problems, including supply chain and regulatory issues, have resulted in cost and schedule increases. For example, for the AP1000 units under construction at the V.C. Summer Nuclear Station in South Carolina, NRC inspectors determined that the rebar spacing and depth was not in alignment with the design certification document, which required reanalysis and resulted in about a six month delay. Quality control issues with key submodules for this same reactor have also caused a schedule delay and cost increases.

37 There are four reactor units—two at each location—under construction at the Vogtle Plant in Georgia and V.C. Summer Nuclear Station in South Carolina. There is one additional unit under construction at the Watts Barr Nuclear Power Plant in Tennessee.

because of a decline in profitability as low natural gas prices have influenced the relative economics of NGCC and nuclear plants. Since 2012, five nuclear power reactors representing 4.2 GW of capacity have ended power production, and a sixth, the Oyster Creek plant in New Jersey, is expected to shut down in 2019. For example, the Vermont Yankee Nuclear Power Station in Vernon, Vermont, began operations in 1972, and the owners obtained a renewed license in 2011 to operate the plant for an additional 20 years. However, in December 2014, the owners permanently shut down the plant. According to the owners, their decision to shut down the plant was driven in part by lower natural gas prices, which had reduced the comparative profitability of the plant. However, in the future nuclear power could become more economically competitive if factors affecting the costs of producing electricity change. Such changes may include increases in the cost of natural gas or coal, further innovation in nuclear technology that could reduce future costs, increased emphasis on power reliability or diversity of energy sources, or changes in state or federal energy or environmental policy, such as increased requirements to reduce emissions from fossil fuel powered electricity generators or the adoption of a carbon tax.[38]

In addition to low natural gas prices, DOE officials and members of our expert group told us that renewable energy sources, such as wind or solar, can also exert economic pressure on nuclear reactors. Some renewables are intermittent power sources that are prioritized as electricity sources by grid operators because of green energy usage requirements and their near-zero operating costs when that energy source is available. These sources can cause fluctuations in electricity generation that can cause problems for baseload power plants, including nuclear power plants, because they cannot rapidly increase or decrease their power production to meet hourly demands without additional wear on their fuel and equipment. DOE officials and some reactor designers told us they are exploring the use of hybrid energy systems that could develop a way for different power sources to better integrate with each other to allow nuclear power, which could include light water SMRs or advanced reactors, to remain an economic source of electricity.

Changing perceptions of nuclear safety can create uncertainty in the demand for nuclear power

In March 2011, a 9.0-magnitude earthquake and subsequent tsunami devastated northeastern Japan and resulted in equipment failure at the Fukushima Daiichi nuclear power plant. The resulting radiological emergency involved the most extensive release of radioactive material at a nuclear power plant since the 1986 Chernobyl accident. Following this release, the Japanese government evacuated people within 12 miles of the plant, and later extended the evacuation zone to 19 miles. In total, almost 150,000 people were evacuated. In response to the incident, Japan shut down all of its nuclear power reactors, and concerns heightened worldwide about the safety of commercial nuclear power plants. For example, Germany closed 8 of the country's 17 reactors and decided to shut down the remainder by 2022, resulting in more carbon-intensive

[38] For example, an executive order issued on March 19, 2015 regarding federal leadership in sustainability and greenhouse gas reductions specifically noted using small modular reactors among other alternative energy options as a way to meet clean energy targets for federal agencies.

energy production as the country attempted to use more renewable energy in a baseload capacity manner and compensated for the loss of nuclear generation through the increased use of fossil fuels. In the United States, the Fukushima incident affected some plans to build new nuclear power plants. For example, in 2011, one partner in an ongoing nuclear project in Texas cited multiple uncertainties around nuclear development in the United States related to the Fukushima incident as a reason to stop capital investment in the project.

In response to the Fukushima incident, the federal government established or strengthened a number of standards and requirements related to nuclear energy. For example, NRC accepted 12 recommendations from a task force that NRC had convened in 2011 to review its processes and regulations and determine whether lessons learned from the Fukushima accident could inform its oversight processes. The task force recommended that NRC require licensees to reevaluate and upgrade seismic and flooding protection of reactors and related equipment, strengthen capabilities at all reactors to withstand loss of electrical power, and take other actions to better protect their plants for a low-probability, high-impact event. NRC's activities to strengthen the safety and security of nuclear power plants after the Fukushima incident have increased the costs associated with some existing LWRs, thereby providing a disincentive for nuclear power production. However, these activities could create incentives for new nuclear reactors that will not have costs associated with retrofitting and may be inherently safer. As of October 2014, the two most recent nuclear reactor designs certified by NRC—the Westinghouse AP1000 and the GE Hitachi ESBWR—have more passive safety systems than existing LWR designs. Light water SMRs and advanced nuclear reactors will have to meet or exceed NRC's current safety requirements.

Access to potential export markets may influence reactor designers

In case light water SMRs or advanced reactors are exported, there are non-proliferation safeguards in some of the new reactors. According to DOE officials and reactor designers, some advanced reactors use fuel encapsulated in materials such as silicon carbide, which make it difficult to access the fuel, potentially making the fuel safer in the event of an accident and more proliferation resistant. Some advanced SMR designers go a step further and claim that their designs could be "black boxed" (that is, they could be deployed already fueled and sealed), and once the fuel is spent, the entire unit could be shipped back to the factory for waste handling and reprocessing. If responsibility for the fuel cycle were thus taken out of the hands of the reactor operator, then risks of proliferation could potentially be reduced. DOE officials told us that these safeguards make such reactors attractive for export purposes. However, the details of how to provide assurance that such reactors remain sealed or how to determine if there has been an attempt to open the reactor have yet to be resolved.

Reactor designers have mixed opinions regarding the feasibility of obtaining export authorization, but most agree that more could be done to ease the process. In addition, we previously recommended that DOE improve its export control process, including efficiency in reviewing applications and found that U.S. designers were at a disadvantage for exporting nuclear designs compared to foreign-state owned or supported nuclear industry.[39] However, some reactor designers are still pursuing international markets, particularly in China, for constructing their reactors, because higher fossil fuel prices in other countries may make their designs more economically competitive. Further, by first demonstrating the construction and operation of a reactor in another country, designers may reduce challenges associated with certification or licensing and construction of their designs in the U.S. market.

[39] GAO, *Nuclear Commerce: Governmentwide Strategy Could Help Increase Commercial Benefits from U.S. Nuclear Cooperation Agreements with Other Countries*, **GAO-11-36** (Washington, D.C.: November 4, 2010), and *Nuclear Commerce: Additional Actions Needed to Improve DOE's Export Control Process*, **GAO-15-124** (Washington, D.C.: October 14, 2014).

5 Concluding observations

While commercial nuclear reactors provide nearly 20 percent of the electricity in the United States, the existing large LWR fleet is aging while electricity demand in the coming decades may increase. Five large LWRs are currently under construction, but reactor designers have also been working on small modular reactors and advanced reactors that can provide different sets of capabilities than large LWRs. One light water SMR designer may begin its DC application with NRC in late 2016 with a planned 12-reactor power plant completed as early as 2023, while advanced reactors are likely at least 5 years from submitting a design certification application.

New SMR designs and advanced reactor concepts are intended to provide certain benefits. Light water SMRs could expand commercial applications for nuclear power by offering power plants that are lower in construction and financing cost—although with smaller generating capacities—and that have shorter construction times. These smaller reactors can provide more flexibility in siting options and with rural or remote grid locations. Advanced reactors can achieve higher temperatures than LWRs and thus can be used directly for certain industrial applications that currently rely on fossil fuels to achieve high temperatures. Certain advanced reactors, such as fast reactors, may also provide additional fuel cycle flexibility and nuclear waste management capabilities.

While light water SMRs and advanced reactors may provide some benefits, their development and deployment face a number of challenges. Both SMRs and advanced reactors require additional technical and engineering work to demonstrate reactor safety and economics, although light water SMRs generally face fewer technical challenges than advanced reactors because of their similarities to the existing large LWR reactors. Depending on how they are resolved, these technical challenges may result in higher-cost reactors than anticipated, making them less competitive with large LWRs or power plants using other fuels. However, nuclear reactors, including these new reactors, may still be attractive for their reliability, zero carbon emissions, and as a means to diversify energy sources. In the future, nuclear power could become more economically competitive with other energy sources if factors affecting the costs of producing electricity change. Such changes may include increases in the cost of natural gas or coal, further innovation in nuclear technology that could reduce future costs, or changes in state or federal energy or environmental policy, such as increased requirements to reduce emissions from fossil fuel powered electricity generators or the adoption of a carbon tax.

Both light water SMRs and advanced reactors face additional challenges related to the time, cost, and uncertainty associated with developing, certifying or licensing, and deploying new reactor technology, with advanced reactor designs generally facing greater challenges than light water SMR designs. It is a multi-decade process, with costs up to $1 billion to $2 billion, to design and certify or license the reactor design, and there is an additional construction cost of several billion dollars more per power plant. Furthermore, the licensing process can have uncertainties associated with it, particularly for advanced reactor designs. A reactor designer would need to obtain investors or otherwise commit to this development cost years in advance of when the reactor design would be certified or available for licensing and construction, making demand (and customers) for the reactor uncertain. For example, the price of competing power production facilities may make a nuclear plant unattractive without favorable rates set by a public authority or long term prior purchase agreements, and accidents such as Fukushima as well as the ongoing need for a long-term solution for spent nuclear fuel may affect the public perception of reactor safety. These challenges will need to be addressed if the capabilities and diversification of energy sources that light water SMRs and advanced reactors can provide are to be realized.

6 Agency and third party comments and our evaluation

We provided a draft of this report to DOE for review and comment. DOE did not provide a written response, but did provide technical comments that we incorporated as appropriate throughout the report.

We provided a draft of this report to NRC for review and comment. NRC provided a written response which is included in appendix I. NRC also provided technical comments that we incorporated as appropriate throughout the report.

We provided a draft of this report to 18 members of our expert group for review and comment and received comments from 17 of them. The majority of the comments were generally favorable. These comments included technical corrections and suggestions that we incorporated throughout the draft as appropriate.

A couple members of our expert group indicated that the report would benefit from more balance with increased input from utility representatives and environmental groups. We did gather information from representatives of some of these groups over the course of this work or related work, and we believe that this report is appropriately balanced with respect to the stated objectives. A couple members of our expert group noted that the report did not directly address structural issues that affect nuclear reactor development, including the need for test facilities or the implications of government support for this work. One member of our expert group suggested a review of the last several decades of government-supported advanced reactor development, and one member of our expert group suggested a more general discussion of the importance of a robust U.S. nuclear industry. While these are all relevant to the topics addressed by this report, we limited the scope of this work to the stated objectives and the supporting information needed for general context.

Several members of our expert group suggested that we include a discussion of the effect of subsidies for renewable energy or fossil fuel sources on the competitiveness of nuclear energy or otherwise include a more comprehensive discussion of the economic role of nuclear energy, including factors such as the prioritized use of renewables over other sources of electricity, improved energy efficiencies, or improved energy storage technologies. One member of our expert group identified reliability issues with some advanced reactors that had operated in the past and questioned the economic viability of reactors, particularly fast reactors operating as burners for fuel cycle flexibility. While these topics are relevant to some of the stated objectives of this report, we determined that a full, balanced study of energy subsidies, the energy market, and the highly uncertain nature of future energy markets, was beyond the scope of this work.

Several members of our expert group commented that the NRC regulatory process was insufficient for licensing new types of reactors—particularly non-light water reactors, such as advanced reactors—without introducing excessive risk for the reactor designer, for example through the necessary use of exemptions. One member of our expert group suggested we provide a comparison of the NRC process to other regulatory structures in the United States and noted the NRC process encourages delays in investment in reactor designs until one designer acts as a first mover and resolves perceived licensing uncertainties. Some members of our expert group suggested changes in the licensing process to reduce this uncertainty, for example by using phased licensing, provisional licensing, or otherwise encouraging NRC to set requirements earlier in the process. Other members of our expert group disagreed and told us such criticism of NRC is largely misplaced, for example by stating the licensing uncertainties are not due to the process but rather to uncertainties in the safety of the designs themselves or a lack of operating experience, and pointing out that if NRC sets requirements earlier in the process, NRC will have less flexibility later in the process when more is known about the reactor design. This report discusses the potential challenges related to licensing that reactor designers perceive as well as steps NRC and DOE are taking to look at the licensing process, and a comparison of the NRC regulatory processes to those of other U.S. regulatory agencies is outside the scope of this work.

We are sending copies of this report to the appropriate congressional committees, the Secretary of the Department of Energy, the Chairman of the Nuclear Regulatory Commission, and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff members have any questions about this report, please contact Timothy M. Persons at (202) 512-6522 or personst@gao.gov or Frank Rusco at (202) 512-3841 or ruscof@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix III.

Sincerely yours,

Timothy M. Persons, Ph.D.
Chief Scientist

Frank Rusco
Director, National Resources and Environment

Appendix I: Comments from the Nuclear Regulatory Commission

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

July 17, 2015

Mr. Ned Woodward, Assistant Director
Natural Resources and Environment
U.S. Government Accountability Office
441 G Street, NW
Washington, D.C. 20548

Dear Mr. Woodward:

Thank you for providing the U.S. Nuclear Regulatory Commission (NRC) with the opportunity to review and comment on the U.S. Government Accountability Office's (GAO's) draft report GAO-15-652, "Technology Assessment: Nuclear Reactors, Status and Challenges in Development and Deployment of New Commercial Concepts." The NRC has reviewed the draft report, and has a few minor comments for GAO consideration. Please see the comments in the enclosure to this letter.

If you have any questions regarding the NRC's response, please contact Jesse Arildsen by phone at (301) 415-1785 or by email at Jesse.Arildsen@nrc.gov.

Sincerely,

Mark A. Satorius
Executive Director
for Operations

Enclosure:
As stated

Appendix II: Expert participation

At our request, the following individuals helped to provide information about nuclear reactor development, including reactor economics, reactor development, and licensing. They also reviewed and provided comments, which were incorporated as appropriate, on the draft of this report.

Margot Anderson
Executive Director, Energy Project
Bipartisan Policy Center

George Apostolakis
Former Commissioner
U.S. Nuclear Regulatory Commission

Greg Ashley
President
Bechtel Nuclear Business Line

Douglas Chapin
Principal
MPR Associates, Inc.

Thomas Cochran
Consultant and Retired Senior Scientist
Natural Resources Defense Council

Ashley Finan
Senior Project Manager
Clean Air Task Force

Charles Forsberg
Director, High Temperature
Salt-Cooled Reactor Project
Massachusetts Institute of Technology

Philip Hildebrandt
Special Assistant to Laboratory Director
Idaho National Laboratory

Andrew Kadak
President
Kadak Associates, Inc.

John Kelly
Deputy Assistant Secretary
for Nuclear Reactor Technologies
U.S. Department of Energy

Jim Kinsey
Regulatory Affairs Director
Idaho National Laboratory

Edwin Lyman
Senior Scientist
Global Security Program
Union of Concerned Scientists

William Madia
Vice President for
SLAC National Accelerator Laboratory
Stanford University

David Matthews
Director New Reactor Licensing (retired)
U.S. Nuclear Regulatory Commission

Regis Matzie
Senior Vice President and
Chief Technical Officer (retired)
Westinghouse Electric

Per Peterson
Professor
University of California at Berkeley

Harold Ray
Executive Vice President (retired)
Southern California Edison

Everett Redmond
Senior Director for Policy Development
Nuclear Energy Institute

Jose Reyes
Chief Technology Officer
NuScale Power

Kevan Weaver
Director of Technology Integration
TerraPower, LLC.

Appendix III: GAO Contacts and Staff Acknowledgements

GAO contacts

Timothy M. Persons, (202) 512-6522 or personst@gao.gov

Frank Rusco, (202) 512-3841 or ruscof@gao.gov

Staff acknowledgments

In addition to the contacts named above, Ned Woodward (Assistant Director), R. Scott Fletcher, Katrina Pekar-Carpenter, and Frederick K. Childers made key contributions. John Barrett, Amy Bowser, M. Greg Campbell, Ellen Fried, Cindy Gilbert, Dani Greene, Michael Krafve, Mehrzad Nadji, Cynthia Norris, Dan Royer, and Walter Vance also made important contributions.

Related GAO products

Electricity: Generation Mix Has Shifted, and Growth in Consumption Has Slowed, Affecting System Operations and Prices. **GAO-15-524**. Washington, D.C.: May 29, 2015.

Nuclear Commerce: Additional Actions Needed to Improve DOE's Export Control Process. **GAO-15-124**. Washington, D.C.: October 14, 2014.

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