Milestones in nuclear power development

BY GAIL H. MARCUS

A collection of nuclear industry "firsts" in one book should help provide a more complete picture of how the industry arrived at where it is today.

A COUPLE OF YEARS ago, it occurred to me that for about the last 20 years I had been attending conferences and reading articles about 50th anniversaries in the nuclear field. When I started to sort them all out, I realized that I had the beginnings of a series of milestones in nuclear power development.

I had attended two conferences in 1989 to celebrate the 50th anniversary of nuclear fission (one in Leningrad and the other in Washington, D.C., that was cosponsored by the American Nuclear Society and the National Institute of Standards and Technology); the ANS/ENS International Meeting in November 1992 on 50 years of controlled nuclear chain reaction; a special event at the November 2001 ANS Winter Meeting in honor of the 50th anniversary of electricity from the atom; and a celebration of the first 50 years of the American Nuclear Society at the June 2004 ANS Annual Meeting.

I also knew that a conference was held in Moscow in 2004 to mark the 50th anniversary of the use of nuclear power to provide electricity to the public, and I had read numerous articles in 2007 celebrating 50 years of commercial nuclear power. In 2008, my alma mater (the Massachusetts Institute of Technology) and several other university nuclear engineering departments celebrated their 50th anniversaries, and in 2009, ANS's *Nuclear News* celebrated its 50th anniversary.

Clearly, though, some milestones were missing. The industry did not go from the first controlled chain reaction to a commercial reactor in just a couple of steps. Like many people, I had a hazy idea of some of the intermediate steps, but I certainly did not have a complete picture. As I started talking to my colleagues at various national laboratories and other sites, I realized that many of them knew about the developments that had occurred where they worked, but not about those at other locations. Even the people who worked on some of the early projects didn't necessarily know about all the work that was going on. In part, of course, that was because much of the early work was secret. In addition, the work was being done in several locations across the country, a number of different technologies and concepts were being explored in parallel, and developments were occurring very quickly.

I began to squirrel away news items on various 50th, and then 60th, anniversaries, and articles about firsts of a kind for the different types of reactors, the various parts of the nuclear fuel cycle, and related developments. At some point, it occured to me that this collection of "firsts" would make a good subject for a book. Thus evolved *Nuclear Firsts: Milestones on the Road to Nuclear Power Development,* which is to be published later this year by the American Nuclear Society.

Although a short article cannot possibly cover in full the milestones of nuclear power development, it can perhaps provide some sense of how much was going on in the early days of nuclear power development, and how many different projects helped lay the groundwork for the industry as we know it today.

First fission to first electricity (1942–1951)

The early history of nuclear power is, of course, inextricably tied to the development of nuclear weapons during World War II. No one would dispute that the speed with which the technology was developed, the range of activities that were carried on in parallel, and the number of new laboratories that started from scratch around the United States and elsewhere would not have occurred for a peacetime power development project. Even so, I was impressed as I reviewed the number of developments that occurred in just a nine-year period. And it became obvious to me that during this initial development period, people could already see beyond the weapons program to other applications.

Within a year after the first demonstration of controlled fission in the Chicago Pile-1 reactor at Stagg Field at the University of Chicago, a second, larger reactor—the Oak Ridge Graphite Reactor—was built and put into operation, and less than a year after that, a much larger reactor, Hanford B, was built and put into operation at the Hanford Site. At the same time that Hanford B was being built, scientists were pursuing several parallel paths to develop both enrichment and reprocessing techniques. Two small-scale plutonium separation processes were tested at

Gail H. Marcus is a consultant for nuclear technology and policy. Previously, she served as deputy director general for the OECD Nuclear Energy Agency, principal deputy director of the Department of Energy's Office of Nuclear Energy, and in various senior-level positions at the Nuclear Regulatory Commission. She is also a past president of ANS (2001–2002).

The Oak Ridge Graphite Reactor was the first reactor designed and built for continuous operation. (Photo: ORNL, managed for the U.S. DOE by UT-Battelle, LLC)

Oak Ridge National Laboratory, and a larger-scale facility using one of these processes was built at Hanford. Likewise, pilot plants were built at Oak Ridge for several enrichment methods, leading to the construction of the K-25 Gaseous Diffusion Plant at Oak Ridge, which at the time was the world's largest building structure.

What may be less well recognized is that a number of different reactor technologies were also being explored at the same time. As enriched uranium and plutonium became available, researchers could branch out from the original graphite designs and explore aqueous homogeneous, heavy-water, liquid-metal, and heterogeneous light-water reactor concepts.

Very soon after the war ended, researchers began to develop other applications of nuclear technology. First among them was the use of the Oak Ridge Graphite Reactor for the production of medical radioisotopes, and, later, industrial radioisotopes as well. At Brookhaven National Laboratory, researchers explored the use of a reactor for neutron beam medical therapy.

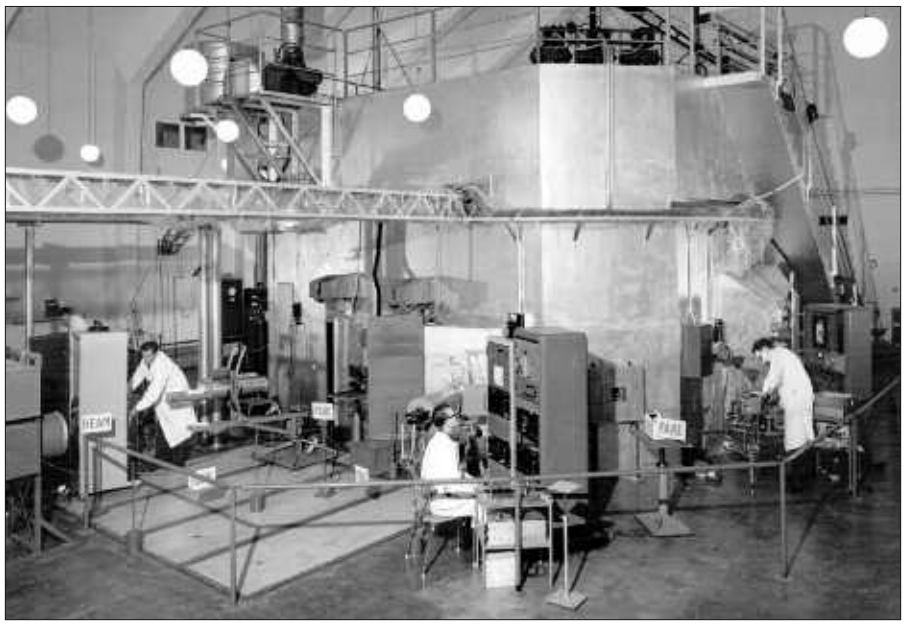
Of course, the United States was not alone in its interest in nuclear technology, both for weapons and for peaceful purposes. The first countries outside the United States to enter the nuclear business were, not surprisingly, the countries that had been involved in weapons development programs. These included Canada and the United Kingdom, both of which had worked with the United States on the Manhattan Project; Russia, which was pursuing an independent weapons development program; and France, which had an early weapons development effort that had been stalled when it was occupied during the war. All of these countries started operating experimental reactor facilities before 1950.

What is perhaps more surprising, however, is that several nonweapons countries also took a very early interest in nuclear power. In particular, a few months *before* the famous demonstration of electricity production at Arco, Idaho, the Norwegians and Dutch collaborated on a reactor program, and their first reactor went critical in Norway.

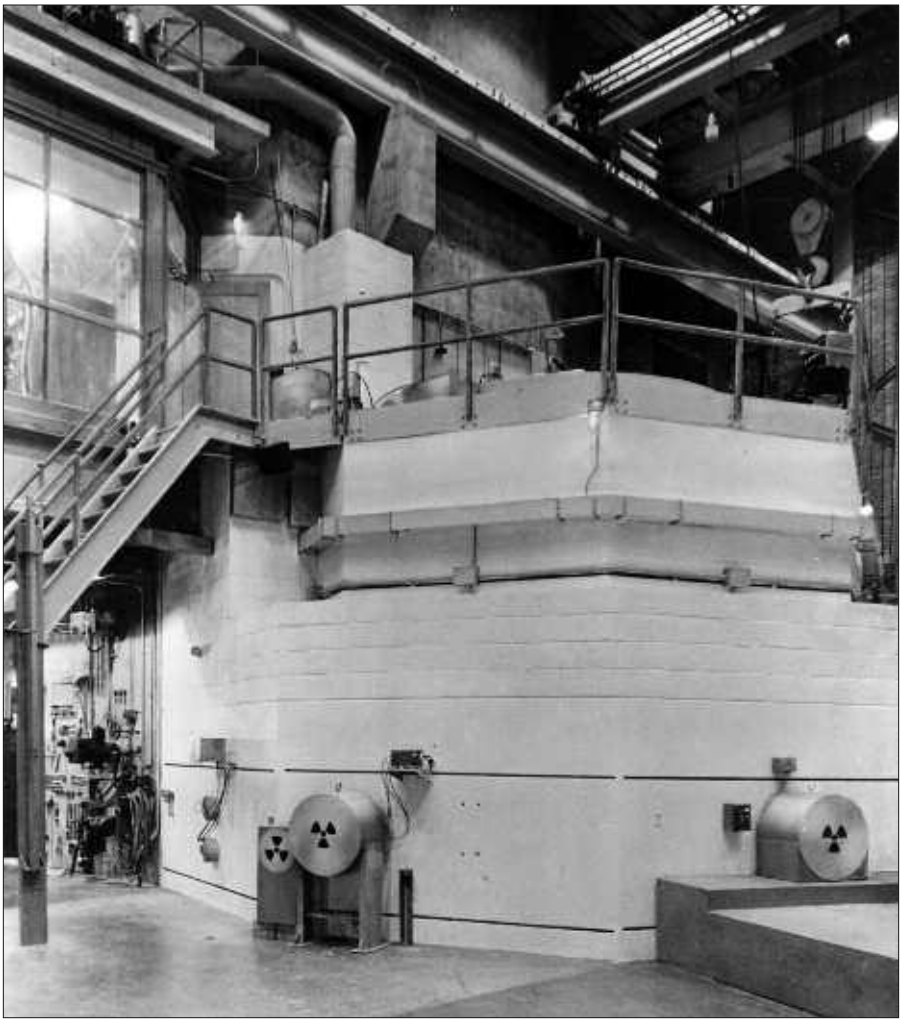
In addition, several important institutions that were focused on nuclear technology were established during this early period. In 1945, France was the first to form a civilian nuclear government agency, the Commissariat à l'Énergie Atomique (the French Atomic Energy Commission), devoted to the development of nuclear technology, and the United States established the U.S. Atomic Energy Commission (AEC) a little over a year later. These agencies had dual missions, but their establishment moved the technology programs from the military to the civilian sector. At the same time, universities began to offer courses, and then programs, and then degrees in this new technology. Some of the earliest offerings were primarily to government employees, and in fact, some of the early courses were classified, but those restrictions did not last long.

Perhaps, though, the most surprising "discovery" I made was that the very first demonstration of electricity production occurred at Oak Ridge, three years before the Experimental Breeder Reactor-I (EBR-I) produced electricity in Idaho. This is not a secret. The information is on the Oak Ridge Web site, although it seems not to be well known. In fact, it proved somewhat difficult to pin down an exact date for this event. The amount of electricity produced was very tiny—less than a watt—and the event did not appear to have been publicized at the time, nor was it repeated. Perhaps the fact that the amount of electricity generated did not seem to be at a practical level and did not produce any visible manifestation that could be photographed doomed this event to relative obscurity.

This small demonstration does not in any way take away from the milestone of EBR-I in demonstrating that electricity could be produced at usable levels. It was graphic proof to me, however, that most of us don't really know the whole story.



The JEEP-I reactor (Joint Establishment Experimental Pile), which went critical in July 1951, was the result of a collaboration between Norway and the Netherlands. (Photo: Institute for Energy Technology, Norway)



Experimental Breeder Reactor-I demonstrated that electricity could be produced at usable levels. (Photo: Argonne National Laboratory)

Start of commercial nuclear power production (1952–1957)

The next six years saw the continued intensive development of nuclear power, and the reactor technologies that are most prevalent today began to take shape. A decision to make pressurized water reactors the technology of choice for nuclear-powered submarines gave that technology an early lead, and the USS *Nautilus* launched the first use of nuclear power for propulsion in 1955.

Less well known is that the U.S. Navy also had a second track to develop a sodium reactor for submarine use. This led to the development of a sodium-cooled reactor in the 1950s, and even its use, for a short time, in a submarine. The PWR technology proved more reliable, however, and was adopted as the reactor technology of choice for nuclear submarine propulsion.

Despite the Navy's efforts on the PWR, work continued on boiling water reactor designs. In fact, the first PWR (a land-based prototype for the submarine reactor), and the first BWR (BORAX-I) were both built at the National Reactor Testing Station (now the Idaho National Laboratory) in Idaho and went critical within a few months of each other.

Developments also continued on the various parts of the fuel cycle. In the reprocessing area, first the REDOX and then the PUREX technologies were developed. During these early years of the Cold War, the PUREX plants built in the United States and elsewhere were largely devoted to weapons production. Nevertheless, this technology, first used on a large scale in 1954, was later used for fuel reprocessing, and it remains the dominant reprocessing technology in use around the world today. In Russia, the first full-scale centrifuge enrichment plant went into operation by the end of this period, although it took a number of years before the use of the technology began to spread. It is now the state-of-the-art technology for uranium enrichment.

University programs continued to develop and expand, and in 1958, four nuclear engineering departments were established in the United States: at the Massachusetts Institute of Technology, the University of California at Berkeley, Kansas State University, and the University of Michigan. In addition, the first university reactor was started at North Carolina State College (now University) in the early 1950s, followed soon thereafter by another reactor at Pennsylvania State University, and the first operator's license was issued to William Breazeale at PSU. Besides having taken the reactor operator exam, it is alleged that Breazeale had written and graded it as well.

This period also saw the ramping up of important institutions for nuclear energy. In the United States, the Atomic Industrial Forum (now the Nuclear Energy Institute) was established to serve the industry, and the American Nuclear Society was founded to serve the professional community. Also, the International Atomic Energy Agency was established as an intergovernmental body to serve the international community as a center for the promotion of safe, secure, and peaceful nuclear technologies.

The early history of nuclear reactors for power production is particularly interesting. Although Americans are most familiar with

USS *Nautilus* (SSN-571) was the first nuclear-powered submarine and launched the use of nuclear power for propulsion. (1964 U.S. Navy photo supplied to the Historic Naval Ships Association by the U.S. Naval Institute)

The Obninsk plant near Moscow, Russia, was the first nuclear power plant to be connected to an electricity grid to provide power to residences and businesses. (Photo: Petr Pavlicek/IAEA)

the use of the BORAX-III reactor to power the town of Arco, Idaho, in 1955, in fact, the Soviet Union had produced electricity from a reactor more than a year before the Arco demonstration. A reactor at the Institute for Physics and Power Engineering began supplying electricity to the Obninsk area on a routine basis in 1954. In contrast, the Arco demonstration was conducted in the middle of the night, when demand was low, and lasted only an hour. Although the Russian achievement has now become fairly widely known, the story still persists that Arco was the first town in the world lighted by electricity from nuclear power. What may be true is that it was technically the first town lighted *100 percent* by nuclear power (albeit for only a short time and during a period of low demand). It also appears that at that time, the Soviet achievement was not widely reported, and the Americans were able to make a big announcement of the U.S. achievement at an international conference a month after the event.

Likewise, the United Kingdom began the operation of a large reactor at Calder Hall a year after the Arco demonstration and more than two years before the Shippingport reactor was started up. This achievement also sometimes appears to be slighted in the annals of nuclear history, particularly in American accounts. In this case, Calder Hall was primarily a production reactor. Electricity was generated as a by-product of the waste heat from the plant. Therefore, it remains true that Shippingport was the first large reactor to supply commercial power that was built entirely for peaceful purposes.

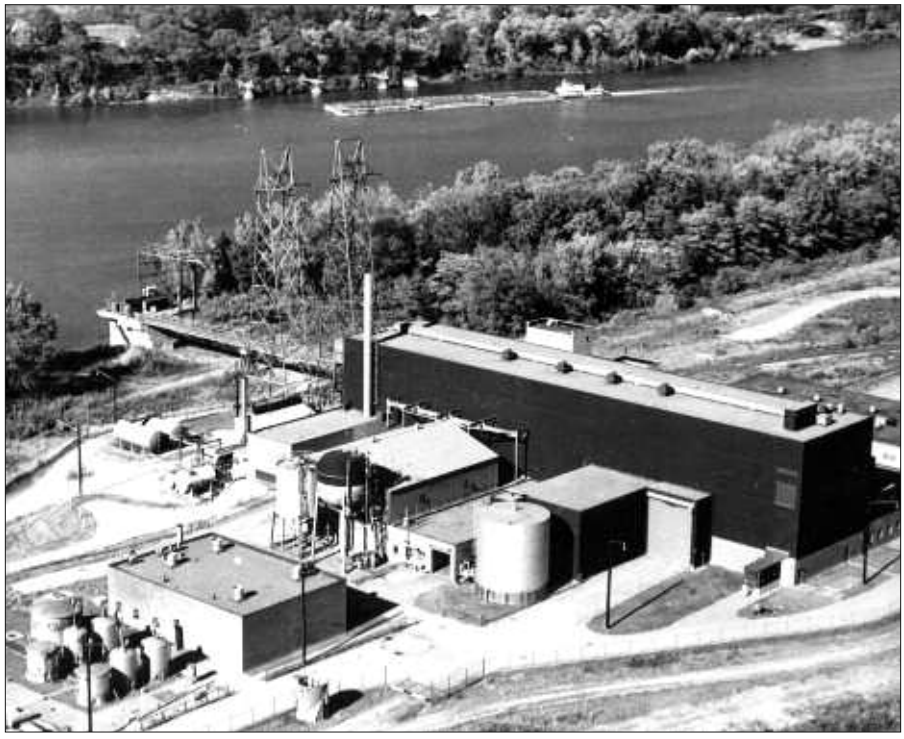
Even in the United States, it is often not recognized that no fewer than four small U.S. power reactors went into operation in the year before Shippingport started up. Although three of these reactors were government-owned, one was private, and, in fact, received Power Reactor License #1. Despite that, all four of these reactors were very small and are often overshadowed in historical discussions because of the opening of the much larger Shippingport station in that same time period. Also, because of their small size, these reactors are often not included in tables listing power reactors.

The growth of nuclear power applications (1957–1965)

By the time Shippingport began operation in 1957, interest in nuclear power had spread beyond the countries that had been involved in weapons development. Several multinational research programs were started over the next few years. Two of them were located in Belgium and Norway, countries that had not been directly involved in weapons development efforts. These programs, which began in the late 1950s, initially were European, but one—the Halden Project, in Norway—expanded its membership by the early 1960s to include the United States, thereby becoming a truly international project (that is, extending beyond Europe's borders). Notably, the Halden Project is still active more than 50 years after its launch. The Halden Project also used a novel technology, a boiling heavy-water reactor design.

During this period, other new reactor technologies emerged, including the first high-temperature gas-cooled reactor (HTGR) and the first organic-moderated and -cooled reactors. (The start of molten salt reactor technology is often attributed to the Molten Salt Reactor Experiment [MSRE], which also went into operation during this period, but in fact, another experimental molten salt reactor operated prior to the MSRE.) Most of these reactors were research facilities, but in the United States, in several cases, experimental power stations were built to further test the novel technologies. These reactors were built as part of the AEC's Power Reactor Demonstration Program. A number of nuclear power plants no longer in service (see page 72, this issue) were constructed under this program and include the following:

- Yankee-Rowe, Rowe, Mass., a 175-MWe PWR.
- Fermi-1, Monroe, Mich., a 61-MWe LMFBR.



The Shippingport station, in Pennsylvania, was the first nuclear power plant to generate commercial electric power on a large scale for peaceful purposes. (Photo: Westinghouse)

■ Hallam, Hallam, Nebr., a 75-MWe liquid-metal graphite reactor.
■ Piqua, Piqua, Ohio, a 12-MWe organic reactor.
■ Elk River, Elk River, Minn., a 23-MWe super-heated BWR.
■ Pathfinder, Sioux Falls, S.D., a 59-MWe super-heated BWR.
■ Carolinas-Virginia Tube Reactor, Parr, S.C., a 17-MWe PHWR.
■ Peach Bottom-1, Delta, Pa., a 40-MWe HTGR.
■ BONUS, Rincon, Puerto Rico, a 72-MWe BWR.
■ La Crosse, Genoa, Wis., a 50-MWe BWR.
■ Big Rock Point, Charlevoix, Mich., a 67-MWe BWR.
■ San Onofre-1, San Clemente, Calif., a 436-MWe PWR.
■ Connecticut Yankee Haddam Neck, Haddam Neck, Conn., a 582-MWe PWR.

These plants are listed in the book, but not all are firsts, and so not all are profiled.

In addition, some utilities and vendors, convinced that nuclear technology was competitive in the marketplace, built reactors without government support, with Dresden becoming the first "full-scale," privately financed nuclear power plant to go into operation in the United States.

Outside the United States, the use of nuclear reactors for electricity production was also on the rise. Canada built its first nuclear power plant, and three European countries that had not been involved in weapons development also built their first nuclear power plants.

Work on other applications of nuclear power also continued. Russia built the first surface vessel to be powered by a nuclear reactor. It was a civilian vessel—an ice-breaker—but several types of nuclear-powered military surface vessels soon followed.

At the same time that nuclear power was under development, the field of space travel was also developing, with advanced, long-range rockets and early satellites allowing for the beginning of space exploration. It was perhaps natural that the two fields should find some common ground. The United States started a program to develop a nuclear-powered rocket, and although the program was later canceled, a number of experimental reactors were developed to prove the concept. In parallel, efforts were also under way to develop reactors that could provide the much more modest levels of power needed in orbiting spacecraft. Although the power levels were not challenging, the weight restrictions were, and so in addition to requiring lighter-weight reactors, the satellite applications also required the development of direct thermoelectric conversion of the reactor heat. The United States launched one satellite powered by such a system before canceling its program. The Russians, however, flew a number of such satellites.

The maturation of the industry (1966–2009)

By the mid-1960s, a number of nuclear power plants were operating around the world, and nuclear technology could be considered relatively mature. It is therefore not surprising that the rate of new "firsts" began to slow down. Nevertheless, until the accidents at Three Mile Island and Chernobyl, substantial progress was made in several areas, and recently there has been renewed progress on a number of fronts.

First, the use of nuclear power spread beyond North America, Europe, and Russia, with plant projects initiated in Asia, South America, and Africa.

Second, new types of reactors continued to be developed and used for electricity production. The first "full-scale" liquid-metal fast breeder reactor, pressurized heavy-water reactor, and commercial high-temperature gas-cooled reactor went into service. A gas-cooled heavy-water reactor was also put into operation. Experimental work was conducted on the pebble bed reactor concept, and Shippingport was tested in a light-water breeder reactor configuration.

The United States was also using small reactors in several remote locations around the world. One of them, in Antarctica, provided the first demonstration of desalination using a nuclear reactor. Another, in the Panama Canal, was the first floating reactor. Nuclear-powered desalination was later used commercially and is still in use today in some parts of the world, and the floating reactor concept is receiving renewed interest in Russia.

In addition, the reprocessing of fuel from civilian power reactors was started, and considerable work was conducted on nuclear waste disposal during this period. The first low-level waste repository actually started in the late 1950s, and other low-level, surface waste repositories followed. It was not until the late 1960s, however, that the use of underground repositories for nuclear waste began, and several facilities expanded the types of waste stored in such repositories.

Although unique to the United States, it is worth mentioning that the first power reactor license renewals were issued, starting with Calvert Cliffs, in 2000. In 2009, Oyster Creek became the first plant to operate under a renewed license.

A challenge, with surprises

Exploring the history of nuclear power has proven to be an interesting challenge, and has brought me a number of surprises. The summary above merely skims the surface.

The biggest surprise to me was the discovery of a few facts that seem to be relatively unknown, such as the first tiny trickle of electricity from the Graphite Reactor at Oak Ridge. A second surprise was that the identification of firsts was not as clear and unambiguous as I had thought it would be. The following questions were among those that I grappled with:

■ What is the importance of a first if it was kept secret at the time? It may be the *publicized* firsts that really captured imaginations and triggered the most progress.
■ What is the value of a first if there was no further development of that particular technology? Can something be a first if there is no second?
■ Every research reactor made some unique contributions to the development of our understanding. Does that make every one of the hundreds of reactors that have been built a first?
■ Research reactors experimented with a dizzying array of fuels, coolants, and moderators, and with different mixes and configurations of each. Is each of these a first?
■ How much of a change must there be from its predecessors for a reactor to be considered a first of a kind? I am reminded of the statement reputedly made by former NRC Chairman Ivan Selin: "In France, there are 365 kinds of cheese and one kind of reactor. In the United States, it's the opposite." Is every different reactor in the United States really a first?
■ Do I identify as firsts activities that are under way but have not yet been completed? I hope that a future book will tell of the startup of the first Generation-III+ reactor and the opening of the first high-level waste repository, but in my book, I chose not to label a plan or an ongoing construction project as a first.

These questions seemed strangely philosophical for a book on a technical subject. I tried to steer a middle course and select firsts that I thought most people would agree were significant for one reason or another. No doubt there are people who will disagree with some of the firsts I have profiled, and others who will disagree with some that I left out. I also tried to cover items that other sources have called "firsts," and to clarify in what sense they were or were not firsts. Despite my extensive research, I know that it is still possible that I have overlooked something. I realize that the original secrecy surrounding nuclear activities and the passage of time have made it difficult to confirm some of the details of the early reactors and perhaps have obscured something that would have merited inclusion.

Nevertheless, I think the book largely succeeds in pulling together, for the first time, a story of nuclear power development in terms of the steps and milestones that occurred between the first demonstration of controlled fission and the 439 reactors in 30 countries that operate today and are included in the World List of Nuclear Power Plants in this issue. I find it a fascinating story, and I hope others will as well. NN