The next generation of advanced nuclear reactors

by Mark Wilsey

Nuclear energy plays an important role, a role that should grow, in the future health of any nation's economy. And, while in recent years, the United States has neglected nuclear energy, other nations, such as France and Japan, have moved forward. Japan, which is 80% dependent on energy imports, is actively pursuing its goal of a nuclear-powered economy. Ironically, it is there that the U.S. company General Electric has just built its new, state-of-the-art nuclear power plant. The American nuclear energy industry may soon be able to stage a dramatic comeback on building this new generation of advanced nuclear reactors.

The shocking fact is, that it has been nearly two decades since the last nuclear power plant was ordered in the United States; nonetheless, nuclear engineers have been developing an array of new nuclear technologies, and the new crop of power plants will be more economical to build and operate, and will have improved safety features compared to conventional reactor designs.

It was never the case that nuclear power is not economical; what is true is that, over the decades, the opponents of nuclear energy have worked to create an environment in which bureaucratic red tape and legal maneuverings added massively to the costs and time of constructing a nuclear plant, to the point that nuclear power has become nearly prohibitive for utilities to use.

The major thrust in developing these new advanced reactors is not only to address various concerns regarding nuclear power, but also to come up with standard designs, which could be used as a common blueprint for a host of future nuclear power plants. Currently the design of each new nuclear plant has to be reviewed and approved by various regulatory agencies, even if the plans are the same as those of a previously built plant. Now, reforms are beginning to take place in the regulatory process, which would allow plants to be built on a standard design, once the design has been certified. Such an approach would greatly streamline the approval process to begin construction of a nuclear power plant.

Much of the new work has gone into advancing the designs of light-water nuclear reactors. For 40 years, these reactors have been a mainstay of the industry, which uses ordinary H_2O (hence "light water"), in contrast to other designs that use "heavy water" which is made with the heavy isotope of hydrogen, known as deuterium.

Advanced light-water reactors

There are two basic types of light-water reactors: the boiling water reactor and the pressurized water reactor. In nuclear fission, the heat source comes from the nuclear reactions occurring inside the reactor. Atoms in the fuel, which is generally uranium, are constantly splitting apart, releasing energy and neutrons; these, in turn, bombard other atoms, causing them to split, thus sustaining the nuclear reaction.

In the boiling water reactor, the heat from the reaction boils water inside the reactor, converting it directly into steam, which is used to turn a turbine and generate electricity. In a pressurized water reactor, the reactor is sealed inside a pressure vessel. Under high pressure, water can be heated well above its boiling point and, yet, remain a liquid. The superheated water is piped into a heat exchanger and back into the reactor. Inside the heat exchanger, cool water is circulated over the pipes of super-hot water to generate steam, which then goes to the turbine.

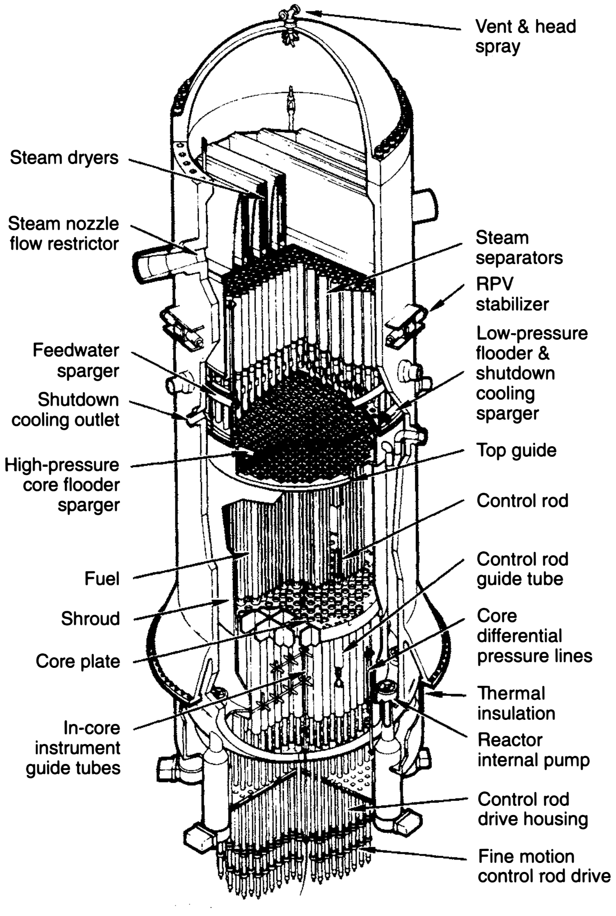
Aside from the reactor and related systems, the rest of the nuclear power plant is very similar to a fossil fuel plant. A significant difference is the density of energy represented by a nuclear reactor over a coal-fired furnace. One pound of uranium can produce as much heat energy as burning three million pounds of coal.

Two of the main developers of advanced light-water reactors are General Electric, with its Advanced Boiling Water Reactor (ABWR) (see **Figure 1**) and Westinghouse, with its advanced pressurized water reactor, the AP600. Both Westinghouse and GE have a great deal of expertise in the nuclear field, and both have other nuclear programs. Here, however, we will take the ABWR and the AP600 as examples of the sort of innovations the nuclear industry is producing.

Of the two, the AP600 is the smaller, rated at 600 megawatts (MW), compared to 1,356 MW for the ABWR. Both are designed to be more compact than a conventional reactor of similar output. The ABWR is just 70% the size of a typical boiling-water reactor. The ABWR and AP600 are both designed to use modular construction. Major components can

FIGURE 1

Advanced boiling water reactor assembly



Source: General Electric.

be contained in a single module. For example, the ABWR's control room, reactor pedestal, and the turbine-generator pedestal, are each modules that can be assembled on site. Parts of the AP600 can be prefabricated and shipped to the site. The modular design allows for sections of the plant to be built in parallel rather than sequentially.

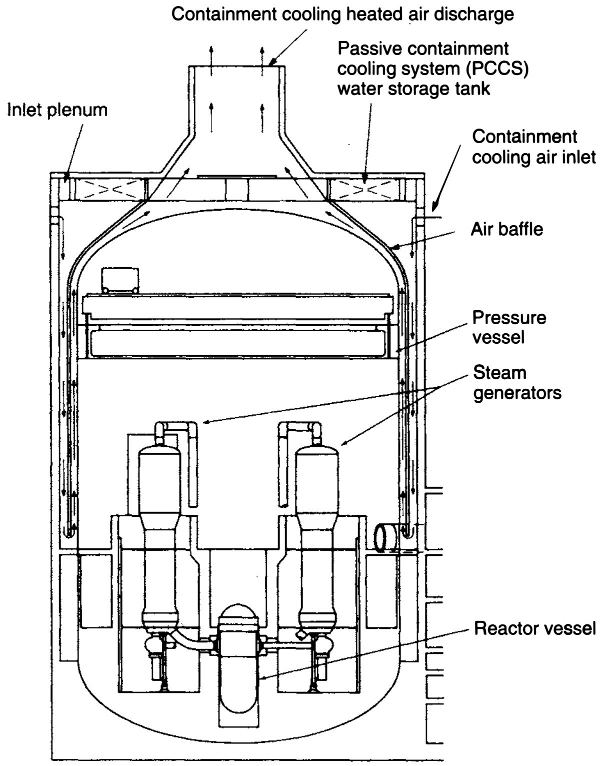
Among the benefits of compact design and modular contruction are reductions in construction time and cost. In Japan, GE has just completed a first-of-its-kind ABWR for the Tokyo Electric Power Company in just 52 months, some 10 weeks ahead of schedule. Westinghouse estimates that an AP600 could be built in three years.

Overall safety improvements

Westinghouse also estimates the AP600 would use 50% fewer valves, 80% less piping, and 70% less cable than a conventional nuclear power plant of similar size. In large part, this is due to streamlining the plant's layout, but some of the need for the extra hardware is eliminated by the approach AP600's designers took to improve safety.

FIGURE 2

Passive safety systems in the AP600



Source: Westinghouse

Safety is one of the top priorities in nuclear plants. The design of nuclear plants in the West makes the chances of a Chernobyl disaster very remote. By any standard, our nuclear plants are safe. But some raise the concern that, as plants become more complex, with numerous systems and subsystems (many of which are added for safety reasons), a point may be reached at which this purpose is defeated. Another safety approach is to develop features that do not rely on the active intervention of an operator or automated mechanical system: Such measures are called passive safety or inherent safety features, in which the engineer creatively uses the laws of physics to his advantage in enhancing the safety of his design.

For example, because the AP600 is a mid-size nuclear plant, its designer could employ safety features that use gravity and natural thermal convection (see **Figure 2**). The reactor's steel containment vessel is enclosed in a concrete building, where air is permitted to circulate in the space between them. Warm air flows upward along the containment vessel removing thermal energy, carrying it out of the building into the atmosphere, and cooler air is drawn in.

Atop the containment building is a huge pool of water. In the event that emergency cooling is needed, some 3 million gallons of water can be released to flood over the containment structure. This gravity-driven cooling system does away with the piping, valves, and pumps that would be needed in a similar mechanical system.

Both the AP600 and ABWR use fiber optic cable for data and voice communications, eliminating much of the copper cable used in previous reactor designs. Fiber optics have the advantage of higher speeds and greater volume of traffic, and, in reactors, are not as subject as copper to ravages of a corrosive atmosphere. In the case of the ABWR, that comes to a savings of 1.3 million feet of copper cable.

Another advance in the ABWR is that its control rods, which are used to regulate or shut down the nuclear reaction, are electro/hydraulic, in contrast to hydraulic systems in conventional reactors. The additional drive mechanism improves reliability and performance.

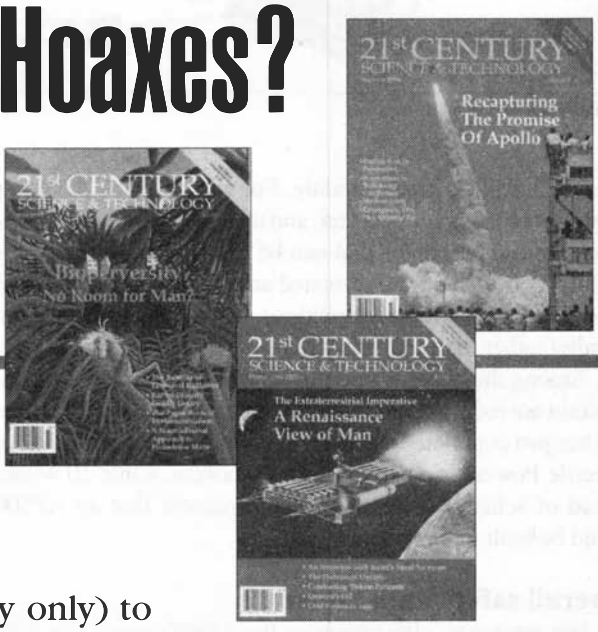
The major components of both the ABWR and the AP600 have been designed for ease of access, in order to minimize the time required for inspection, service and maintenance, thus reducing downtime. The fact that components are easier to get to and work with, also lowers the amount of time workers are exposed to radiation—a highly desirable safety feature. Designers have also chosen materials that reduce human radiation exposure: Wherever possible, the engineers have tried to reduce or eliminate the use of cobalt alloys, because cobalt, when bombarded with neutrons, becomes cobalt 60 and emits gamma-rays. Low-cobalt steel is used in the core and piping, and no cobalt is used in the control-rod pins, roller, and gate valves. The turbine condenser is made of titanium.

Another feature of the ABWR, is that remote-controlled transport devices will be used to handle reactor equipment, such as internal pumps and control-rod drives. The devices will transport the equipment through hatches in the containment vessel, and into service rooms. There, the irradiated equipment can be decontaminated and repaired.

Other advances in design

General Electric is also developing a smaller advanced reactor called the Simplified Boiling Water Reactor (SBWR). Like the Westinghouse AP600, GE's SBWR is 600 MW. Conversely, Westinghouse has plans for a couple of larger reactors, in the 1,000 and 1,300 MW range, called the Advanced Pressurized Water Reactor, or APWR 1000 and APWR 1300.

There are also other companies with advanced pressurized light water reactor designs: ABB Combustion Engineering Nuclear Power has the System 80+, a 1,300 MW reactor. Nuclear Power International (NPI), a joint subsidiary of France's Framatome and Germany's Siemens, is developing



the 1,450-megawatt European Pressurized Water Reactor (EPR). ABB Atom has a 640 MW reactor called PIUS, an acronym for Process Inherent Ultimate Safety.

While the name may be a bit high-sounding, the PIUS does have a unique design, in that it does not have control rods. The reactor sits at the bottom of a large pool of boronated water. Boron asorbs neutrons and acts to moderate the nuclear reactions in the core. Most nuclear plants which have control rods, also have boronated water on hand as a backup measure to ensure reactor shutdown. However, the power level of the PIUS reactor is controlled by adjusting the water's boron content and by adjusting the flow rate of the water. As an inherent safety feature, the pool is large enough that, in the event of a shutdown, natural circulation of the water will still remove heat from the core.

Other advanced nuclear reactor designs do not use water as the primary medium to extract heat from the core: Two examples are the gas-cooled reactor, in which a gas, such as helium, is circulated through the reactor; and the liquid-metal reactor, in which a molten metal, such as sodium, is pumped through the core.

Liquid-metal coolant systems are generally associated with what are called fast-neutron reactors. The neutrons are at a higher energy level than in a conventional reactor. The liquid metal has a greater capacity than water to remove heat at higher power levels. The fast reactors were developed out of the "breeder" program, in which uranium fuel inside the reactor is bred into plutonium that can then be processed and used as fuel.

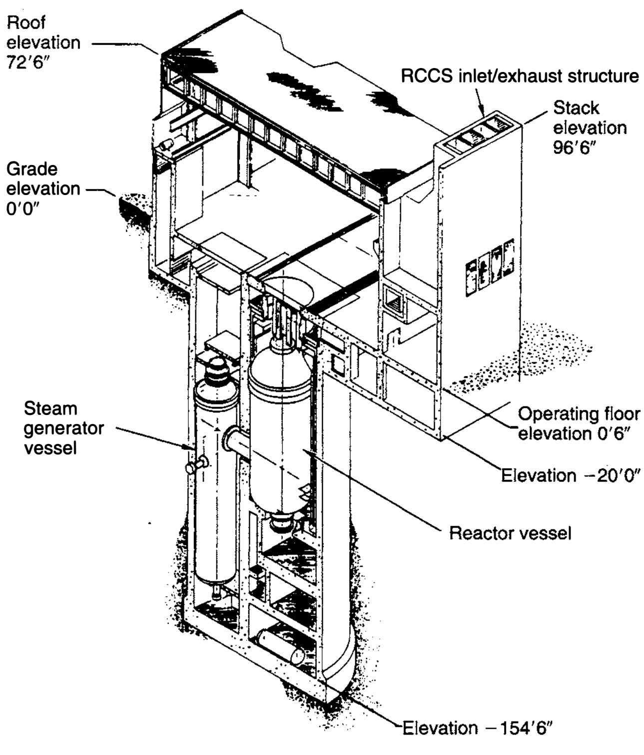
A couple of years ago, the United States abdicated its leadership in the fast reactor technology with the cancellation of the Integral Fast Reactor (IFR) at Argonne National Laboratory's Idaho site. The IFR had already demonstrated that it could burn a variety of fuels, from weapons-grade plutonium to the nuclear waste from other reactors. The next phase would have been to prove its fully integrated fuel cycle, which would have shown that spent fuel could be reprocessed on site and returned to the reactor. In such a facility, nuclear materials would not need to go anywhere. Currently, other countries, including Japan and France, have ongoing liquid metal fast reactor programs.

The helium gas-cooled reactor

The gas-cooled reactor concept has been explored by various countries over the past 40 years. In the United States, General Atomics is developing the helium gas-cooled reactor (HGR) (see **Figure 3**). There are a number of features which make this type of reactor attractive. The primary coolant, helium, does not change phase, in that it can not go from a liquid to gaseous state, so there is no chance of the reactor boiling away its coolant. When the heat from the reactor is transferred to the helium gas, the heated gas is sent to a steam generator; the steam then drives a turbine and generates electricity; or, in some designs, the hot helium gas can be sent directly to the turbine.

FIGURE 3

Reactor building cutaway of the modular high-temperature gas-cooled reactor



Source: General Atomics

There is no need for a containment building. The fuel itself has its own measures for containment. Each particle of fuel is encased in layers of heat and pressure-resistant materials that would lock in the fission products at the highest reachable temperature.

Another advantage of the HGR is its high operating temperature, more than twice that of a light-water reactor, which means that it is more thermodynamically efficient. It can also be used for process heating for industry or district space heating. Yet, because the core is designed to be small, it cannot become hot enough to damage itself. The small size is, in and of itself, a basic safety feature.

The size of the HGR limits its output. One unit can produce about 125 MW. A 500 MW power plant would have four HGR units or modules. If more generating capacity is needed, more modules could be added. The small size means that the major components of the HGR could be produced in a factory and shipped to the construction site. Moreover, since a number of units will be needed, the economy of mass production would lower the cost of the units. The HGR could do for the nuclear industry what the Model-T did for the automobile industry.