New nuclear reactor types

What characteristics should any new reactors have?

Desirable features to be included in any industry standard for a reactor include the following.\(^{45-49}\)

- Downsizing reactors into modules. This keeps the heat generated smaller (increasing safety), means a smaller inventory of radioactive materials in the reactor if something goes awry, and allows the modules to be fabricated in a factory, where economies of scale can work to lower the costs. Smaller reactors can also be cooled more easily.
- Lowering the concentration of the fuel to keep excess thermal energy from being generated.
- Use of fewer welds and less piping, so there will be smaller risks of corrosion damage and leaks.
- Use of natural convection instead of pumping the hot fluid to the heat exchanger, thus lessening dependence on mechanical parts of the system that are prone to failure.
- Building in of passive safety measures from the beginning; this means that there is no reliance on pumps or valves, and all emergency coolant is transported by gravity or natural convection. For example, chimneys promote natural convection of air for cooling the reactor core; or gravity-fed water stored above the reactor could be used to wet the top of the vessel enclosing the core if there is an accident. Other designs use the weight of the water itself to force water downward to cool the core after an accident.\(^{48,49}\)
- A goal of no reliance on offsite energy. In accidents and terrorist attacks, the situation often becomes confused, so the offsite energy to power the emergency mechanical systems could fail. Onsite energy would allow the shutdown to proceed despite onsite or offsite confusion attendant on an accident or terrorist attack.
High temperature gas-cooled reactors

High temperature gas-cooled reactors (HTGRs) can operate at higher temperatures and so achieve a greater thermodynamic efficiency than BWRs or PWRs. Many (millions of) tiny ceramic coated spheres are distributed in cylindrical rods inside large six-sided graphite vertical blocks. The 330 MW_e prototype reactor at Ft. St. Vrain, Colorado, operated at a low 39.2% efficiency between 1978 when it opened and 1989 when it closed.\(^{(34,50-52)}\) The gas coolant in this and in most HTGRs is helium, and the reactor operates at about 70 times atmospheric pressure and at a temperature of nearly 700 °C. The Ft. St. Vrain reactor had continuing problems with its coolant system during its life.\(^{(53)}\) However, the HTGR at Jülich, Germany, has operated for 15 years without incident.\(^{(54)}\) It was subjected to a severe planned test that involved removal of all control rods and coolant; it came through with flying colors and no melted or released fuel.\(^{(55)}\)

HTGRs have historically had high costs, low reliability, and troubles with coolant flow. Nevertheless, they are attractive because of their high degree of safety. General Atomic is working on development of an American version of a modular gas-cooled reactor.\(^{(48)}\)

Passively safe reactors

One relatively old proposal for an “inherently safe” reactor is PIUS (process inherent ultimately safe).\(^{(48,49)}\) Originally a Swedish design (ABB-Atom of Sweden), it has never been built. The reactor would shut itself down in the event of accident, sabotage, or abandonment. It is designed to be made of 500 MW_e modules. The reactor and cooling lines are in a pool of water that is pressurized and has boric acid in it. The water would get into the coolant line if a leak occurred since the surrounding borated water would be at higher pressure than the interior of the reactor, and since the boric acid is a neutron
absorber, the reactor would shut down. The water would also serve to cool the reactor. The only major downside is the possible failure of the prestressed concrete containment vessel in a military or terrorist attack. In addition, maintenance appears to be difficult, and a PIUS reactor may turn itself off too easily to allow reliable operation.

The major advance of PIUS is the focus on “passive” safety equipment. This refers to equipment that will work even in the absence of offsite energy. Much can be done by putting emergency cooling water in reservoirs above the reactor, for example, so gravity flow can occur whether or not there is power available.

The South African utility Eskom has been experimenting with pebble bed modular reactor technology since 1993 and construction of a 110-megawatt demonstration module is expected beginning in mid-2003. South Africa obtains about 5% of its energy from nuclear facilities and is willing to explore increasing its reliance on nuclear energy.\(^{(14)}\)

Pebble-bed reactors are made with many (about 400,000) small graphite balls containing uranium oxide fuel (about 9% enriched uranium) poured into a reactor vessel. Helium is circulated and its temperature rises. The hot helium flows through turbines, producing electricity. The lower-temperature helium is then “recuperated” and cycled back through the reactor. Eskom estimates a construction cost of $1000/kW and an electricity production cost of $0.016/kWh.\(^{(56,57)}\)

South Africa’s Pebble Bed Modular Reactor (PBMR) technology is based on building house-sized power plants in the factory as small modules, siting the plants appropriately, then joining the modules to the grid.\(^{(56)}\) Because cooling water is not needed, the plants could be sited where they are needed. Additionally, the reactor is equipped with passive safety equipment. If something fails, the reactor would automatically shut itself down.
Thus, the pebble bed reactor includes passive safety from the inside out. Work on these reactors is continuing in the U.S., France, Japan, Russia; South Africa will build a moderate-sized reactor, and China and Japan have already built small units.\(^{(58)}\)

**Evolutionary advanced reactors**

General Electric and Westinghouse are working on versions of the BWR and PWR, respectively. The utilities want a reactor to be inexpensive, cheap to maintain and operate, last a long time, operate reliably, and shut down safely. The goals of the nuclear industry have become simplification, more assured safety, higher reliability than at present, and reduction in capital, operating expenses, and maintenance compared to that of coal-fired energy. The industry wants the NRC to provide one-step licensing procedures for any really standardized design and no retrofit orders. All these goals are attainable, and the NRC is cooperating.

In GE’s advanced BWR, power generation is limited by using bubbles in the water to control the rate of reaction. The greater the volume of the bubbles, the slower the rate of reactions (fewer neutrons can be slowed enough to make more fissions), so water flooding can shut it down while boiling cannot destroy it. The 1300 MW\(_e\) GE Advanced Boiling Water Reactor is designed to have passive emergency core flooding, manual alternative control for control rods. Instead of large external pumps to circulate water, ten smaller internal pumps were used. GE has built two 1,350-megawatt “advanced boiling water reactors” in Japan in cooperation with Tokyo Electric Power Co.\(^{(59,60)}\) There are an additional six under construction, four in Japan and two in Taiwan. The two Japanese plants took just a bit longer than four years to build; it is expected that the process would be similar in the United States should a utility decide to purchase one.\(^{(43)}\)
For the Westinghouse AP-600 600 MW$_e$ design,\(^{(47)}\) the number of valves is reduced by 50\%, the number of large pumps is reduced by 35\%, the amount of piping is reduced by 80\%, the number of heat exchangers is reduced 50\%, the amount of ductwork is decreased by 35\%, there are 80\% fewer heating, ventilating, and cooling units, and the length of control cables is shortened by 70\%.\(^{(59)}\) The valves are fail-safe; if the power fails, they would close because they require the electricity to be held open.\(^{(59)}\) The AP-600 is expected to be much less likely to fail than previous models of PWR. The smaller size of the new AP-600 means that convection allows sufficient heat transfer away from the core in the event of an accident, so no offsite power to run a pump is required, which is required for larger reactors.\(^{(60)}\)

Japan has also supported development work on the design of both Westinghouse and GE. The Tokyo Electric Power Co. has built a Westinghouse PWR.\(^{(48)}\) The core is larger, the reactor features improved steam generators, copper wires are replaced by fiber optics, and automatic and “smart” systems interface with operators through computers.

The Westinghouse System 80+ and the AP-600 and the GE Advanced Boiling Water Reactor plant designs have been certified by the Nuclear Regulatory Commission (NRC).\(^{(60)}\) The AP-600 is the most innovative, but so far, none have been sold.\(^{(57)}\)

As with all nuclear reactors, if the reactors are built, they will be licensed for a 40-year period. The NRC allows a further 20-year period to be allowed after application to NRC. In 2000, the NRC granted its first extensions to permit a company to operate two nuclear reactors 20 years beyond their initial 40-year operating licenses.

According to the NRC,\(^{(61)}\) “These new plant designs can be anticipated to introduce concepts, such as seismic base-isolation, advanced energy-absorbing supports, and
advanced construction techniques and materials to reduce the costs of earthquake resistant designs. ... The use of on-line monitoring techniques is expected to supplement advanced non-destructive examination and inspection techniques.”

**Breeder reactors**

A prototype of a fast neutron reactor, a very small 25 kW reactor, was built in 1949 at Los Alamos. The core of a fast neutron reactor would be a mixture of plutonium and uranium. Thermal energy would be transferred from the core using a liquid metal. The Los Alamos reactor used mercury, and designers have focused on liquid sodium as the coolant (both mercury and lead, also contenders, are more dangerous). Liquid metal reactors are breeders (see the breeder reactor section in this chapter) and can “burn” nuclear waste. But liquid sodium reacts strongly with both air and water.

In the LMFBR (liquid metal fast breeder reactor), the uranium dioxide or plutonium oxide fuel rods are sealed in stainless steel tubing. The reactor core is cooled by a loop of liquid sodium (much as occurs using water in the PWR), with the heat exchanged to another liquid sodium loop and finally to a water steam loop. This can give a high actual efficiency, estimated to be about 41%, because the boiling point of liquid sodium is 892 °C. Sodium is used as a coolant because it is not a moderator (as water is) and breeder reactors are very fast reactors. A breeder’s core would be very compact and dense to capture enough neutrons. Fast neutrons are captured by $^{238}$U in breeders, and the breeders would be disabled as breeders by slowing down the neutrons. Proponents of the breeder reactor point out that it promises essentially unlimited nuclear energy to rescue us from a possible future resource bind. In the breeder, 70% to 80% of fertile material produced is available for energy production.$^{(1)}$
There are problems with what is known as “partitioning,” which means the separation of the isotopes produced in the breeder. The difficulties experienced in the reprocessing program for conventional power plants should shatter any illusions that this separation and disposal will be clean and risk free. An entire technology would need to be developed, and decisions made as to whether to use “the option of ‘homogeneous recycling,’ where the radionuclides to be transmuted are intimately mixed with the fuel, as opposed to ‘heterogeneous recycling,’ where they are physically separated from the fuel.”

While the United States has dropped its breeder program because of doubts about safety, the French government is proceeding with the development of the Phénix and Superphénix breeder reactor. The French are heavily committed to nuclear energy (currently, ~80% of the energy in France is generated in nuclear facilities) and are worried about cutoff of foreign supply; most other nuclear countries have access to potentially large amounts of uranium from domestic sources. For this reason, the French were willing to spend $2800 per installed kilowatt for Superphénix at a time when the normal French reactor costs about $1200 per installed kilowatt.

The Phénix breeder has long been closed. The Superphénix project was plagued by many shutdowns (one 2 years long) after it began operation. Superphénix operated only 153 days after opening. The reactor was closed for good in 1997.

In addition, the breeders produce plutonium that can be diverted to nuclear weapons. For this reason, the Royal Society and Society of Engineering study group recommended “A massive expansion of the contribution of nuclear energy based on presently established technology of breeder reactors which would involve their location in many parts of the world, with fuel transported from remote pre-processing centres, would in our view significantly raise the danger of proliferation.”
The “energy amplifier”

The use of “subcritical assemblies,” nuclear materials that cannot sustain a chain reaction, which then are bombarded by protons from a proton accelerator was originally intended to make plutonium for the weapons program. However, it was later realized that reactor waste in subcritical mass could be cleansed through accelerator-driven transmutation, and some research was focused on this possibility. This led to the “energy amplifier” scheme described in Ref. 58, in which a close-to-critical subcritical assembly is hit by 1 GeV protons, causing transmutation and thermal energy, which is captured and brought to a turbine through a heat exchanger using a lead-bismuth liquid coolant. This produces ~ 0.5 GW of electricity that powers the proton accelerator and sends the extra to the grid.

The proponents claim that this technique will “destroy over 99.9% of the actinides; destroy over 99.9% of the Tc and I—two of the major long-lived radiotoxic radionuclides; separate Sr and Cs; separate uranium; generate electricity. ... 10–15% of this electricity will be used to power the accelerator.”(66) While this is not quite a reactor, it would have to be run much as a reactor is run, with additional problems such as interfacing the accelerator’s vacuum system for the proton beam with the assembly. Many technical details would need to be worked out before such a scheme could be realized, and this research would involve a substantial investment (perhaps a billion dollars or more).(66) This is not highly probable, given the antinuclear attitude characteristic of most of the world’s public. This option would also be problematic in some countries, because it is possible to redirect the program so the assembly becomes a source of weapons-grade plutonium.
Reactors for the Third World

Lawrence Livermore Laboratory has developed an idea for what is called SSTAR: small, sealed, transportable, autonomous reactor.\(^{(67)}\) The design is shown in Fig. E19.5.1.

Fig. E19.5.1 Artist’s conception of SSTAR. (LLNL, Ref. 68)

The idea of a sealed reactor is that it would never be refueled. It would be very difficult to tamper with, an important concern. The module could generate electricity for perhaps 30
years before it would need to be replaced. It could satisfy concerns about the Nuclear Nonproliferation Treaty, because the country would not have to develop its own nuclear supply system, which could be raided for weapons-grade uranium. Because the module would be returned to the U.S., the reprocessing problem would also be avoided.\footnote{67}

SSTAR is a lead-cooled fast reactor. It adopted some of the ideas used by the Rubbia’s reactor (see below). This is a type of breeder reactor. It makes fuel as it burns fuel. This allows the system to be closed as well, not relying on external water sources for cooling. It is expected that the design could be produced in sizes between 10 MW and 100 MW, suited to the recipient. A steam generator would operate inside the sealed container.\footnote{67} The lead coolant allows the cooling to occur to the air using simple fins as heat exchangers without pumps.\footnote{68} The reactor would incorporate passive safety features.\footnote{67}

SSTAR could be shipped whole to whatever its destination is. Figure E19.5.2 shows the design idea for overseas transport.

\begin{figure}
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\includegraphics[width=\textwidth]{figE1952}
\caption{Fig. E19.5.2 Artist’s conception of SSTAR modules being loaded on a container ship. (LLNL, Ref. 68)}
\end{figure}

There are difficulties to be overcome, such as that the lead-bismuth coolant is corrosive. However, the group working on the problems thinks they are resolvable.\footnote{67}
The Nuclear Regulatory Commission (NRC) plans to certify the design by the “license-by-test” approach, on which the prototype actual reactor is subjected to tests beyond what would be expected in normal use. The group plans to test the reactor in 2015.

Thorium fuel

While thorium itself is not fissile, under exposure to reactor neutrons, thorium-232 can be turned into uranium-233 inside a reactor. An advantage of a thorium-based nuclear economy is that the plutonium produced is not suitable for bombs. Additionally, the amount of waste produced is considerably less than found with uranium-fueled reactors.\(^{(69)}\)

The Rubbiatron

Carlo Rubbia, who won the Nobel Prize in physics, developed a reactor that would work using wastes in addition to or in replacement of, normal reactor fuel. The safety of the reactor is assured because it would need to be supplied with particles from another source to work.\(^{(70)}\)

The reactor would be an “energy amplifier.” The particles would be supplied by an external 1 GeV cyclotron. For this reason, the device is sometimes called the “Rubbiatron.” If the particles from the cyclotron stop, the reactor would shut off automatically. The steam cycle would use a lead coolant. The presence of lead assures that all the waste elements would suffer transmutation to another form.\(^{(68,70)}\)
This reactor combines two advantages—inherently safe operation, and cleansing of radioactive wastes.\textsuperscript{(68,70,71)} Its use as a waste incinerator could make the process economic. The electricity would be a bonus.

A prototype was tested at CERN, the European nuclear research center. An operational model is being built in Rome as of this writing.