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The Nuclear Power Deception

Chapter 2: Electricity Production and Nuclear Reactors

An energy source cannot be inexhaustible in the economic sense unless it is priced so low that it can be used in essentially unlimited quantities. After all, solar energy is "inexhaustible" in a physical sense in that we have a continual, huge, and, from a human point of view, essentially endless supply. Yet it is not in widespread use as an energy source because of the relatively high cost of putting it into a usable form, such as electricity. Thus, for solar energy or any other energy source to be "too cheap to meter" it must not only be plentiful in physical terms; it must also satisfy minimal economic criteria. Even fossil fuels resources are huge, if resources such as oil shale are included. But oil shale and similar low-grade resources are generally not included in estimates of the recoverable fossil fuel resource base because they are economically and environmentally unviable. Let us take a look at the elements of the cost of a large scale electricity generating system, such as would be typical of nuclear power.

Electricity on a large scale is produced by forcibly spinning conducting wires (usually made of copper) through a magnetic field. Such a device is called an electric generator. The energy required to spin the generator and supply the current to the devices that use electricity must come from somewhere. This is the energy source for the electric power station. For instance, falling water is an energy source that is used to spin water turbines, which, in turn, drive electric generators.

The most common energy sources for electricity generation are fossil fuels, which release their energy in the form of heat upon being burned. This heat is converted into mechanical energy in a "heat engine." An internal combustion engine, such as that in a car fueled with gasoline or diesel, is one example of a heat engine. A boiler combined with a steam turbine is another way in which the chemical energy in fuels is converted into mechanical energy.

The electricity from a large-scale generating station is transmitted at high voltage (to minimize transmission losses) to the areas where it will be used. Finally, there are extensive networks of wires and transformers that distribute electricity to consumers at the voltages they require for their applications. This scheme is used in all central-station electricity generation.[23] Figure 1 [sorry, not available in on-line version of report] shows the basic elements of a nuclear power plant. The basic arrangement of a coal-fired power plant is the same, except that the reactor and steam-generator are replaced by a coal-fired boiler.

The cost elements of an electricity generation system based mainly on central station plants such as that diagrammed in Figure 1 are:

- capital cost of the power plant, including the boiler and steam turbine (or other source of mechanical energy) to drive the electricity generator and the generation system
- transmission lines
- distribution network for connecting the main electricity grid of transmission lines to consumers
- operating and maintenance cost other than fuel
- fuel cost.

The most important thing to note about this list when evaluating the official claims that nuclear energy could one day be too cheap to meter, is that all the cost elements of a nuclear electricity system other than the fuel would be common between an electric power station that used coal (or another fossil fuel) and one that used nuclear fuel (either uranium or plutonium or some combination of the two).

The principal difference between a nuclear power station and, say, a coal-fired power plant, is in the nature of the fuel. In the one case, it is coal, which is burned in a boiler to generate hot gases, which in turn heat up water to produce steam. The boiler for using coal (or oil or natural gas) is designed to burn the fuel chemically. Nuclear energy does not come from chemical reactions, such as burning, but from nuclear reactions. The nuclear reactor merely replaces the boiler in a conventional fossil fuel power station. It generates the steam that drives the turbine. In other words, a nuclear power station differs from a conventional power station only in the fuel and the details by which the fuel is used in the boiler to generate heat. An important detail here is that the nuclear fuel is much more compact because each fission releases about 200 MeV (megaelectron volts) of energy, while burning one atom of carbon and turning it into carbon dioxide releases about 4 electron volts (eV). The higher energy per fission means that the volume of nuclear fuel per unit of power output is far smaller than for fossil fuels.

Let us now look at the actual costs of electricity generation at the time that Lewis Strauss made his famous "too cheap to meter" remark. The price of electricity in 1954 to very large industrial consumers (which is close to the cost of generation, since transmission and distribution costs for these consumers tend to be low) was about 1 cent per kilowatt-hour of electric energy generated (about 5.7 cents in 1995 dollars using the consumer price index). Subtracting the fuel cost for coal of about 0.4 cents per kilowatt hour (average price of coal, plus average coal transportation cost), we get an estimate of all other aspects of the cost of electricity generation in the mid-1950s other than fuel. This amounts to about 0.6 cents per kilowatt hour in the mid-1950s.

Since all other aspects of electricity generation were common between coal-fired and nuclear power station, the *minimum conceivable charges* for nuclear electricity as calculated for costs prevailing in 1954 would be 0.6 cents per kilowatt-hour. Thus, for the largest industrial consumers with factories near generating stations, the costs of nuclear electricity could be expected to be at least 60 percent of the costs of coal under assumptions so optimistic that they were considered unrealistic.

For small consumers, the cost reduction from this most optimistic assessment of nuclear energy would be far lower. This is because transmission and distribution constituted the lion's share of the cost of electricity for households and small businesses, that is for the overwhelming majority of consumers. The average price of electricity to small consumers in 1954, the year of Strauss's speech, was 2.7 cents per kilowatt hour, of which only about 0.4 cents was the cost of coal (in the case of coal-generated electricity). Thus, even if all fuel costs were eliminated, the average price of electricity to homes and small businesses would still have been 2.3 cents per kilowatt hour or about 85 percent of the full price. That was the best that nuclear energy could be expected to do.

Such cost estimates had, even on the surface, two unrealistic assumptions:

- Nuclear fuel would be so plentiful and so easy to produce that its costs would be insignificant compared to coal.
- Nuclear reactors and associated equipment would cost no more than conventional boilers, despite the greater technical complexity, high energy density, and radioactivity associated with nuclear energy.

Let us take a look at each of these elements of the cost of nuclear power that were readily apparent in the 1950s. (At that time, radioactive waste disposal issues were not forecast to pose serious economic or political constraints on the development of nuclear energy.)

A. Nuclear Fuel

There are two basic fuels that are used in nuclear power reactors: uranium-235 and plutonium.[24] Natural uranium is the basic raw material for them both. Thorium-232, which occurs in nature, is also potentially a nuclear energy resource. Like uranium-238, thorium-232 is not fissile and cannot sustain a chain reaction. However, neutron absorption by a thorium-232 nuclear converts it into uranium-233 in a manner analogous to the conversion of uranium-238 into plutonium-239. Uranium-233 is fissile and can be used for both nuclear weapons and nuclear power. However, no schemes for using thorium-232 as an energy source have been commercialized. Nor has uranium-233 been used in nuclear weapons, so far as public information indicates.

1. Uranium fuel

Uranium is ubiquitous in very low concentrations. For instance, it is present in surface waters at concentrations of about 0.7 parts per billion (by weight) and in soil typically at concentrations of two or three parts per million. But it is too costly to extract pure uranium for use in nuclear reactors from such sources. Uranium ores typically contain two-tenths of one percent to roughly one-half percent uranium by weight.[25] Therefore, it is necessary to mine two hundred to five hundred metric tons of ore to get one metric ton of pure uranium. Of this, only about 7 kilograms is the fissile isotope uranium-235.

Uranium is present in nature in many different chemical forms. The ores are processed in factories called uranium mills, where the other minerals and materials are separated from uranium. The wastes, containing thorium-230 and radium-226, which are radioactive materials associated with the decay of uranium-238 (see Factsheet on Uranium), are discharged into tailings ponds. These tailings also contain non-radioactive toxic materials such as arsenic, molybdenum, and vanadium.[26] Uranium mills produce uranium in the form of uranium oxide (U_3O_8), also called yellow-cake.[27] Before it can used in reactors, the uranium must be put into a suitable chemical and physical form and it must have the appropriate content of fissile uranium-235. For most reactors, the proportion of uranium-235 in reactor fuel must be considerably greater than the 0.7 percent concentration found in natural uranium (see table on reactor and fuel types). A large amount of processing is needed to accomplish this. The most expensive step is uranium enrichment, so called because it increases the proportion of uranium-235 in the fuel. This process produces another stream of uranium, called depleted uranium, which has a uranium-235 content far lower than natural uranium (usually about 0.2 to 0.3 percent uranium-235). Figure 2 [not available in on-line version of report] shows the steps in converting uranium into a fuel for light water reactors, the most common kind of nuclear reactor used in power generation today.

As a consequence of the practical necessities of uranium extraction and processing, the reality of the amounts of materials that needed to be handled and processed is far different than the romantic accounts of pellets the size of vitamin pills. While one gram of uranium-235 was equivalent to 3 metric tons of coal, it typically required 200 grams of natural uranium to obtain a gram of uranium-235 in a practical fuel. And it took on the order of 50 kilograms of uranium ore to produce 200 grams of uranium. Roughly an equal amount of low grade material littered the mine sites. In sum, about 100 kilograms of ore and rejects had to be unearthed to produced a single gram of uranium-235 fuel. Coal typically came in far richer seams, so that, for high-grade deposits, such as are commonly found in the western United States and elsewhere, the amount of additional material handled at the mine site was not far greater than the end product.

2. Plutonium Fuel

In the minds of its promoters, the promise of endless nuclear energy depended centrally on the conversion of uranium-238 into plutonium-239. A suitably romantic term was given to uranium-238, which was not a fissile material and hence not suitable as a reactor fuel. Uranium-238 was called a "fertile" material because it gave birth to plutonium-239, a fissile nuclear fuel.

As we have noted, uranium-238 is converted into plutonium-239 by bombardment with neutrons. Since a very large number of atoms of uranium-238 nuclei must be so converted to produce substantial quantities of fuel, uranium-238 must be placed in a situation where a correspondingly great numbers of neutrons are being continually generated. This happens in a nuclear reactor when uranium-235 (or another fissile material) is undergoing fission at a suitable rate.

Some of the plutonium produced in a nuclear reactor also undergoes fission, contributing to energy generation. But the rest cannot be directly used as a nuclear fuel because it is mixed with large quantities of unconverted uranium-238, residual uranium-235 and highly radioactive fission products. In order to use plutonium as a reactor fuel (or as a material for nuclear weapons), it must first be separated from the fission products and remaining uranium in the reactor fuel.

Table 1 shows an example of one possible composition of reactor fuel when it is inserted into a reactor and the final composition when it is discharged from the reactor (when it is called "spent fuel," though irradiated fuel would be a more accurate term).

Table 1: Fresh enriched uranium fuel and spent fuel composition

Substance	Initial percentage by weight in fuel	Percentage by weight in spent fuel after 3 years
Uranium-238	97	95.1
Uranium-235	3	0.8
Plutonium, fissile isotopes	0	0.7
Other plutonium isotopes	0	0.2
Fission products	0	3.2

Adapted from Lamarsh, Fig. 4.25, p. 150. Figures are rounded. Small quantity of uranium-234 present in fresh and spent fuel is not listed because, while it is radiologically important, it is not relevant as an energy source.

The set of steps required to extract plutonium from spent fuel is called "reprocessing" because it involves processing the fuel a second time around (the first time being when the fuel is first fabricated for use in a reactor). Reprocessing is very costly for five reasons:

- Fission products are highly radioactive and must be handled remotely.
- Large quantities of corrosive chemicals are needed to separate the plutonium from the fission products and then from the residual uranium.
- Since uranium and plutonium have similar chemical properties, a large number of steps is required to separate them from each other.
- Since plutonium can be assembled into a critical mass, the processing equipment must be specially designed and all operations carried out with extreme care to prevent accidental criticality.
- Radioactive waste management and disposal is expensive.

A number of plutonium isotopes are created in a nuclear reactor. Once uranium-238 is converted into plutonium-239, some atoms of the latter absorb neutrons and change into heavier isotopes of plutonium, namely plutonium-240, plutonium-241, and plutonium 242. Plutonium-238 is also created via two different sets of nuclear reactions, one starting with uranium-238 and the other with uranium-235. All these plutonium isotopes, including plutonium-239, are far more radioactive than either uranium-235 or uranium-238. Like natural uranium isotopes, most plutonium isotopes made in nuclear reactors emit alpha radiation, but far more intensely. Alpha radiation consists of fast nuclei of helium, which cannot penetrate the dead layer of the skin. But, when lodged inside the body, alpha particles cause radiation damage to the living cells around them. Plutonium-239 can be relatively easily shielded and is thus hard to detect if it is stolen and removed from the confines of safeguarded facilities. At the same time it is dangerous to process because small quantities once lodged inside a worker's body could greatly increase cancer risk.

The dangers of plutonium were discovered and reasonably well-understood during the course of the Manhattan Project. Their practical effect for nuclear power would be that it would be difficult and costly to fashion plutonium into fuel for nuclear reactors due to the protection from radioactivity exposures and the security precautions that would always be needed.

While it was understood that reprocessing would involve substantial costs, the magnitude of these costs was not fully realized until commercial reprocessing was attempted on a large scale from the 1960s onwards and numerous difficulties were encountered in the 1970s. The high cost and unexpected technical difficulties were associated at least partly with the far larger quantities of fission products present in reactor fuel relative to irradiated uranium used for military plutonium production (see below).

At the same time, it was commonly believed until well into the 1970s that uranium was a very scare resource. A corollary belief was that large-scale utilization of nuclear power would necessitate the use of plutonium as a fuel. This view continues to have a large number of adherents in the nuclear establishment despite the high expense of plutonium as a fuel relative to uranium for at least the next few decades.

B. Nuclear Reactors

> Nuclear power plants, it should be clear, are complex installations and by their nature, they must be designed with care.
>
> --John R. Lamarsh, Introduction to Nuclear Engineering, a textbook[28]

As we have discussed, energy from nuclear fission comes from the transformation into energy of a small amount of the mass of a heavy nucleus when it is split. When the nucleus of uranium-235 or plutonium-239 is fissioned, the resulting energy takes many forms. Some of the energy is released in the form of high speed neutrons, some appears as electromagnetic radiation (gamma rays); most is released as vibrational energy of the fission fragments. Almost all this energy is quickly transformed into thermal energy, or heat. A nuclear reactor is basically a vessel that is designed to capture this heat energy in a liquid or gas medium called a coolant in a sustained and controlled way. A nuclear reactor must have the following features:

- It must accommodate a sufficient number of fuel rods to sustain a chain reaction at the maximum level of thermal power to be generated. (Power is defined as the rate of energy production).
- It must incorporate ways to control the chain reaction, so that the level of power output can be maintained constant at the required level or varied from zero to the maximum, as necessary, without the danger of severe runaway nuclear reactions.
- There must be ways to capture the energy from the fission reactions and radioactive decay of the fission products and transport it out of the reactor vessel.

- The vessel must be strong enough to withstand high temperatures and (in most cases) high pressures, as well as intense neutron bombardment.
- The vessel and the structure in which it is located must contain the radiation within them so far as possible to minimize radiation doses to workers and off-site populations.

The central function of the nuclear reactor is to generate heat at the required rate in order to drive a heat engine. A number of different reactors have been designed to accomplish this. Another function of reactors is to convert uranium-238 into plutonium-239, though in most commercial reactors this has become a secondary function. In fact, in the context of non-proliferation, it is a problem. Reactors designed specifically to produce more fissile material than they consume as a result of the conversion of uranium-238 into fissile plutonium isotopes are called "breeder reactors."29

Reactors are classified into two types: *thermal reactors,* which use thermal (or "slow") neutrons to sustain the chain reaction, and *fast reactors,* which use fast, or energetic, neutrons to sustain the chain reaction.

1. Thermal reactors

The design of nuclear reactors depends centrally on the type of coolant that is used to carry off the heat produced in the reactor vessel. For thermal reactors, it also depends on the choice of a material called the *moderator,* which slows down the fast neutrons emitted in the process of fission.

Sustained chain reactions can be achieved with smaller proportions of fissile isotopes in the reactor fuel if the neutrons emitted from fission reactions are slowed down. For instance, some reactors that use slow neutrons can even use natural uranium as a fuel, even though it contains only about 0.7 percent of fissile uranium-235. Slow neutrons, called thermal neutrons, have energies of a fraction of an electron-volt (eV). Neutrons from fission reactions typically have energies of several megaelectron-volts (MeV) at the time they are emitted.

The process of slowing down neutrons in a nuclear reactor is called *moderation.* It is achieved by putting a moderator in a nuclear reactor. A moderator should preferentially be a light element so that neutrons can slow down when they collide with its atoms. For the most part, this happens by elastic collisions. This process is analogous to that by which billiard balls slow down when they collide with balls of similar weight. Heavy atoms would make less suitable moderators since neutrons would not lose as much energy to them in collisions. This can be visualized as billiard balls simply bouncing off when they collide with the (far heavier) edge of the pool table. Many collisions are needed to slow down fast neutrons to thermal energies. These collisions convert the kinetic energy of the fast neutrons into heat, which is randomized rather than directed kinetic energy. Finally, the moderator must also not absorb too many neutrons in the process of slowing them down. Otherwise sufficient neutrons will not remain to sustain a chain reaction.

Transfer of energy out of the reactor vessel requires that a coolant flow through it. Without a coolant, continued production of fission energy would cause the reactor vessel and its contents to get very hot. This would rapidly lead to a melting of the fuel and fuel rods, a phenomenon called a "meltdown." The coolant must also carry away the heat generated by the radioactive decay of fission products, which build up in the reactor as the fission process continues. When a reactor has been operating for a long-time, the heat from decaying fission products alone amounts to several percent of the full power rating. Loss of coolant in a reactor can produce a meltdown in such cases just due to the failure to carry away the decay heat from the fission products. For instance, this was the cause of the partial meltdown in Three Mile Island Unit 2 in 1979.30

In some reactors, the coolant and moderator are the same material. Hydrogen is an excellent moderator, being light and having a low neutron absorption cross-section (or probability). However, hydrogen gas is explosive and so it is used in the chemical form of ordinary water, H2O, also called light water. Further, the density of hydrogen in water (that is, the number of hydrogen atoms per unit volume of water) is far greater than that of hydrogen gas. Thus, a smaller volume of water gives the same amount of moderation as a far greater volume of hydrogen gas. Besides working well as a moderator, water is also a good coolant. Thus, the most common reactor types in the world use light water as a coolant and moderator. They are called light water reactors or LWRs.

Figure 3 [not available in on-line version of report] shows a schematic diagram of one type of light water reactor called a boiling water reactor, called a BWR. In these reactors, developed by General Electric, the water that serves as a coolant and moderator in the reactor is boiled directly in the reactor. This steam is used to drive a turbine. The main advantage of the BWR design is that it does not require an expensive boiler apart from the reactor. There are a number of disadvantages however, including higher emissions of radioactive gases and the fact that the turbines are exposed to radioactive steam.

Light water reactors are also used in another design, called a pressurized water reactor (PWR). This design, which is the most common power reactor design today, has two water circuits. The primary circuit is the high pressure water in the reactor vessel. This water is kept under such high pressure that it does not boil. The hot, high pressure water is passed though a heat exchanger, called a steam generator, where it heats up water in the secondary circuit and converts it into steam, much as the hot gases in a conventional boiler convert water in a boiler into steam. There are usually three or four steam generators in a PWR. The steam generators add considerable expense to the nuclear reactor but keep the radioactive primary coolant out of the turbines. The line diagram of a nuclear power station in Figure 1 above shows a power plant with a steam generator. That figure differs from a PWR only in that it indicates a solid moderator, whereas in a PWR the coolant and moderator are the same -- ordinary water.

Deuterium, or heavy hydrogen (symbol: D), whose nucleus consists of one proton and one neutron, can also be used as a moderator. It is the best moderating material from the point of view of low neutron absorption. Like ordinary hydrogen gas, it is explosive and so is used in the chemical form of water, called heavy water (symbol: D_2O). In contrast to LWRs, heavy water moderated reactors (HWRs) can use natural uranium as fuel. Figure 4 [not available in on-line version of report] shows a diagram of an HWR used for power generation in Canada, called a CANDU (CANada Deuterium Uranium) reactor.

Carbon in the form of graphite is also a good moderator, but carbon-moderated reactors need a separate coolant. The most common coolants are helium gas, carbon dioxide gas, or water. Reactors of the Chernobyl design (called RBMK reactors) use carbon in the form of graphite as a moderator and water as a coolant.

It is also necessary to control the chain reaction in order to vary the power output of the reactor. To maintain power at a sustained fixed level each fission of a heavy nucleus must produce exactly one more fission. This means that only one of the neutrons arising from fission must give rise to another fission. The ratio of the number of fissions that each fission reaction gives rise to (on average) is called the *multiplication factor.* For a sustained power level, the multiplication factor must be precisely equal to one. At this point, the reactor is *critical* and the nuclear chain reaction will sustain itself at constant power output. If the multiplication factor falls below one, the reactor becomes *subcritical* and the chain reaction will stop. If it rises above one, the reactor is *supercritical* and the power level will increase.

A parameter, called *reactivity,* is often used to describe reactor control. It is related to the multiplication factor in the following way: If the multiplication factor is exactly one, the reactivity is exactly zero; if the multiplication factor is greater than one, the reactivity is positive (but less than one). If the multiplication factor is between zero and one, the reactivity is negative. Reactivity is a convenient way to describe reactor control because positive reactivity means a supercritical reactor, zero reactivity means a critical reactor, and negative reactivity means a subcritical reactor.

Start-up, shut down, or change in power level -- that is, control -- of a reactor is accomplished by changing the reactivity.31 This is done by controlling the number of nuclear fission reactions per second that typically occur in a reactor. A neutron-absorbing material, like boron, is made into rods ("control rods") which are interspersed with the fuel rods and which can be inserted into or removed from the reactor core.32 This controls the number of neutrons available for fission reactions and the rate of energy production (or power output). A nuclear reactor can be shut down by making the reactivity negative. This is accomplished by inserting the control rods into the reactor far enough so that they will absorb the quantity of neutrons needed to stop the chain reaction. Raising the control rods temporarily makes the reactivity positive, that is, it makes reactor slightly supercritical for a short period of time, enabling an increase in the power level. The reactor is returned to the critical state (reactivity equal to zero) when the desired level of power is achieved.

Control of a reactor can be lost if the reactor continues to stay supercritical (that is, if the reactivity stays positive) for longer than intended. An increase of the multiplication factor is also called a *reactivity insertion.* The intense heat generated by excess fission could overwhelm the cooling systems, causing a severe accident. The most severe accident in nuclear power history, which occurred in reactor number 4 at the Chernobyl power plant on April 26, 1986, involved a loss of control of the nuclear chain reaction.

The time in which reactor power level increases by a factor of about 2.7 (or more accurately, by a factor equal to *e*, the base of natural logarithms) is called the *reactor period.* This quantity depends on the design of the reactor and the composition of the fuel. Power reactors are designed to have long reactor periods in order have slow, smooth increases and decreases in reactor temperature. This minimizes thermal stresses and allows for longer reactor operating lifetime. A typical reactor period in a power reactor would be on the order of one hour.

Control of the reactor is facilitated by the fact that while most (generally more than 99 percent) neutrons from the fission process are emitted essentially at the same time as the fission occurs, a small proportion are emitted after a relatively long time. The former are called prompt neutrons, while the latter are called delayed neutrons. If a reactor becomes critical with only prompt neutrons, the reactor period would be only a tiny fraction of a second, so that control of the reactor would be essentially impossible. But if the reactor is designed so that it does not become critical with prompt neutrons only, then the reactor period and the time available to control it can be increased greatly.

But accidental "prompt criticality" remains a safety concern, since control of the reactor could be lost if a reactor becomes critical with prompt neutrons only. The proportion of delayed neutrons in an LWR is about 0.0065 (that is about two-thirds of one percent).33 So long as the reactivity of the reactor stays below the proportion of delayed neutrons, the reactor cannot become prompt critical, and can be controlled. An increase of reactivity above the delayed neutron fraction results in the loss of control of the reactor. For comparison, fast neutron reactors using uranium-233 or plutonium-239 fuel are even more difficult to control, since the delayed neutron fraction is only about 0.0020.

Reactors such as LWRs in which fuel is loaded in batches require more complex systems to ensure control because when the fuel is fresh, reactivity increase can be large for a modest movement of control rods. During such periods, reactor control is enhanced by adding neutron absorbing chemicals to the water. As noted above, this is known as chemical shim.

The ejection of control rods from a reactor that has relatively fresh fuel in it could result in a total loss of reactor control. This is more of a potential problem with batch-fueled reactors, such as LWRs, than with continuous fueled reactors, such as the Canadian heavy water reactor (CANDU).

Commercial light water reactors use uranium fuel enriched to between 3 and 5 percent as a fuel. Graphite or heavy water moderated reactors can use natural uranium as a fuel. This is a considerable advantage in countries that do not have uranium enrichment plants. It was a principal factor that led a number of countries, including the Soviet Union, France, and Britain, to choose graphite-moderated reactors when they began their military plutonium production. U.S. naval reactors use highly enriched uranium (up to 97.6 percent enrichment) as a fuel because this enables the reactors to operate for longer periods without refueling.

Table 2 shows various types of thermal reactors, along with the coolants, moderators, and fuel types they use.

2. Breeder Reactors (Fast Neutron Reactors)

As we have discussed above, of the fissile materials usable for practical nuclear energy production, only uranium-235 occurs in any substantial quantities in nature. The other two, plutonium-239 and uranium-233, must be made from uranium-238 and thorium-232 respectively, which are far more abundant than naturally-occurring fissile uranium-235. The process of converting "fertile" uranium-238 and thorium-232 into fissile materials is called "breeding," evidently by analogy with biological reproduction.

Commercial nuclear power reactors use natural or "low-enriched" uranium as fuel. Natural uranium contains 0.711% uranium-235 and "low-enriched" reactor fuel contains from 1% to 5% uranium-235, depending on reactor design. Almost all the rest is uranium-238.

Some of the neutrons in a nuclear reactor convert uranium-238 into plutonium-239. In other words, there is "breeding" of plutonium in all commercial reactors containing uranium-238. However, the term "breeder" reactor is reserved for those reactors in which the production of plutonium-239 (or uranium-233) from fertile materials is greater than the amount of fissile material consumed in the reactor. The ratio of the number of fissile atoms produced to that consumed is called the "breeding ratio" or "conversion ratio." A reactor that is designed so that the breeding ratio can exceed one is called a "breeder reactor." When this happens, the fuel output is greater than the fuel input. This (potential) feature was one of the reasons that nuclear energy was often described as a magical energy source.

In commercial reactors now in operation around the world, like LWRs and HWRs, the breeding ratio is less than one; they are referred to as "converter reactors." Typically, a light water reactor converts just under two percent of the uranium-238 into plutonium isotopes, about two-thirds of which consists of the fissile isotopes plutonium-239 and plutonium-241, while the rest consists of the non-fissile isotopes, mainly plutonium-240. Almost half of this plutonium is consumed during normal reactor operation, leaving the rest in the spent fuel. The plutonium consumed during reactor operation typically contributes about one-fourth to one-third of the energy generated in light water reactors.34

Theoretically, it is possible to use breeder reactors to vastly increase the amount of fissile material available for future use while producing energy for current use. The amount of time required to double the quantity of fissile material is called the "doubling time." For breeder reactors that convert uranium-238 into plutonium-239, theoretical doubling times are 9 to 16 years, depending on reactor design; for reactors that convert thorium-232 into uranium-233, doubling times are estimated at 91 to 112 years. A longer doubling time means that a larger resource base of relatively scarce uranium-235 would be required to create an extensive nuclear energy system.

Since doubling times for breeding U-233 are far longer than for breeding Pu-239, almost all breeder reactors so far have been built to breed Pu-239. A further disadvantage of thorium-232-based breeder reactors cycle is the high gamma radioactivity due to contaminants in recovered uranium-233. This radioactivity arises mainly from the decay products of uranium-232, which is created in thorium-uranium fueled breeders by various nuclear reactions.35 India seems to be the only country with a substantial active program to pursue U-233 breeding, since it has very large thorium-232 reserves, which are far greater than its domestic uranium-238 resources.

The number of neutrons per fission required for successful operation of a breeder reactor is considerably greater than for a converter reactor. This is because in addition to the one neutron per fission required to maintain the nuclear chain reaction in the reactor, at least one more is required to convert one atom of U-238 into an atom Pu-239 in order to maintain a breeding ratio of one or more. In practice, since some neutrons are absorbed by the moderator, by other materials in the reactor vessel, and by the reactor vessel itself, the number of neutrons required for a breeding ratio greater than one is considerably more than two per fission.

The number of neutrons produced per fission from U-235 or Pu-239 when fissioned by slow (thermal) neutrons is 2.07 and 2.14 respectively; neither of these ratios is sufficiently large to permit the breeding ratio to be greater than one. In other words, there are not enough neutrons available to produce enough plutonium so it will exceed the fissile materials consumed and simultaneously maintain the chain reaction, given other neutron loss mechanisms.

To overcome this problem, breeder reactor designers take advantage of the fact that if the nuclei of U-235 or Pu-239 are bombarded by fast neutrons (energies of several hundred KeV or more), then the number of neutrons per fission increases substantially. For instance, the number of neutrons per fission for 5 MeV neutrons rises to about 3 for U-235 and to about 3.5 for Pu-239. Pu-239 breeder reactors employ this property by using fast neutrons to accomplish both fuel breeding and energy production. Breeder reactors using fast neutrons are also called "fast breeders" or "fast neutron reactors."

Fast breeders, by definition, need no moderators which slow down neutrons, since they use fast neutrons for fission and breeding. They cannot use ordinary water or heavy water as a coolant because these materials also act as moderators. Gases, which have low density, or atoms with heavy nuclei (mass numbers much greater than one), such as sodium metal, can be used as coolants in fast breeders. Molten salt has also been proposed. Liquid sodium, which has a mass number of 23, compared to 1 for ordinary hydrogen and 2 for deuterium, is the most common breeder reactor coolant. Since a coolant must continually flow across fuel elements, it must be a gas or liquid. Since sodium is a solid at room temperature, it must be maintained in liquid form in a breeder reactor by heating it continually, even when the reactor is shut down.

The most common type of breeder reactor is called the Liquid Metal Fast Breeder Reactor (LMFBR). Figure 5 [not available in on-line version of report] shows a schematic diagram of an LMFBR. A more recent variant of the liquid metal fast reactor design was being developed by Argonne National Laboratory until it was canceled in 1994. It was called the Integral Fast Reactor (IFR). This design had an electrolytic reprocessing plant that accompanied it. Electrolytic reprocessing, called electrometallurgical processing or pyroprocessing, is still being pursued by the DOE at Argonne West in Idaho.36

Sodium catches fire on contact with air and explodes on contact with water. Further, the nucleus of ordinary sodium absorbs a neutron and turns into a highly radioactive isotope sodium-24. This is a major threat in case of a breeder reactor accident. To prevent leakage of sodium-24 into the environment, sodium-cooled reactors are designed with two liquid sodium loops. The secondary, non-radioactive sodium loop draws heat from the primary loop and, in turn, is used to boil water in a steam generator. The December 1995 accident at the Japanese breeder reactor at Monju involved a large leak of sodium from the secondary loop.

Despite its theoretical attractiveness in converting non-fissile into fissile material, the breeder reactor has turned out to be a far tougher technology than thermal reactors. Despite five decades of effort during which many pilot and "demonstration" plants have been built, the sodium-cooled breeder reactor design remains on the margin of commercial nuclear technology. The magic of fuel multiplication has not yet been realized on any meaningful scale relative to nuclear electricity generation levels. Plutonium can also be mixed with uranium for use in thermal reactors. Generally, both plutonium and uranium are mixed after conversion into a dioxide chemical form. For this reason, the plutonium-uranium fuel mixture is called "mixed oxide" fuel, or "MOX" fuel for short.

C. The "Nuclear Fuel Cycle"

Nuclear power as initially conceived was to be based on using both the natural fissile material uranium-235 and increasing the amount of fissile material by converting uranium-238 (or thorium-232) into fissile materials. In this scheme of things, uranium mining and milling would eventually be a supplement to the creation of fissile materials from an initial stock of fertile uranium-238 and thorium-232 in nuclear reactors.

Reprocessing plants would separate the fissile isotopes from the spent fuel for use in fuel fabrication plants. Many of the long-lived highly radioactive fission products resulting from power generation would be used for a variety of purposes, ranging from nuclear medicine to food irradiation to thermoelectric generators to a vast array of science fiction type of applications that became the subject of much swooning prose in the decade that followed the end of World War II. There would be little waste. There would be a nuclear fuel cycle.

However, it was recognized even in the early years that large scale use of nuclear energy would produce fission products in such huge quantities that some arrangements would have to be made for their disposal. But expectations that disposal in salt mines would be a relatively straightforward matter proved too optimistic, like so many other prognostications regarding nuclear power. (See Chapter 6.)(Not available on-line.)

To complicate matters further, reprocessing and fabrication of plutonium into reactor fuel (whether for breeder reactors or light water reactors) turned out to be very expensive, while uranium resources were far more plentiful than anticipated in the 1950s. This made the use of plutonium as a fuel uneconomical, leading to a build-up of spent fuel (which is irradiated fuel discharged from a reactor) at power plant sites. The mounting plutonium stocks, both separated and in spent fuel, are a major source of concern as regards their proliferation potential.