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April 1967

P-3589

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An important shift from coal and oil power plants to nuclear power plants has occurred within the past year in the new equipment orders of the electrical utilities in the United States. Because these new orders signal greatly enhanced prospects for widespread commercial use of nuclear energy, for the first time it has become imperative to plan for the time when industrial economies will be based to a considerable degree on nuclear fuels.

While the development of nuclear energy creates the prospect of almost unlimited sources of cheap power, it also creates the possibility of the worldwide spread of nuclear weapons. Almost all the reactors being installed, or planned for the next ten or fifteen years, will be fueled with natural or slightly enriched uranium and will produce fissile plutonium as a by-product. The slightly enriched uranium cannot be exploded, but plutonium is one of the two important nuclear explosives (the other is uranium-235) and can easily be adapted for use in weapons.

Although the various present systems of international and bilateral safeguards are directed primarily toward detecting any illegal diversion of plutonium from the power reactors, plutonium might still be diverted to military purposes and lead to the acquisition of nuclear weapons by many countries that do not now possess them.

The possibility of controlling plutonium in the future will be strongly influenced by its role in the nuclear economy. For example, if it were just a nasty but economically useless by-product it would be easier to control then if it were very useful and all countries

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wanted to have some. It turns out that plutonium can be used as a reactor fuel and, in fact, it is generally accepted in the nuclear industry that plutonium will eventually displace uranium as the primary nuclear fuel. Economics is driving nuclear power technology to develop advanced plutonium-fueled fast breeder reactors that produce more plutonium than they consume in the generation of power, thereby providing a cheap, virtually inexhaustible, supply of energy. But breeder reactors will also lead to the presence of enormous, rapidly increasing, amounts of plutonium wherever electrical power is generated. Thus, the implications of this coming revolution in the generation of power clearly go beyond economics; they relate directly to the political problems concerning the spread of nuclear weapons.

Because obtaining the necessary nuclear explosives is an essential, and probably the most difficult, part of the development and production of simple nuclear warheads it is reasonable to suppose that knowing the amount of nuclear explosives material available in a civilian nuclear economy gives a fairly good idea of its nuclear military potential. This is probably the most accurate of all the common oversimplifications, though it needs to be kept in mind that delivery vehicles, planes or missiles, are essential parts of complete weapon systems.

The urgency of these questions concerning the risks posed by the advance of civilian nuclear technology with respect to the major industrial non-nuclear countries has been dramatically heightened by the recent extraordinary, and unexpected, boom in nuclear power in the United States.

GROWTH OF CIVILIAN NUCLEAR POWER

Ever since the splitting of the atom, enthusiasts have predicted that economical nuclear power was just around the corner and that nuclear fuel would displace coal and oil in the generation of power. These overly optimistic predictions were announced with such regularity that they came to be discounted and eventually ignored by the public so that a dramatic change which occurred during 1966 was largely unnoticed outside the power industry. At the end of 1965 only a few commercial nuclear power plants, generating less than 1 percent of the nation's power, were operating in the United States. By the end of 1966, nothing had happened to change this situation. But it was clear that nuclear power had become competitive with coal and oil for the generation of electricity. During the year 1966 more than half of the newly ordered electric power capacity was in the form of nuclear plants.

The forecasts for the future growth of nuclear power have been rising rapidly over the last few years. In 1962 the Atomic Energy Commission reported to the President on the future of civilian nuclear power. It predicted that in 1980 there would be a nuclear powered electrical generating capacity of about 40,000 megawatts in the United States. (By comparison, the total installed electrical generating capacity in the United States in 1966 was about 250,000 megawatts.) The total demand for electricity doubles about every ten years, so in 1980 the total capacity will probably be over 500,000 megawatts. The prediction that almost 10 percent of this might be nuclear was treated with derision by the skeptics. But by 1964 the prospects for civilian nuclear power had so improved that the AEC raised its prediction for 1980 to 60-90,000 megawatts. And the most recent 1966 AEC predictions for 1980 are 80-110,000 megawatts. By comparison, General Electric predicts 125,000 megawatts, while Westinghouse estimates 150,000 megawatts. There has clearly been a revolution in the thinking of the nuclear industry. Moreover, there are many indications that a similar boom in nuclear power is about to take place in other industrial countries. A recent A. D. Little study for the AEC, "The Growth of Foreign Nuclear Power," published in April 1966, predicted that by 1980 the total installed nuclear capacity in Western Europe, Canada, and Japan would be about 130,000 megawatts, or about one and a half times the total for the United States. Actually, at the present time, Europe has several times the nuclear power capacity of the United States. In fact, about ten percent of Britain's power comes from nuclear reactors. But up to now European reactors have been installed in order to obtain nuclear experience, to diversify energy sources, or to further a national policy of nuclear armament. European utilites are only now beginning to accept nuclear power because of economics. It is generally expected that in the next year or two orders for nuclear power plants by European and Japanese utilites will accelerate rapidly.

HOW MUCH PLUTONIUM WILL THERE BE?

In terms of plutonium production, 100,000 megawatts of nuclear power forecast for the United States in 1980 corresponds to an annual production of about 25,000 kilograms of plutonium. World production would be about 65,000 kilograms per year. Of the countries that do not already have nuclear weapons but plan large civilian programs the most prominent are the Federal Republic of Germany and Japan. The cumulative total plutonium stocks available from West German thermal reactors are expected to be about 500 kilograms in 1970, about 6000 kilograms by 1975, and about 20,000 kilograms by 1980. The Japanese nuclear program will produce the first 1000 kilograms in the early 1970's and will probably roughly keep pace with the German program. To put these numbers in perspective it helps to compare them with the amount of plutonium needed for one nuclear weapon. This is approximately equal to the critical mass of a plutonium sphere surrounded by a good neutron reflector--about 6 kilograms of plutonium.

THERMAL REACTORS

It is a familiar fact that the operation of a reactor depends on a neutron "chain reaction." The reaction is maintained because whenever a scarce uranium-235 nucleus is split by a neutron a couple of neutrons emerge, only one of which is needed to keep the reaction going. The emergent neutrons are rapidly slowed down by collisions with a "moderator" (water, heavy water, or carbon) to speeds associated with the thermal motion of atoms. At "thermal" speeds, the neutrons have a better chance to fission uranium-235 nuclei than to get captured in the more plentiful uranium-238 nuclei. Reactors which depend on "thermal" neutrons are called "thermal" reactors. All of the reactors involved in the above estimates are of this type.

As we have already mentioned the slightly enriched uranium fuel cannot be exploded. But the neutrons lost to the chain reaction through capture in the uranium-238 add a new element to our picture--they transform the inert uranium-238 into fissile plutonium-239, the other important nuclear explosive aside from uranium-235. This is, in fact, how plutonium for weapons is produced. In a commercial power reactor much of the plutonium produced is subsequently fissioned, as is the uranium-235, but there is always some plutonium present when the fuel is removed.

A NEW POSSIBILITY

Nuclear power can compete with conventional power because the lower nuclear fuel costs more than offset the somewhat greater fixed costs of nuclear plants. But the present generation of thermal reactors still use uranium rather inefficiently. Because they burn mainly the scarce isotope uranium-235, they use only about 1 percent of the mined uranium and, as a result, require large amounts of uranium.

This suggests that a further decrease in nuclear fuel costs could be achieved if the uranium could be used more efficiently. But we know that the bulk of natural uranium, the uranium-238, which is normally discarded, can be burned if only it is first converted into plutonium. This is the idea behind an advanced type of reactor system, the plutonium-fueled "fast breeder." It "breeds" more plutonium from uranium than it consumes in the generation of power; therefore, the net fuel costs are very low. "Fast breeders" get their name because they use fast neutrons, and not because they breed fast. It is expected (or hoped) that the fast breeders can be built for roughly the same cost as thermal reactors so that the breeders will lead to a net reduction in power costs. It is generally expected in the nuclear industry that these reactors will eventually take over the generation of electrical power in industrial countries.

Why can't we breed in a uranium-fueled thermal reactor? Because there are just not enough neutrons available to permit a net gain of plutonium. However, plutonium fissions caused by fast neutrons release enough extra neutrons to permit the conversion of uranium into plutonium at a faster rate than the plutonium is used.

FAST BREEDERS

The basic element of a fast breeder is a relatively small core of fissile plutonium mixed with some uranium. The active core is surrounded by a "blanket" of uranium-238 which captures neutrons and is thereby slowly converted to plutonium. The core and blanket are periodically reprocessed, the plutonium core is replenished, and the excess plutonium is used to fuel new fast breeders. The net input to the system is natural or depleted uranium and the net output is power and excess plutonium.

An interesting comparison has been presented by Kenneth Jay in his book Nuclear Power:

> Contrary to appearnces, this is not a magical process for getting something for nothing, but is a matter of using neutrons to convert an unburnable material into a burnable one. A similar, though not exactly analogous, process would be one in which wet wood was piled round a wood-burning stove and some of the heat from the stove used to dry the wet wood and make it fit for burning in the stove. In this analogy, the fresh fuel (the dried wood) is obtained at the expense of heat that might have been used for some other purpose. In the nuclear furnace, the fresh fissile material is obtained at the expense of neutrons, which have a cash value and can be used in other ways, and of course of fertile material, which also costs money. This is a conversion process and both the material to be converted and the means by which the conversion is achieved have to be provided.

The ratio of the plutonium produced to the plutonium used up (called the "breeding ratio") depends on the design, but it can be about one and a half. This does not completely characterize the breeder because it doesn't indicate how long the process takes. The time required to accumulate enough excess plutonium to start another reactor of the same size (the "doubling time") is typically about

10 years. The core of a fast breeder contains about 3000 kilograms of plutonium per 1000 megawatts of electrical output. (This would correspond to one large reactor.) As noted above, a minimum critical mass, roughly the amount required for a weapon, is only about 6 kilograms.

DEVELOPMENT PROGRAMS

Experimental fast breeders have been operating for some time in the United States. It was an American experimental fast breeder (EBR-1) that was the world's first nuclear reactor of any type to generate electrical power in December 1951. There are also experimental fast breeders in the Soviet Union, Britain, and France. West Germany has a vigorous research and development program and Japan is about to embark on an ambitious ten year program. Despite our headstart the United States does not appear to be the leader in this field. The Soviet Union and Britain have medium size fast breeder prototypes (300 megawatts of electrical output) under construction. All of the countries mentioned here plan to have commercial 1000 megawatt fast breeder units in operation around 1980.

SOME OTHER ADVANTAGES

Because fast breeders make almost complete use of the mined uranium they use only about one percent of the uranium required in thermal reactors. Early introduction of fast breeders, say in 1980, would reduce by about one half the total amount of uranium required by <u>all</u> reactors up to the year 2000. Furthermore, since most of this uranium would probably be used in slightly enriched form, the requirement for enriched uranium is sharply decreased. The rate at which breeders will take up the major share of the generation of power will strongly influence the need for new isotope separation facilities. A number of countries, for example Germany, and Japan, find rather appealing the prospect of using breeders to decrease their dependence on United States enrichment facilities without having to build their own facilities.

One might ask, if breeders are so efficient why not just build breeders? The reason is that although the "fertile" material, uranium-238 occurs in relatively large quantities in the earth's crust, the necessary fissile fuel, plutonium-239 does not occur naturally. The only naturally occuring fissile material is uranium-235 and it must therefore be the starting point of all nuclear power. Only when enough plutonium-239 is produced in thermal convertors can breeders be started in significant numbers. Even the major industrial countries will not be in this position for about ten years. For some time after that breeders as a whole must be net consumers of fissile materials, rather than net producers.

In any case the change to breeders must come eventually. Whether there is enough cheap uranium to fuel the planned installation of thermal reactors for the rest of the century is a subject of some controversy, but it is generally acknowledged that nuclear power can be the major source of power far into the future only if the fuel is burned in breeder reactors. It is interesting to note that the time it takes a fast breeder to accumulate enough excess plutonium to start another breeder of the same size--about ten years--is about the same as the present doubling time for the growth in world electrical power demand. Thus, if all the world's power were produced by breeders there could be enough excess fuel to keep up with the increasing demand for power. Fast breeders provide essentially a permanent solution to the increasing energy demand of the world. It is, in fact, the only working system for which there is sufficient fuel for thousands of years.

SOME CONSEQUENCES OF BREEDING

We have seen that the present transition from conventional fuels to nuclear fuels will greatly increase plutonium availability. It now seems likely that about thirty years from now large numbers of plutonium breeders will be installed around the world, wherever large amounts of electrical power are generated. In fact, plutonium will be essential to the industrial life of advanced countries. Plutonium will therefore necessarily be physically available. Whether it will be available for military purposes will turn on future political decisions, decisions which will be greatly influenced by the military policies pursued in the intervening years by various countries, but especially the present nuclear powers.

Although for some time--perhaps 20-30 years--most of the plutonium will come from thermal reactors, the existence of fast breeders will influence stockpiling and will encourage countries to develop plutonium industries. But even in the early years fast breeder plutonium may be significant; the plutonium bred in the breeder blanket, about half of the total, is adaptable to military use much more easily than plutonium normally produced by a commercial thermal reactor.

To get some idea of how much plutonium there will be available eventually, imagine that all the electrical power capacity in the United States were in the form of fast breeders, instead of the present coal and gas burning plants. This would imply a total plutonium inventory, in the cores of all the fast breeders, of about 600,000 kilograms--about 3 kilograms of plutonium per 1000 persons, or about a critical mass (about one weapon) for every 2000 persons. This total would then be doubling about every ten years. According to present estimates of the number of fast breeders to be installed in the world by the year 2000 there will then be several million kilograms of plutonium--doubling about every ten years.

Even now the anticipation of fast breeders in large part determines the attitude of industrial countries toward plutonium. It is naturally regarded by economic planners as a substance of considerable industrial importance. Therefore, it must be expected that countries will be little inclined to relinquish national ownership of plutonium or to accept safeguard systems that interfere with its industrial use. For the future, international ownership of plutonium stocks would imply significant international control of the generation of electrical power and hence of industry. This seems impractical at present. The greatest challenge facing the architects of future nuclear policy is how to make the plutonium in civilian reactors unavailable for military purposes without impairing the very real usefulness of this fissile material, or the industrial independence of the owner.