Nuclear fission reactors

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The story of fission is a story of drama and emotion, and it is a story that demonstrates possibly better than any other the overwhelming importance of modern physics to the events of this past century. Its discovery, or more properly, its identification, was delayed for a surprisingly long time after the phenomenon had in fact been induced in several of the first-rank laboratories in the world. Over four years passed without its recognition, but when recognition did come, it came at the most dramatic possible time. It was just before the war that engulfed the world, and knowledgeable physicists in every country were in a position to guess at its possible military significance.

The delay in the identification of the phenomenon of fission was caused by misdirection, in that the experimenters expected another result, based on the understanding of the day. When this was combined with measurement imprecision inherent in the techniques used in the experiments, proper interpretation of the results was obscured. For the discovery of fission rested on delicate radiochemical separations of unknown elements created in tiny amounts by neutron bombardment of uranium. The systematics of similar experiments in lighter elements suggested that new transuranic elements, heavier than uranium, were to be expected. The results therefore were interpreted in this way, but with increasing puzzlement as time passed. Nevertheless, confidence in this interpretation caused even the evidence provided by large fission pulses actually seen in a few ion-chamber measurements to be attributed to instrument malfunction. Recognition of fission was therefore delayed from 1934 to 1938, and it was very late in 1938 when the phenomenon was recognized unequivocally for what it was.

Once the fact of fission was recognized, however, its implications, military and otherwise, were very quickly grasped. With World War II rapidly coming on, the most interesting and important physics of the day appeared briefly, then disappeared from the technical journals of the time, first through a form of secrecy self-imposed by the scientists involved, and then by the heavy formalized security of wartime. Behind this wall of secrecy, the key technical issues were quickly settled—the presence of neutrons from fission itself in sufficient number to sustain a chain reaction ($2\frac{1}{2}$ neutrons in uranium) and the adequacy of two different materials, heavy water and graphite,[1] the latter readily available, to moderate the energy of the neutrons from fission to energies such that there could be sufficient neutron capture in uranium to make a self-sustaining fission reaction possible.

The principles underlying the first successful reactor demonstration were quite simple. The principal obstacle to overcome was the fact that the fuel had to be uranium that contained only the naturally occurring trace concentration (0.7%) of the actual fissile element U-235. No enrichment facilities to increase the concentration of U-235 had yet been contemplated. Absorption of neutrons in the fuel itself therefore needed to be maximized, useless neutron absorption in nonfuel materials minimized, the surface where neutrons could leave the system, also uselessly, minimized with respect to the volume where useful absorption could take place, and finally, absorption of neutrons in the fuel had to take place at the (low) energies where the probability of fission was high. Only then could criticality be achieved and a chain reaction begin to proceed at steady power. The probability of fission is highest at thermal energies. An efficient moderating material was needed to moderate the energy of neutrons released in fission all the way to thermal energies without the moderator itself absorbing an inordinate number of neutrons. Both graphite and heavy water would work, if free of impurities, and as we shall see, both were in fact used exclusively in the early programs, but the ready availability of graphite led to its choice for the world's first nuclear reactor.

Graphite as the moderator and natural uranium as the fuel became the basis for the world's first reactor, Chicago Pile #1, or CP-1. Assembled by Enrico Fermi and his group at the University of Chicago, following measurements by the same group indicating feasibility both in number of neutrons and in moderator efficiency, it went critical on December 2, 1942, under cover of complete secrecy. And in total secrecy research facilities, production reactors, processing plants, and ancillary facilities were quickly constructed at places such as Los Alamos, Hanford, and Oak Ridge. The scale of the effort was extraordinary, urgency was felt at every step, and it led in just two and a half years from the successful CP-1 demonstration to the successful development of the "atomic bomb."

Secrecy came to an abrupt end with the explosions in August of 1945 over Hiroshima and Nagasaki. The use of the "atomic bomb" to end World War II, so controversial later, was greeted with overwhelming relief and approval by the public of the Allied Nations at the time. Such feeling is captured in the reaction of a young Australian woman, her husband an American captain serving in the Pacific. "At that moment," she said, "I knew God was on our side."

[1]The advantage of heavy water (D_2O) over light water (H_2O) lies in the far smaller neutron absorption cross section of D compared to H.

Such strong emotion, for and against, has been the hallmark of nuclear development throughout its history. It provided the driving force for the huge national programs after World War II, on the one hand, and on the other hand it fueled the intense organized opposition to further development seen in recent years.

In the months following World War II, while the world grappled with the stupendous implications of the existence of fission, those nations in a position to do so turned quickly to exploiting the fission process. Driven in part by the desire to attain, or in the case of the U.S., to maintain, military advantage, the national programs that were put in place nevertheless explored on a very large scale the science, the technology, and the potential, civilian as well as military, of fission-based nuclear energy. In particular, programs that would lead to rapid development of commercial nuclear electric power were soon in place in six nations of the world: the U.S., the U.K., Canada, France, the U.S.S.R., and Sweden. All other nations that deployed nuclear power transferred the necessary technology from these six. United States technology, and to a much lesser extent, Canadian technology, eventually predominated.

At the end of the war the United States had an impressive lead, for the wartime projects provided a very broad technological base—of knowledge, processes, and facilities—for further nuclear power development. The passage of the Atomic Energy Act of 1946 established the Atomic Energy Commission, and the principle of civilian control of nuclear activities; it provided the framework for private industrial involvement and it began the system of great national laboratories created specifically for the development of nuclear energy. Argonne National Laboratory, established on July 1, 1946, was the first, and in 1948 it became the designated center for reactor development for the nation. Progress was rapid. On December 20, 1951, the first electricity produced by nuclear energy was generated by the Argonne group in the Experimental Breeder Reactor #1, at the newly commissioned National Reactor Test Station on the Great Basin Desert in Idaho.

Principal among the myriad problems faced by the early reactor inventors and designers were problems with materials. They needed materials that first of all were suitable in nuclear properties, but that also had adequate corrosion resistance, radiation resistance, and fabricability. The characteristics of any reactor are very largely set by the choice of fuel material, moderator materials, and coolant material. Insightful design can ameliorate disadvantages and emphasize corresponding advantages, but once the main material choices are made the principal characteristics of that reactor type are set. Because the U.S. had uranium isotopic enrichment facilities from the wartime project, and, in fact, for a considerable time had a monopoly on such facilities, the constraint put on material choice by the need to use only natural uranium did not exist for the U.S. As a result an astonishing array of material choices and combinations were exploited in the first demonstration phase of reactor prototypes in the U.S. This remarkably diverse set of utility-operated reactors had powers generally in the tens of MWe range,[2] too small to be economic, but large enough to firmly establish technical feasibility, and they were deployed by the late 1950s and early 1960s.

The goal of that first U.S. demonstration phase was an admirable one. It aimed at establishing as much information as possible concerning the strength and weaknesses of various reactor possibilities, at a time when the actual need for early deployment of nuclear power was not pressing. Alternatives could then be weighed and the best possible choices made. However, events of the day quickly overtook this studied approach. The head start given by the Naval Reactors program to their choice of light-water reactor technology—a single-minded choice that meant rapid development of that technology for Navy purposes—and the political imperative of the day to show a successful reactor type in operation combined to settle the question of civilian reactor technology choice. The pressing need to show successful reactor commercialization arose from the U.S.-led Atoms for Peace initiative of 1955. The promise of successful civilian power technology to other nations was felt to be necessary, in return for nonproliferation commitments. Light-water reactors were the natural choice, as the easiest, the fastest, and the most established technology. It is important to note today that the considerations of the time did not give the slightest weight to whether this technology would be the right long-term choice for large-scale permanent deployment. In fact, it was assumed that it certainly would not be the best long-term choice, but that it would probably make a perfectly suitable choice for a first generation of nuclear power.

It was in this way that the light-water reactor came to dominate the U.S. market, as it eventually came to dominate that of the entire world. The distinction of being the first commercial reactor in the U.S. is credited to the 620-MWe General Electric Boiling-Water Reactor ordered in 1963 by Jersey Central Power and Light. With it, a commercialization rush began. In 1966, 20 plants were ordered, 30 more in 1967. By 1974, the last big year for reactor orders in the U.S., well over a hundred large nuclear power plants were on the books of U.S. nuclear vendors. In later years some were canceled, as over-capacity, cost overruns, and a new, much more skeptical environment for nuclear power diminished the early optimism. Some reactors have now reached the end of their useful life, and some, after many years of operation, have been closed down simply as an economic business decision. Nevertheless, today the U.S. has 108 nuclear power plants in operation, supplying 22% of the nation's electricity.

The pattern in other parts of the world initially differed from the U.S., principally because of the U.S. mo-

[2]MWe is the abbreviation for megawatts of electrical power and makes the distinction between electrical power output and total (or thermal) power output, denoted by MWt. The difference is the waste heat.

nopoly on enrichment capacity. In other nations natural uranium with its low (0.7%) fraction of the fissile element U-235 had to be utilized, at least initially. Essentially, each nation had to start with its equivalent of CP-1, in most cases using graphite as the moderator. The principal design consideration was correct arrangement of the graphite and uranium to make the array as reactive as possible, as this combination of materials gives little margin in reactivity, but CP-1 had shown the way. Two nations, Canada and Sweden, had sufficient heavy water, a much superior moderator, for their prototypes. Because heavy water gave a satisfactory system using natural uranium, Canada was able to base its successful development of the commercial CANDU reactor on the technology of its earliest prototypes. The same was not true of the nations forced to use graphite-moderated systems. Eventually all such national programs were displaced by U.S. light-water technology.

In each nation such a natural-uranium-based reactor was assembled within a year or two of the war's end, and its technology became the basis for the early power reactor programs. In the U.S.S.R., the U.K., and France, the programs were graphite-moderator based because of the inexpensive availability of graphite and the simplicity that was possible in the initial designs. But the simplicity, even crudity, of the early graphite-based designs led directly to two of the three major reactor accidents that the world has seen: The Windscale production reactor accident in 1957 in the U.K. and the 1986 accident at Chernobyl, both of which spread radioactive contamination beyond, and, as the world knows, in the Chernobyl case, far beyond, the boundary of the reactor site itself.[3] Both accidents resulted from poor operator understanding of the characteristics of a primitive reactor whose design made little allowance for operator misjudgments.

The successful Canadian reactor, CANDU, still based on natural uranium and heavy water, needing neither enrichment nor reprocessing facilities, has been deployed in several countries of the world. Several percent of the world's nuclear electrical capacity is based on this reactor, most of it, of course, in Canada itself.

In France, after a relatively short graphite-based phase, a very successful program began, based on the Westinghouse PWR, that transformed the nation's electrical system largely to nuclear generation. It led to an electrical system in France that is now 77% nuclear, with nuclear electricity now being exported to neighboring countries, and a very stable domestic electrical system with by far the highest nuclear portion of any of the large industrialized countries.

The U.K. stayed with a relatively successful graphite-moderated, gas-cooled program for a considerable time, but it too, in its recent reactor additions, has turned to the light-water reactor.

[3]The other was the TMI-2 event in 1979, where a commercial LWR, lacking cooling, melted a substantial fraction of its core.

In the countries of the former Soviet Union, the graphite-based design RBMK continued to be deployed, even after the light-water reactor technology was phased in and, as mentioned, it was the former reactor type that was involved in the Chernobyl event. Although some RBMK's remain in operation, the former Soviet Union nations now largely use light-water technology as well.

Around the globe, the world's nuclear capacity is about 350 GWe, about 18% of the total world electricity generation, as other nations have adopted the technology of the pioneers. Essentially all capacity is based on light-water technology. It is widely known that the light-water reactor cannot be the sole long-term choice for nuclear deployment, as it uses the uranium resource very inefficiently, but there is little incentive, or, indeed, will, at present to do more. The R&D programs, once so large, have shrunk in all countries, and in many have been eliminated entirely. Any change in this picture will require a change in today's attitudes towards the place of nuclear power in the energy mix worldwide. For nuclear technology is capable of more, much more.

Thus it is of the greatest importance to examine what is required of nuclear technology to make it a large, permanent solution to world's energy needs. Clearly, technological improvements are needed, and these we shall examine here. Though all reactors function in basically the same way, in that the fuel material is very gradually consumed by fission, they can differ appreciably in characteristics, depending on the choice of materials used. The fuel material, always, is basically uranium—it may actually be uranium, or it may be substances, principally plutonium, derived from uranium. Whatever the material, it is usually fabricated in pencil-sized rods and enclosed in a sleeve of some ordinary metal like steel. Several thousand of these rods make up the core of any nuclear reactor, assembled in a fairly close-packed array several feet in diameter and several feet high. Circulating around the rods is some kind of cooling fluid. When the fuel mass is sufficient, the fission process becomes self-sustaining and the reactor is said to be "critical."

The fission process in a critical reactor steadily produces heat, and it can quickly and easily be adjusted to produce steady heat at any rate that is desired. But the right rate is just the rate at which heat can get out of the fuel and be carried away by the coolant. This rate varies in the different kinds of reactors made of different materials. Fuels, for example, can be metals or ceramics; coolants can be liquids—water or liquid metals are used routinely—or gas. Both helium and carbon dioxide have been used. Whatever the coolant, its heat is used to produce steam which in turn generates electricity. Now cooled, it is circulated back to carry heat away from the reactor core again.

The essential point is that the heat generation in the fuel must match the rate at which the heat can be removed by the coolant. This is not difficult to do, and reactors tend to run very stably and evenly. But in the matching of heating to cooling lies the basis for understanding reactor safety. All of the serious accidents that can happen to a nuclear reactor involve upsetting this balance. There is really no nuclear accident unless radioactivity is released. As long as the sleeve around the fuel, the ''fuel cladding,'' remains intact, radioactivity is contained in the fuel and no-one, worker or public, can be affected. The only way to get widespread cladding failure is by melting. Melting occurs in only one way: from an imbalance between heat generation in the fuel and heat carried away by the coolant. If the fuel generates more heat than the coolant can carry away, the temperatures of both—fuel and coolant—rise. Unless corrective action is taken, temperatures can rise to a point at which the cladding melts and radioactivity is released from the fuel (which itself may also be molten). The initial release of radioactivity is to the coolant. To reach the outside atmosphere, the radioactivity must first get out of the vessel and piping containing the coolant and then out of the containment building, which itself is constructed expressly to prevent contamination of the outside atmosphere in just such situations. These multiple barriers to the escape of radioactivity have generally been very effective, but clearly, it is much better if the first barrier, that is, the fuel cladding, never fails. If that is achieved, then there can be no radioactive release, no ''meltdown,'' in fact, no effect on the public at all.

These potentially dangerous imbalances between heat generation and heat removal can happen due to mechanical failure or simply to mistakes, as in any other machine. The corrective action to prevent cladding failure is always the same: the heat production—the power that is being generated—must be reduced quickly to match the heat removal capability that remains after the mechanical failure. (Typical mechanical failures are coolant pumps failing, pipes breaking, valves not working, and so on—all the things to be expected occasionally in a large hydraulic system.)

Normally, power is reduced (but never entirely shut off) by inserting neutron-absorbing safety rods into the reactor to stop the fission process. This, too, relies on mechanical devices' functioning properly—sensors, motors, springs, relays, etc. Such safety systems are always designed to be redundant, so if one device fails there is backup. But reactors can also be developed that shut themselves down harmlessly under these conditions without the need for mechanical devices' functioning properly. These reactor concepts are said to be ''passively safe'' or ''inherently safe.'' In essence, they automatically match heat production to heat removal. Thus under conditions in which heat removal is failing, the balance is maintained without the need for mechanical devices like safety rods to reduce the heat production.

The principle underlying passively safe behavior is quite simple: choice of reactor materials to give a strongly negative temperature coefficient of reactivity overall, with little contribution to the coefficient from the fuel itself. Under these conditions, if heat removal begins to become inadequate for the power being generated, the resulting temperature rise is immediately offset by reactivity reduction and consequent power reduction due to the overall negative temperature coefficient. This power reduction drops the fuel temperature, and in the absence of a significant contribution to the coefficient by the fuel itself—in particular, no significant positive contribution from the dropping fuel temperature—the power simply adjusts to the level of cooling available. The reactor remains critical, the coolant temperatures remain at operating levels, the fuel temperatures are reduced, and the power level steadies at the new equilibrium level. An entire class of possible serious accidents can be avoided in this way.

In essence, this is how reactors work; this is what can go wrong with them; and this is the basis for improved safety in advanced reactors.

World consumption of coal, oil, and gas now generates 90% of the world's energy, about 300 quads/yr, and growing.[4] The ability of nuclear energy to displace a significant fraction of this fossil fuel usage depends on the amount of uranium needed to produce a given amount of energy. World uranium resources, while large by present standards, are not large when set against future needs for energy. It is important to understand that energy production for a given amount of uranium varies very greatly with the type of reactor used. In present-day light-water reactors uranium is used very inefficiently. Less than 1% is actually used, and all the rest is waste. In fact this makes up a large part of the nuclear waste that eventually has to be placed in a repository. No state wants to host such a repository, although Nevada has been selected at the present time. Ninety-nine percent of the uranium that goes into light-water reactors therefore is part of a problem—the nuclear waste problem—and not part of any energy solution.

By present estimates the total world's known uranium resources, if used in today's reactors, would produce electricity equivalent to about 40% of present world energy generation for 30 years. Even if the estimates of uranium resources are wrong by a large amount, even by a factor of 2, the conclusion would be the same: This amount of energy is useful in the overall picture but is not a permanent solution to the world's needs for energy.

If reactors other than the light-water reactor of today were to be developed, reactors that have the property of breeding, thus making much better utilization of the uranium resource, nuclear power could be a large part of a permanent solution to the world's long-term needs for energy. Breeding causes the 99% of the uranium that is now a part of the waste to be gradually converted to a new fuel material—plutonium—that can be burned just as the fraction of 1% of the uranium that is burned today. In this way, all, or essentially all, uranium is burnable fuel and the entire uranium resource can be used.

The breeder reactor is the only reactor that can substitute for a large part of fossil fuel usage for a long period of time and thus impact in a significant way greenhouse gas increase. With uranium utilization at least a factor of 70 greater than today's reactors, the breeder reactor could theoretically displace all fossil fuel

[4] 1 quad=1 quadrillion BTU=1.055 exajoule=1.055×10^{18} J.

consumption for at least 1000 yr. If electricity generation could be made half the total world energy generation, the current economically recoverable uranium reserves would last for 2000 yr. Nuclear power then becomes a significant part of a permanent solution.

Breeding today is controversial, because of its focus on the conversion of nonfissile uranium to a fissionable plutonium fuel, and the concomitant concern about the use of such plutonium to make nuclear weapons. Such concerns, however, eventually must be reconciled with energy needs. If nuclear energy is to contribute substantively to meeting mankind's future energy needs and maintain the present atmospheric environment, as it is capable of doing, breeding is a fundamental requirement. The concomitant proliferation problem is one that needs to be solved by the world community, a problem that is beyond the scientific and engineering efforts discussed in this article.

There are other implications for the long term. Assume, for illustration, that just half the present rate of world energy usage is electric and its generation is all nuclear. About 1500 1000-MW reactors would be needed today, increasing each year with further world energy growth. In the present reactors a plant performance goal of 10^{-4} reactor yr^{-1} for a large-scale core melt accident is agreed to be a reasonable standard. That is, the probability of widespread melting of fuel and cladding should not be greater for any single reactor than 0.01% a year. Accepting this as a goal, we can see that 1500 reactors imply a serious accident every seven years and, of course, with growth, even more. Such an accident rate is unacceptably high for long-term widely deployed reactor usage, and the adoption of passive safety features may be wise in the long run.

There are implications for the nuclear waste as well. From a global perspective, the present reactor system converts the world's supply of uranium to a form that is a cancer risk to man for tens of thousands of years, orders of magnitude worse than the ore it was mined from. This can be defended on the basis of our need for energy, but it is useful to remember that in the present reactors this will have been done without significantly affecting the long-term consumption of carbon fuels or the long-term outlook for global climate change, and the opportunity for doing better will have passed.

Just as the type of nuclear reactor dictates the magnitude of its energy contribution, the reactor type and the choice of the fuel cycle can have a radical effect on the nuclear waste, too. It is unlikely that nuclear power will develop in an orderly way on the scale required without a solution to the nuclear waste problem. Many people do not have confidence that wastes can be isolated for the millions of years that they are harmful. There is a consensus in the scientific community, by no means unanimous, that this can be done, but the public is skeptical. Present policy is to bury the fuel coming out of light-water reactors. Burying this spent fuel, as it is called, buries much of the uranium's energy potential and commits the burial ground—the repository—to 1 000 000-yr isolation.

But just as there are different types of reactors, so too are there different types of fuel cycles. The fuel cycle is the way the spent reactor fuel is treated and, in the case of the breeder reactor, cycled back to the reactor. Fuel cycle alternatives can have great impact on the waste issue. The actinide elements, uranium and the derivatives of uranium created while the fuel is in the reactor, cause the 1 000 000-yr problem. Practically everything else that is radioactive in the waste will become relatively harmless in a few hundred years. A fuel cycle that removes the actinides from the waste changes the isolation period necessary for it from millions of years to hundreds of years. Structures to isolate waste from the environment can be designed with confidence for such periods. As for the actinide materials themselves, in the right breeder reactor type they can be destroyed by fissioning them. Such fissioning in turn creates energy rather than a 1 000 000-yr waste commitment. If all actinide elements, not just plutonium, are recycled, the usefulness of such material for weapons is substantially lessened.

The point in all of this, therefore, is that improved reactor types are needed and that from a global perspective, the characteristics they should have are clear—in breeding, in safety and in waste. New technologies, new processes, new ways of exploiting basic properties of reactor materials can fundamentally alter the role nuclear power can and will be allowed to play in our future. Nuclear power may even be essential to a stable environment with a climate as we now know it. Of the technologies known to be feasible today, it alone is capable of the magnitudes required to supply future energy needs. Advanced reactor development that promises to radically improve the outlook for large-scale nuclear power may be one of the most important challenges presented to man. But undertaken successfully, nuclear fission could well have beneficial effects on the next centuries even greater than its effect in this century of its discovery.