NUCLEAR POWER: AN OVERVIEW OF THE PRINCIPAL TECHNICAL CONCERNS

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The introduction of electricity-generating nuclear power plants has been the focus of one of the most intense controversies of our era. While opposition in the United States to the new plants began in a limited manner about twenty years ago, it has grown in intensity and has spread to most of the other countries in which nuclear power has been or is being introduced.

The causes of controversy are complex and are almost as controversial as nuclear power itself. The purpose of this paper is to examine the principal technical concerns about nuclear power; in doing so, I shall explore their origins, their history, and their current state. As I have been either intimately involved in or close to many of these developments, much of the material for this paper is drawn from personal recollection. Because the scientific evidence is limited and occasionally in dispute, unassailable conclusions are not always possible. Where my analysis differs from the views of others, I shall clarify the bases of my views.

This paper cannot purport to be exhaustive, because the technical concerns regarding nuclear power are manifold. This paper will instead focus on three of the principal areas of concern. The first involves early fears about the safety of nuclear power plants. Those fears have been largely dispelled. The second involves the more recent controversy over nuclear power plant safety. The third involves the relation between nuclear power and nuclear weapons.

I

OPERATION

The first nuclear power plant in the United States began to operate in 1956, so this is the twenty-fifth year of the commercial nuclear era. There are now about seventy power plants operating in this country, generating about twelve percent of our electric power and about four percent of our total energy consumption. Close to eighty additional plants are being built.

All nuclear reactors operate through the process of fission. "Fission" is the splitting of the central nuclei of elementary atoms into two parts, thereby liberating an enormous amount of heat energy. The materials used in nuclear reactions are particular isotopes of uranium and plutonium.

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Uranium is found in nature, but primarily in a non-fissile form. It is processed for reactors to increase the quantity of the fissile isotope, uranium 235, beyond the level found in nature. This process is called enrichment. Plutonium, furthermore, does not occur in nature. It is created and destroyed in nuclear reactions.

Otherwise, all nuclear power plants generate electricity in the same way as conventional power plants. The heat liberated by nuclear fission boils water at high temperature and pressure. The steam from the boiling water drives a turbine, which is forced to spin rapidly. The turbine is attached to a generator which also spins rapidly, creating electricity.

Almost all American reactors are water reactors. They use water to transform the thermal energy created by fission into electrical energy. There are two forms of water reactors. Boiling water reactors generate steam by boiling water in the central core. Pressurized water reactors, on the other hand, heat water in the core which is pressurized to prevent boiling, and that pressurized, heated water then boils water in another, separate system.

Finally, the "ashes" of nuclear fission are the fragments of nuclei that have been split. These fragments are themselves nuclei of other chemical elements in the periodic table, such as cesium, strontium, and krypton. Most fission products are radioactive, but radioactivity naturally decreases or decays with time. Thus, old fission products are not as radioactive as new fission products. Radioactive decay is a kind of liberation of heat. Fresh fission products liberate a great deal of heat, the rate of which decreases as the radioactive element decays. Exposure to too much radioactivity can cause severe burns or death.

II

Can Reactors Explode Like Atom Bombs?

In the late 1940's and the early 1950's, most scientists saw little difference between the dynamics of nuclear reactors and of nuclear explosives. Many similarities were apparent. The two kinds of devices utilize the same fission process and the same fissionable types of uranium and plutonium. In many respects, the theoretical operation of nuclear power reactors and explosives is quite similar, at least in their mathematical structures. Additionally, the analytical study of the control and safety of nuclear reactors had not progressed very far in those early days. The physical intuition that results from both breadth and depth of understanding remained to be established. The building of this intuitive grasp was also slow because it was then necessary to explore theories without the use of large, high speed digital computers.

One of the first concerns about the safety of nuclear reactors therefore was that accidents might occur with the effects of an atomic bomb. The first experimental programs on reactor safety addressed these possibilities. In a test at the Argonne National Laboratory, scientists destroyed a small research reactor by rapidly ejecting the control elements from its core.[1] A long series of experiments with other simple reactors at the National Reactor Testing Station near Idaho Falls, Idaho, systematically probed the causes and results of the destruction of small research reactors.[2] These were called the Special Power Excursion Reactor Tests (SPERT). In a number of these tests the sudden increase in reactivity approached a level which could damage the reactor. In final tests, this addition of reactivity was large enough and rapid enough to destroy the reactor.[3]

One set of SPERT tests used a reactor core of slightly enriched uranium oxide rods in stainless steel tubes. Although this core resembled that of a commercial pressurized water reactor, there were important differences. The final test in this series involved the rapid addition of enough reactivity to destroy the core, at least in principle. The effects were, however, relatively mild. A few of the weakened fuel rods burst and expelled their uranium oxide into the surrounding water. This led to a large and rapid decrease of reactivity that stopped the whole process without real violence. These tests, however, were never carried far enough to determine whether the same mitigation would occur in a reactor core more nearly like that of a commercial reactor.

More information on the effects of the rapid addition of reactivity was obtained in an unfortunate way, through an accident at the SL-1 experimental reactor at the National Reactor Testing Station.[4] Three men were killed, and the reactor was ruined. The reactor had been built from a flawed design which permitted a large amount of reactivity to be added accidentally. Though extensive investigation has never revealed the exact sequence of events in the SL-1 accident, it is clear that one of the three operators present caused the accident by rapidly removing a central control rod by hand. A burst of fission occurred, destroying the reactor and shutting down the reaction. The sudden generation of steam shot some control rods out of their guide tubes into the air. The operator who initiated the accident was apparently killed by a control rod acting as a missile. The other two operators were apparently killed by the burst of radiation.

In the early 1960's, it was becoming clear that the early concerns as to possible bomb-like accidents were unfounded. Although it was possible to make reactor cores destroy themselves with some violence, the level of violence was always relatively low, far below anything resembling that of

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1. J.R. Dietrich, *Experimental Determinations of the Self-Regulation and Safety of Operating Water-Moderated Reactors, reprinted in* 13 PROCEEDINGS OF THE FIRST INTERNATIONAL CONFERENCE ON THE PEACEFUL USES OF ATOMIC ENERGY 88, 98-99 (1956).

2. *See* W.E. Nyer & S.G. Forbes, *SPERT I Reactor Safety Studies, reprinted in* 11 PROCEEDINGS OF THE SECOND UNITED NATIONS INTERNATIONAL CONFERENCE ON THE PEACEFUL USES OF ATOMIC ENERGY 470-80 (1958).

3. *See* T.J. THOMPSON & J.G. BECKERLEY, 1 THE TECHNOLOGY OF NUCLEAR REACTOR SAFETY 682-85 (1964).

4. *See id.*, at 653-82.

atomic weapon. Theoretical analysis had shown that this difference in explosiveness is a fundamental feature of reactors as opposed to bombs. The two simply work on very different time scales. An atomic bomb or a hydrogen bomb completes it action in about one millionth of a second, liberating between 10^{14} and 10^{16} joules of energy[5] in the process. A violent excursion of power in a nuclear reactor may take one thousand times as long and liberate one million to one hundred million times less energy than an atomic bomb. These are the most important differences, though other factors of a more technical nature also contribute to the lower severity of a nuclear power plant excursion. These fundamental facts underlie the modern realization that nuclear plants cannot become atomic bombs.

III

Severe Damage from Other Causes

To understand the most important issues of reactor safety, it is necessary to comprehend the significance of the fission products, the atomic cinders of the fission process. As mentioned above, most fission products are radioactive, and their radioactivity diminishes with time. A thick shield of concrete protects those nearby from the radioactive fission products and from the fission process itself.

One of the early safety committees of the old Atomic Energy Commission, a predecessor of the current Advisory Committee on Reactor Safeguards, invented the first protective measure against the accidental release of fission products. This committee recommended the construction of a special, leak-tight building around the experimental submarine reactor prototype that was then being built near Schenectady, New York.[6] This structure was a tight steel sphere. It was the world's first containment building, the precursor of those currently built around all reactors in the United States and in many other countries.

Concern for reactor safety inspired the use of full containment. Lacking experience with nuclear reactors, the safety committee could neither conclude that there was no chance of fission products escaping in an accident nor estimate what kinds of accidents might cause such a release. Erring on the side of caution, the committee demanded a tight building as a backup measure to contain the fission products in case they were not retained by the reactor. This early application of precautionary engineering was to be invaluable at the Three Mile Island II reactor some twenty-five years later, where a sophisticated containment building that had descended from the structure near Schenectady protected the people around Harrisburg, Pennsylvania.

5. A joule is the absolute mks (meter-kilogram-second) unit of energy equal to 10^7 ergs or approximately 0.2390 gram calories (0.7375 foot-pounds) when the point of application of a force of one newton is displaced through a distance of one meter. S. Dresner, Units of Measurement 57 (1971).

6. U.S. Atomic Energy Commission (classified document).

As the nuclear industry developed, containment buildings were made stronger. They were built to withstand very high internal pressures without rupturing, and cooling systems were added to protect against accidents that might generate very high temperatures. Modern containment structures are made of thick, reinforced concrete with inner liners of steel.

The first nuclear power plants in the late 1950's and the early 1960's were experimental, and many designs were used. The reactor designers also incorporated a number of ideas for backup protection from accidents in addition to containment. For example, reactor designers began to add engineered features to provide backup cooling in case of accidents and to prevent the reactor core from melting. The Advisory Committee approved these new methods of insuring reactor safety. The plan was to wait and see how these new designs worked and then to determine their efficacy.

In 1967 and 1968 there were intensive studies of the potential consequences of a melt-down.[7] These reviews were conducted with great urgency because utilities were beginning to order nuclear power plants in great numbers. It was important to understand this new safety question before all the new plants came into existence.

It was soon realized that if much of the reactor core were to melt, cooling it might be difficult. If the heat could not be removed, the core would remain molten, and it would in time melt its way through the bottom of the thick steel vessel in which it was to be housed. It would then fall or drip onto the floor of the reactor building. An accumulation of molten core debris on the floor would steadily increase in temperature and melt into the floor of the building. With the passage of time, the rate of heat generation by fission products would diminish, and the radioactive puddle would become more and more dilute with other molten matter. As a result, the melting would stop. But it was unclear in 1969 whether the process would stabilize before the base pad, which is about fifteen feet of reinforced concrete, would melt or whether it would penetrate into the subsoil before stopping. It is still unclear. This scenario was facetiously named "the China Syndrome," a term that became popular a few years later.

There were also concerns as to what might happen if the molten core were suddenly to come into contact with large amounts of water. There have been industrial accidents in steel mills in which the molten contents of large furnaces or ladles have suddenly fallen into pools of water; sometimes this resulted in a severe "steam" explosion. If steam explosions were to occur in the reactor vessel or in the containment building, then they could conceivably cause a breach of containment.

It was then realized that backup cooling systems were essential design features, and not merely supplemental. As a result, in 1970 new regulations

7. An inspiration for these studies was a controversy concerning the validity of a 1957 AEC study of potential major accidents at commercial nuclear power plants. U.S. ATOMIC ENERGY COMMISSION, THEORETICAL POSSIBILITIES AND CONSEQUENCES OF MAJOR ACCIDENTS IN LARGE NUCLEAR POWER PLANTS, WASH-740 (1957). *See generally* D. OKRENT, NUCLEAR REACTOR SAFETY 98-102, 107-11 (1981).

set out interim criteria which emergency core cooling systems (ECCS) were required to meet.[8] Those requirements, however, were based on decisions made rapidly against a background of imperfect understanding.

This led to one of the most traumatic events in the history of nuclear power regulation, the Atomic Energy Commission's convening of the Emergency Core Cooling Hearings of 1972-1973. This long series of public hearings generated a record of over 20,000 pages of transcript and even more of documentation.[9] In the course of the hearings, many earnest and informed scientists at AEC laboratories expressed reservations about the interim acceptance criteria. Critics did not attack the propriety of the interim criteria, but simply questioned whether their adequacy had been sufficiently established given the importance of nuclear power plant safety.

After the hearings, the Commission issued its conclusions, instructing the regulatory staff to rewrite the ECCS criteria to incorporate all of the principal reservations expressed during the hearings. The Commission also made a public commitment to strengthen its program of research in reactor safety, a program that now has a budget nearly ten times as large as it did in the early 1970's.

The national laboratories, a number of universities, and some industrial organizations participated in a program to resolve the questions raised during the Hearings on Emergency Core Cooling. This activity has shown that the treatment of emergency core cooling which the AEC mandated in response to the hearings was conservative. That is, where it erred, it erred on the side of caution. This was not a formal conclusion, but I believe it is now the almost universal view of the research community that has followed the developments in the intervening years.

In the meantime other questions have arisen. In 1974, the Atomic Energy Commission issued a draft document called *The Reactor Safety Study,* sometimes called the Rasmussen Report.[10] This voluminous study, full of facts and analysis, attempted to determine the probability and consequences of large reactor accidents. The consequences considered were death from radiation (either through acute radiation effects or through delayed incidence of cancer), genetic effects, and property damage.

The main conclusions of the *Reactor Safety Study* were surprising to workers in the field. Large accidents involving a reactor core melt-down were much more likely than had been believed, but their consequences were

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8. General Design Criteria for Nuclear Power Plants, 36 Fed. Reg. 3,255 (1971). *See generally* 10 C.F.R. § 50, app. A (1981) (Design Criteria as amended at 36 Fed. Reg. 12,733 (1971)); 41 Fed. Reg. 6,258 (1976); and 43 Fed. Reg. 50,163 (1978).

9. U.S. Nuclear Regulatory Commission, Acceptance Criteria for Emergency Core Cooling Systems for Light Water Cooled Nuclear Power Reactors, RM-50-1 (1973).

10. U.S. Nuclear Regulatory Commission, Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, NUREG-75/014, WASH 1400 (1975).

not as severe as previously considered. In short, the study predicted that nuclear power plant accidents causing deaths in their vicinity were highly unlikely. In round numbers, the *Study* concluded that an accident causing extensive injuries and deaths could be expected to occur during a period of one thousand to one million years of operation of a reactor, and an accident that kills more than three thousand people could be expected to occur in one billion years of operation of a reactor.[11]

The *Reactor Safety Study* has been highly controversial. Some believe that probabilities as small as those estimated in the *Study* cannot be meaningful. Some believe that assumptions used in the analysis were wrong. In contrast, others believe that the *Reactor Safety Study* is almost as good as revealed truth.

About three years ago the NRC formed a small committee of scientists to review the *Reactor Safety Study*. This group, of which I was a member, was chaired by Dr. Harold Lewis of the University of California at Santa Barbara. Our final report to the Commission found that the *Study* was not very readable, that some of the calculations were faulty, and that the data used in its analysis were not ideal.[12] Although we could not decide whether reactors were more or less safe than the *Study* had concluded, our principal conclusion was that the mathematical uncertainty of those estimates was larger than the *Study* had indicated. We also found that the executive summary issued with the *Study* was badly written and that it should have been issued separately with another title because it was not really an executive summary. But we also noted that the *Reactor Safety Study* was the best tool of its kind and that its methods should be applied where they were most appropriate and most valid.

As a result of our report, the Commission discontinued circulation of the executive summary and severely criticized the *Study*. Most of us on the Lewis Committee were appalled by this reaction, because despite the *Study*'s defects we thought it was a remarkably good piece of work in many ways. More recently, the Commission has effectively withdrawn much of its condemnation and is utilizing probabilistic risk assessments in many contexts. In fact, the Commission's use of probabilistic risk assessments may now be too extensive.

But the real importance of all of these developments is the insights that the *Reactor Safety Study* and its successor analyses have given us. It became clear that a loss of coolant accident caused by a rupture of a large pipe is not the most likely risk. The failure of smaller pipes is more likely. But even though the effects are probably less dangerous if small pipes break, the higher probability overrides the lesser consequences. It was also found that transient effects, such as those following an extended loss of electric power, contribute more to risk than large pipe breakages. Analyses have also

11. *Id.*, Executive Summary at 9-10.

12. Risk Assessment Review Group, Report to the Nuclear Regulatory Commission, NUREG/CR-0400 (1978).

revealed poor design features in operating and nonoperating plants. These problems are not severe enough to cause us to lie awake nights, but they are matters that need correcting. Some weaknesses found in plants by the original *Reactor Safety Study* were soon corrected, and the process of improvement is still underway.

The Three Mile Island accident raised a different type of problem for the nuclear industry. To say that it was a severe blow to the industry is an understatement. The accident did not kill anyone, and it is unlikely that there will be any human medical impact, either observed or unobserved. The reason for this is in part the containment building, which retained the fission products just as the old safety committee had planned. Other chemical factors also reduced the release of radioactive material to very low levels.

The nuclear industry has expressed relief over the lack of human injury, but the final cost of the accident is staggering. No utility wishes to be faced with an appreciable chance of a similar accident and its effects, and such an accident could ruin a small utility. Life in the nuclear power field will never be the same after Three Mile Island, but it is still unclear how it will affect the economics, operations, and even safety of nuclear power in the future.

How safe are reactors now? Certainly the general level of reactor safety is higher than it was two or three decades ago. Some of the deepest concerns have diminished or been dispelled. We have had many hundreds of reactor years of operating experience with commercial nuclear power plants without an accident that has injured anyone. That is a remarkable record for a new, complex technology. The accident which killed three people and largely destroyed a research reactor may have increased overall safety through the lessons it taught us. On the other hand, there are nuclear power plants in operation and under construction which do not embody the level of safety that I consider satisfactory. Measures must be taken to correct this situation.

IV

Nuclear Explosives and Safeguards

Officials once believed that secrecy would preclude other countries from obtaining nuclear explosives. The United States was shocked in 1949 when the Soviets tested their first atomic bomb and tended to blame Soviet success on espionage. Since then, the United Kingdom, France, China, and India have achieved nuclear capability, and many believe that other countries are seeking to or have already learned to build nuclear weapons without testing. We never exclusively owned "the" secret or any secret for nuclear weaponry.

It has been an objective of the United States since the beginning of the nuclear age to discourage the spread of nuclear weapons capability. In 1950 there was a "third nation problem." In 1954 there was a "fourth nation problem," since the United Kingdom had become the third. In 1959 there was an "n^{th} nation problem," France having become the fourth. And there still is an n^{th} nation problem. The controversy now involves Pakistan and South Africa.

The United States has consistently used political means to slow or to prevent the spread of nuclear weapons capability. Such a policy is like trying to prevent sin in Eden after news of the apple has gotten around. But so far, despite the failures just referred to, the policy has worked fairly well. Many other countries would have nuclear explosives now if nothing had been done to discourage their spread.

The first move of the United States was the Baruch proposal,[13] under which it would have relinquished its nuclear weapons primacy for a regime of international ownership of fissionable material. This proposal was repeatedly rebuffed by the Soviets, who realized that we would still have a tested weapons capability. Following this, in a speech before the United Nations in 1953, President Eisenhower proposed the formation of the International Atomic Energy Agency (IAEA) to oversee the transfer of fissionable material from one country to another.[14] The IAEA would own all nuclear material and could inspect to ensure that fissile material transferred to a non-weapons country would not be diverted to weapons use. In return for this control, the nations providing the material were also to share their nuclear technology for peaceful purposes.

In 1970 the Nuclear Non-Proliferation Treaty became effective.[15] Most nations of the world have now signed. The non-weapons countries that signed agreed not to make nuclear weapons and to permit the IAEA to inspect all of their nuclear material. The weapons countries promised not to assist non-weapons countries to develop nuclear weapons and to share peaceful nuclear technology. Since then, the United States and the United Kingdom have also agreed to place their peaceful nuclear activities under IAEA safeguards, though this of course did not affect their weapons capacity. The list of non-signatory nations is more interesting than the list of signatories: Israel, most Arab countries, Pakistan, India, South Africa, Spain, Brazil and Argentina, among others. This list includes most countries that are believed to have nuclear ambitions and some that are believed to have already acquired nuclear weapons.

Will the Non-Proliferation Treaty prevent further spread of nuclear weapons? I doubt it. What can be hoped for is that the Treaty will continue to retard the process. This pathway for preventing proliferation was once more promising than it is now. The United States had an unchallenged position of leadership in all aspects of nuclear power, and it was constantly expected to act accordingly. Its views were actively sought and listened to. In the past few years its position of leadership has eroded and other countries have assumed much of its former technical leadership.

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13. *See, e.g.,* N.Y. Times, Dec. 17, 1946, at A4; N.Y. Times, Jan. 5, 1947, at 1.
14. 8 U.N. GAOR (470th meeting) par. 79, U.N. Doc. A/PY.470 (1953).
15. Treaty on the Non-Proliferation of Nuclear Weapons *effective date* March 5, 1970, 21 U.S.T. 483, T.I.A.S. No. 6839, 729 U.N.T.S. 161.

The real danger, of course, lies in the nuclear arsenals of the United States and the Soviet Union. Those arsenals seem to grow uncontrollably in size and destructive ability. Even the Strategic Arms Limitation Treaty sets the level of arms higher than before. Until this process ends and reverses, there is no firm moral platform from which the United States can dissuade countries that seek to equal us in power. I think it would be a mistake to reduce arms unilaterally. But the attitude of the United States must change; each superpower cannot be more powerful than the other.

The nuclear weapons controversy, however, has nothing to do with commercial nuclear power. Every country that has nuclear power plants and nuclear weapons has kept the two activities separate. No country has yet used its civilian power program to develop nuclear weapons because this would be an inferior method.

Fortunately, it is not as easy to make a nuclear explosive as some commentators suggest. It is easy to say that it is easy, and it is even easy to make drawings with associated calculations that resemble aspects of nuclear explosives. But their actual manufacture requires tremendous resources and a great deal of knowledge. This can be illustrated by the following example from the international field. A poor nation like Pakistan can set a national goal of building nuclear weaponry, and with concentration of resources, help from others, and passage of time it can succeed. But this is very different from casual construction in someone's cellar. The national effort in Pakistan has been underway for about seven years but has not yet succeeded.

There have already been thirty-five years of nuclear weapons and twenty-five years of commercial nuclear power, and the United States has not become a police state as a result. I can discern no such trend among any of the countries that have adopted nuclear power. Normal vigilance against abuses and usurpations by the state should work now as effectively as it has throughout American history.

V

Conclusion

There are few definitive answers to the myriad questions which nuclear power raises. First, to set up a straw man: Is nuclear power safe? Nothing is safe in an absolute sense, and nothing is unsafe in an absolute sense. Safety should be thought of quantitatively. One thing can be less safe than another, or it can be safer than another. But it is not absolute.

There are risks in nuclear power, and I have explicated some of them. Some believe that these risks are too great, but I do not. When I compare nuclear power with the alternatives, it seems less risky. If people would stop fearing nuclear power and start fashioning solutions to the problems that concern us, then it may become the energy source that it was once considered to be.