UNITED STATES OF AMERICA
NUCLEAR REGULATORY COMMISSION

BEFORE THE ATOMIC SAFETY AND LICENSING BOARD

JAN 17 1983
Office of the Sec.
& Serv.
Branch

In the Matter of

THE REGENTS OF THE UNIVERSITY
OF CALIFORNIA

(UCLA Research Reactor)

Docket No. 50-142

(Proposed Renewal of
Facility License)

DECLARATION OF DR. THEODORE B. TAYLOR

I, Theodore B. Taylor, declare as follows:

1. From 1949 to 1956 I worked on the design of nuclear explosives at the Los Alamos Scientific Laboratory. From 1956 to 1964 I worked at the General Atomic Division of General Dynamics Corporation, during which period I helped design the TRIGA research reactor. From 1964 to 1966 I was deputy director (scientific) of the Defense Atomic Support Agency in Washington. The following years have been spent as an independent consultant to the U.S. Atomic Energy Commission and a number of other organizations, working on nuclear safeguards issues and other energy-related matters. I served on the Presidential Commission on the Accident at Three Mile Island. I am co-author of Nuclear Theft: Risks and Safeguards, as well as a number of other books and articles dealing with nuclear safeguards and related subjects. A more detailed statement of my professional qualifications is attached hereto.

2. It is my understanding that the University of California, as part of its license renewal application for the UCLA Argonaut-type research reactor, has requested a Special Nuclear Materials license to possess Highly Enriched Uranium (HEU). I understand that the initial request was for 9400 grams of uranium-235 at 93% enrichment, but that it has since been amended to 4999 grams at the same enrichment.

3. Barring some extraordinary circumstance of which I am unaware, it is my opinion that UCLA's request for kilogram quantities of HEU should be denied. I know of no reason that could justify the unique safeguards risks associated with grant of a license to UCLA for materially so internationally dangerous. I come to this conclusion as a former designer of both nuclear weapons and research reactors, and from extensive involvement in the field of nuclear safeguards. The basis for this conclusion is as follows.

4. Uranium enriched to 93% in the isotope ^{235}U is weapons-grade. It is weapons-grade because it is directly usable in nuclear weapons without any further isotopic enrichment.

5. Because it is weapons-grade material, 93% enriched uranium is a potentially attractive target for theft or diversion by terrorist groups or nations intent on acquiring nuclear weapons. The potential consequences of such theft or diversion are very grave.

6. A group or nation capable of making nuclear weapons from 93% enriched uranium would not have any significant difficulty in separating the uranium from the uranium-aluminum eutectic in which it is found in flat-plate MTR-type research reactor fuel. The methods for doing that are widely published and fairly straightforward.1/

7. Such a national or subnational group would also not have substantial difficulty in removing the uranium from MTR-type research reactor fuel that had been irradiated sporadically in a low-power reactor (e.g., a few hours per week at a maximum power of 100 kw_{th}). It is more difficult than separating the uranium from unirradiated fuel plates, but it is something that could be done with techniques that are widely published. If the safety rules are compatible with a high degree of military urgency to obtain the uranium for weapons purposes, then the fact that the fuel contained some fission products would not get in the way very much.

1/ One such simple method is described on page 97 of John McPhee's The Curve of Binding Energy, Random House, NY, 1973, 1974, attached.

8. Furthermore, the fact that some of the HEU at UCLA might be in the form of irradiated fuel, either in the core or in storage holes, while other material was in the form of fresh fuel in separate storage, would be little if any deterrent to theft of all the material. Dose rates far in excess of what the UCLA reactor appears capable of routinely producing in its fuel bundles would be necessary, in my opinion, for the fuel to be "self-protecting." If the calculations in Dr. Roger Kohn's September 4, 1982, declaration are correct, fuel bundles in the UCLA reactor drop below 100 rem/hour (at three feet from any accessible surface without intervening shielding) after just 8 hours of shutdown, below 34 rem/hour after one day, and apparently down to a few rem per hour after a shutdown or storage period of a few weeks. If correct, and assuming that the reactor operates only a few hours per week, neither irradiated fuel in storage nor in the core would be self-protecting and would be little deterrent to dedicated individuals or groups intent on acquiring nuclear weapons material.

9. To assert that the nearly 5000 grams of uranium-235 at 93% enrichment in the form of uranium-aluminum flat plate fuel, as requested by UCLA, would be of no interest to someone intent on manufacturing a nuclear weapon would be simply incorrect. It is, in my opinion, a credible threat that people might break into a research reactor facility such as UCLA's in order to acquire HEU. Particularly if one supposes a blackmarket and people selling stolen HEU at, say, a hundred thousand dollars per kilo.

10. It is my opinion that the original request for 9400 grams of uranium-235 was excessive. It is my opinion that the current request for 4999 grams is also excessive. Anything more than a kilogram, in my opinion, would be clearly excessive. From a proliferation standpoint there should be a significant burden upon the University to demonstrate that it could not perform the functions for which the reactor was intended without the requested highly enriched uranium. I would say that even more broadly: highly enriched uranium should not be used in quantities more than a few hundred grams under any circumstances unless there is an absolutely compelling reason to do so. I know of no such reason that would be relevant to the UCLA reactor.

11. It is my opinion that the enrichment requested by UCLA (93%) is excessive. For general use, for research, the only advantage in going from 20% enriched uranium to 93% enriched uranium is that the neutron flux may increase somewhat, at the same power level. I don't know what that increase in flux is for this specific reactor, but it is very hard to imagine that it would change significantly the nature of the experimental program they would carry out with it if the enrichment were reduced. Everybody wants to have all the neutrons they can get, but UCLA has already limited itself, by limiting the reactor to 100 kilowatts, and if they wanted more neutron flux they might go to 120 kilowatts, for example. One is talking about not anywhere near doubling the flux by increasing the enrichment.

12. 4.9 kilograms of uranium-235 in 93% enriched form would have, by far, greater potential consequences if stolen than an equal or even somewhat larger amount of uranium-235 in 20% enriched fuel. The critical mass of fully enriched uranium in metallic form with an ordinary reflector is roughly 20 kg. It depends on what the reflector is. With a more efficient reflector, the critical mass is considerably less. For example, critical mass with a thick reflector made of beryllium is approximately 11 kg of uranium-235.[2] For 20% enriched uranium in metallic form with an ordinary reflector, the normal density critical mass of contained uranium-235 rises to over 50 kg. It is possible to make a nuclear explosive with 20% enriched uranium but it would be very heavy, very inefficient and difficult to handle. You would need approximately three times as much uranium-235 in the 20% enriched form as you would in the 93% enriched form in order to make a critical mass, but more important than that is the fact that you would be dealing with three times five or fifteen times as much uranium, which is harder to move, harder to compress, much harder to move, much harder to compress.

2/ These figures are for the critical mass of uranium-235 at normal density. When compressed, the critical mass is considerably less. As I wrote in Nuclear Theft: Risks and Safeguards (Ballinger, Cambridge, Mass., 1974) at p. 20 (attached): "If, on the other hand, the material is to be used in an implosion type of fission bomb, the amount required may be significantly lower than these quantities. Materials that are compressed above their normal densities have a lower critical mass than when they are uncompressed. In the special case when both the core and the reflector are compressed by the same factor, the critical mass is reduced by the square of that factor. Thus, when a spherical core and reflector assembly that is initially close to one critical mass is compressed to twice its initial density, it will correspond to about four critical masses." The maximum compression achievable in an implosion type fission weapon, and thus the minimum amount of uranium necessary to make such a weapon, depends upon the knowledge, skill, equipment and facilities of the bomb maker.

JBT 12/16/8

13. The potential consequences of theft of 4.9 kilograms of 93% enriched uranium would thus, in general, be considerably greater than those arising from the theft of a single kilogram at 20% enrichment. Comparing 4.9 kilograms with one kilogram, both at 93% enrichment, however, in some circumstances the consequences might not be very different, those circumstances being if someone simply needed one kilogram to supplement an amount already obtained or if they needed or wanted some highly enriched uranium, for example, to send to the threatened authority in some kind of blackmail threat to make them take them more seriously. To send a few grams would be so relatively easy to do that it might not have much effect on the credibility of the threat. To send a kilogram begins to be quite significant and they can simply say we haven't sent you more because, as you know, that is a significant fraction of the total amount we would need. We just want you to know we have kilogram quantities of this material and here is a kilogram. So, in that restricted arena of types of threats, the difference between one kilogram of 20% enriched and several kilograms of 93% enriched is not very much. So far as what is necessary to make a bomb there is a great deal of difference between those numbers.

14. Therefore, in my view, a request by an institution such as UCLA for nearly five kilograms of highly enriched uranium would be excessive unless there is some overriding reason that I cannot imagine, some reason involving national defense research, and even then I know of no such research which would require HEU fuel for such a reactor. There is no crucial research at university reactors of which I am aware that would require weapons-grade uranium. I would say, in fact, that for uses of any kind, any quantity of HEU would be excessive. I say that because even in gram quantities there should be a special reason why people must have it because that material in gram quantities could be extremely helpful to people making a threat. Which might not necessarily be a hoax. It just reduces the amount of material they need in order to make a bomb, and also establishes credibility for a threat.

15. I have been informed that the original Argonaut reactor operated on 20% enriched fuel and that a number of other Argonauts have likewise operated on 20% enriched fuel. Assuming that that is correct, I know of no reason--and find it hard to imagine one--why UCLA's Argonaut reactor should not likewise operate on 20% enriched uranium. I have also been informed that

University of Florida's Argonaut reactor was to be involved in testing some 4.8% enriched uranium oxide fuel. Assuming that that also is correct, that kind of fuel would likewise seem to me as something worth pursuing for other Argonaut reactors such as UCLA's because it is even further away from weapons material.

16. I have also been informed that General Atomic currently has available low enriched TRIGA fuel for conversion of research reactors presently utilizing highly enriched MTR-type plate fuel. I would view conversion of the UCLA reactor to low enriched TRIGA fuel as a favorable alternative to the granting of the request for highly enriched uranium because it is much more difficult to make weapons of any kind out of lower enrichment uranium and the compromises in neutron flux, which I think is the main concern, are not large, if present at all.

17. Besides significant safeguards advantages in making a conversion to low-enriched TRIGA fuel, there would also be significant safety benefits. There certainly was a major safety benefit in the TRIGA fuel when we designed it and the TRIGA reactor.3/ The main feature is a very strong prompt negative temperature coefficient, much higher than other research reactors, which meant that even if it went prompt critical the rise in temperature would extremely rapidly stop the chain reaction. That still stands. There is, of course, a level of excess reactivity above which that safety feature of not being able to damage any of the fuel with an accidental excursion is no longer true, and you can always make it over-critical by design, to make it not have that self-limiting feature, but I don't see any excuse for doing it with any medium power research reactor, up to a megawatt at least.

18. The level of excess reactivity at which the prompt negative temperature coefficient ceases to be an effective self-limiting feature would be much, much higher for a TRIGA reactor or a reactor with TRIGA fuel than for the Argonaut with MTR-type fuel. At comparable levels of excess reactivity,

---

3/ A good description of the origins, intent, and basic operating principles of the TRIGA and its fuel can be found in Freeman Dyson's Disturbing the Universe (Harper & Row, NY, 1979), pgs. 94-102, attached.

the TRIGA fuel would definitely have significant safety advantages.

19. The difference in the TRIGA fuel is due to the fact that when the ratio of captures (in the water and other materials) to fissions (in the fuel) goes up, the reactivity goes down. That effect is produced by a change in temperature in the fuel itself, relative to the cooling water, and thus requires no heat conduction. It happens instantaneously because the heat is liberated by the fission reaction right in the fuel. In MTR-type research reactors the heat has to be transferred to the water, which takes a while, to make it expand. It is the expansion of that water plus some other effects that have to do with the water having to heat up that makes the reactivity go down. Because of this time-delay involved with the transfer of heat from the fuel meat to the water in MTR-type reactors, the shutdown mechanism is slower, permitting greater energy release before shutdown for an excursion of the same exponential period and a greater opportunity for fuel melting to occur before the excursion terminates than is true with the TRIGA.

20. That shutdown mechanism in the MTR-type reactors, requiring transfer of the heat to the water to cancel the reactivity, can produce effects in the water like boiling or a sudden expansion of the coolant which can, in effect, do some damage, even if fuel melting does not occur. The likelihood of there being changes in the fuel arrangement or in the grid supports or whatever is less for the TRIGA than for the Argonaut, according to the comparative designs when I knew about them. I was familiar with the Argonaut design at the time we designed the TRIGA.

21. In addition to the TRIGA fuel having a negative temperature coefficient that is far more prompt (i.e., it comes into play much faster), the size of the negative coefficient is also far larger, so the excursion is terminated much sooner, providing substantial additional protection against fuel melting.

22. The conversion to lower enriched uranium fuel, be it TRIGA fuel or flat plate fuel, would likely increase the negative temperature coefficient because of another factor, the Doppler effect. I can't be absolutely sure there aren't some compensating factors, but the Doppler broadening coefficient contribution to the temperature coefficient will go up and I don't know of any reason why other things would happen to make it go down.

23. A reduction in enrichment of the fuel can thus decrease the possibility or consequences of a destructive power excursion or criticality accident. Low enriched fuel has a contribution to limiting an excursion, an abating effect, that is the cancelling out of the reactivity because of the increased capturing by uranium-238. I can't make the blanket statement that for any reactor design that it would be safer; it would be dependent upon a given change in the reactivity.

24. I understand that UCLA has, in addition to requesting HEU, requested a license for 32 grams of plutonium-239 in a plutonium-beryllium neutron source, and that when the reactor was first constructed the Pu-Be source was requested as a start-up source but was soon replaced with a millicurie radium-beryllium source because the Pu-Be was too strong a source for the intended use. If this is true, I think it would be irresponsible not to ask UCLA whether they still have a significant need for that plutonium and to have a fairly detailed set of criteria on which to base a judgment as to whether to grant the requested license for the material.

25. I would have security concerns about a 2 curie plutonium source, not in terms of anything like the security that one would argue for regarding kilogram quantities of plutonium or highly enriched uranium, but I would want to restrict access to it fairly severely. Two curies is a large source. It can be used in a threatening way. Under certain circumstances it might be used to distribute radioactivity.

26. In <u>Nuclear Theft: Risks and Safeguards</u>, relevant portions[4] of which are attached hereto as an exhibit, Mason Willrich and I discussed the potential consequences of use of a few grams of plutonium-239 as a radiological weapon[5]:

> We have already stated that plutonium, in the form of extremely small particles suspended in air, is exceedingly toxic. The total weight of plutonium-239 which, if inhaled, would be very likely to cause death by lung cancer is not well known, but is probably between ten and 100 micrograms (millionths of a gram). Even lower internal doses, perhaps below one microgram, might cause significant shortening of a person's life. The total retained dose of plutonium that would be likely to cause death from fibrosis of the lung within a few days is about a dozen milligrams (thousandths of a gram). . . .

---

[4] chapters 1, 2, 6. and 7, which address both the issue of plutonium as a potential radiological dispersal weapon and HEU as potential material for a clandestine fission explosive.

[5] quoted from pages 24-26

> In terms of the total weight of material that represents a lethal dose, plutonium-239 is at least 20,000 times more toxic than cobra venom or potassium cyanide, and 1,000 times more toxic than heroin or modern nerve gases. It is probably less toxic, in these same terms, than the toxins of some especially virulent biological organisms, such as anthrax germs.
>
> The amounts of plutonium that could pose a threat to society are accordingly very small. One hundred grams (three and one half ounces) of this material could be a deadly risk to everyone working in a large office building or factory, if it were effectively dispersed. In open air, the effects would be more diluted by wind and weather, but they would still be serious and long-lasting.

27. In Nuclear Theft, we calculated the area in square meters that could experience lethal inhalation doses and the area that could experience significant contamination requiring some evacuation and cleanup, given release of different quantities of plutonium-239. Based on these calculations, release of 32 grams of plutonium-239 could create lethal doses throughout 16,000 square meters of building and significant contamination requiring some evacuation and cleanup of 1,600,000 square meters. (This assumes release of the material in the form of an aerosol of finely divided particles uniformly in air throughout the building and one hour exposure.) By comparison, we indicated in Nuclear Theft that 500 square meters corresponds to the area of one floor of many typical office buildings and 50,000 square meters is comparable to the entire floor area of a large skyscraper. We concluded: "Even a few grams of dispersed plutonium could pose a serious danger to the occupants of a rather large office building or enclosed industrial facility."

28. The situation for dispersal out-of-doors would be somewhat different. We said in Nuclear Theft: "The dispersal in large open areas of plutonium with lethal concentrations of radioactivity is likely to be much more difficult to carry out effectively than dispersal indoors. . . . With a few dozens of grams of plutonium, however, it would be relatively easy to contaminate several square kilometers sufficiently to require the evacuation of people in the area and necessitate a very difficult and expensive decontamination operation." We said further: "After the plutonium-bearing particles settled in an area, they would remain a potential hazard until they were leached below the surface of the ground or were carried off by wind or surface water

drainage. . . . Thus, in an urban area with very little rainfall, a few grams of plutonium optimally dispersed out of doors might seriously contaminate a few square kilometers, but only over a very much smaller area would it pose a lethal threat." And we determined that "[a] variety of ways to disperse plutonium with timed devices are conceivable. These would allow the threatener to leave the area before the material is dispersed. Any plutonium contained inside such a device would not be a hazard until it was released."

29. Thus, 32 grams of plutonium-239 can be used in a threatening way, with significant radiological consequences. On the other hand there are lots of other things around universities that can be used in threatening ways too. And I have never come to a clear set of decisions about what to do about gram quantities of plutonium. 2 curies of plutonium-239 is a lot of radioactive material, with a half life that is long enough to be important, and it should be looked after carefully. Whether security for it should be better or not as good as security for some cultured viruses in a bacteriological laboratory, that I can't answer. I would say, however, that because there is a radiological hazard involved with the potential use of such a plutonium source as a radiological weapon, unless there is a strong reason for UCLA to have it, it would be an unnecessary hazard.

30. In terms of what kind of security would be sufficient to satisfactorily minimize the risk of theft or diversion of 4.9 kg of HEU, consistent with the potential consequences of its theft, I would say that it should not be possible for a group of people that are quite knowledgeable about security and how to defeat it to describe to a group of experts a credible scenario for stealing the material. In other words, I'm thinking in terms of a sort of jury situation, with people who are professionals in one way or another in knowledge of security, thefts, and how they get carried out. I would say that security would be adequate if, and only if, such a group of people could not be presented with a theft plan that they thought had a reasonable chance of working.

31. I would say that an almost exclusive reliance on intrusion alarms tied into a campus police station would absolutely not be adequate in my view, because that does not say anything about the ability of the campus police to effectively intercept people carrying out the theft. Now, if it happens, if there were an intrusion alarm, between the point of entry and the material, and such physical barriers in between that they couldn't be credibly penetrated until the campus police and a little force had gotten there, then I would say that would be effective. But by definition I'm saying that there is something more than an intrusion alarm, that is, barriers, very heavy containers or equivalent, something that would create a physical delay of some significance, greater than the time that there would be an assurance of getting protective people there. When I say protective people, I do not mean simply one or two watchmen checking in but a force capable of doing something to successfully prevent the theft. To argue that detection of the theft or post-theft reporting would be sufficient would be, in my opinion, highly irresponsible and not at all consistent with the potential consequences of theft of 4.9 kg of HEU, consequences which could be very, very significant. Failure to adequately protect against theft, rather than merely being able to detect and report theft, would be unconscionable.

32. If 4900 grams of uranium-235 at 93% enrichment in uranium-aluminum fuel plates were stolen, I would view that as having extremely significant potential consequences, simply because of the fact that it was being stolen. What I mean by this is that it is no longer a hypothetical question. When it has actually happened, it means that some people have gone to the trouble to steal that material. Having done so, it could be entering the black market, it could be joined with other materials which are on the black market, it could go in the direction of being the start of the construction of weapons. I would say that if I heard that there are 4.9 kilograms of highly enriched uranium that had been stolen, I'd be extremely concerned. That would have international implications of great importance.

Conclusion

29. I would say in conclusion that an application for a license to use highly enriched uranium in quantities more than a few grams should put the burden of proof on the applicant to make it very clear that it is truly necessary to use HEU as opposed to using 20% or less enriched uranium. I have not seen that case made at UCLA. I suspect that case has not been made by a number of other installations that have the same material. The reason why this is so important is that this material can be used for making nuclear weapons, and the hazards of nuclear weapons being produced do not necessarily disappear if the quantities themselves are not sufficient to make one nuclear weapon, because these sources could be pooled.

30. I do not know whether the Licensing Board knows what the minimum quantities of uranium-235 necessary to make a nuclear weapon are. I suspect they don't, and it is very important to know these numbers in making rational decisions about the consequences of the theft of those materials. I would say flatly that I would be <u>very</u> concerned about theft, clear evidence of theft, certainly of a kilogram or more of highly enriched uranium, and I think everyone should be. If you ask how much less than a kilogram, I really couldn't go into that, and I want to make sure I am not being taken to say that one kilogram of highly enriched uranium is the minimum quantity necessary to make a bomb. That minimum quantity is not a well defined number at all. It depends on the talents, experience, requirements and so on of the designers.

31. From the point of view of a person who has designed nuclear weapons, 4.9 kilograms of 93% enriched uranium is certainly a significant quantity. There is no question about that. It should not be around in situations where theft could occur unless there is some vast overriding reason such as national defense, and I know of no such reason which could be remotely applicable to UCLA.

32. It is my opinion that HEU should be prohibited internationally, and we have the mechanisms set up to do that in the United States. HEU should be prohibited except under conditions that I would say are extraordinary. The prohibition should come first and the exception should come later. No one should have that quantity of HEU under any circumstances for any purpose. I note that the NRC has recently (August 24, 1982) issued a statement of policy committing itself to exercising its licensing authority to reduce, "to the maximum extent possible," the use of HEU in domestic and foreign research reactors. (47 FR 37007). It appears to me very important that the Atomic Safety and Licensing Board carry out that NRC policy in the case of the UCLA application for HEU now pending before it.

33. Therefore, it is my opinion that UCLA's application for kilogram quantities of 93% enriched uranium, given what I know about what it can be used for in terms of construction of a nuclear weapon or making of a nuclear threat, and also based on what I know about the needs of research reactors, should not be granted. If it is important that the reactor continue to operate because of its contribution to research or education, UCLA should be directed to use fuel of a lower enrichment.

34. I would say further that in every case the institutions that are using research reactors should look very carefully at the risks in using them versus the benefits obtained--and the risks are significant--and treat them as potentially very dangerous pieces of equipment. The danger is especially worrisome when there are kilogram or more quantities of nuclear materials from which nuclear weapons can be made. The whole institution, not merely the nuclear engineering department, should make that assessment. My advice would be to avoid having reactors unless you absolutely have to.

35. If you must have a reactor, always use the lower enrichment and keep the lowest quantity of uranium on hand. I doubt that there is any crucial research at a university requiring weapons-grade uranium.

I declare under penalty of perjury that the above is true and correct to the best of my knowledge and belief.

Theodore B Taylor

Theodore B. Taylor

Executed at Damascas, Maryland, this 16 day of December, 1982.

Professional Qualifications

DR. THEODORE B. TAYLOR

My name is Theodore B. Taylor. I am Chairman of the Board of Taylor, Kirkpatrick, Inc., a technical consulting firm.

I received my BS degree in physics in 1945 from the California Institute of Technology and my PhD degree in theoretical physics from Cornell University in 1954.

From 1946 to 1949 I worked as a theoretical physicist at the University of California Radiation Laboratory in Berkeley.

From 1949 to 1956 I was on the staff of the Los Alamos Scientific Laboratory, working on the design of nuclear explosives. One of my primary assignments at Los Alamos was to design fission bombs of very small physical dimensions and mass.

In 1956 I joined the General Atomic Division of General Dynamics Corporation where, along with Edward Teller, Freeman Dyson, and others, I helped design the TRIGA research reactor. While at General Atomic I was also technical director of the Nuclear Space Propulsion Project (Project Orion).

From 1964 to 1966 I was deputy director (scientific) of the Defense Atomic Support Agency, U.S. Department of Defense.

I spent the following two years in Vienna, Austria, as an independent consultant to the U.S. Atomic Energy Commission and several other organizations, working on the subject of international safeguards for nuclear materials.

In 1967 I founded the International Research and Technology Corporation, a company primarily concerned with studies of the impact of technology on society, which I served as Chairman of the Board until 1976.

From 1976 to 1980 I was Visiting Lecturer with rank of Professor in the Mechanical and Aerospace Engineering Department at Princeton University.

In the aftermath of the accident at the Three Mile Island nuclear power plant, I served as a Commissioner on the President's Commission on the Accident at Three Mile Island (the "Kemeny Commission.")

I am a member of the American Association for the Advancement of Science and the American Physical Society, and have served as a consultant to the Air Force Science Advisory Board, 1955-58, Los Alamos Scientific Laboratory, 1956-64, Aerospace Corporation, 1960-61, Atomic Energy Commission, 1966-70, Defense Atomic Support Agency, 1966-69, Rockefeller Foundation, 1977-79, and was chairman of the Los Alamos Study Group, Air Force Space Study Commission, 1961.

In 1965 I was one of the recipients of the Ernest O. Lawrence Memorial Award of the AEC for work on the development of nuclear explosives and the TRIGA research reactor.

I am co-author of The Restoration of the Earth (1973), Nuclear Theft: Risks and Safeguards (1974), Nuclear Proliferation (1977), Energy: The Next Twenty Years (1979), and author of numerous articles on nuclear safeguards and proliferation in technical journals and popular media. A more detailed account of my activities in the safeguards field can be found in John McPhee's book, The Curve of Binding Energy (1973, 1974).

I maintain an active "Q" clearance.

THE CURVE OF BINDING ENERGY

John McPhee

BALLANTINE BOOKS • NEW YORK

Published in the United States by Ballantine Books, a division of Random House, Inc., New York, and simultaneously in Canada by Random House of Canada, Limited, Toronto, Canada.

The text of this book originally appeared in *The New Yorker*, and was developed with the editorial counsel of William Shawn and Robert Bingham.

Library of Congress Catalog Card Number: 74-1226

ISBN 0-345-28000-8

This edition published by arrangement with
Farrar, Straus and Giroux

Manufactured in the United States of America

First Ballantine Books Edition: June 1975
Fourth Printing: December 1979

First Canadian Printing: July 1975

and say, 'O.K.'—or they file a statement of lack of compliance, and *this* has to be good enough to stand up in court."

"The present safeguards system is not a system for the future," Suda said. "In order to prove suitable, it has to shape the developing industry, rather than play catch-up all the time."

What, then, if someone did have a few flasks of uranium hexafluoride? Fully enriched. Took it off a truck outside a McDonald's in Wheeling, West Virginia. Took it out of a freight room in a New York airport. It does not matter where or how the material was obtained, whether the theft was a hit or an inside job. It is hardly arguable that the material is there for the taking. If Ted Taylor, imagining himself to be the thief, had enough uranium safely sequestered, what would he do with it to convert it to a form that could be used in a bomb?

In rural Maryland, no more than thirty miles from Washington, a friend of mine has about a hundred acres of land with a cabin in the center of it. A stream runs past the cabin, and hillsides that are covered with deep deciduous forests rise away on every side. The cabin has a big fireplace, no electricity, kerosene lanterns, and a roof that projects six or eight feet over a front porch, on which there is a table and some chairs. Taylor and I went there almost every day for a week or so, sat on the porch, and looked across the stream and meadow into the woods. The place was convenient. It was near his home. He had a pair of binoculars, with which he followed birds, and a slide rule, with which he created imaginary weapons. I had notebooks and pencils, the table to write on, and a lot of leisure time, because he spoke slowly, if at all, making sure that everything he said was in a context as available to the world in public print as it was to him from memory. Nothing he said there crossed barriers of secrecy that had not already been taken down. He was pursuing, in its many possible forms, the unclassified atomic bomb.

There would be a scale of convenience. It would be

much simpler to use "broken buttons"—chunks of metallic uranium-235—than uranium oxide, for example. It would be easier to begin with the right form of uranium oxide than with uranium hexafluoride. Concomitantly, though, a clandestine bombmaker would have to settle for what he could get, on a scale of availability, and he could use uranium-235 in almost any form. There is no absolute need to have uranium metal. If the oxide were used, the sacrifice in yield would not be prohibitive. The oxide is a powder, easy to handle, easy to pour. It could be packed into a box.

I asked if there would not be a density problem in using a material so relatively fluffy compared to metal.

He said, "Any high explosive that you have in the thing will see to it that the density problem disappears." The more he thought about it, he said, the more convinced he had become that the oxide would be particularly serviceable for a crude bomb, and convenient as well, for great amounts of U-235 in oxide form move around the country.

I asked him what someone would do who wanted to change the oxide into metal.

Taylor said he would put about four and a half kilograms of the powder on a vibrating tray in a laboratory furnace, and then heat up some hydrofluoric acid in a stoppered flask. Through a tube in the top of the flask, hydrogen-fluoride gas would move into the furnace. Heat the furnace up to five hundred degrees centigrade. The hydrogen fluoride and the uranium-oxide powder form water and uranium tetrafluoride, also a powder. In a ratio of six to one, put uranium tetrafluoride and powdered magnesium into a graphite crucible. Add potassium chlorate as a chemical heat generator. Put the crucible into a strong steel container. Using electrical ignition wire—like the wire in a toaster—get the temperature of the material in the crucible up to six hundred degrees. At that temperature, the uranium tetrafluoride and the powdered magnesium ignite. In combustion, they become uranium metal and magnesium fluoride. Let cool to a hundred degrees. Now spray water on the crucible to bring it to room temperature. The metal inside is known as a derby. Four kilograms of U-235. Repeat the process.

For the various procedures involved in converting uranium from one compound to another, or for bringing it ultimately to metallic form, the necessary equipment can be made at home, or can be sought in the Yellow Pages of the telephone directory, under "Laboratory Equipment & Supplies," or, for that matter, under "Hardware—Retail." Most useful of all would be the catalogue of a large chemical-supply house, such as Fisher Scientific, which has branches in most cities. The furnace costs less than a hundred dollars. A graphite crucible costs three dollars. Hydrofluoric acids costs seven dollars a quart, and magnesium oxide costs twenty-one dollars a pound. A vibrating tray is simple to make. It works with a little motor and vibrates like a bed in a Holiday Inn. Uranium oxide on a vibrating tray will mix more readily with hydrogen fluoride to form uranium tetrafluoride and water.

In 1969, Vincent D'Amico, a safeguards specialist at the Atomic Energy Commission, got word that an air shipment of fifteen kilograms of uranium hexafluoride, in a steel cylinder, was missing. He went out to search the country for it, and eventually found it in a freight room at Logan Airport, in Boston. UF_6 is the most abundant form in which fully enriched uranium travels. It comes out of Portsmouth, Ohio, in steel bottles and is distributed to conversion plants that change it to oxide or metal.

"How would you—if you had stolen some—turn UF_6 into metal?"

"Mix it with carbon tetrachloride in an evacuated nickel container. Four parts of carbon tetrachloride to one part UF_6. Heat the mixture—a stove will do—to a hundred and fifty degrees centigrade. The contents react and form uranium tetrafluoride and fluorinated carbon chloride. The UF_4 is a loose cake of solid material. Wash it with weak acid or alcohol. From there, it's the same as it was with the conversion of uranium oxide. Add powdered magnesium to the UF_4, burn it, and you get a derby of uranium metal."

The fuel plates that run certain research and test reactors are thin strips of metal only about two feet long and four inches wide. What could someone do with a stack of those?

Put them in an aqueous solution of lye and fertilizer. The lye would have to be quite pure, though—good sodium hydroxide. The fertilizer would be sodium nitrate. The fuel plates consist of an aluminum-uranium alloy sandwiched between layers of uncomplicated aluminum. After five hours in the lye and fertilizer, the aluminum has dissolved and the uranium is in suspension. Add barium nitrate to keep the uranium from dissolving. Then put the whole business into a centrifuge—say, a six-hundred-dollar centrifuge from Fisher Scientific. Whirl it there for twenty minutes at eight hundred Gs. Pour off the aluminum solution. In the bottom of the centrifuge tubes is solid uranium-235.

"Uranium-zirconium hydride is the fuel for about half the research reactors," Ted continued. "And uranium-zirconium alloy is a step along the way to making it. The alloy is stockpiled in significant amounts, depending on business. Fuel for TRIGA reactors, for example, is made in San Diego and then shipped all over the world. If you wanted the pure alloy, you would have to steal it in San Diego. If you want the hydride, go to Bandung, or wherever, or get it in transit. The core of a standard TRIGA contains only two to six kilos of uranium, so a bombmaker would probably have to collect the stuff. If you were stealing fuel being shipped, you would have to perform at least four thefts. The reactors use cylindrical rods of hydride, clad in aluminum or stainless steel. You burn off the hydrogen at a thousand degrees, and dissolve the zirconium in sodium hydroxide."

"How much uranium is the least you might need?" I asked him.

"The classical figure for the critical mass is twenty kilograms of fully enriched uranium," he said. "The classical statement is that it takes that much to make a bomb. That statement isn't true. It takes much less—and how much less depends on how good you are at making bombs."

"How much less?"

"All I can say is it's not a nit-pick. It isn't a matter of saying twenty and meaning eighteen. It matters a lot how much less, but that is classified, and there is nothing we can do about that, I guess. But if someone gets hold of the Los Alamos critical-mass summaries, he can see how much material is critical in various forms—various ways of shaping the metal, various reflectors wrapped around it. You write to the National Technical Information Service, in Washington, for the critical-mass summaries. They cost three dollars. In one of them it says that the critical mass varies inversely with the square of the density of the metal and reflector. If both the reflector and the core are compressed by the same amount—remember, this is an implosion system—the critical mass is reduced by the square of that amount. This is as close as you can sidle up to this classified point."

Dusk had long since come down. We quit for the day. The corners of Taylor's mouth turned down for a moment, and he said, "A small group has not had the opportunity before to rearrange people and buildings this way."

Not long thereafter, when we were in Los Alamos, Carson Mark talked about clandestine bombmaking, and he said, "Everybody has it in mind that it would be impossible to do. They say you would need your own Manhattan Project. They speak of the scale of ingenuity, of the required genius; they think of it as a tremendous operation. But the context has changed. It would not be impossible now. It does not take a fleet of Einsteins to accomplish, or even Ted Taylors, for that matter. It is not beyond reach. It is much within reach. There's a great difference between 1942 and now." Mark went on to explain that the people in Project Y (the Los Alamos part of the Manhattan Project) had

faced eight principal requirements in 1942. They needed nuclear and neutronic data—energy estimates, and so forth. They needed equation-of-state data to estimate assemblies or explosions. They needed to know the probability of initiating a neutron chain. They needed a way to estimate the dependence of efficiency on various parameters—such as the mass of material, energy generation, and features of disassembly—or it would be impossible to decide if, say, five critical masses were needed for an effective bomb, or one and one-tenth, or whatever. They needed to develop numerical techniques for making neutron multiplications. They needed hydrodynamic calculations. They needed computing equipment. "And, finally," Mark said, "they needed people who could ask the right questions and suggest the significance of the answers when they found them—call them physicists, if you want. When the United States began work, it was well equipped on Item Eight—the people who could ask the questions—and on nothing else. Those people were the constellation of Los Alamos. That is what is assumed is needed now—but it is not so. You now *have* Items One to Seven. You don't need to ask the questions. You need an ingenious fellow, perhaps, but not really all that much so. He is hitchhiking on the talents of others. You don't need a lab anymore to measure cross-sections. They're all measured and published. If you need equation-of-state data, you can go over to the high school and find out what it is. Everything is unclassified except plutonium. But equations of state for heavy elements tend to be identical. See the *Rare Metals Handbook*. Any reactor-theory textbook now will tell you the probability of initiating a neutron chain. The work that has been done on maximum-credible reactor accidents will tell you what you need to know about efficiency. You can get neutron calculations by mail. For hydrodynamic calculations, read Richtmyer and von Neumann on how to avoid the discontinuity of shocks. As for adequate computers, most airline offices have them. When people first began work here at Los Ala-

A Report to the Energy Policy Project of the Ford Foundation

Nuclear Theft:
Risks and Safeguards

Mason Willrich
Theodore B. Taylor

Ballinger Publishing Company • Cambridge, Mass.
A Subsidiary of J.B. Lippincott Company

Published in the United States of America by Ballinger Publishing Company
Cambridge, Mass.

Library of Congress Catalog Card Number: 73-19861

International Standard Book Number: 0-88410-207-6 HB
0-88410-208-4 PB

Printed in the United States of America

Library of Congress Cataloging in Publication Data

Willrich, Mason.
Nuclear theft: risks and safeguards.

Bibliography: p.
1. Atomic energy industries—Security measures.
I. Taylor, Theodore B., 1925- joint author.
II. Ford Foundation. Energy Policy Project.
III. Title.
HD9698.A2W54 658.4'7 73-19861
ISBN 0-88410-207-6 HB
0-88410-208-4 PB

Table of Contents

List of Tables ix

List of Figures x

Foreword *McGeorge Bundy* xi

Preface *S. David Freeman* xiii

Acknowledgments xv

Chapter One
Introduction 1

Chapter Two
Nuclear Weapons 5

Overview 5
Resources Required To Make Fission Explosives 10
Effects of Nuclear Explosions 21
Radiological Weapons 24
Pure Fusion Explosives 28

Chapter Three
Nuclear Fuel Cycles: 1973-80 29

Introduction 29
Power Reactor Fuel Cycles 30
Research and Development Uses of Nuclear Materials 56

Chapter Four

Nuclear Power Scenarios: 1980–2000 59

Introduction 59
Alternative Mixes of LWR, HTGR, and LMFBR Power Plants 60
Other Types of Fission Power Plants 71
Controlled Thermonuclear Power (Fusion) 74

Chapter Five

U.S. Safeguards Against Nuclear Theft 77

Introduction 77
Historical Development: Mid-1960s to Present 78
Existing Requirements 82
Regulatory Approach 100

Chapter Six

Risks of Nuclear Theft 107

Introduction 107
Theft by One Person Acting Alone 109
Theft by a Criminal Group 112
Theft by a Terrorist Group 114
Diversion by a Nuclear Enterprise 116
Diversion by a Political Faction Within a Nation 117
Nuclear Black Market 119

Chapter Seven

Nuclear Safeguards: Basic Considerations 121

The Context 121
Purposes of a Nuclear Safeguards System 122
Functions of a Nuclear Safeguards System 125
Framework 127

Chapter Eight

Safeguard Measures 135

Measures to Prevent Theft 135
Detection of Completed Nuclear Thefts 148
Recovery of Stolen Nuclear Materials 152
Responses to Nuclear Threats 155
The Principle of Containment 159

Chapter Nine

Costs of Safeguards 163

Costs of Effective Safeguards 163
Allocation of Safeguards Costs 165
Costs of Ineffective Safeguards 166

Chapter Ten

Conclusions and Recommendations 167

Conclusions 167
Recommendations 171

Appendices

Appendix A Historical Background 175
Appendix B Foreign Nuclear Power: Reactor Types and Forecasts 193
Appendix C U.S. AEC Regulatory Guide 5.7–Control of Personnel Access to Protected Areas, Vital Areas, and Material Access Areas (June 1973) 203
Appendix D Risks of Governmental Diversion in Non-Nuclear-Weapon Countries 215
Appendix E Reviewer Comments 237

Bibliography 241

Index 245

About the Authors 251

Tables

Tables

2-1 Damage Radii for Various Effects of Nuclear Explosions as Functions of Yield 23
2-2 Lethal and Significant Contamination Areas for Release of Air Suspensions of Plutonium Inside Buildings 25
3-1 Characteristics of Typical U.S. Reactors 50
3-2 Forecasts of U.S. Nuclear Power and Associated Nuclear Material Flows–1972–1980 52
3-3 Total Masses of Material that Contain One Fast Critical Mass of Material, if Separated from other Materials and Converted to Metal (Total Mass in Kilograms) 54
3-4 Fuel Cycle Materials Rank Ordered by Increasing Weights Required to Yield One Critical Mass of Fission Explosive Material in Metallic Form without Uranium Enrichment 54
3-5 Fuel Cycle Materials Rank Ordered by Increasing Weights Required to Provide One Critical Mass of Fission Explosive Material without either Chemical Processing or Isotope Enrichment 55
4-1 U.S. Nuclear Power Forecast 60
4-2 Nuclear Power Options, 1980–2000 63
4-3 Annual Production Rates of Nuclear Weapon Materials 65
7-1 Possible Nuclear Material Categories for a System of "Graded" Safeguards 130
B-1 Characteristics of Typical Foreign Reactors 195
B-2 Forecasts of Foreign Nuclear Power and Associated Nuclear Material Flows–1972–1980 196
B-3 Foreign Nuclear Power, by Country 197
B-4 Foreign Forecast of Installed Nuclear Power Capacity (Thousands of Megawatts) Excluding Communist Countries 198

B-5 Plutonium and Highly Enriched Uranium Inputs and Outputs for Foreign Reactors, Excluding Communist Countries for the Years 1981-2000 (Tonnes) 199
B-6 Total Plutonium Output and U-235 Input (in Tonnes) at the end of the Year 200

Figures

3-1 Light-Water Reactor (LWR) Fuel Cycle 33
3-2 High-Temperature Gas-Cooled Reactor (HTGR) Fuel Cycle 44
3-3 Liquid Metal-Cooled Fast Breeder (LMFBR) Fuel Cycle 48
C-1 Secure Access Passageway into Protected Area (Unattended) 208
C-2 Secure Access Passageway at Entrance to Protected Area (Attended) 208
C-3 Secure Access Passageway between Change Rooms 210
C-4 Secure Access Passageway at Exit from Material Access Area 211

Foreword

In December 1971 the Trustees of the Ford Foundation authorized the organization of the Energy Policy Project. In subsequent decisions the Trustees have approved supporting appropriations to a total of $4 million, which is being spent over a three-year period for a series of studies and reports by responsible authorities in a wide range of fields. The Project Director is S. David Freeman, and the Project has had the continuing advice of a distinguished Advisory Board chaired by Gilbert White.

This analysis of "Nuclear Theft" is an early result of the Project. As Mr. Freeman explains in his Preface, neither the Foundation nor the Project presumes to judge the authors' specific conclusions and recommendations. We do commend this report to the public as a serious and responsible analysis which has been subjected to review by a number of qualified readers.

This study, like many others in the Project, deals with a sensitive and difficult question of public policy. Not all of it is easy reading, and not all those we have consulted have agreed with all of it. Nor does it exhaust a subject which is complex, rapidly moving, and partly hidden under classifications both reasonable and unreasonable. The matters it addresses are of great and legitimate interest not only to those who are investing heavily in nuclear power but also, by their very nature, to every citizen and community in the country, and the perspectives of these interested parties are not likely to be identical.

In this last respect the present study reflects tensions which are intrinsic to the whole of the Energy Policy Project—tensions between one set of objectives and another. As the worldwide energy crisis has become evident to us all, we have had many graphic illustrations of such tensions, and there are more ahead. This is what usually happens when a society faces hard choices, all of them carrying costs that are both human and material.

But it is important to understand that there is a fundamental difference between present tension and permanent conflict. The thesis accepted by our Board of Trustees when it authorized the Energy Policy Project was that

Chapter One

Introduction

This book is about a narrow but important energy policy issue. We analyze the possibility of nuclear violence using fissionable material that might be stolen from the U.S. nuclear power industry, and we discuss what can and should be done to prevent that from happening.

Nuclear energy is rapidly becoming a major source of electric power in the United States and a growing number of other countries. Nuclear power requires the production, processing, and use as fuel of very large amounts of plutonium and high-enriched uranium. However, only a few kilograms of these fissionable materials are enough for a nuclear explosive capable of mass destruction, and tens of grams of plutonium are enough for a device capable of causing widespread radioactive contamination. Moreover, the design and manufacture of a crude nuclear explosive is no longer a difficult task technically, and a plutonium dispersal device is much simpler to make than an explosive.

Therefore, measures are necessary to ensure that the materials intended for use as nuclear fuel are not diverted for use in acts involving nuclear threats or violence. These measures, or safeguards, must be effective, because a successful nuclear theft could enable a small group to threaten the lives of many people, the social order within a nation, and the security of the international community of nations.

Experts in government and industry have known of the security risks inherent in nuclear power for many years. They have worked long and hard to develop safeguards against the dangers of nuclear theft. However, many governmental policymakers and industrial leaders in the energy field are only vaguely aware of the problem, and most of the general public does not know that it exists.

This study is intended, therefore, to contribute to public understanding of the technical facts and policy issues involved. We believe that these facts and issues affect substantially both the development of nuclear power and the security of the American people. Of course, we hope that our study will also stimulate thought and action among experts.

Obviously, there is no perfect solution to the problem of nuclear theft, any more than there is a final solution to the problem of crime in society. But there are safeguards which, *if implemented,* will reduce the risk of nuclear theft to a very low level—a level which, in our opinion, is acceptable. Moreover, we are convinced that the costs of effective safeguards will be small compared to the total costs of nuclear power.

A swirl of controversy has engulfed the nuclear power industry from the beginning. Power reactor safety, emergency core cooling systems, radioactive effluents, thermal pollution, and radioactive waste disposal have each been the subject of interminable legal proceedings, protracted political maneuvering, costly delays in construction schedules, and sensational newspaper headlines.

We have attempted, to the best of our ability, to make this book an objective statement of the issues arising in one particular area of risk related to the development and use of nuclear power—an area in which we feel qualified to comment. Our purpose is to provide a means whereby the risk of nuclear theft and the cost of effective safeguards can be weighed, along with other risks and costs, against the very large benefits of nuclear power. We hope our work will be useful to all participants in the decisionmaking process concerning the role of nuclear power in meeting the needs of our nation and the world for energy in the future. The promoters of nuclear power may deplore it—and its critics may welcome it—as an attack on the U.S. nuclear industry and government policy affecting the industry. That is not our intention.

Our study contains no classified information. Drawing from the wealth of unclassified data available, however, it does describe in general terms how nuclear explosives and radiological devices can be made, where in the nuclear power industry the materials for making such weapons are present, and why and how various groups within society might attempt to obtain such materials and to use them to threaten or cause catastrophic destruction.

This information and the analysis derived from it are necessary in order to understand the security risks inherent in the development and widespread use of nuclear power, and to provide a basis for consideration of various safeguards against nuclear theft.

But how much does the public need to know about these matters? This question haunts us, and we believe it merits discussion before proceeding further.

To us, the most compelling argument against informing the public about the risks of nuclear theft is that such an effort might inspire warped or evil minds. Scenarios of nuclear hijackings or bomb threats might become self-fulfilling prophecies. This argument is especially forceful when acts of terrorism are widespread and organized crime appears to be flourishing. However, it ignores the fact that a large amount of information in much greater detail than we present here is already in the public domain. Moreover, it assumes that criminals are no more perceptive than the general public about opportunities to pursue criminal purposes.

But the basic flaw in the argument against informing the public is that it ignores the nature of the security risks in nuclear power. If the risks were temporary, the danger of inspiring nuclear theft might well justify withholding information from the public. However, when security risks are inherent in a long-term activity, which is clearly the case with nuclear theft, the public in a democratic society has a right to know, and those with knowledge have a duty to inform. Indeed, informed public opinion is essential to effective safeguards.

A second argument is based on timing. It may be conceded that the dangers of theft are serious and should be brought to the attention of the public. Yet, it may be argued, to do so at this time is unfortunate, since the responsible agencies of government and the nuclear power industry itself are already hard pressed to deal with reactor safety and environmental problems. The nuclear theft issue is easy to distort and sensationalize. Groups unalterably opposed to nuclear power could inject the issue into nuclear plant licensing hearings and other regulatory proceedings, and thereby cause further costly and dangerous delays in meeting future demands for electric power.

We find this line of argument to be without merit, and chief among our reasons is timing. The years just ahead provide the last chance to develop long-term safeguards that will deal effectively with the risks of nuclear theft. Once the material-flows in the nuclear power industry are as enormous as expected a few years from now, it will be too late. Moreover, the failure to deal with a problem of such critical importance to the future success of nuclear power cannot be justified on the ground that the industry simultaneously faces several other difficult problems.

A third basic argument is that the possibility of nuclear violence as a result of material being diverted from industry is not a real problem. Various reasons are put forth to support this argument.

Some experts assert that those who are alarmed tend to underestimate the difficulties of manufacturing nuclear explosives, or to overestimate the willingness of groups within society to resort to threats of mass destruction. Although we recognize that these are debatable issues, we are convinced that the risks are real and serious. This book sets forth the reasons for our conviction in detail.

In addition, it is sometimes asserted that if a criminal or terrorist group really wanted nuclear weapons, then the group would be more likely to attempt to steal a finished and sophisticated device from the U.S. military stockpile than to steal materials from which it could make its own crude explosives. Our reply is that if military stockpiles are not adequately protected against theft at present (and we express no opinion on this point), then existing protective measures should be strengthened. But this does not preclude protecting basic materials as well.

Finally, it may be argued that if some group were intent on extreme violence to achieve its ends, there are many powerful chemical and biological agents that can be obtained more easily and used more effectively than nuclear weapons. We agree that there are many non-nuclear ways to inflict enormous harm on large numbers of innocent human beings, and we deplore the fact. Specific threats of nuclear violence should be compared with other lethal threats when deciding upon an acceptable level of effectiveness for safeguards against nuclear theft. There may well be certain biological agents whose violent uses could create as much damage as plutonium dispersal devices. The risks of nuclear explosives are, however, incomparable and unprecedented.

Our hope is that you who read this book will thereafter have a better idea of how effective *you* want safeguards against nuclear theft to be. For in the final analysis, the level of risk accepted will affect us all and future generations as the nuclear age unfolds. The choice is ours to make as a nation, and we believe it should be made on broad economic and social grounds after full public discussion.

Chapter Two

Nuclear Weapons

OVERVIEW

The first question we must explore is whether a successful theft of nuclear materials from the nuclear power industry would pose a genuine threat. Could some of the materials used as nuclear fuel in the power industry be used in weapons? Are these materials present in the industry in forms and quantities that are practical for the illicit manufacture of bombs? If a thief succeeds in making a nuclear weapon from these materials, how much damage might he cause?

Every educated person already knows the single most essential fact about how to make nuclear explosives: they work. Before the first atomic bomb exploded in the Trinity test near Alamogordo, New Mexico, in 1945, no one knew for certain that it would work. There was a possibility that the kind of fission chain reaction which had been sustained in the Chicago pile could not be accelerated to produce a large explosion. Indeed, some of the Los Alamos weapon design group strongly suspected that Trinity would not explode. A "pool" of yield estimates made before the test ranged from little more than the yield of the high explosive used to trigger the nuclear explosion to several tens of kilotons. (A kiloton is a unit of energy equal to the energy released by the explosion of one thousand tons of TNT. A megaton corresponds to the energy released by exploding one million tons of TNT.) The actual yield, close to twenty kilotons, was significantly greater than most of the estimates made before the test.

The certainty that an idea will work in principle is a large step toward finding ways to carry it out. During the twenty-eight years since the Trinity test much has happened to make it easier to design and fabricate a nuclear explosive, and to provide a high degree of confidence that the design will be successful. The first fission explosives built in the USSR, the United

Kingdom, France, and China apparently worked quite well. A number of nuclear explosives with design features very different from the Trinity device, including the bomb exploded over Hiroshima, worked well the first time they were used or tested.

Ever since the successful test of the "Mike" device at Eniwetok in 1952, it has been known that fission explosions can be used to initiate thermonuclear explosions with yields in the megaton range. All governments that have developed fission explosives have also successfully developed high yield thermonuclear explosive devices. Less than three years elapsed between China's first detonation of an A-bomb and its first test of a thermonuclear explosive device—compared to seven years for the U.S., four for the USSR, five for the United Kingdom, and eight for France.

Until 1954, most of the information required for the design and construction of fission chain reacting systems, both reactors and fission explosives (A-bombs), was classified. A large body of this information was declassified in conjunction with President Eisenhower's "Atoms for Peace" speech before the United Nations on December 8, 1953, the enactment of the Atomic Energy Act of 1954, and the first international Conference on the Peaceful Uses of Atomic Energy at Geneva in 1955. Subsequent further declassification and public dissemination of new information of this type has been extensive.

In the initial draft of this book that was circulated to reviewers, we included in this chapter a rather extensive set of references to unclassified technical publications that would be available to a fission explosive design effort, particularly one with the objective of making a compact, efficient explosive with a reasonably predictable yield. The entire draft, including the references, was also submitted to the U.S. Atomic Energy Commission (AEC) for formal classification review and was determined to contain no classified information. Nevertheless, a number of the reviewers recommended that the set of references for this chapter and some of the text not be included in the published form of this book. They believed this information, though obtainable by a systematic literature search, would provide more assistance to an illicit fission explosive design team than would be prudent to collect together in one publication. We have made appropriate deletions in the published version. We believe, however, that the concern about the republication in a book such as this of certain unclassified information and references supports the central point we will develop: if the essential nuclear materials are at hand, it is possible to make an atomic bomb using information that is available in the open literature.

To give the reader some idea of the detail in which fission explosive design principles are described in widely distributed publications, and also to provide a point of departure for other parts of this chapter, we present below a rather extensive quotation from the article about nuclear weapons in the *Encyclopedia Americana*[1] by John S. Foster, a well-known expert on nuclear weapon technology and formerly Director of the Lawrence Radiation Laboratory in California and Director of Defense Research and Engineering in the Department of Defense:

> . . . It must be appreciated that the only difficult part of making a fission bomb of some sort is the preparation of a supply of fissionable material of adequate purity; the design of the bomb itself is relatively easy . . .
>
> *Fission Explosives*—The vital part of fission explosives is the fissionable material itself. The two elements commonly used are uranium and plutonium. Each of these elements can exist as isotopes of several different atomic weights according to the number of neutrons included in corresponding nuclei, as in U-232, U-233, U-234, U-235 . . . U-238, Pu-239, and Pu-240. Not all of the isotopes of these elements are suitable for use in a nuclear explosive. In particular, it is important to use a material with nuclei that are capable of undergoing fission by neutrons of all energies, and that release, on the average, more than one neutron upon fissioning. The materials which possess these properties and can be made available most easily in quantity are U-235 and Pu-239.
>
> The immediate consequence of a nuclear fission is:
>
> U-235 or Pu-239 + neutron + 2 fission products + 2 or more neutrons
> (average) + 2 gamma rays (average)
>
> The total prompt energy release per fission is about 180 million electron volts. This means that the complete fissioning of 1 kilogram (2.2 lb) of U-235 or Pu-239 releases an energy equivalent to about 17,000 tons of chemical explosive.
>
> *Critical Mass*—However, 1 kilogram of U-235 or Pu-239 metal, which is about the size of a golf ball, will not explode by itself. The reason for this is that, if one of the nuclei is made to fission the neutrons produced would usually leave the metal sphere without causing a second fission. If, however, the sphere contained about 16 kilograms (35.2 lb) of Pu-239 (delta phase) or fifty kilograms (110 lb) of U-235, the mass would be critical. That is to say, for each fission which occurs, one of the neutrons produced would on the average cause a further fission to occur. If more material were added, the number of neutrons in the assembly would multiply.
>
> The mass of fissionable material needed to achieve a critical mass is also determined by the type and amount of material placed around it. This external material, called a tamper, serves to reflect back into the fissionable material some of the neutrons which would otherwise leave. For example, the presence of a tamper made of U-238 one inch thick around a sphere of plutonium reduces the mass required to produce criticality from 16 kilograms to 10 kilograms (22 lb).

> To produce a nuclear explosion, one must bring together an assembly which is substantially above critical, or supercritical. For example, suppose that by some means a mass of material equal to two critical masses is assembled, and a neutron is injected which starts a chain reaction. Within two millionths of a second or less, the energy developed within the fissionable material will cause it to explode and release a nuclear yield equivalent to several hundred tons of high explosive. The actual yield depends on the particular characteristics of the masses and types of materials involved.
>
> *Initiation of the Explosion*—Because a supercritical assembly naturally tends to explode, a major aspect of the design is related to the way in which the material is brought together. The simplest form involves a procedure by which two or more pieces, which by themselves are subcritical, are brought together. One can imagine, for example, a hollow cylinder inside of which two cylindrical slugs of fissionable material are pushed together by chemical propellant. While such an approach can be used to provide a nuclear explosion, a considerable mass of fissionable material is required. Nuclear explosives involving considerably less fissionable material use a technique by which the nuclear material is compressed, or imploded.
>
> A simple picture of this so-called implosion technique can be gained by imagining a sphere of fissionable material and tamper which is slightly below critical. Under these conditions, a neutron born in the central region of the fissionable material has almost an even chance of producing a fission before it leaves the metal. If the assembly is now compressed to twice the original density, the radius is then reduced to about 8/10 of its initial value. A neutron leaving the central region under the compressed conditions must pass through atoms which are more closely spaced by a factor of two, although the total distance is reduced only 20 percent. Consequently, the chance of causing a fission is actually increased by approximately 2 × 0.8, or 1.6 times. The assembly is now obviously very supercritical, although only one critical mass was used.
>
> The trick, of course, is to compress to several times normal density the mass of fissionable material and tamper. This requires pressures above 10 million pounds per square inch. Such pressures can be developed through the use of high explosive. The nuclear core could be placed in the center of a large sphere of high explosive. Compression of the fissionable material is attained by lighting the outer surface of the high explosive simultaneously at something like 100 points spaced roughly evenly over the surface. This procedure produces a roughly spherical, in-going detonation wave which, on striking the metal core, provides the necessary compression to lead to a nuclear explosion.

This encyclopedia article presents a description of the general principles for the design of nuclear explosives. In addition, information

originally classified but now in the public domain includes: the measured and calculated critical masses of various fission explosive materials[a] in various types of tampers or reflectors; the nuclear properties of materials used in fission explosives, and practically all information concerning the chemistry and metallurgy of plutonium and uranium.

A fission explosive design team working in 1973 thus has available to it, in the unclassified technical literature, considerably more of the relevant information, with one possible exception, than was available to the Los Alamos designers when the Trinity device was tested. The exception is experimental and calculated data related to the actual performance of the non-nuclear components of specific bomb assemblies. The mathematical and experimental tools one needs to acquire such data, however, are extensively described in the technical literature on nuclear reactor engineering, on high explosive technology, and on the behavior of materials at very high pressures and temperatures.

It is generally known that fission explosions can serve as a trigger to ignite thermonuclear fuels such as deuterium or tritium (which are variant forms of hydrogen, the lightest element). When the atomic nuclei of these light elements fuse together, huge amounts of energy are released. A considerable amount of the information that is needed for the design and construction of thermonuclear explosives (H-bombs) has been made public, especially the results of intensive unclassified work in the United States and other countries on controlled thermonuclear (fusion) reactor systems. The basic design principles for thermonuclear explosives, however, remain classified. How long the "secret" of the H-bomb will be kept out of the public domain is speculative. There are thousands of people who know and understand the basic principles from personal experience working within the security classification systems of the five nations that have tested H-bombs, and their number continues to increase. Further unclassified development of controlled thermonuclear power concepts is also bound to make access to classified information less important to an H-bomb design team as time passes. As a result, it seems reasonable to conclude that the H-bomb "secret" will not be kept from public view through the end of this century.

Since, however, it is impossible to discuss fission-fusion explosives in any detail in an unclassified publication, we have concentrated our attention on fission explosives in this book. Furthermore, as long as some kind of fission explosion is required to ignite the thermonuclear fuel in an H-bomb, the controls

---

[a] We define "fission explosive materials" to mean those materials that, without further chemical processing or isotope separation, can be directly used as the core material for fission explosives. We define "nuclear weapon materials" to mean those materials that can be used as the core material for fission explosives after chemical conversions involving processes much simpler than chemical reprocessing of irradiated nuclear materials or isotope separation. Hence, fission explosive materials is a narrower term than nuclear weapon materials. As we shall see, these two categories of nuclear materials are the primary concern of this study.

to prevent illicit use of fission explosive materials have a direct bearing on the control of illicit production of H-bombs. Finally, the damage that could be inflicted by fission explosions provides, we believe, sufficient justification for effective safeguards designed to prevent theft or illicit production of fission explosive materials. The possibility of pure fusion explosives is discussed briefly at the end of this chapter.

Nuclear materials do not necessarily have to explode to cause severe damage over large areas. Some radioactive materials, including many that are produced in nuclear power reactors, are among the most toxic substances known. Radiological weapons that would disperse fission products or other radioactive materials have been seriously considered for military use. We have no evidence, however, that any government has found such weapons to be sufficiently effective, compared to chemical or biological warfare agents and other weapons (including nuclear explosives), to include them in military arsenals. Nevertheless, we have considered several types of radiological devices that might be used by terrorists or other non-governmental groups—or perhaps even by individuals—to expose large numbers of people to radiation or to cause the evacuation of urban areas or major industrial facilities. We have given particular attention to possibilities for dispersing plutonium since that material is present in large quantities in nuclear power fuel cycles and is exceedingly toxic if breathed into the lungs in the form of very small particles.

RESOURCES REQUIRED TO MAKE FISSION EXPLOSIVES

Objectives

The time and resources required to design and make nuclear explosives depend strongly on the type of explosive wanted. It is much more difficult to make large numbers of reliable, efficient, and lightweight nuclear warheads for a national military program than to make several crude, inefficient nuclear explosive devices with unpredictable yields in the range of, say, one hundred to several thousand tons of ordinary high explosive. This is one reason why experts in the design and construction of nuclear explosives often disagree with each other about how difficult it is to make them. Those who have worked many years on the development of nuclear warheads for ever more sophisticated nuclear-tipped missile systems often base their opinions on their own experience, without having thought specifically about nuclear explosive devices that are designed to be as easy to make as possible. Unlike most national governments, a clandestine nuclear bomb maker may care little whether his bombs are heavy, inefficient, and unpredictable. They may serve his purposes so long as they are transportable by automobile and are very likely to explode with a yield equivalent to at least 100 tons of chemical explosive.

Thus, aside from the essential fission explosive materials, there is a wide range of resources required to make different types of nuclear explosives for any of a variety of purposes and under diverse circumstances. In view of this situation, we concentrate in the following parts of this chapter on a discussion of the *minimum* time and resources required to make a fission explosive with a yield that could be expected to be equal to at least a few tens of tons of high explosive.

Fission Explosive Materials

A material must have certain characteristics to be usable directly in the core of a fission bomb. First of all, it must be capable of sustaining a fission chain reaction. This means the material must contain isotopes[b] that can be split or fissioned by neutrons, releasing in turn more than one neutron as a consequence of fissioning. Second, the average time between the "birth" of a neutron by fission and the time it produces another fission, called the neutron "generation time," must be short compared to the time it takes for pressure to build up in the core. Too much pressure early in the chain reaction can cause the core to expand sufficiently to become sub-critical, i.e., to lose so many neutrons by leakage from the surface that the chain reaction cannot be maintained. Third, the critical mass and volume of the fission explosive material must be sufficiently small so that the size and weight of the mechanism for assembling more than one critical mass—whether based on the "gun" or "implosion" design—will be small enough to suit the purposes of those who want to use the fission bomb.

The quantities of fission explosive materials that would be required to make nuclear explosives, and the problems an illicit bomb maker would face in using them, depend on which fission explosive materials are involved. The distinctive characteristics of each fission explosive material must be understood in order to determine where in the nuclear power industry the key materials are to be found, to assess the specific risks of nuclear theft, and to decide which safeguards measures are appropriate in particular circumstances. We shall briefly summarize some of the most important characteristics of plutonium, uranium that is highly enriched in the isotope uranium-235, and uranium-233. All three of these materials are or will be used in large quantities as nuclear fuel to produce electric power, and all three can be used, separately or in combinations with each other, to make fission explosives.

---

[b] An element such as uranium or hydrogen occurs in a number of different "isotopes." This means that different atomic nuclei of the element may contain different numbers of neutrons, although the number of protons in the nuclei and the number and arrangement of the electrons revolving around the nuclei will be the same. The numbers of protons and electrons bound together largely determine the chemical properties of the element, which will be basically the same regardless of the isotope involved. However, different isotopes of the same element may have very different nuclear properties. Hence, certain isotopes of uranium, a very heavy element, are likely to split or fission when struck by a neutron, while some of the isotopes of hydrogen, a very light element, are likely to combine or fuse together under certain conditions. Both fission and fusion reactions convert mass into energy.

At the outset, it is useful to bear in mind that, of the three basic constituents of the nuclear age, neither plutonium nor uranium-233 occur in nature in significant amounts, and uranium as [illegible]ture contains less than one percent uranium-235.

Plutonium. Plutonium is produced in nuclear reactors that contain uranium-238, the most abundant isotope of natural uranium. Neutrons released in the fission process are captured in uranium-238, forming uranium-239. This radioactively decays, with a half-life[c] of about twenty minutes, to neptunium-239, which subsequently also decays, with a half-life of a little more than two days, to form plutonium-239. This isotope of plutonium is relatively very stable, with a half-life of more than 24,000 years. It is the plutonium isotope of greatest interest for use as the core material in fission explosives.

Another isotope that is made in nuclear reactors, plutonium-240, is also important to our discussion. A plutonium-239 nucleus occasionally captures a neutron without fissioning, to produce plutonium-240. Plutonium-240 cannot be fissioned by neutrons of all energies. This isotope, instead of fissioning, is more likely to capture another neutron, resulting in plutonium-241. Thus, plutonium-240 tends to act as a "poison" in a chain reacting system and it cannot be used, by itself, as the core material for a fission explosive.

Plutonium-240 has another property that is important to a bomb designer seeking to use plutonium made in power reactors. It occasionally fissions spontaneously, without being struck by a neutron, and in so doing, releases several neutrons. The neutron production rate resulting from spontaneous fission may be sufficient to influence the chain reaction. Under some conditions, one of these neutrons might start a fission chain reaction in the core material of a fission bomb before the core is assembled into a highly compressed, supercritical state. This might cause the bomb to "predetonate" and release considerably less energy than it would if the start of the chain reaction had been further delayed.

The relative amount of plutonium-240, compared to plutonium-239, increases with the length of time the plutonium is exposed to neutrons in a nuclear reactor. In typical power reactors now in operation in the United States, plutonium-240 accounts for 10 to 20 percent of the plutonium in the fuel assemblies when they are removed from a reactor for reprocessing. This concentration is sufficient to make the presence of plutonium-240 an important consideration in the design of a fission bomb. But it does not prevent the plutonium produced in nuclear power reactors from being usable in fission bombs that would be very likely to produce explosions in the kiloton range.

[c] The half-life of a radioactive isotope is the average time required for half of a given quantity of the isotope to decay and form some other isotope.

Another characteristic of plutonium that has considerable importance in the construction of a nuclear explosive is that, with proper precautions, it can be handled safely. The products of plutonium-239 and 240 radioactive decay are primarily helium nuclei called "alpha particles." These particles have very small penetrating power, a millimeter or less in human tissue, compared to the very high energy x-rays, or "gamma rays," that are emitted in large numbers by many other radioactive isotopes. Plutonium-241 primarily emits electrons, or "beta rays," which also have very little penetrating power. And the spontaneous fission neutrons produced in plutonium-240 are too few to constitute a radiological hazard. As a consequence of these characteristics, plutonium can be a severe radiological hazard only if it is retained inside the human body, especially in the lungs.

Airborne plutonium particles, small enough to be barely visible, are among the most toxic substances known. Inhalation of particles the size of specks of dust and weighing a total of some ten millionths of a gram is likely to cause lung cancer. A few thousandths of a gram of small particles of plutonium (taken together, about the size of a pinhead), if inhaled, can cause death from fibrosis of the lungs within a few weeks or less. As long as it is not breathed in or otherwise injected into the bloodstream or critical organs, however, large quantities—many kilograms—of plutonium can be safely handled for hours without any significant radiological hazards. Therefore, plutonium that is being processed must be always kept inside some kind of airtight container such as a plastic bag or one of the increasingly familiar "glove boxes" that are standard equipment in laboratories that handle highly toxic materials. In short, plutonium must be handled with considerable respect.

The optimal chemical form of plutonium to use in a fission bomb is generally the pure metal. Metallic plutonium occurs in several different "phases" with different densities. So-called "alpha-phase" plutonium (which has nothing to do with alpha particles) has a density about nineteen times greater than water at normal pressure, while delta-phase plutonium is about sixteen times more dense than water. The critical mass of a sphere of dense alpha-phase plutonium-239 inside several inches of beryllium metal (an especially good neutron reflector) is about four kilograms and about the size of a baseball. The critical mass of a sphere of delta-phase plutonium that contains percentages of plutonium-239, 240, and 241 typical of plutonium made in today's nuclear power reactors is about eight kilograms when it is inside a several-inch thick reflector of steel or copper (neither of which is as good a neutron reflector as beryllium).

Plutonium oxide, which is used as fuel material in some types of nuclear power reactors, could also be used directly in a nuclear explosive. The oxygen in plutonium oxide, which has the chemical formula PuO_2, affects the ability of the plutonium to sustain a rapid chain reaction in several ways. The oxygen takes up space, thereby reducing the number of atoms of plutonium per cubic centimeter. This tends to increase the critical mass, since a neutron must travel further than it would in plutonium metal before making a fission. But oxygen atoms are much more effective than the much heavier plutonium atoms in slowing down neutrons by billiard-ball type collisions. In the language of nuclear engineers, oxygen is a neutron "moderator." Since the probability that a neutron will cause a fission in plutonium-239 tends to *increase* as the neutron slows down, this effect of the presence of oxygen (or some other moderator) tends to *decrease* the critical mass. But the increase in fission probability resulting from slower neutron velocities cannot compensate for the effect of the decreased concentration of plutonium atoms contained in plutonium oxide, so that the net effect is that the critical mass of the oxide is somewhat greater than that of plutonium metal. When well compacted, plutonium oxide has a critical mass that is about one and a half times as large as the critical mass of metallic plutonium.

A particular number of assembled critical masses of plutonium oxide will also explode less efficiently than the same number of critical masses of metallic plutonium. The reason is that the neutron generation time is longer in plutonium oxide than in the metal, since the average distance between plutonium atoms is greater and the neutrons are generally moving more slowly. Consequently, if plutonium oxide is used instead of the metal, less energy would be released by the time the buildup of pressure in the core caused it to expand to the point where increased leakage of neutrons from the core would cause the chain reaction to stop.

An illicit bomb maker who possessed plutonium oxide would have two options. Either he could use it directly as bomb material and settle for a bomb that was somewhat inefficient, or he could go to the trouble of removing the oxygen so that he would need to use only about two-thirds as much plutonium and would achieve a higher explosive yield. Whichever way he chose, however, the bomb maker would have to be extremely careful always to keep the plutonium inside airtight enclosures, and to monitor all steps in the process with some kind of radiation detector to make sure he never accidentally assembled a critical mass.

The processes for converting plutonium oxide to metallic plutonium are described in detail in widely distributed, unclassified publications. Moreover, all the required equipment and chemicals can be purchased from commercial firms for a few thousand dollars or less. We find it credible that a person with experience in laboratory chemistry and metallurgy could assemble all the required information, equipment, and chemicals, and safely carry out all the operations needed to reduce plutonium oxide to metal in a clandestine laboratory in a few months.

The preceding discussion is based on the assumption that a bomb maker would have acquired plutonium oxide before it had been mixed with other oxides. When plutonium oxide is used in nuclear power reactors, it is often intimately mixed with an oxide of uranium that is slightly enriched with uranium-235. Whether or not such an oxide mixture could be used, even in principle, as the core material for a fission bomb depends on the relative concentrations of plutonium and uranium. Mixed uranium-plutonium oxide fuel suitable for use in the kinds of power reactors now operating in the United States has much too low a concentration of plutonium (in the range of 1 to 5 percent) to make the fuel material directly usable in a fission bomb. The processes necessary to extract the plutonium from such a mixture, in the form of reasonably pure plutonium oxide, are less complicated than those required to reduce plutonium oxide to metallic form, and they are also thoroughly described in unclassified publications. Once having separated the plutonium oxide from the uranium oxide, an illicit bomb maker would have the same choice we previously described.

Mixtures of plutonium and uranium oxides suitable for use in the kind of "fast breeder" reactor now under intensive development could, in principle, be used without further chemical separation as core material for a fission bomb. In order to produce the same explosive yield, however, the amount of plutonium required would be at least several times greater than if the plutonium oxide were separated. Thus, the additional effort required to separate the plutonium, at least as the oxide from the plutonium-uranium mixture used in breeder reactor fuel, would generally be worthwhile.

After plutonium has been produced from the uranium-238 in a reactor, it is extracted from spent fuel at a fuel reprocessing plant. It is then in the form of a liquid plutonium nitrate solution. Plutonium nitrate solution can sustain a fission chain reaction; in fact, the minimum critical mass of plutonium in solution is considerably smaller than the critical mass of metallic plutonium. This is because hydrogen atoms in the solution are very effective in slowing down the neutrons, thereby increasing the chances they will cause fission. Under some conditions, the critical mass can be as small as a few hundred grams. However, unlike the oxide, plutonium nitrate solution cannot be used directly in the core of a nuclear bomb. The reason is that the neutron generation time of the plutonium in solution is much too long. The solution would form steam bubbles that would disassemble the bomb before the nuclear energy had built up to explosive proportions.

Plutonium nitrate solution is not difficult to convert to usable form. It is easier to make plutonium oxide from plutonium nitrate solution than it is to separate mixed oxides in order to reduce plutonium oxide to metal. A solution of sodium oxalate, a common chemical, added to plutonium nitrate solution, will form a precipitate of plutonium oxalate which is insoluble in water. The plutonium oxalate can be separated from the solution by simple filtration and then heated in an oven to form plutonium oxide powder. As long as the steps are carried out with small batches of plutonium—a few hundred grams at a time—there is no danger of accidentally forming a supercritical mass.

The person performing these operations would, of course, have to take the precautions mentioned above in order to keep from getting significant internal doses of plutonium.

High-enriched Uranium. Natural uranium contains 99.3 per cent uranium-238 and about 0.7 percent uranium-235. Uranium-238 cannot, by itself, sustain a fission chain reaction under any conditions. Nearly pure uranium-235 (more than 90 percent U-235), on the other hand, is very suitable for making fission explosives. A given number of critical masses of uranium-235 will explode with lower efficiency and, generally, a somewhat lower explosive yield than the same number of critical masses of plutonium-239.

The spherical critical mass of uranium-235 at normal density, which is close to twenty times the density of water, is between about eleven kilograms and twenty-five kilograms, depending on the type of neutron reflector that surrounds it. This is about three times the critical mass of alpha-phase plutonium-239. Without any reflector at all, the critical mass of uranium-235 is slightly more than fifty kilograms.

Unlike plutonium, uranium-235 is not particularly toxic. No radiation shielding or protective coverings are necessary to handle it safely in quantities less than a critical mass. Uranium-235 does not fission spontaneously at a significant rate, thus releasing neutrons that might prematurely initiate a nuclear chain reaction before a weapon assembly has become highly supercritical.[d] The critical mass of uranium-235 in the form of oxide (UO_2) or carbide (UC_2), which are forms used as fuel in some types of nuclear reactors, is about 50 percent greater than the critical mass of the metal. Either the oxide or the carbide can be used directly as the core material for a bomb. The steps required for converting uranium oxide to metal are similar to those for the conversion of plutonium oxide, except that the safety precautions are much less stringent. Generally speaking, uranium is easier to convert from one chemical or physical form to another than is plutonium.

Uranium-235 must be "enriched" above its concentration in natural uranium in order to make it usable as the core material in a fission bomb. The degree of enrichment required is difficult to define with any precision. Below an enrichment level of about 10 percent (i.e., the fraction of all uranium atoms that are uranium-235 in a mixture of U-235 and U-238 atoms is equal to 10 percent), uranium cannot be used to make a practical fission bomb, even though it can be used with a neutron moderator to sustain a "slow" fission chain in a reactor. This is basically for the same reasons that a solution of plutonium nitrate cannot be used to make a nuclear explosion.

---

[d] Uranium 238, however, does spontaneously fission at a rate that, though roughly 1,000 times slower than plutonium-240, can under some circumstances affect the course of a chain reaction in a fission bomb.

At enrichment levels above 10 percent, the situation becomes complicated. The critical mass of metallic uranium at 10 percent enrichment, with a good neutron reflector, is about 1,000 kilograms, including 100 kilograms of contained uranium-235. Though very heavy, this would still be a sphere of only about a foot and a half in diameter. At 20 percent enrichment, the critical mass drops to 250 kilograms (fifty kilograms of contained uranium-235), and at 50 percent enrichment it is fifty kilograms, including twenty-five of uranium-235. At 100 percent enrichment, the critical mass of uranium-235 is about fifteen kilograms, and about the size of a softball.

It is probable that some kind of fission explosive with a yield equivalent to at least a few tens of tons of high explosive could be made with metallic uranium at any enrichment level significantly above 10 percent, but the required amount of uranium-235 and the overall weight of the bomb is reduced dramatically as the enrichment is increased to about 50 percent. Since most nuclear power reactors use uranium fuel that is either enriched below 10 percent or above 90 percent, we are primarily concerned with uranium enriched above 90 percent. Unless otherwise noted, we use the term "low-enriched uranium" to mean uranium enriched above its natural concentration, but below 10 percent; "intermediate-enriched uranium" to mean uranium enriched between 10 percent and 90 percent; and "high-enriched uranium" to mean uranium enriched above 90 percent.

Natural or low-enriched uranium in the form of a gas, uranium hexafluoride (UF_6), can be further enriched in an isotope enrichment plant in order to obtain high-enriched uranium. After enrichment, the gas can be liquified under pressure for storage and shipment. Uranium hexafluoride is relatively easy to convert to uranium oxide or metal.

Two methods for enriching uranium that have been highly developed are gaseous diffusion and gas centrifugation. As far as we know, gaseous diffusion is the only method that has been used thus far for large scale separation of uranium isotopes. Many important details of the gaseous diffusion isotope separation process remain classified. It is well known, however, that it requires very large amounts of electric power (enough to meet the needs of a U.S. city with a population of several hundred thousand), and large capital investments (of the order of hundreds of millions of dollars, at least) in complex equipment and huge facilities.

As far as we have been able to determine, the performance characteristics of gas centrifuge techniques for uranium isotope separation have not been discussed in detail in the unclassified literature. It is generally claimed that the electric power and capital investments required for a gas centrifuge plant would be substantially lower than for a gaseous diffusion plant. But gas centrifuge systems are extremely complex. They require very many individual centrifuges which must be designed to exceedingly close physical tolerances.

A third method for uranium enrichment would make use of laser beams to stimulate atomic or molecular transitions in U-235 (but not in U-238). Laser techniques have recently received considerable attention, and may conceivably lead to large reductions in the cost and complexity of uranium isotope separation in the future. At the present time and for at least a few more years, however, isotope enrichment facilities for converting either natural or low-enriched uranium to high-enriched uranium will be extremely costly and complex, and probably beyond the reach of any but the highly industrialized nations.

High-enriched uranium hexafluoride is too dilute to use directly in any practical type of fission bomb. It is easier to convert the fluoride to uranium oxide than to metal, but both conversions could be carried out, conceivably in a clandestine laboratory, using chemicals and equipment that can easily be purchased commercially. High-enriched uranium hexafluoride is likely to be less attractive to a nuclear thief than the oxide or metal, but it is likely to be considerably more attractive than low-enriched or natural uranium.

Uranium-233. This isotope is produced in nuclear reactors that contain thorium. When a neutron is captured in thorium-232, the isotope of thorium that occurs in nature, it forms thorium-233. This radioactively decays, with a half-life of about twenty minutes, to protactinium-233, which subsequently also decays, with a half-life of about a month, to uranium-233. This isotope is relatively very stable, with a half-life of about 160,000 years. The critical mass of uranium-233 is only about 10 percent greater than the critical mass of plutonium, and its explosive efficiency, under comparable conditions, is about the same as plutonium. It is much less dangerous to work with than plutonium.

In ways that are analogous to the production of variant forms of plutonium in a uranium-fueled reactor, several other isotopes of uranium, besides uranium-233, are formed in a reactor that contains thorium. Some of these, such as uranium-234, act as a dilutant, thereby increasing the critical mass of uranium-233 about ten to twenty percent. None of these isotopes, however, fission spontaneously at a rate high enough to affect the course of a chain reaction during assembly of more than one critical mass in a fission bomb. In this respect, uranium-233 is similar to uranium-235.

One of the uranium isotopes formed in reactors that contain thorium is uranium-232. This decays through a rather complicated radioactive chain to form several isotopes that emit gamma rays, a particularly penetrating form of radiation. Uranium-232 is not separated from uranium-233 at a nuclear fuel reprocessing plant, the chemical properties of different isotopes of the same element being practically identical. Uranium-233, as used in the nuclear industry, will therefore contain enough uranium-232 (typically several hundred parts per million) to require concrete or other types of gamma ray shielding to protect workers in plants that routinely handle large quantities of the material. These gamma rays do not necessarily present a dangerous hazard to an illicit bomb maker who is working, without any shielding, close to kilogram quantities of uranium-233. However, the total time of direct, close-up exposure to the material must be limited to several dozen hours in order that the cumulative dose of gamma rays received amounts to no more than about a dozen chest x-rays. Although such exposure within a few months or less is considerably greater than that permitted workers at nuclear facilities, it might be of little concern to an illicit bomb maker.

Uranium-233 is much less dangerous to breathe or ingest than plutonium, but it is more dangerous in this respect than uranium-235. People working with unconfined uranium-233 could simply take the precaution of wearing masks designed to filter out small particles, and of making sure they do not work with the material when they have any open wounds. Alternatively, they could take the same precautions as those required for handling plutonium.

Since the chemistry and metallurgy of uranium-233 are practically identical to those of uranium-235, its conversion from one form to another requires the same processes. As is the case for plutonium or high-enriched uranium, the oxide or carbide forms of uranium-233 could be used as core material for fission bombs. Similarly, this would require about 50 percent more material, and produce a somewhat lower yield than if metal were used in the same type of bomb.

"Strategically Significant" Quantities of Fission Explosive Materials. Our discussion so far may have suggested to some readers that the minimum quantity of a fission explosive material required to make some kind of fission bomb, sometimes called the "strategically significant" quantity, is roughly equal to the spherical critical mass of that material, in metallic form, inside a good neutron reflector, or tamper. This is not the case. The amount required depends on the particular type of fission explosive in which it is used.

If the material is to be used in a gun-type of fission explosive, which becomes supercritical when more than one critical mass is assembled at normal density, the additional amount depends on the desired explosive yield. In his *Encyclopedia Americana* article, Foster states that a nuclear yield equivalent to several hundred tons of high explosive will be released if a mass of material equal to two critical masses is assembled and a neutron is injected to start the chain reaction. The actual yield depends on the particular characteristics of the masses and types of materials involved. On this basis one might argue that, to be on the safe side with regard to protecting nuclear materials from theft, the "strategically significant quantity" of a material should be its critical mass, as a sphere of the material in metallic form, inside a thick tamper of beryllium. We have chosen this arrangement because it corresponds to the lowest critical masses of fission explosive materials that are given in published reports. For plutonium, high-enriched uranium, and uranium-233 these masses are, respectively, about four, eleven, and four and one half kilograms.

If, on the other hand, the material is to be used in an implosion type of fission bomb, the amount required may be significantly lower than these quantities. Materials that are compressed above their normal densities have a lower critical mass than when they are uncompressed. In the special case when both the core and the reflector are compressed by the same factor, the critical mass is reduced by the square of that factor. Thus, when a spherical core and reflector assembly that is initially close to one critical mass is compressed to twice its initial density, it will correspond to about four critical masses. The dependence of the densities of heavy elements on their pressures and temperatures (their "equations of state"), and the pressures that can be achieved in various types of chemical explosive assemblies are described in unclassified publications. But this information alone does not tell one how high are the compressions that can actually be achieved in practical implosion systems. The reason is that the compressions achieved in an actual device depends, in detail, on how the device is designed. In particular, the compression achieved depends on how close the implosion is to being perfectly symmetrical.

Therefore, the minimum amount of fission explosive material required to make a reasonably powerful implosion type fission bomb depends on how much the bomb maker knows, on his ability to predict the detailed behavior of implosion systems during the implosion and the chain reacting phases, and on the skills, equipment, and facilities at his disposal for building the device.

One might argue that, to be on the safe side again, a strategically significant quantity of plutonium, high-enriched uranium, or uranium-233 should be defined as the smallest amount that could reasonably be expected to be used in a fission bomb designed by the best experts in nuclear explosive technology. Even if such quantities were defined, they would be highly classified. Nevertheless, the issue of what should be considered as a strategically significant quantity of fission explosive material for purposes of developing an effective system of safeguards against nuclear theft is one that recurs at various points throughout this study. Suffice it to say at this point that it is an important policy question for which there can be no purely technical answer.

Skills and Non-Nuclear Resources Required to Make Fission Bombs

As a result of extensive reviews of publications that are available to the general public and that relate to the technology of nuclear explosives, unclassified conversations with many experts in nuclear physics and engineering, and a considerable amount of thought on the subject, we conclude:

Under conceivable circumstances, a few persons, possibly even one person working alone, who possessed about ten kilograms of plutonium oxide and a substantial amount of chemical high explosive could, within several weeks, design and build a crude fission bomb. By a "crude fission bomb" we mean one that would have an excellent chance of exploding, and would probably explode with the power of at least 100 tons of chemical high explosive. This could be done using materials and equipment that could be purchased at a hardware store and from commercial suppliers of scientific equipment for student laboratories.

The key persons or person would have to be reasonably inventive and adept at using laboratory equipment and tools of about the same complexity as those used by students in chemistry and physics laboratories and machine shops. They or he would have to be able to understand some of the essential concepts and procedures that are described in widely distributed technical publications concerning nuclear explosives, nuclear reactor technology, and chemical explosives, and would have to know where to find these publications. Whoever was principally involved would also have to be willing to take moderate risks of serious injury or death.

Statements similar to those made above about a plutonium oxide bomb could also be made about fission bombs made with high-enriched uranium or uranium-233. However, the ways these materials might be assembled in a fission bomb could differ in certain important respects.

We have reason to believe that many people, including some who have extensive knowledge of nuclear weapon technology, will strongly disagree with our conclusion. We also know that some experts will not. Why is this a subject of wide disagreement among experts? We suspect that at least part of the reason is that very few of the experts have actually spent much time pondering this question: "What is the easiest way I can think of to make a fission bomb, given enough fission explosive material to assemble more than one normal density critical mass?" The answer to this question may have little to do with the kinds of questions that nuclear weapon designers in the United States, the Soviet Union, the United Kingdom, France, or Peoples Republic of China ask themselves when they are trying to devise a better nuclear weapon for military purposes. But the question is likely to be foremost in the mind of an illicit bomb maker.

Whatever opinions anyone may have about the likelihood that an individual or very small group of people would actually steal nuclear materials and use them to make fission bombs, those opinions should not be based on a presumption that all types of fission bombs are very difficult to make.

EFFECTS OF NUCLEAR EXPLOSIONS

Even a "small" nuclear explosion could cause enormous havoc. A crude fission bomb, as we have described it, might yield as much as twenty kilotons of explosive power—the equal of the Nagasaki A-bomb. But even much less powerful devices, with yields ranging down to the equivalent of one ton of chemical high explosive, could cause terrible destruction.

A nuclear explosion would generally produce considerably more damage than a chemical explosion of the same yield. A nuclear explosion not only releases energy in the form of a blast wave and heat, but also large quantities of potentially lethal penetrating radiations (gamma rays and neutrons) and radioactive materials that may settle over a large area and thereafter lethally irradiate unsheltered people in the "fallout" area. The relative importance of these different forms and effects of nuclear energy in producing damage depends on the size of the explosion, the way the explosive is designed, and the characteristics of the target area. Radiation released within a minute after the explosion (so-called "prompt" radiation) tends to be more important in small explosions than large ones. The total amounts of prompt radiation released in two different nuclear explosions with the same overall explosive yield may differ, by a factor of ten or more, depending on how the bombs are designed. The relative importance of the effects of fallout, compared to other effects, depends on the local weather conditions, the nature of the immediate environment of the explosion, and the availability of shelter for people in the vicinity of the explosion. A nuclear explosion in the air generally produces less local fallout than a comparable explosion on the ground. The damage produced by the blast wave from an explosion also depends on the topography of the immediate surroundings, and on the structural characteristics of buildings in the target area.

We can illustrate such differences by a few examples. A nuclear explosion with a one-ton yield in the open in a sparsely populated area might produce slight damage. But the same explosion on a busy street might deliver a lethal dose of radiation to most of the occupants of buildings, as well as to people along the streets, within about 100 meters of the detonation. A nuclear explosion with a yield of ten tons in the central courtyard of a large office building might expose to lethal radiation as many as 1,000 people in the building. A comparable explosion in the center of a football stadium during a major game could lethally irradiate as many as 100,000 spectators. A nuclear explosion with a 100-ton yield in a typical suburban residential area might kill perhaps as many as 2,000 people, primarily by exposure to fallout. The same explosion in a parking lot beneath a very large skyscraper might kill as many as 50,000 people and destroy the entire building.

To give the reader some idea of the distances within which various types of damage might be produced by nuclear explosions of different yields, we have prepared the estimates presented in Table 2-1. These estimates are only rough approximations for the reasons given above.

Prompt radiation released during or very soon after the explosion can be in two forms, gamma rays and neutrons, both of which can easily penetrate at least several inches of most materials. Gamma ray and neutron dose

Table 2-1. Damage Radii for Various Effects of Nuclear Explosions as Functions of Yield

Yield (High Explosive Equivalent)	Radius for Indicated Effect (Meters)						
	500 REM Prompt Gamma Radiation	*500 REM Neutrons*	*Fallout (500 REM Total Dose)**	*Severe Blast Damage (10 psi)*	*Moderate Blast Damage (3 psi)*	*Crater Radius (Surface Burst)*	*Crater Radius (Underground Burst)*
1 ton	45	120	30-100	33	65	3.4	6.7
10 tons	100	230	100-300	71	140	6.8	13.3
100 tons	300	450	300-1,000	150	300	13.6	26.5
1 kiloton	680	730	1,000-3,000	330	650	27	53
10 kilotons	1,150	1,050	3,000-10,000	710	1,400	54	104
100 kilotons	1,600	1,450	10,000-30,000	1,500	3,000	108	208
1 megaton	2,400	2,000	30,000-100,000	3,250	6,500	216	416

*Assuming one-hour exposure to fallout region, for yields less than 1 kiloton, increasing to twelve hours for 1 megaton.

levels can be stated in terms of the REM, which is related to the Roentgen, a unit often used for measuring x-ray dosages. A radiation exposure of about five hundred REM of either gamma rays or neutrons absorbed over a person's entire body (a so-called "whole body" dose) would kill half the people so exposed within a few weeks or less. A radiation dose of about 1,000 REM would kill almost all the people exposed. The prompt radiation is released so rapidly that there would not be time for people in the vicinity of the explosion to take cover in shelters or behind buildings.

Delayed radiation from the fallout of a nuclear explosion could deliver lethal doses to people who remain in the open where radioactive debris has settled long enough for them to receive a total dose of roughly 500 REM. The ranges of distances indicated in Table 2-1 for radioactive fallout are based on the assumptions that the wind velocity in the area is about five miles per hour, and that exposed people remain within the area for one hour, for yields less than one kiloton, increasing to twelve hours for a yield of one megaton. These distances are the most uncertain of any shown in the table, since they depend strongly on the local weather conditions, the amount and characteristics of the surface material that would be picked up in an explosion's fireball and later deposited on the ground, the extent to which people would be able to take cover or leave the area quickly after an explosion, and many other factors.

The distances indicated in Table 2-1 for severe and moderate blast damage and cratering are considerably more predictable than the distances for severe damage by radiation. A peak overpressure of ten pounds per square inch would be likely to cause very severe damage to almost all residential and office buildings, and moderate damage to heavily reinforced concrete buildings. Three pounds per square inch would cause severe damage to wood frame residential buildings.

To summarize, the human casualties and property damage that could be caused by nuclear explosions vary widely for different types of explosions detonated in different places. Nevertheless, it is clear that under a variety of circumstances, even a nuclear explosion one hundred times smaller than the one that destroyed Hiroshima could have a terrible impact on society.

RADIOLOGICAL WEAPONS

Plutonium Dispersal Devices

We have already stated that plutonium, in the form of extremely small particles suspended in air, is exceedingly toxic. The total weight of plutonium-239 which, if inhaled, would be very likely to cause death by lung cancer is not well known, but is probably between ten and 100 micrograms (millionths of a gram). Even lower internal doses, perhaps below one microgram, might cause significant shortening of a person's life. The total retained dose of plutonium that would be likely to cause death from fibrosis of the lung within a few days is about a dozen milligrams (thousandths of a gram). All these estimates, particularly those related to shortening of life from lung cancer, are uncertain, partly because the responses of different individuals to the same doses of plutonium are likely to vary considerably. For purposes of this discussion, particularly for comparisons with other toxic substances, we assume that fifty micrograms of plutonium-239 represent a "lethal" dose, i.e., the amount that would be very likely to cause eventual death if it were internally absorbed.

In terms of the total weight of material that represents a lethal dose, plutonium-239 is at least 20,000 times more toxic than cobra venom or potassium cyanide, and 1,000 times more toxic than heroin or modern nerve gases. It is probably less toxic, in these same terms, than the toxins of some especially virulent biological organisms, such as anthrax germs.

The amounts of plutonium that could pose a threat to society are accordingly very small. One hundred grams (three and one half ounces) of this material could be a deadly risk to everyone working in a large office building or factory, if it were effectively dispersed. In open air, the effects would be more diluted by wind and weather, but they would still be serious and long-lasting.

The quantities of plutonium that might produce severe hazards in large areas are summarized in the very crude estimates presented in Table 2-2. To estimate the areas within which people might be exposed to lethal doses inside a building, we assume that dispersed plutonium is primarily plutonium-239 in the form of an aerosol of finely divided particles distributed uniformly in air throughout the building. We also assume that exposure of people to the contaminated air is for one hour, that ten percent of the inhaled particles are retained in their lungs, and that, as stated earlier, the lethal retained dose of plutonium is fifty micrograms. These conditions might be achieved by carefully introducing the plutonium aerosol into the intake of a building's air conditioning system. This might be quite difficult to do in many cases.

Table 2-2. Lethal and Significant Contamination Areas for Release of Air Suspensions of Plutonium Inside Buildings

Amount of Plutonium Released	*Inhalation Lethal Dose of Suspended Material (area in square meters)*	*Significant Contamination Requiring Some Evacuation and Cleanup (area in square meters)*
1 gram	~500	~50,000
100 grams	~50,000	~5,000,000

An area of 500 square meters (about 5,000 square feet) corresponds to the area of one floor of many typical office buildings. An area of 50,000 square meters (about 500,000 square feet) is comparable to the entire floor area of a large skyscraper. Even a few grams of dispersed plutonium could pose a serious danger to the occupants of a rather large office building or enclosed industrial facility.

The areas in which plutonium contamination would be significant enough to require evacuation and subsequent decontamination are roughly estimated to be about 100 times the areas subjected to a lethal dose. About a dozen grams of plutonium dispersed throughout the largest enclosed building in the world might make the entire building unusable for the many weeks that would be required to complete costly decontamination operations.

The dispersal in large open areas of plutonium with lethal concentrations of radioactivity is likely to be much more difficult to carry out effectively than dispersal indoors. The height of the affected zone would be difficult to hold down to a few feet. Even a very gentle, two-mile-per-hour breeze would disperse the suspended material several kilometers downwind in an hour. This would make it extremely difficult to use less than about one kilogram of plutonium to produce *severe* radiation hazards. With a few dozens of grams of plutonium, however, it would be relatively easy to contaminate several square kilometers sufficiently to require the evacuation of people in the area and necessitate a very difficult and expensive decontamination operation.

After the plutonium-bearing particles settled in an area, they would remain a potential hazard until they were leached below the surface of the ground or were carried off by wind or surface water drainage. As long as the particles remained on the surface, something might happen to draw them back into the air. Contamination levels of about a microgram of plutonium per square meter would be likely to be deemed unacceptable for public health. Thus, in an urban area with little rainfall, a few grams of plutonium optimally dispersed out of doors might seriously contaminate a few square kilometers, but only over a very much smaller area would it pose a lethal threat.

So far in our discussion, we have considered only plutonium-239, the isotope of plutonium that is produced in the largest quantities in nuclear reactors. Plutonium-238, which is also made in significant quantities in some reactors, is considerably more toxic than plutonium-239. Its half-life for emitting alpha particles is only about eighty-seven years, instead of about 25,000 years; one gram of plutonium 238 therefore emits alpha particles at approximately 300 times the rate that plutonium-239 does. As a result, the lethal dose of plutonium-238 is about 1/300 of what it is for plutonium-239. We mention this because plutonium-238 has been used in radioisotope-powered nuclear "batteries," and is being seriously considered for use in power supplies for heart pumps in people suffering from certain types of heart disorders. As much as sixty grams of plutonium-238, the equivalent in toxicity of almost twenty *kilograms* of plutonium-239, may be in each such heart-pump battery. This is enough material to produce serious contamination of hundreds of square miles, if dispersed in the form of small particles.

A variety of ways to disperse plutonium with timed devices are conceivable. These would allow the threatener to leave the area before the material is dispersed. Any plutonium contained inside such a device would not be a hazard until it was released.

People who absorb lethal but not massive doses of plutonium would not sense any of its effects for weeks, or perhaps years. The presence of finely divided plutonium in an area could be detected only with sensitive radiation monitoring equipment. Such equipment is now only used to monitor the presence of plutonium or other dangerously radioactive materials in nuclear installations. Except in such installations, therefore, people would not know they were exposed until they were told, either by those responsible for the threat, or by someone in authority who happened to detect the plutonium with instruments.

We are not aware of any successful non-military attempts to use chemical, bacteriological, or radiological poisons to contaminate large areas. Whether any such means will be used in the future for criminal or terrorist purposes is, we believe, an even more speculative question than whether nuclear explosives will be so used. Many types of potentially lethal poisons are no more difficult to acquire than chemical high explosives. However, high explosives are being used with greater frequency and in increasing amounts by terrorists and extortionists, while we have found no evidence that they have ever used poisonous agents. The practically instantaneous, quite obvious destruction that is produced by an explosion apparently better suits the purposes of terrorists and extortionists than poisons that act more slowly and subtly, but that are at least as deadly. Unlike other poisons, however, plutonium can be used either as a poison or as explosive material. Accordingly, a threat using a plutonium dispersal device could conceivably be followed by a threat involving plutonium used in a nuclear explosive.

Other Types of Radiological Weapons

As part of our research for this study, we considered, in some detail, the effects that might be produced by dispersing radioactive materials other than plutonium, or by purposely pulsing various types of unshielded nuclear reactors to destruction without achieving a real nuclear explosion. We conclude that neither type of weapon would be as effective as a plutonium dispersal device or a low-yield fission bomb.

Spent nuclear reactor fuel and the fission products separated from reactor fuels at a chemical reprocessing plant are, potentially, extremely hazardous if dispersed in a populated area. But they would also be very dangerous to handle in sufficient quantities to pose a threat to a large area because they emit highly penetrating gamma rays, thus requiring heavy shielding to protect thieves or weapon makers. In short, plutonium would be easier to use for destructive purposes than radioactive fission products.

If a nuclear reactor core were pulsed to destruction, it would release a comparatively small amount of energy equivalent to, at most, a few hundred pounds of high explosive from a device weighing several tons. It would also release amounts of radiation and radioactive materials that would be very small compared to a low-yield nuclear explosion unless the reactor had been operated at high power levels for some time before use as a weapon. Under such conditions, it would have to be transported in heavy shielding and would pose even greater handling problems than stolen spent nuclear reactor fuel. Generally speaking, therefore, it would be easier to make and use a fission bomb than to make and pulse a nuclear reactor core in a way that would produce damage on the scale of a fission bomb.

PURE FUSION EXPLOSIVES

A pure fusion explosive would be a device that would not require any fission "trigger" to initiate explosive thermonuclear (fusion) reactions in very light hydrogen isotopes such as deuterium and tritium. There is considerable discussion in the unclassified literature concerning the possibility of developing this type of explosive. No successful development has yet been announced, and we have no reason to believe it has taken place.

Recent papers suggest that it may be possible to use intense laser pulses to implode small "pellets" of deuterium and tritium (and possibly pure deuterium) in such a way as to cause the pellets to explode. The concept is described in the context of its possible use for the generation of electric power. Very small thermonuclear explosions would be confined, possibly with magnetic fields, and the explosion energy would be extracted to produce electricity.

Intensive research and development on such systems is under way in AEC laboratories and at least one industrial laboratory. Some people working on laser-induced fusion suggest that the scientific feasibility of the concept may be successfully demonstrated within a year or two. There is considerable controversy, however, about when the practicality of laser-induced fusion may be demonstrated. Whether or not laser-triggered fusion could be developed into practical and transportable nuclear explosives with yields equivalent to or greater than tons of chemical high explosives is not revealed in the unclassified literature, and the answer may well be unknown.

In any case, we do not believe that pure fusion explosives could be made clandestinely in the foreseeable future without highly sophisticated equipment and exceptionally highly skilled and experienced specialists.

NOTES TO CHAPTER TWO

1. John S. Foster, "Nuclear Weapons", Encyclopedia Americana, Volume 20, pp. 520-522, Americana Corporation, New York, 1973. Reprinted with permission of the Encyclopedia Americana, copyright 1973, The Americana Corporation.

Chapter Three

Nuclear Fuel Cycles: 1973-1980

INTRODUCTION

In Chapter 2 we considered the nuclear materials and other resources required to make fission bombs and described the damage that could result from nuclear explosions or the dispersal of plutonium. In order to appreciate the risk that nuclear weapon materials might be stolen from the nuclear power industry, our next step is to describe the facilities and operations that, taken together, comprise the "nuclear fuel cycles" required to support each major type of reactor used to generate electric power. A typical nuclear fuel cycle includes facilities for mining, converting, enriching, fabricating, using, reprocessing, and recycling nuclear fuels. It also includes all the transportation links between these facilities.

We want to know which points in each fuel cycle need safeguards against theft. Where can materials be found, both now and in the future, that are usable for making nuclear weapons? What quantities of these materials, in what physical and chemical forms, could thieves expect to find at different stages of a fuel cycle? How heavy and how large are the units that contain these materials likely to be? In short, we intend to provide in this chapter a factual basis for deciding which parts of nuclear fuel cycles are *inherently* most vulnerable to attempted thefts of nuclear weapon materials. We will then be prepared to consider various measures to safeguard against nuclear thefts in subsequent chapters.

We also briefly discuss in this chapter certain research applications of nuclear energy because they now involve considerable quantities of nuclear weapon materials, sometimes in forms that are especially susceptible to theft. We do not mean to imply, however, that these are the only civilian applications of nuclear energy where a risk of nuclear theft may exist. Other serious possibilities might arise beyond 1980. We restrict ourselves to the risks of theft primarily

511-13, 749; pt. 4, p. 2431 (1972). The AEC Budget for Fiscal Year 1974 does not break out the comparable figures for safeguards activities. The safeguards research and development budget was increased slightly to $4.4 million for all operations. Report by the Joint Committee on Atomic Energy, *Authorizing Appropriations for the Atomic Energy Commission for Fiscal Year 1974*, 93d Cong., 1st Sess., p. 12 (1973).

Chapter Six

Risks of Nuclear Theft

INTRODUCTION

It is all too easy to imagine innumerable possibilities for nuclear theft—a parade of horrors. It is extremely difficult, however, to determine where the line should be drawn between credible and incredible risks, between risks that should be safeguarded against and those that can be safely ignored. An assessment of the risks of nuclear theft is even more speculative than an analysis of the risks of major accidents in the operation of nuclear power reactors. With respect to reactor operation, risks to public safety arise primarily from the possibilities of malfunctioning machines. In regard to nuclear theft, however, the risks to national and individual security arise primarily from malfunctioning people.

Nevertheless, the safety risk analysis applicable to reactor accidents and the analysis of security risks applicable to nuclear theft have two difficulties in common. In the first place, both types of analysis deal with very low probability risks of very great damage. It is noteworthy, however, that the damage which might result from a nuclear theft is potentially much greater than the damage that could result from the maximum credible accident in the operation of a nuclear power reactor. Second, as to both areas of risk, there is, and hopefully will continue to be, a lack of actual experience involving substantial damage to the public on which to base predictions.

As fuel for power reactors, nuclear weapon material[a] will range in commercial value from $3,000 to $15,000 per kilogram—roughly comparable to the value of black market heroin. The same material might be hundreds of times more valuable to some group wanting a powerful means of destruction.

---

[a] Throughout chapter 6 and the remainder of this book, we use "nuclear weapon material" to mean material that can be used in fission explosives or, in the case of plutonium, in dispersal devices either directly or with chemical conversions that are much simpler processes than those involved in reprocessing irradiated nuclear fuels or in isotope enrichment.

Furthermore, the costs to society per kilogram of nuclear material used for destructive purposes would be immense. The dispersal of very small amounts of finely divided plutonium could necessitate evacuation and decontamination operations covering several square kilometers for long periods of time and costing tens or hundreds of millions of dollars. The damage could run to many millions of dollars per gram of plutonium used. A nuclear explosion with a yield of one kiloton could destroy a major industrial installation or several large office buildings costing hundreds of millions to billions of dollars. The hundreds or thousands of people whose health might be severely damaged by dispersal of plutonium, or the tens of thousands of thousands of people who might be killed by a low-yield nuclear explosion in a densely populated area represent incalculable but immense costs to society. These intrinsic values and potential costs should be borne in mind throughout our analysis of the risks of theft of nuclear weapon material from the nuclear power industry.

The analysis which follows focuses exclusively on the potential security risks involved in the development and use of nuclear power. We have avoided analogies to a multitude of other security risks, some of which appear equally deserving of study and concern. For example, biological or chemical agents might be diverted from their intended medical or industrial uses for use in very powerful weapons, or they might be produced in clandestine laboratories operated by criminal groups. Chemical high explosives have been frequently used for criminal and terrorist purposes, often with devastating effects. Thus, it is important to view the security risks implicit in nuclear power as a cost to be weighed against the benefits of nuclear energy as a source of electric power, and also as an integral part of the general problem of violence that afflicts society.

With these cautionary thoughts in mind, we may explore the possibilities for and consequences of diversion of nuclear material from the nuclear power industry to illicit use. Our analysis is mainly intended to provide readers with a more informed basis for making their own judgments concerning the credibility of the risks involved—judgments which can be expected to differ widely since they will be necessarily based on individual views of human nature.

We consider the risks of nuclear theft by different types of potential thieves: one unstable or criminal person acting alone; a profit-oriented criminal group; a terrorist group; a nuclear enterprise; and a political faction within a nation. For each type of potential risk, we outline the reasons for theft, the scope of the risk, and various methods of thievery. Finally, we examine the main problems associated with nuclear black market operations. The nature and extent of such a market, if any, generally affects the specific risks of theft previously considered.

Although our study concerns primarily the theft of nuclear material from the U.S. nuclear power industry, the risk analysis is also applicable to possibilities in other countries with nuclear power industries. Indeed, some of the risks would seem to be greater in other countries than in the U.S., while others may be greater in the U.S. than elsewhere. Moreover, material stolen from the U.S. nuclear power industry might be used to threaten the security of people in foreign countries and their governments. Similarly, material diverted from the nuclear industry in a foreign country might form the basis for a nuclear threat within the U.S. (The related risks of governmental diversion in non-nuclear-weapon countries are considered in Appendix D).

THEFT BY ONE PERSON ACTING ALONE

Reasons

The possible reasons for one person to attempt to steal nuclear weapon material from the nuclear power industry cover a broad spectrum. On one end of the motivation spectrum is financial gain, and on the other is a sick expression of extreme alienation from society as a whole. In between lie such motives as settling a grudge against the management of a nuclear plant, or a strong conviction that nuclear weapon proliferation is a good thing. Money would seem to be the most likely general motive for an individual to steal nuclear material, assuming a buyer were available. (The terrorist would normally be operating as part of a group rather than alone.)

More specifically, the lone person who contemplates theft of nuclear weapon material may do so with any of a large number of particular uses for the material in mind. Possible uses include the following:

Black Market Sale. The entire amount of stolen material might be sold in one transaction, if a large quantity of nuclear material would bring a premium price. Alternatively, small amounts might be sold over long periods of time in separate transactions, if the thief viewed his ill-gotten gains as something like a very precious metal to be liquidated in installments as income is needed.

Ransom of Stolen Material. If carefully worked out, the thief might be able to obtain at least as high a ransom for the stolen material as he would be able to get by sale in a black market. The nuclear enterprise stolen from would be one possible target of such a blackmail scheme; another might be the U.S. government. The nuclear enterprise, the government, and—depending on his tactics—the thief himself, might have a strong interest in keeping from the public any information about a nuclear theft. This possibility raises two questions: In what circumstances do the American people have a right or a need to know about a theft of material from the U.S. nuclear power industry? And, furthermore, do other governments have a right or a need to be informed about such a theft, if circumstances indicate that the stolen material has likely been taken out of the country?

Fabrication of a Weapon and Actual Nuclear Threat. As indicated in Chapter 2, the manufacture of a fission explosive or plutonium dispersal device may be within the capabilities of one person working alone, assuming he possesses the requisite technical competence. But what would the individual do with his nuclear weapon? As with stolen material, he might sell the device in the black market or ransom it. Any level of government—municipal, state, or federal—might be a target for blackmail of this type, and a governmental authority might be prepared to pay a very high price to gain possession of the device. The blackmailer would, of course, have to establish the credibility of the nuclear threat, but this would not seem difficult. One easy way to do so would be to send the authorities a design drawing of the device, perhaps together with a sample of the nuclear material used and photographs of the actual device.

As with the ransom of stolen nuclear material, the blackmailer could make his demands and conduct the entire transaction in secret, or he might from the outset or at some stage in the negotiations make his demands known to the public. The governmental authorities would probably wish to keep the matter secret, at least until an emergency evacuation became necessary. If the nuclear threat were disclosed to the public, serious panic could result. The threatener would have to be sure that, whatever his demands, they were satisfied prior to or simultaneously with the government's gaining possession of the device. This might be very difficult to arrange, especially for a lone individual.

Nuclear Hoax. If a design description plus a sample of nuclear material would establish the credibility of a nuclear threat, why would the threatener have to actually fabricate and emplace a fission explosive or plutonium dispersal device in order to obtain satisfaction for his demands? If government authorities were willing to pay off a nuclear bluff or hoax, the potential profit or political utility of a small amount of nuclear weapon material would be increased substantially. One or a series of such hoaxes would greatly complicate the problem facing a government. Even the appearance of succumbing to a nuclear threat, whether genuine or not, might be an added incentive to potential thieves.

If a person perpetrates a nuclear hoax on a government that has previously experienced one or more bomb threats, made payoffs, and recovered the devices, the hoax will probably be successful. If, however, a government has made payoffs as a result of credible hoaxes, but not recovered any devices, it may establish a policy of no more payoffs. This could create a situation of extreme danger. The next credible bomb threat might be the real thing, and a nuclear catastrophe would be the probable result.

On the one hand, a government policy of paying off all credible nuclear bomb threats would probably increase the frequency of such threats to intolerable levels. The results could be a large drain on financial resources, great anxiety in people living in urban areas, and widespread loss of confidence in the ability of governmental institutions to cope with the security problem. On the other hand, if a policy of not paying off on any nuclear bomb threat were adopted, it might have to be accompanied by strict and enforceable urban evacuation plans which could be carried out immediately upon receipt of a credible threat. If credible nuclear threats occurred often, an urban community would be paralyzed at enormous costs to society as a whole. The alternative would be to assume the risk and ignore any nuclear bomb threat.

If the government adopted a policy of trying as best it could to distinguish between the actual nuclear threat and the hoax, the consequences of a wrong choice would again be nuclear catastrophe. Therefore, the acceptability of such a policy would depend on a foolproof method of discriminating between the real threat and the hoax. It is difficult to imagine such a method.

Scope of the Risk

Fortunately, not everyone is a potential thief of nuclear material. The greatest risk of nuclear theft by one individual acting alone is posed by persons authorized access to nuclear material at facilities (mainly nuclear industry employees), and to persons authorized control over nuclear material during shipment between facilities in the various fuel cycles. This considerably narrows the scope of the risk of individual theft. But it also means that someone who is in a position to steal nuclear material by himself may well possess the technical knowledge required to handle it safely and use it destructively.

However, anyone can make a nuclear threat simply by lifting a telephone. A very large number of people could make a nuclear threat that is credible—at least up to a point—but still be a hoax. At least one such threat has already occurred. (This was the extensively reported Orlando nuclear bomb hoax described in Chapter 5.)

Options. The lone thief who is an employee in a nuclear facility or somewhere in the transportation system for nuclear material has two basic options for acquiring material for fission explosives or radiological weapons: (1) he can attempt to steal a large amount of material at one time; or (2) he can take a small amount each time in a series of thefts. One possible scenario for a large theft by an individual from a nuclear facility would be to fake an accident involving the risk of employees being exposed to high radiation levels, or some other emergency condition which requires the immediate evacuation of all persons from the facility. The thief might then be able to make off with a significant quantity of material through the emergency safety exits. Individual acts of theft of nuclear material in transit or in storage during transit could also result, if successful, in the loss of large amounts of material.

The possibility and significance of a series of thefts of small amounts of nuclear material would depend on the detection threshold and the elapsed time between the events and discovery of their occurrence. It seems that materials accountancy alone would provide insufficient protection against small thefts by a plant employee given the limit of error of material unaccounted for (LEMUF) in any such system, as discussed in Chapters 5 and 7, and the knowledge the employee would normally have of what the LEMUF was.

THEFT BY A CRIMINAL GROUP

Reasons

There are two reasons why a criminal group might want nuclear weapon materials. One is obvious: money, which might be obtained through black market or ransom dealings in the materials themselves, in fabricated fission explosive devices, or in fabricated plutonium dispersal devices. The corollary reason is that the possession of a few fission explosives or radiological weapons might place a criminal group rather effectively beyond the reach of law enforcement authorities. A criminal organization might use the threat of nuclear violence against an urban population to deter police action directed against its nuclear theft operations. The organization might also use nuclear threats to extort from the government a tacit or explicit relaxation of law enforcement activities directed against a broad range of other lucrative criminal operations.

Scope of the Risk

To what extent would criminal groups become interested in the potential for financial gains in illicit trade in nuclear material? It may be argued that the potential gains are so large that a wide variety of criminal organizations would attempt to exploit the possibilities of nuclear theft. To the contrary, however, it may be argued that criminal groups primarily interested in money are likely to be politically conservative, and that they would not develop a black market in a commodity such as nuclear material which could have revolutionary political implications. Moreover, a large nuclear theft might prompt a massive governmental crackdown and lead to a widespread public outcry, whereas the continued existence of organized crime on a large scale might depend on the susceptibility of some government officials to corruption and on a degree of public indifference.

The possession of a few nuclear weapons as a deterrent against law enforcement may be viewed by a criminal group as more of a risk than a benefit. In order to obtain the advantage of a deterrent effect, the criminal group possessing such weapons would have to be willing to inflict large scale, indiscriminate harm on society. Moreover, like nuclear war between nations, if the deterrent failed and a criminal group either used nuclear weapons or failed to use them, the group itself would probably not survive the crisis as an organization.

Options

It seems very likely that a criminal group would be able to develop a capability to apply sophisticated means, including substantial force if necessary, in order to carry out a nuclear theft. Therefore, the analysis which follows focuses on the technical capabilities a group might have for dealing with nuclear material, not its capabilities to use force or stealth to obtain it.

Minimal Nuclear Capability. At a minimum, a group contemplating nuclear theft would have to be able to recognize precisely the material it wanted and to understand the procedures required for its safe handling. Regarding the tactics of nuclear theft, a criminal group with such a minimal nuclear capability would have two basic options. In the first place, it could attempt to infiltrate nuclear industry or transportation facilities through which nuclear material passes, and then attempt to steal very small quantities of material without being detected. Secondly, it could attempt to burglarize a nuclear facility or hijack a vehicle carrying a nuclear shipment and take a large amount at one time.

If successful with either a series of small nuclear thefts or a single large one, a criminal group with minimal technical competence would possess material that it could sell to others or use to blackmail the enterprise stolen from. These are basically the same options available to one person acting alone. However, an organized group would have much greater capabilities than one person to make arrangements for either the black market sale or the ransom of stolen material to a nuclear enterprise or a governmental authority.

Capability to Manufacture Nuclear Weapons. A criminal group could acquire the technical competence to fabricate nuclear weapons in a number of ways. A group member with a well-developed scientific and mathematical talent could develop the required competence on his own without formal training; or a group member with some aptitude and a college education might be sent to a year or two of graduate school; or the group might recruit, or kidnap and coerce someone already possessing the requisite technical skills. Alternatively, someone with the requisite skill might decide to pursue a career in crime rather than lawful industry and take the initiative to form his own criminal group in order to profit from nuclear theft.

A favorable location could be selected for the weapon manufacturing facilities. This might be in the midst of an intensively industrialized area or it might be in a remote and inaccessible region. Some foreign government might be willing to host a clandestine manufacturing operation outside the U.S. Any government opposed to nuclear weapon proliferation might find it extremely difficult to deal with a criminal group which had the capability to manufacture nuclear weapon devices if the group's manufacturing facilities were located on territory under the jurisdiction of a government that was amenable or indifferent to such proliferation.

The capabilities and preferences of potential buyers—terrorist groups, national governments, or political factions within national governments—could well be the decisive factor determining whether a profit-oriented criminal group would develop its own capability to manufacture nuclear weapons. For example, national governments interested in the clandestine acquisition of nuclear weapons might prefer to purchase the requisite material in order to manufacture weapons tailored to their particular requirements. However, terrorist groups might provide a ready market for fabricated nuclear explosive devices.

Capability to Manufacture Nuclear Weapon Material. It seems very unlikely that a criminal group could develop its own capability to produce significant amounts of plutonium or uranium-233. The operations required are numerous and complicated, and on too large a scale. There are a number of reasons why it is also unlikely that a criminal group would be capable of enriching uranium, at least in the near future. The technology to separate uranium isotopes by means of centrifugation, one alternative method to diffusion (which requires huge facilities), is being developed in various countries under conditions of governmental or commercial secrecy. The operation of centrifuges would be a demanding task technically. The criminal group would have to steal a number of centrifuges in order to acquire a capability to produce significant quantities of high-enriched uranium from stolen low-enriched or natural uranium. Given the cost of one centrifuge, inventory controls capable of detecting the theft of one or more centrifuges would seem justified. If a theft were promptly detected, it would seem that the government would have a relatively long time to recover the stolen centrifuges. However, the successful development and widespread application of laser techniques for isotope separation would seem to have substantial implications for the spread of uranium enrichment capabilities, possibly to criminal groups as well as to many commercial enterprises.

THEFT BY A TERRORIST GROUP

Reasons

Although financial gain should not be excluded as a possibility, the dominant motive of a terrorist group attempting to obtain nuclear material would probably be to enhance its capabilities to use or threaten violence. An important, though secondary purpose might well be to provide itself with an effective deterrent against police action. In these respects, a terrorist group possessing a few nuclear weapons would be in a qualitatively different position offensively and defensively from such a group possessing only conventional arms. Hence, theft of fuel from the nuclear power industry might place nuclear weapons in the hands of groups that were quite willing to resort to unlimited violence.

Scope of the Risk

The scope of the risk of theft by terrorist groups would seem to depend largely on how widespread terrorist behavior becomes in the future. Although any assessment in this regard is highly speculative, present trends appear discouraging. The incidence of violence initiated by various terrorist groups seems to be increasing in many parts of the world. Terrorist organizations are increasing their technical sophistication, as evidenced by the armaments and tactics they use. Such groups are also rapidly developing transnational links with each other in order to facilitate the flow among countries of arms and ammunition and even of terrorist personnel. Whatever works as a terrorist tactic in one part of the world appears likely to be picked up and possibly emulated elsewhere. One wonders how in the long run nuclear power industries can develop and prosper in a world where terrorist activities are widespread and persistent. For if present trends continue, it seems only a question of time before some terrorist organization exploits the possibilities for coercion which are latent in nuclear fuel.

Options

Terrorist groups might become a large source of black market demand for nuclear weapons. However, such a group may prefer, for various reasons, to develop its own capabilities of stealing and using nuclear materials. A terrorist group may wish to be independent of any ordinary criminal enterprise; the group may believe that a spectacular nuclear theft would serve its purposes; or the group may be able to obtain the material it wants more cheaply by stealing it than by buying it on the black market. It is difficult to imagine that a determined terrorist group could not acquire a nuclear weapon manufacturing capability once it had the required nuclear weapon materials. In this regard, a terrorist's willingness to take chances with his own health or safety, and to use coercion to obtain information or services from others, should be contrasted with the probably more conservative approach of persons engaged in crime for money.

The theft options of a terrorist group would not differ substantially from those available to a profit-oriented criminal group. But whereas there may be incentives working on all sides to keep the fact of theft by a profit-oriented criminal group secret from the public, there may be reasons why a terrorist group would want a successful nuclear theft to be well publicized. Theft of a large amount of nuclear material would not only acquire for the terrorist group a significant capacity for violence or the threat of violence, but also the process of executing a successful theft could itself generate widespread anxiety. People would become concerned, not only in the country where the theft occurred, but also in a country or countries against which the group's activities might be ultimately aimed. However, one important reason why a terrorist group may prefer to keep its nuclear theft operations a secret, if possible, would be its own vulnerability to swift and forceful government action during the period between nuclear theft and completion of the fabrication of fission explosive devices or radiological weapons.

The ability of a government, whether U.S. or foreign, to deal with an emergent terrorist nuclear threat would depend on the location of the group's base of operations, particularly the location of its weapon manufacturing facilities. This may be unknown and hard to determine, or it may be located on territory subject to the jurisdiction of a government that is for some reason not prepared to take decisive action against the group involved.

Once a terrorist group possesses fission explosives or radiological weapons, the group's options for their coercive use, both aggressively and to deter enforcement action against it, cover the complete range of options discussed previously for an individual acting alone and for profit-oriented criminal groups. However, if a terrorist group were involved, doubts concerning the credibility of many options previously considered would be substantially removed, and the inner logic of the possibilities for nuclear coercion would control. These possibilities would be exploited by a group of people who might be quite free of the practical, intellectual, or emotional restraints that tend to inhibit the use of violence by other groups.

DIVERSION BY A NUCLEAR ENTERPRISE

Options

We consider here only the risk that the managers of a nuclear enterprise might divert to an illicit use some of the material flowing through facilities under their operational control. The most likely diversion option would be for the managers of processing facilities to manipulate material balances within the margins of uncertainty in the accountancy system. The nuclear material input of a fuel reprocessing or fabrication plant is not known to anyone exactly. Therefore, the input could be stated to be at the lower limit of the range of uncertainty, or in other words at the lower limit of the limit of error of material unaccounted for (LEMUF). The output could then be stated to be either at the lower or at the upper limit of the LEMUF. If the material output were stated to be at the lower limit, the excess material, if any, could be diverted and secretly kept or disposed of. If, however, the output were stated at the upper limit, the plant management might be able to charge its customers for more material than was actually present.

Reasons

The managers of a nuclear enterprise may want to divert material in order to cover up previous material losses known to the management but not yet discovered by the AEC authorities. The managers may want to have some clandestine material on hand simply as a convenient way to remove material accountancy anomalies as they arise—an easy way to balance the books. Furthermore, the managers of a nuclear facility may view manipulation of material balances as a way to increase slightly the profitability of the enterprise. (The possibility of collusion between the managers of civilian nuclear operations and government authorities in the clandestine diversion of nuclear material for use in a broad range of government military programs, which is a concern primarily with respect to non-nuclear-weapon countries, is considered in Appendix D.)

Scope of the Risk

The risk that nuclear enterprise managers might manipulate material balances to their own advantage seems to be inherent in the nuclear power industry because of the high intrinsic value of the materials involved and the fact that no one will know exactly how much is actually flowing through a major facility. In addition to the presumed honesty of nuclear plant managers, however, there are limitations on the scope of this particular diversion risk. If an "arms length" commercial relationship exists between the operators of distinct steps in the fuel cycle, the possibilities for diversion by materials balance manipulations would be lessened. In addition, since one person could probably not get very far in a complicated manipulation process, a conspiracy within the plant would be necessary. This would substantially increase both the difficulty of diversion and the risk of detection.

Government materials accountancy requirements could arguably have the effect of either increasing or reducing incentives within industry to manipulate nuclear materials balances. Vigorous government enforcement of stringent materials accountancy requirements might increase the incentives for plant managers to cheat the system in order to be sure they could balance the books and keep their facilities operating efficiently. However, a lax governmental attitude towards materials accountancy might reduce incentives for discipline within industrial operations, open up opportunities for much larger manipulations of materials balances, and perhaps create conditions in which large scale diversions by criminal or terrorist groups could occur without timely detection.

DIVERSION BY A POLITICAL FACTION WITHIN A NATION

Scope of the Risk

The government of a nation is normally not of one mind. The possession by a faction or interest group within the government of enough nuclear material in a suitable form to make a few weapons might significantly affect the internal balance of political forces within a nation. This particular risk of nuclear diversion would seem negligible in the U.S. However, it could be substantial in a nation where force was commonly used as a means of transferring governmental power and authority. It should be noted that in countries where force is frequently used as an instrument for political change, the line between political faction and criminal group would sometimes be difficult to draw. This diversion risk is considered briefly here because of its potential bearing on U.S. foreign relations and its relevance to the possible development of a nuclear black market.

Reasons For Diversion

The overriding reason why a political faction within a government might want to divert nuclear weapon material would be to enhance its power to achieve its own immediate or future political objectives. The specific objectives might be either domestic or international.

In terms of domestic politics, preemptive diversion by a political faction in order to shore up its power base is one possibility. Protective diversion by a faction fearing it was about to be suppressed or outlawed is another. In either of these circumstances, the reason for nuclear diversion would be to assure stability or to deter the use of violence against themselves. The credibility of the threat or use of nuclear force in a *coup d'etat* would seem difficult to establish, however.

In terms of international policy, whether or not to acquire nuclear weapons is an issue that is likely to be on the governmental agenda of many non-nuclear-weapons nations from time to time in the future. Adherence to the nuclear non-proliferation treaty and acceptance of International Atomic Energy Agency safeguards cannot be expected to settle the issue permanently, although such governmental action should substantially strengthen the position of those within a government who are opposed to the acquisition of nuclear weapons. Those who favor the development of such weapons may view diversion of material from nuclear industry as a convenient and effective way to confront the government with a *fait accompli*, and to reverse in fact the non-nuclear-weapon decision.

Options

A political faction planning a nuclear diversion might have two ways to accomplish the result that would not be available to criminal or terrorist groups. First, the owners or managers of an industrial facility with an inventory of nuclear weapon materials might actively support one faction against another in an internal power struggle. Therefore, they might be quite willing to transfer some of the material under their control to the faction they were supporting, and perhaps to provide assistance in weapons manufacture. Second, the armed forces, or particular units of the armed forces, might be persuaded to participate in the plot and to seize the nuclear material that the governmental faction wanted.

Finally, it may be noted that in a country where violence is considered to be a necessary catalyst for political change, a political faction may decide to drop out of the government, take to the hills, and begin a civil war. A group which carried with it a significant quantity of nuclear weapon material would be in a far different political position than one which took along only conventional arms and chemical explosives.

NUCLEAR BLACK MARKET

The existence or lack of a market for stolen nuclear material, and the characteristics of such a market, would substantially affect the diversion risks previously considered. In general, the profit incentives for nuclear diversion would be increased greatly if stolen nuclear material were easy to dispose of in transactions on a black market. Although the obstacles in the way of black market development appear quite large, the potential for profits by the middlemen in the market could also be very great.

Sellers in a nuclear black market might be any of the potential thieves previously discussed. A ready market could increase not only the incentives for thefts, but also the probability that stolen material could be successfully ransomed as an alternative to marketing it. The existence of a well-developed black market would perhaps be especially pernicious because it would ease the problems an individual acting alone would otherwise face in disposing of any nuclear material he might steal.

Terrorist groups and national governments are the more likely customers in a black market. There would also seem to be possibilities for the operators of a nuclear black market to stimulate demand. Terrorist groups often appear to emulate each other's tactics. Moreover, an initial sale or two of nuclear weapons to petty dictators with dreams of glory might thereafter enable the operators in a nuclear black market to play on the fears of more responsible leaders, who would then have no way of knowing which nations had secret nuclear weapon stockpiles. A nuclear black market could offer the governments of nations without *any* previous civilian or military nuclear capabilities opportunities for acquiring nuclear weapons. Such a development could, therefore, greatly increase the dangers of nuclear weapon proliferation throughout the world.

A black market in nuclear material would seem to require a subtle and complex structure, possibly composed of several loosely affiliated groups. The market would probably become transnational in scope since demands for stolen nuclear material or fabricated weapons would not necessarily come from a country that has the sources of supply. Weapon fabrication or material processing services may or may not be part of the market operations. If they were, these activities might take place in remote areas or where a government was willing to look the other way.

A criminal or terrorist group might thus target its efforts on especially vulnerable nuclear fuel or facilities anywhere in the world. The stolen material might then be passed through various middlemen and processing steps and sold ultimately to purchasers in other countries far away from the scene of original theft.

The evolution of a nuclear black market would be a hazardous and uncertain affair. It may be doubted whether such a market could ever achieve the institutional stability or long term viability that would pose a major threat. If one or more major nuclear thefts occur, governments everywhere may be prompted to act swiftly and decisively to foreclose any possibilities for disposition of stolen material. From the preceding analysis it would seem, however, that a few successful thefts could increase incentives for black market formation, and that an incipient nuclear black market would increase the likelihood of nuclear theft or other types of diversion attempts. It should be noted that no national government acting unilaterally could prevent a nuclear black market from developing if the conditions were ripe. Like the risks of nuclear theft, the dimensions of a nuclear black market are potentially global.

Chapter Seven

Nuclear Safeguards: Basic Considerations

Thus far in this study we have examined the magnitude of the U.S. nuclear power industry and the potential risks of nuclear theft. We have also discussed the present AEC regulatory requirements designed to protect and account for nuclear materials, and observed that a safeguards system is not yet fully developed. Clearly, much remains to be done—and urgently—if an effective system of safeguards against nuclear theft is to be fully operational before very large amounts of fission explosive materials begin to flow through the U.S. nuclear power industry.

In this chapter we explore a number of basic issues related to the development of a nuclear safeguards system, including how effective such a system should be, and we also suggest a framework for the development of a variety of safeguard options. In chapters 8 and 9 we analyze specific safeguard measures and consider the costs of a safeguards system.

THE CONTEXT

We are concerned in this study with safeguards to ensure that nuclear material is not diverted from civilian industry to an illicit use. This particular objective should be viewed as part of regulating and controlling the civilian nuclear power industry in order to achieve several important purposes that are in the public interest. Aside from safeguards to prevent or detect theft, the control of nuclear material is necessary for two major reasons: to ensure that valuable materials are used efficiently as fuel for the generation of electric power or heat; and to ensure that radioactive materials that could endanger human health are used safely and are not inadvertently released to the environment in dangerous quantities or willfully dispersed by acts of sabotage. Controls designed to avert inefficient or unsafe use of nuclear material may either complement or conflict with safeguards to ensure against theft.

For example, governmental material accountancy requirements may largely build upon inventory controls adopted by the plant management in the interest of efficient processing operations. As another example, both public health and safety and safeguards against theft point toward the use of specially developed heavy containers for the shipment of nuclear materials. However, plutonium that is shipped in the form of an oxide powder is less hazardous to public health, but slightly more of a bomb risk in the event of theft, than plutonium that is shipped in the form of a liquid nitrate solution.

PURPOSES OF A NUCLEAR SAFEGUARDS SYSTEM

Perhaps the most difficult task of all in developing and implementing a nuclear safeguards system is the formulation of meaningful objectives. It was relatively easy to develop an objective for the U.S. space program in the 1960s. President Kennedy did this in 1961 when he said: "We shall place man on the moon and bring him back to earth before the end of this decade." It is also possible to develop "full employment" as a continuing national goal and then to define a 4 or 5 percent level of unemployment as unsatisfactory performance. Though it is much more difficult for the United States to maintain full employment than to place a man on the moon, both objectives are meaningful to government, to industry, and to the man in the street.

When it comes to nuclear safeguards, what should be the objective of U.S. policy? We may initially and tentatively state the purpose of a nuclear safeguards systems as follows: *to provide effective assurance against acts of nuclear violence using material unlawfully obtained from the nuclear power industry*. When words are strung together in this way, the result is an opaque and abstract statement of the problem. However, it should be noted that many statements of purpose in legislation and administrative regulations are even more vague and less meaningful. For example, the legislative standard in the Atomic Energy Act for evaluating U.S. nuclear materials safeguards is that the controls must provide assurance against activities "inimical to the common defense and security or to the health and safety of the public." Nevertheless, our tentative formulation of purpose set forth above is useful as a point of departure.

We have avoided use of the word "goal" in our statement regarding safeguards because this word seems to imply the existence of some milestone which, if reached, signals the completion of a task. The risks of nuclear theft will persist in the foreseeable future, though it will be possible to reduce their likelihood and impact considerably. Consequently, the development and maintenance of effective safeguards will require continuing effort. Specific goals and objectives will probably have to be revised often in the light of advances in nuclear technology, growth of the nuclear industry, changes in the level and character of acts of violence (not necessarily nuclear), national and international political upheavals, and, perhaps above all, shifts in public attitudes towards violence.

This much having been said, in order to move further in our analysis we must grapple with the term "acts of nuclear violence," and with the term "effective assurance." In attempting to give more concrete meanings to such terms, we must distinguish the practical from the impractical, the obtainable from the unobtainable.

"Acts of nuclear violence" might encompass an infinite variety of circumstances ranging from hoaxes, to threats involving actual nuclear weapons, to actual fission explosions or intentional plutonium dispersal. At one extreme, it is impossible to provide assurance against the occurrence of nuclear threats that are hoaxes. As we saw in Chapter 6, all sorts of people could make a nuclear threat that is credible—at least up to some point—and still be a hoax. It is doubtful that any responsible government would completely ignore a nuclear bomb threat, much less publicly declare it to be a hoax simply because the threat was not substantiated by receipt of a nuclear explosive design or a small amount of fission explosive material. Threats using radiological weapons could be even more credible with minimal amounts of substantiating information. The real question, therefore, is whether a nuclear safeguards system can provide assurance that hoaxes can be distinguished from real threats, and that real threats would be most unlikely.

At the other extreme in the range of acts of nuclear violence are unannounced fission explosions in urban areas. Here again we must conclude, regrettably, that regardless of its effectiveness, a nuclear safeguards system applicable to the nuclear power industry in this country cannot provide complete assurance that unannounced fission explosions will not occur in the United States in the future. Apart from the fact that a foreign government might accidentally or intentionally explode a nuclear weapon in the United States, a fission explosive might be smuggled from a foreign country by a terrorist group and then detonated.

Furthermore, the possibility that a past, undetected theft is the source of a real nuclear threat cannot even now be discounted entirely. The amount of fission explosive material unaccounted for in the U.S. nuclear power industry and industrial enterprises performing work under contract for the AEC has already exceeded the point where complete assurance against bomb threats using diverted material is possible. Moreover, no future safeguards system that will be practical can offer 100 percent assurance against theft.

Then who is to decide, and on what basis, what level or risk of nuclear violence can or should be acceptable as a social cost of the use of nuclear energy to meet future needs for electric power? Is the explosive destruction or plutonium contamination of a large urban area somewhere in the world to be tolerated if it does not occur more than once a year? Once every fifty years? Never? These questions need to be addressed by political leaders, not professional experts. We do not presume to answer them in this study.

Very difficult issues also arise when we try to define "effective assurance" in our tentative statement of purpose of nuclear safeguards. Even if agreement could be reached concerning some maximum acceptable level of risk of nuclear violence using material stolen from the nuclear power industry, how *effective* should the assurance be that the specified thresholds of violence will not be exceeded? Who should decide, on what basis, what level of effectiveness is sufficient, given the fact that 100 percent assurance is impossible, no matter what we do? Perhaps a look at more familiar hazardous human activities can shed some light on these questions.

Are present highway, vehicle, and operator licensing safeguards against serious automobile accidents in the U.S. "effective?" The American people are apparently willing to tolerate more than 50,000 deaths per year as a result of automobile accidents, and many drivers still object to the cost or inconvenience of rudimentary safeguards, such as seat belts and shoulder straps. Measures that would reduce the highway death rate to, let us say, 500 people per year would probably be called *highly* effective, yet they would not lessen the grief of someone whose wife or husband or child was one of the 500 fatalities.

We accept a low commercial aircraft accident rate, and an even lower train accident rate, and delegate to experts the decision as to how safe our commercial aircraft or railroads should be. In these and other matters of public safety, the level of risk demanded by society as a whole, and even by individuals, is never zero. A combination of attention by safety experts, promotion by people who make a living from the hazardous activity, and public outcries when the risks begin to loom too large, tends to produce a level of risk that is generally accepted. Perhaps the acceptable level of effectiveness of nuclear safeguards could evolve in a similar way over time.

Before adopting this approach, however, several distinguishing factors should be taken into account. In transportation accidents the number of human casualties per crash, a few in the case of automobiles and one hundred or more in airplanes, is comprehensible. The frequency of accidents involving fatalities in relation to passenger-miles traveled can be determined. These statistics provide a basis whereby persons can make individual judgments concerning levels of risk involved in travel by a particular mode, and voluntarily decide whether the benefits to them are worth the risk.

When it comes to the risks associated with various levels of effectiveness of a nuclear safeguards system, tens of thousands of human beings may be killed in a single act of nuclear violence, and such acts will occur seldom at most and hopefully never. This leaves us with no basis for weighing the probabilities involved.

This seems to make it even more important for the people in a democratic society to have an opportunity to consent, in some way, to the risk of nuclear violence implicit in a particular level of effectiveness of safeguards. Such consent cannot be presumed from an absence of broad public concern when the man in the street remains unaware of the nature and scope of the risk to which he will be exposed. Nor can general public consent be inferred from broad legislative delegations of relevant authority to the AEC and the Joint Committee on Atomic Energy of the Congress, when public hearings on this specific nuclear risk have never been held, and when most members of Congress remain as uninformed in this respect as the people that elected them.

Finally, the problem of nuclear theft exists wherever nuclear power industries exist. A successful nuclear theft in one country may result in widespread destruction in another, far distant country a few weeks or several years later. Attitudes toward levels of risk and effectiveness of nuclear safeguards can be expected to cover at least as wide a range between countries as between groups within one country, such as the United States.

Given the difficulties discussed above, it seems that all attempts to develop a meaningful statement of overall goals for a nuclear safeguards system may well end in frustration. However, our discussion thus far does lead us to conclude as follows: In view of the seriousness of the risks arising out of a successful nuclear theft, the safeguards system applicable to the nuclear power industry should employ the *best available* technology and institutional mechanisms. The safeguards system should be developed and implemented with a view to keeping the risks of nuclear theft *as low as practicable*. We believe these statements can serve as a useful guide to the development and implementation of a nuclear safeguards system that will function effectively in a dynamic world in which technological, economic, social, and political factors are changing rapidly.

FUNCTIONS OF A NUCLEAR SAFEGUARDS SYSTEM

In order to provide effective assurance against acts of nuclear violence using material stolen from the nuclear power industry, a nuclear safeguards system as a whole should perform four interrelated functions:

1. prevention of theft;
2. detection of theft;
3. recovery of stolen material;
4. response to threats of nuclear violence.

"An ounce of prevention is worth a pound of cure." The relevance of this old saw to a nuclear safeguards system is apparent from the risk analysis in Chapter 6. Nevertheless, by far the most effort to date has been devoted to the development of means to *detect* unlawful diversion after it has happened. The detection method that has received the most attention until very recently has been accountancy—record keeping, inventory controls, reports, and independent audits. It should be noted that accountancy, unlike other possible methods of detecting diversion, such as continuous surveillance, makes little if any contribution to the related function of preventing theft.

Fortunately, the development of means to *prevent* theft is now receiving much greater attention. Such well known and widely used means as physical barriers, locks, alarms, etc., are being required. However, relatively little effort has been devoted either to the use of substantial manpower or to the development of more advanced technological methods for achieving physical security. This is in marked contrast to the efforts that have been devoted to various sophisticated techniques for the assay of nuclear materials, especially the non-destructive measurement of the material content of fuel elements, scrap storage drums, etc.–efforts which are related to the detection of theft after it has happened.

The need for means to *recover* material after it has been stolen is now officially recognized. Very little has been disclosed, about what, if anything, has been actually done to provide for recovery of stolen material or material that is simply lost. Similarly, little has been said about what happens if material is unaccounted for and the amounts involved exceed the allowable limits of error. Furthermore, the government has not yet publicly recognized the need for contingency plans for responses to nuclear threats. Perhaps government officials will continue to respond on an *ad hoc* basis, as in the past, or perhaps plans have been developed but not disclosed.

While efforts to improve non-destructive assay and other accountancy techniques designed to detect material theft should be continued, there are compelling reasons why major efforts should be devoted to development of the best practical measures to prevent theft. For one, detection will merely be the event which triggers recovery operations, and these operations might well fail. For another, some prevention measures are also effective means for detection *before* the successful completion of a theft. The signaling of an alarm may also automatically close exits from a facility, as well as summon on-site security forces promptly to the scene of an attempted theft. Some preventive measures should be plainly visible, both as a deterrent to the potential thief who is only casually investigating a possibility and as a way of building public confidence. The psychological atmosphere created by the nuclear safeguards system may be as important as the technical capability of the system.

The public must be as fully informed as possible about the prevention and detection functions of the safeguards system in order to build confidence in its effectiveness. However, the extent to which the recovery and response phases should be revealed to the public is a difficult question. Revealing the details of these parts of the system in order to produce public confidence in their effectiveness could in itself substantially reduce their effectiveness. However, the general public and, even more importantly, any potential thieves must believe that the government has planned carefully about what will be done to recover any stolen material and to respond to any nuclear threat.

FRAMEWORK

In developing a nuclear safeguards system, it is useful to think from a conceptual framework provided by three basic questions: What may be controlled? Who may do the controlling? And what are the means of control? We will discuss the first two questions here. Specific measures to prevent nuclear diversion, to detect completed nuclear thefts, to recover stolen nuclear materials, and to respond to nuclear threats will be explored in Chapter 8.

What May Be Controlled?

Nuclear *material* flows through and between a variety of *facilities*, from mines to radioactive waste storage. Special *information* is necessary in order to build and operate the facilities and produce, process, and use the materials flowing through the nuclear fuel cycles. And of course, nuclear industry would not happen without *people*. Thus, material, facilities, information, and people may be the subjects of control under a nuclear safeguards system.

Materials. Nuclear safeguards systems are based primarily on controls over materials which flow through the various nuclear fuel cycles. Therefore, detailed discussion of this aspect of safeguards is necessary at this point.

All nuclear material may be subject to safeguards. Control measures may be initially applied to every shovelful of ore containing uranium or thorium that is removed from the ground, or they may even apply to deposits of uranium and thorium ore in the earth's crust. Safeguards may extend to nuclear material as it flows throughout the fuel cycle and continue to apply to material that is recycled after chemical reprocessing. Measures to ensure against theft may apply to the fissionable material that is produced in a nuclear reactor and to each successive generation of fissionable material as it is produced. Safeguards may even extend to radioactive waste material that is stored permanently. Such a comprehensive control scheme is now unrealistic and unworkable. However, the original proposals for nuclear disarmament proposed by the U.S. government at the end of World War II–the so-called Baruch plan–called for just such a comprehensive scheme. At that time, the government believed such a scheme to be necessary as a precondition for the destruction of its own stockpile of nuclear bombs, which was then very small, and as a worldwide regulatory framework for the development of industrial uses of nuclear energy.

Alternatively, a variety of exemptions from a particular safeguards system are possible. Nuclear material may be exempt when it is present only in small quantities or in certain forms. Thus, if the total quantity of plutonium or high-enriched uranium in a country is less than one kilogram, that quantity is exempt from international safeguards under the NPT. Nuclear material may also be exempt from a certain safeguards system, or those safeguards may be suspended and another system imposed if and when the material is being used for certain purposes. Thus, material may be exempt from the safeguards applicable to civilian industry when it is used under governmental authority in the manufacture of nuclear weapons or in military propulsion reactors.

The establishment of safeguards exemption limits for small quantities of material raises a number of difficult questions. Should the exemption limits be related directly to the minimum amount of a particular fission explosive material that is required to make one nuclear explosive? If so, how should this amount be determined, and by whom? In some of our previous discussions, we have used the well reflected, spherical critical masses of plutonium, high-enriched uranium, and uranium-233 at normal densities as points of reference. As discussed in Chapter 2, however, it has been widely published that an implosion system can be used to significantly compress the core of fission explosive material, and the critical mass decreases as the compression increases. Therefore, it would seem possible that significantly smaller quantities of these materials than their critical masses at normal densities can be used to make fission explosives. But how much smaller, and how dependent is the minimum amount on the knowledge and skills of the weapon designers and fabricators? Are thresholds for exemption related to the types of fission explosives that could reasonably be expected to be designed and built by one individual in a basement type operation? By a highly competent, but small non-governmental organization? By the participants in an intensive, long-term effort sponsored by an industrially advanced nation? Given the fact that answers to these questions require access to classified information, how can the public be assured that the limits established are reasonable?

Perhaps even more difficult questions, which are largely matters of subjective judgment, involve the possible eventual pooling of stolen materials, as in a black market. Even if it were possible to specify the minimum amounts of various materials that it is reasonable to expect could be used in an illegal fission explosive manufacturing effort, what portion of these amounts should be exempt from physical protection? Should the specified portions be time-dependent, allowing for the possible buildup of black market stockpiles and rates of flow?

It may also be argued that the establishment of exemption quantities should take into account the potential hazards represented by different materials if they were used for non-explosive radiological threats. As we have seen, very small quantities (grams) of plutonium could be used in radiological weapons, whereas many kilograms of uranium-233 would be required to produce comparable hazards. However, high-enriched uranium, even in very large quantities, is categorically unsuitable for non-explosive radiological weapons.

If risks of theft of plutonium-bearing fuel materials or concentrated fission products for use in radiological weapons are taken into account in setting exemption limits, how are these limits to be chosen, and by whom? Should the limit on plutonium be set at one gram? Ten grams? One hundred grams? In any event, the present exemption limits of one kilogram (IAEA and AEC limits for materials accountancy) or two kilograms (AEC limits for physical protection) are too high if radiological threats with plutonium dispersal devices are taken seriously.

There are also difficult questions concerning the exemption of certain nuclear materials from safeguards requirements for physical protection, based on the extent of the dilution of fission explosive materials by other materials. Dilution of uranium-235 with uranium-238 is a special case of this. Below what enrichment level, if any, should an exemption for uranium be established? The 20 percent enrichment threshold which is presently used by the AEC for physical protection is rather arbitrary, since fast critical assemblies can be made with uranium enriched somewhat below 20 percent, though not as low as the 3 to 5 percent enrichment level used for LWR fuel. But how about other dilutants? It may be argued that the dilution of high-enriched uranium with graphite and silicon carbide as in HTGR fuel assemblies, where the dilutants are very difficult to extract, should be used as the basis for safeguards exemptions similar to the existing exemption for low-enriched uranium.

Alternatively, it may be argued that the present AEC exemption from physical protection requirements of low-enriched uranium should be narrowed. More than half the separative work required to produce 90 percent enriched uranium has been done in enriching uranium to 3 to 5 percent for LWR fuel. It is true that further enrichment of 3 to 5 percent fuel is required in order to use it in a workable nuclear explosive, and the risk that a criminal or terrorist group might possess its own enrichment capability is now very small. But this possibility may become more likely in the future.

Regardless of their quantity, ores containing nuclear material may be entirely exempt from control or exempt up to a large limit because the difficulty and cost of processing the materials to usable form make the risks arising from theft negligible. For similar reasons, quantities of refined U_3O_8 (yellowcake) prior to enrichment may be exempt, although the concentration of uranium in yellow cake is very much greater than its concentration in ore. Here again the justification for the exemption of even these materials from safeguards may be undercut by future developments in enrichment technology.

On balance, given the projected size of the flows of plutonium and high-enriched uranium through the nuclear power industry in the U.S., it is reasonable to expect that potential thieves would prefer these fission explosive materials to low-enriched uranium. Therefore, less stringent controls on low-enriched uranium, as part of the "graded" safeguards system advocated by many governments and industrial officials, seems reasonable for the present and near future. If a graded safeguards approach is adopted, it is also arguable, as indicated above, that fission explosive materials highly diluted by other materials that are very difficult to extract should be subject to less stringent requirements than undiluted fission explosive materials.

Based on the preceding discussion, Table 7-1 is a tentative listing of nuclear material categories. The table is presented to illustrate the concept of "graded" safeguards and is not a specific proposal for a classification system. The various classes are listed in decreasing order by the degree to which safeguards might be applied to a "strategic" quantity of each material.

Table 7-1. Possible Nuclear Material Categories for a System of "Graded" Safeguards

Class	*Examples*
I. Undiluted fission explosive materials.	Metallic plutonium, high-enriched uranium, or uranium-233. Oxides or carbides of above materials.
II. Materials suitable for radiological devices whether or not diluted with materials.	Plutonium.
III. Fission explosive materials diluted by other materials that can be separated without isotope separation or "hot lab" processing facilities.	Plutonium nitrate solution. Mixed plutonium and low-enriched uranium oxides. Mixed thorium and high-enriched uranium oxides. HTGR silicon coated fuel particles.
IV. Low-enriched uranium, whether diluted or not.	LWR fuel (without plutonium recycle).
V. Natural uranium	UF_6 (enrichment plant feed) · U_3O_8 (yellowcake) · Uranium ore.
VI. Thorium	All forms of thorium.

A "strategic" quantity is *related* to the minimum amount required to produce one fission explosive or radiological device that could be used effectively to attack an area of some specified dimensions. The term "strategic quantity" may be very difficult to define for any particular material. We nevertheless see no way to avoid the problem of defining such quantities; otherwise the concept of graded safeguards becomes meaningless and the fact that some nuclear materials are more dangerous than others is ignored.

Therefore, one of the first steps in the detailed design of a safeguards system, must be to establish values for strategic quantities of the various nuclear materials used in all fuel cycles, quantities below which safeguards are not to be applied. For fission explosive materials, values should be established in a classified analysis, although the values determined should be made public. For radioactive materials that could be used in dangerous radiological devices, this could probably be done without reference to classified information.

Table 7-1 shows some materials, such as plutonium in various forms, as falling into two categories (Class II and Class III). One might argue that Class II should be considered separately from the others, or that such materials should be at a different level from the one we have chosen. We have simply found it difficult to decide whether the overall risk of theft of materials for use in fission explosives is greater or less than the risk of theft of small amounts of plutonium which could cause radiological damage over a large area.

Facilities. Safeguard measures may be applied to all or some of the facilities in the fuel cycles through which nuclear materials flow. Controls applied to nuclear facilities could be intended to prevent or promptly detect an illicit use of the facility itself—for example, if the facility were used for the secret processing of nuclear material which was not subject to safeguards. Such controls are important at the international level, although they are effected indirectly through material accountancy requirements. To the extent there is a danger that nuclear enterprises might engage in material diversion, such accountancy requirements would also be important to national governments.

By far the most important controls applied to facilities, however, are those intended to reduce the vulnerability of material in them to diversion. In this respect, the physical protection measures used at different facilities may also be "graded," as suggested in the following examples: storage facilities for high-enriched uranium or plutonium oxides vs. storage facilities for fuel assemblies containing highly diluted nuclear material; transportation systems for shipment of high-enriched uranium hexafluoride vs. those for shipment of low-enriched uranium LWR fuel assemblies; LMFBR fuel fabrication plants and LWR plants with plutonium recycle vs. LWR fuel fabrication plants without plutonium recycle.

Information. Control measures may also be applied to nuclear information. Governmental classification, industrial secrecy and legal protection of trade secrets and patents are examples of kinds of information controls. The U.S. government has adopted a classification scheme and stringent control measures to restrict the flow of certain nuclear information within the United States and from the United States to other countries.

At present, the only remaining areas of classified information relevant to the nuclear theft problem involve uranium enrichment processes and the design and manufacture of explosives. Other information is widely available, including detailed information concerning reactors, fuel fabrication, and reprocessing.

However, just because information is available does not mean that anyone can use or misuse it. Some nuclear processes are complex and are not understood without considerable scientific or technical education. But, in general, the most that should be expected from controls on access to nuclear information is a delay before the "cat gets out of the bag." It is noteworthy that the IAEA is specifically authorized under its statute to establish and administer safeguards applicable to nuclear information, but this authority has remained unused and is generally considered to be unworkable as a basis for safeguards.

People. Finally, controls may be applied to people. These controls may be applied to all persons, or to all those possessing certain knowledge concerning nuclear science or technology, or may be limited to employees of nuclear enterprises and others with access to nuclear activities. Of course, such controls would be a restriction on human freedom, but they may be justified in view of the risks of theft. For example, as mentioned in Chapter 5, the AEC has requested Congress to enact legislation permitting the government to administer an approval program for persons who have access to significant quantities of nuclear weapon material. The legislation is intended to provide a regulatory basis for improving the assurance of the trustworthiness of such persons.

Who May Control?

One or more of a variety of persons and institutions may act as controllers of material as it flows through the nuclear fuel cycles.

Employees. Individual employees of enterprises that produce, process, use, store, or transport nuclear material may be assigned safeguarding duties. Responsibility for safeguards at the employee level may be fixed on one or a few employees at a nuclear facility or spread among all employees. Control responsibilities may be imposed on individual employees by management as an operational procedure, or by a governmental authority as a legal duty.

Given the amount of the nuclear material flows involved, the incentives for theft, and the uncertainties inherent in any technical measures, it seems clear that no nuclear safeguards system can be effective without the participation of the employees of nuclear operations. Each employee should be fully informed about the risks and consequences of nuclear theft where he is employed. He must clearly understand his duties related to its prevention and detection. And finally, he must comprehend that the penalties for failure to perform his safeguarding duties, or for engaging in any unlawful diversion attempt himself, will be swift and severe.

Enterprises. Nuclear enterprises may have safeguarding duties related to the prevention and detection of theft. The managers of an enterprise will, of course, have a vital financial interest in efficient operations. Up to a point, a manager can be expected to take measures to ensure that nuclear material is not lost or stolen. That point will be reached when the marginal cost of safeguards to the enterprise exceeds the prospective cost of material lost, wasted, or stolen, regardless of the potential cost to society as a result of a successful nuclear theft. It is clear that certain measures will be necessary at the enterprise level which would not be developed or implemented by management on its own initiative. A governmental authority must impose these measures as legal duties on the enterprise. At the enterprise level, responsibility for failure to perform, or negligence in performance of safeguarding duties may be imposed on the enterprise as a whole or on the managers of the enterprise, or both.

Governments. Governmental authorities may not only impose duties and fix responsibilities on others regarding implementation of nuclear safeguards, but may themselves perform control functions and assume safeguarding responsibilities. Moreover, various levels—national, state and local—and kinds—licensing and enforcement—of governmental authority may be brought to bear in different ways. What a government *can* do depends on the jurisdictional and constitutional limits of its authority, and by the technology available. What a government *will* do in regard to safeguards is, of course, a political matter.

International Agencies. International organizations may also have duties and responsibilities regarding nuclear safeguards. It is important to recall that the safeguarding duties and responsibilities of an international organization such as the IAEA have been delegated to it by member states. In general, these functions may be exercised on the territory of a member state only with the consent of its government. The United States government has offered to permit the application of IAEA safeguards to all nuclear activities in the United States, except those of direct national security significance. This offer, which is still outstanding and remains to be implemented, is intended mainly for political effect; namely, to play down the discrimination inherent in the Non-Proliferation Treaty between nuclear-weapon and non-nuclear-weapon countries. Neither the offer nor its implementation bears importantly on the problem of theft of material from the nuclear power industry in the U.S. It is intended to help reduce the risk of governmental diversion in other countries through widespread adherence to the treaty.

FREEMAN DYSON

DISTURBING THE UNIVERSE

HARPER & ROW, PUBLISHERS
NEW YORK
Cambridge
Hagerstown
Philadelphia
San Francisco
London
Mexico City
São Paulo
Sydney
1817

PUBLISHED AS PART
UNDATION PROGRAM

9

Little Red Schoolhouse

Eddington the astronomer, in the book *New Pathways in Science,* which I read as a boy in Winchester, not only warned us against nuclear bombs but promised us nuclear power stations. Here is the happier side of his vision of the future:

> We build a great generating station of, say, a hundred thousand kilowatts capacity, and surround it with wharves and sidings where load after load of fuel is brought to feed the monster. My vision is that some day these fuel arrangements will no longer be needed; instead of pampering the appetite of the engine with delicacies like coal and oil, we shall induce it to work on a plain diet of subatomic energy. If that day ever arrives, the barges, the trucks, the cranes will disappear, and the year's supply of fuel for the power-station will be carried in in a tea-cup.

This vision had always remained vivid in my mind, together with the warning against the military use of subatomic energy which appears a few pages later in the book. Eddington used the word "subatomic" to describe what we now call nuclear or atomic energy. We all knew even in 1937 that the world would soon run out of coal and oil. The possible availability of nuclear energy to satisfy the peaceful needs of mankind was one of the few hopeful prospects in a dark period of history.

In August 1955, while I was quietly working on spin waves in Berkeley, a mammoth international conference on the peaceful uses of atomic energy was held in Geneva under the auspices of the United Nations. This was a decisive moment in the development of nuclear energy. American and British and French and Canadian and

Russian scientists, who had been building nuclear reactors in isolation and secrecy, were able for the first time to meet one another and discuss their work with considerable freedom. Masses of hitherto secret documents were presented openly to the conference, making available to scientists of all countries almost all the basic scientific facts about the fission of uranium and plutonium and a large fraction of the engineering information that was needed for the building of commercial reactors. A spirit of general euphoria prevailed. Innumerable speeches proclaimed the birth of a new era of international cooperation, the conversion of intellectual and material resources away from weapon building into the beneficent pursuit of peaceful nuclear power, and so on and so on. Some part of what was said in these speeches was true. The conference opened channels of communication between the technical communities in all countries, and the personal contacts which were established in 1955 have been successfully maintained ever since. To some small extent, the habit of openness in international discussions of peaceful nuclear technology has spread into the more delicate areas of weaponry and politics. The high hopes raised in Geneva in 1955 have not proved entirely illusory.

The technical preparations for the Geneva meeting were made by an international group of seventeen scientific secretaries. The scientific secretaries worked in New York for several months, driving hard bargains on behalf of their governments, making sure that each participating country would reveal a fair share of its secrets and receive a fair share of the limelight. They worked in obscurity and waded through vast quantities of paper. The success of the conference was entirely due to their efforts. One of the two Americans in the group of seventeen was Frederic de Hoffmann, a thirty-year-old physicist then employed as a nuclear expert by the Convair Division of the General Dynamics Corporation in San Diego, California.

As soon as the Geneva meeting was over, Freddy de Hoffmann decided the time had come to give the commercial development of nuclear energy a serious push. For the first time it would be possible to build reactors and sell them on the open market, free from the bureaucratic miseries of secrecy. He persuaded the top management of the General Dynamics Corporation to set up a new division called General Atomic, with himself as president. General Atomic began its life at the beginning of 1956 with no buildings, no equipment and no staff. Freddy rented a little red schoolhouse that had been abandoned as obsolete by the San Diego public school system. He proposed to move into the schoolhouse and begin designing reactors there in June.

Freddy had been at Los Alamos with Edward Teller in 1951 and had made some of the crucial calculations leading to the invention of the hydrogen bomb. He invited Teller to join him in the schoolhouse for the summer of 1956. Teller accepted with enthusiasm. He knew that he and Freddy could work well together, and he shared Freddy's strong desire to get away from bombs for a while and do something constructive with nuclear energy.

Freddy also invited thirty or forty other people to spend the summer in the schoolhouse, most of them people who had been involved with nuclear energy in one way or another, as physicists, chemists or engineers. Robert Charpie, even younger than Freddy, had been the other American in the group of scientific secretaries of the Geneva meeting. Ted Taylor came directly from Los Alamos, where he had been the pioneer of a new art form, the design of small efficient bombs that could be squeezed into tight spaces. For some reason, although I had never had anything to do with nuclear energy and was not even an American citizen, I was also on Freddy's list. Probably this was a result of my encounter with Teller the previous summer. Freddy promised me a chance to work with Teller. I accepted the invitation gladly. I had no idea whether I would be successful as a reactor designer, but at least I would give it a try. For nineteen years I had been waiting for this opportunity to make Eddington's dream come true.

Freddy de Hoffmann was my first encounter with the world of Big Business. I had never before met anybody with the authority to make decisions so quickly and with so little fuss. I found it remarkable that this authority was given to somebody so young. Freddy handled his power lightly. He was good-humored, and willing to listen and learn. He always seemed to have time to spare.

We assembled in June in the schoolhouse, and Freddy told us his plan of work. Every morning there would be three hours of lectures. The people who were already expert in some area of reactor technology would lecture and the others would learn. So at the end of the summer we would all be experts. Meanwhile we would spend the afternoons divided into working groups to invent new kinds of reactors. Our primary job was to find out whether there was any specific type of reactor that looked promising as a commercial venture for General Atomic to build and sell.

The lectures were excellent. They were especially good for me, coming into the reactor business from a position of total ignorance. But even the established experts learned a lot from each other. The physicists who knew everything that was to be known about the physics of reactors learned about the details of the chemistry and engineering. The chemists and engineers learned about the physics. Within a few weeks we were all able to understand each other's problems.

The afternoon sessions quickly crystallized into three working groups, with the titles "Safe Reactor," "Test Reactor" and "Ship Reactor." These were considered to be the three main areas where an immediate market for civilian reactors might exist. In retrospect it seems strange that electricity-producing power reactors were not on our list. Freddy knew that General Atomic must ultimately get into the power reactor business, but he wanted the company to begin with something smaller and simpler to gain experience. The ship reactor was intended to be a nuclear engine for a merchant ship, and the test reactor was intended to be a small reactor with a very high neutron flux which could be used for the testing of component parts of power reactors. Both these reactors would be competing directly with existing reactors that had already been developed for the Navy and the Atomic Energy Commission. Both of them were designed during the summer and then abandoned when Freddy concluded that they had no commercial future. The safe reactor was the only product of our little red schoolhouse which actually got built.

The safe reactor was Teller's idea, and he took charge of it from the beginning. He saw clearly that the problem of safety would be decisive for the long-range future of civilian reactors. If reactors were unsafe, nobody in the long run would want to use them. He told Freddy that the best way for General Atomic to break quickly into the reactor market was to build a reactor that was demonstrably safer than anybody else's. He defined the task of the safe reactor group in the following way: The group was to design a reactor so safe that it could be given to a bunch of high school children to play with, without any fear that they would get hurt. This objective seemed to me to make a great deal of sense. I joined the safe reactor group and spent the next two months with Teller fighting our way through to a satisfactory solution of his problem.

Working with Teller was as exciting as I had imagined it would be. Almost every day he came to the schoolhouse with some harebrained new idea. Some of his ideas were brilliant, some were practical, and a few were brilliant and practical. I used his ideas as starting points for a more systematic analysis of the problem. His intuition and my mathematics fitted together in the design of the safe reactor just as Dick Feynman's intuition and my mathematics had fitted together in the understanding of the electron. I fought with Teller as I had fought with Feynman, demolishing his wilder schemes and squeezing his intuitions down into equations. Out of our fierce disagreements the shape of the safe reactor gradually emerged. Of course I was not alone with Teller as I had been with Feynman. The safe reactor group was a team of ten people. Teller and I did most of the shouting, while the chemists and engineers in the group did most of the real work.

Reactors are controlled by long metal rods containing substances such as boron and cadmium, which absorb neutrons strongly. When you want to make the reactor run faster, you pull the control rods a little way out of the reactor core. When you want to shut the reactor down, you push the control rods all the way in. The first rule in operating a reactor is that you do not suddenly yank the control rods out of a shut-down reactor. The result of suddenly pulling out the control rods would in most cases be a catastrophic accident, including as one of its minor consequences the death of the idiot who pulled the rods. All large reactors are therefore built with automatic control systems which make it impossible to pull the rods out suddenly. These reactors possess "engineered safety," which means that a catastrophic accident is theoretically possible but is prevented by the way the control system is designed. For Teller, engineered safety was not good enough. He asked us to design a reactor with "inherent safety," meaning that its safety must be guaranteed by the laws of nature and not merely by the details of its engineering. It must be safe even in the hands of an idiot clever enough to by-pass the entire control system and blow out the control rods with dynamite. Stated more precisely, Teller's ground rule for the safe reactor was that if it was started from its shut-down condition and all its control rods instantaneously removed, it would settle down to a steady level of operation without melting any of its fuel.

One of the first steps toward the design of the safe reactor was to introduce an idea called the "warm neutron principle," which says that warm neutrons are less easily captured than cold neutrons and are less effective in causing uranium atoms to fission. The neutrons in a water-cooled reactor are slowed down by collisions with hydrogen atoms and end up with roughly the same temperature as the hydrogen in whatever place they happen to be. In an ordinary water-cooled reactor, after the postulated idiot has blown out the control rods, the fuel will be growing rapidly hot but the water will still be cold, with the result that the neutrons remain cold and their effectiveness in causing fission is undiminished, and therefore the fuel continues to grow hotter until it finally melts or vaporizes. But suppose instead that the reactor was designed with only half of the hydrogen in the cooling water and the other half of the hydrogen mixed into the solid structure of the fuel rods. In this case, when the idiot yanks out the control rods, the fuel will grow hot and with it the hydrogen in the fuel rods, while the hydrogen in the water remains cold. The result is then that the neutrons inside the fuel rods are warmer than the neutrons in the water. The warm neutrons cause less fission and escape more easily into the water to be cooled and captured, and the reactor automatically stabilizes itself within a few thousandths of a second, much faster than any mechanical safety switch could hope to operate. So the reactor carrying half of its hydrogen in its fuel rods is inherently safe.

There were many practical difficulties to be overcome before these ideas could be embodied in functioning hardware. The greatest contribution to overcoming the practical difficulties was made by Massoud Simnad, an Iranian metallurgist who discovered how to make fuel rods containing high concentrations of hydrogen. He made the rods out of an alloy of uranium hydride with zirconium hydride. He found the right proportions of these ingredients to mix together and the right way to cook them. When the fuel rods emerged from Massoud's oven, they looked like black, hard, shiny metal, as tough and as corrosion-resistant as good stainless steel.

After we had understood the physics of the safe reactor and the chemistry of its fuel rods, many questions still remained to be answered. Who would want to buy such a reactor? What would they use it for? How powerful should it be? How much should it cost? Teller insisted from the beginning that it should not be just a toy for reactor experts to play with. It must be not only safe, but also powerful enough to do something useful. What could it do?

The most plausible use for a reactor of this kind would be to produce short-lived radioactive isotopes for medical research and diagnosis. When radioactive isotopes are used as biochemical tracers to study malfunctions in living people, it is much better to use isotopes that decay within a few minutes or hours so that they are gone as soon as the observation is over. The disadvantage of short-lived isotopes is that they cannot be shipped from one place to another. They must be made where they are used. So our safe reactor might come in handy for a big research hospital or medical center that wanted to produce its own isotopes. We calculated that for this purpose a power level of one megawatt would be generally adequate. The other uses that we envisaged for our reactor were for training students in nuclear engineering departments of universities, and for doing research in metallurgy and solid-state physics using beams of neutrons to explore the structure of matter. If the reactor was used for neutron beam research, a power of one megawatt would be rather low, and so we also designed a high-powered version that could be run at ten megawatts. Freddy named the safe reactor TRIGA, the letters standing for Training, Research and Isotopes, General Atomic.

In September the summer's work in San Diego was coming to an end and I took a bus ride to Tijuana in Mexico to buy presents for my family. As I was walking through Tijuana after dark, a small dog ran up to me from behind and bit me in the leg. Tijuana was so overrun with sickly and mangy dogs that there was no chance whatever of catching and identifying the animal that bit me. So I went to a clinic in La Jolla every day for fourteen days to take the Pasteur treatment against rabies. The doctor who gave me the injections impressed on me forcefully the fact that the treatment itself was risky, causing in one case out of six hundred an allergic encephalitis which was almost as fatal as rabies. He told me to figure the odds carefully before beginning the treatment. I decided to take the shots, and I was consequently under some emotional strain for the last two weeks of the summer. Edward Teller was extremely helpful. He had in his youth in Budapest lost a foot in a streetcar accident, and he knew how to give effective moral support in a situation of this kind. In Berkeley I had decided not to consider him an enemy. In San Diego he became a lifelong friend.

After Teller and I and the rest of the summer visitors departed, the few people who remained at General Atomic undertook the job of turning our preliminary sketches of the Triga into a working reactor. The final design was worked out by Ted Taylor, Stan Koutz and Andrew McReynolds. It took less than three years from Teller's original proposal in the summer of 1956 for the first batch of Trigas to be built, licensed and sold. The basic price was a hundred and forty-four thousand dollars, not including the building. The Trigas sold well and have continued to sell ever since. The last time I checked the total, sixty had been sold. It is one of the very few reactors that made money for the company which built it.

In June 1959, all the people who had worked in the schoolhouse to get General Atomic started were invited back to attend the official dedication ceremonies of the General Atomic Laboratories. The change in three years was startling. Instead of a rented schoolhouse, Freddy now had a magnificent set of permanent buildings constructed in a modernistic style on a mesa on the northern edge of San Diego. He had well-equipped laboratories and machine shops, with a staff already growing into the hundreds. In one of the buildings was the prototype Triga, fully licensed and ready to perform for prospective customers. Freddy had persuaded Niels Bohr himself, by common consent the greatest living physicist after the death of Einstein, to come from Copenhagen to preside over the dedication.

The climax of the dedication ceremony was a demonstration of the capabilities of the Triga. Freddy had attached to the speaker's podium a switch and a large illuminated dial. At the end of his speech, Niels Bohr pressed the switch and a muffled hiss was heard from the direction of the Triga building. The noise came from the sudden release of compressed air that was used to pull the control rods at high speed out of the Triga core. The pointer on the large dial, which was graduated to show the power output of the Triga in megawatts, swung over instantaneously to 1500 megawatts and then quickly subsided to half a megawatt. The demonstration was over. It had been rehearsed many times before, to make sure there would be no unpleasant surprises. The little reactor did in fact run at a rate of 1500 megawatts for a few thousandths of a second before its warm neutrons brought it under control. After the ceremony we went and saw it sitting quietly at the bottom of its pool of cooling water. Here it was. It was hard to believe. How could one believe that nature would pay attention to all the theoretical arguments and calculations that we had fought over in the schoolhouse three years earlier? But here was the proof. Warm neutrons really worked.

In the evening there was a picnic supper on the beach, with Freddy and Niels Bohr and various other dignitaries. After eating, Bohr became restless. It was his habit to walk and talk. All his life he had been walking and talking, usually with a single listener who could concentrate his full attention upon Bohr's convoluted sentences and indistinct voice. That evening he wanted to talk about the future of atomic energy. He signaled to me to come with him, and we walked together up and down the beach. I was delighted to be so honored. I thought of the abbot in the monastery at the foot of F6, and I wondered whether it would now be my turn to look into the crystal ball. Bohr told me that we now had another great opportunity to gain the confidence of the Russians by talking with them openly about all aspects of nuclear energy. The first opportunity to do this had been missed in 1944, when Bohr spoke with both Churchill and Roosevelt and failed to persuade them that the only way to avoid a disastrous nuclear arms race was to deal with the Russians openly before the war ended. Bohr talked on and on about his conversations with Churchill and Roosevelt, conversations of the highest historical importance which were, alas, never recorded. I clutched at every word as best I could. But Bohr's voice was at the best of times barely audible. There on the beach, each time he came to a particularly crucial point of his confrontations with Churchill and Roosevelt, his voice seemed to sink lower and lower until it was utterly lost in the ebb and flow of the waves. That night the abbot's crystal ball was cloudy.

For Freddy, the Triga was only a beginning. He knew that General Atomic's survival would in the end depend on its ability to build and sell full-scale power reactors. Already in 1959 the major part of the laboratory's efforts were devoted to the development of a power reactor. Freddy had decided to stake his future on a particular type of power reactor, the High Temperature Graphite Reactor or HTGR. All of us who were involved with General Atomic supported this decision. It was a big gamble, and it ultimately failed. But I still think Freddy's decision was right. If he had been as lucky with the HTGR as he was with the Triga, it would have paid off handsomely for General Atomic, and the whole nuclear industry of the United States would be in much better shape than it now is. It is impossible to make real progress in technology without gambling. And the trouble with gambling is that you do not always win.

The HTGR was competing directly with the light-water power reactors which have from the beginning monopolized the United States nuclear power industry. Neither HTGR nor light-water reactors are inherently safe in the sense that the Triga is safe. Both depend on engineered safety systems to push in the control rods and shut down the nuclear reaction in case of any trouble. Both have enough residual radioactivity to vaporize the core and cause a major accident if the cooling of the core is not continued after shutdown. The main difference between the two reactors is that the HTGR has a much bigger core for the same output of heat. The HTGR core has such a great capacity for soaking up heat that it will take many hours to reach the melting point after a shutdown, even if there is a complete failure of emergency cooling systems. A light-water power reactor core will melt in a few minutes under the same conditions. The worst conceivable HTGR accident would be an exceedingly messy affair, but it would be definitely less violent and less unmanageable than a comparable accident in a light-water reactor. In this sense the HTGR is a fundamentally safer system.

The HTGR is not only safer than a light-water reactor but also more efficient in its use of fuel. These are its two great advantages. It has two great disadvantages: It is more expensive to build, and it has more difficulty with controlling the leakage of small quantities of radioactive fission products during normal operation. Freddy gambled on the expectation that superior safety and efficiency would in the long run cause the world to turn to the HTGR for electric power. He may well turn out to have been right, but the long run was too long for his company. In the short run, the disadvantages of capital cost and of complexity of the leakage containment system stopped him from breaking into the market. He sold only two HTGRs and never went into production with a full-scale model. Finally, in the late 1970s the political uncertainties surrounding nuclear power made the outlook for the HTGR seem commercially hopeless. General Atomic canceled its contracts with its few remaining HTGR customers and announced that it was no longer in the fission power reactor business. Several years earlier, Freddy had moved across the street from General Atomic to become president of the Salk Institute for Biological Studies. General Atomic still continues to build and sell Trigas and to support an active program of research in controlled fusion. No longer is nuclear fission power a promising new frontier for young scientists and forward-looking businessmen.

What went wrong with nuclear power? When Freddy invited me to work on reactors in 1956, I jumped at the opportunity to apply my talents to this great enterprise of bringing cheap and unlimited energy to mankind. Edward Teller and the other inhabitants of the schoolhouse all felt the same way about it. Finally we were learning how to put nuclear energy to better use than building bombs. Finally we were going to do some good with nuclear energy. Finally we were going to supply the world with so much energy that human drudgery and poverty would be abolished. What went wrong with our dreams?

There is no simple answer to this question. Many historical forces conspired to make the development of nuclear energy more troublesome and more costly than we had expected. If we had been wiser, we might have foreseen that after thirty years of unfulfilled promises a new generation of young people and of political leaders would arise who regard nuclear energy as a trap from which it is their mission to liberate us. It is only natural that the dreams of thirty years ago should not appeal to the young people of today. They need new visions to keep them moving ahead. It is easy to understand in a general way why the political atmosphere surrounding nuclear energy has changed so markedly for the worse since the days of the little red schoolhouse. But I believe there is a more specific explanation for many of the troubles which now beset the nuclear power industry. This is the fact that within the industry itself, the spirit of the schoolhouse did not prevail.

The fundamental problem of the nuclear power industry is not reactor safety, not waste disposal, not the dangers of nuclear proliferation, real though all these problems are. The fundamental problem of the industry is that nobody any longer has any fun building reactors. It is inconceivable under present conditions that a group of enthusiasts could assemble in a schoolhouse and design, build, test, license and sell a reactor within three years. Sometime between 1960 and 1970, the fun went out of the business. The adventurers, the experimenters, the inventors, were driven out, and the accountants

and managers took control. Not only in private industry but also in the government laboratories, at Los Alamos, Livermore, Oak Ridge and Argonne, the groups of bright young people who used to build and invent and experiment with a great variety of reactors were disbanded. The accountants and managers decided that it was not cost effective to let bright people play with weird reactors. So the weird reactors disappeared and with them the chance of any radical improvement beyond our existing systems. We are left with a very small number of reactor types in operation, each of them frozen into a huge bureaucratic organization that makes any substantial change impossible, each of them in various ways technically unsatisfactory, each of them less safe than many possible alternative designs which have been discarded. Nobody builds reactors for fun any more. The spirit of the little red schoolhouse is dead. That, in my opinion, is what went wrong with nuclear power.

When my father was a young man, he used to travel around Europe on a motorcycle. Sixty years before Robert Pirsig, he learned to appreciate the art of motorcycle maintenance and the virtue of a technology based upon respect for quality. He sometimes came to villages where no motorcycle had been before. In those days every rider was his own repairman. Riders and manufacturers were together engaged in trying out a huge variety of different models, learning by trial and error which designs were rugged and practical and which were not. It took thousands of attempts, most of which ended in failure, to evolve the few types of motorcycle that are now on the roads. The evolution of motorcycles was a Darwinian process of the survival of the fittest. That is why the modern motorcycle is efficient and reliable.

Contrast this story of the motorcycle with the history of commercial nuclear power. In the worldwide effort to develop an economical nuclear power station, less than a hundred different types of reactor have been operated. The number of different types under development grows constantly smaller, as the political authorities in various countries eliminate the riskier ventures for reasons of economy. There now exist only about ten types of nuclear power station that have any hope of survival, and it is impossible under present conditions for any radically new type to receive a fair trial. This is the fundamental reason why nuclear power plants are not as successful as motorcycles. We did not have the patience to try out a thousand different designs, and so the really good reactors were never invented. Perhaps it is true in technology as it is in biological evolution that wastage is the key to efficiency. In both domains, small creatures evolve more easily than big ones. Birds evolved while their cousins the dinosaurs died.

Is there any hope for the future of nuclear power? Of course there is. The future is unpredictable. Political moods and fashions change fast. One fact that will not change is that mankind will need enormous quantities of energy after the oil runs out. Mankind will see to it that the energy is produced, one way or another. When that day comes, people will need nuclear power reactors cheaper and safer than those we are now building. Perhaps our managers and accountants will then have the wisdom to assemble a group of enthusiasts in a little red schoolhouse and give them some freedom to tinker around.

Saturn b

The begin
June 5, 1927,
German town
the Verein fü
Travel Society
for six years b
carried throu
rockets witho
the first roma
organization
the initiative
Braun joined
played an act
a strange way
duced at the
Germany and
Germans of
efforts by the
them. The Vf
a historian,
neer. By his
oblivion, as
him to Cante
Willy Ley
twenty-seven
Space Travel