Chapter VI

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The resources required for the design and construction of nuclear explosives are examined in this chapter. Peaceful nuclear explosives (PNE) are also analyzed to understand their practicality in view of the possibility of weapons tests conducted under a PNE guise. Finally the potential use of nonexplosive nuclear weapons is described under "Radiological Weapons" in this chapter.

NUCLEAR FISSION EXPLOSIVE WEAPONS

A nation that decides to develop nuclear explosive weapens must commit certain resources to the program. The requirements depend on the complexity and quantity of the weapons desired, but a minimal weapons-development program is of particular relevance to proliferation control. This chapter examines the manpower, money, equipment, and time required for such a program. The level of effort required for a non-state adversary to produce a crude nuclear explosive is also considered.

Fissile material is the critical component of a nuclear explosive. Several different materials are considered: U^{233} and U^{235} in varying enrichments, and Pu^{239} with various concentrations of plutonium isotopes, particularly Pu^{240}. Large amounts of all these materials are, or may be, involved in the worldwide nuclear power industry. Two fissile byproducts of nuclear operations, Np^{237} and Pu^{238} are also considered. This chapter analyzes the quantities of various materials required for a practical nuclear explosive and reviews the threshold quantities at which physical security safeguards are required by the Nuclear Regulatory Commission (NRC).

Resources

The minimal weapons program described here is necessarily restricted to designs of relatively low complexity. Devices depending on thermonuclear components have been excluded, and attention has been devoted to those straightforward patterns of assembly that would be the easiest to realize.

A range of minimal efforts exists. At the upper end of this range is a national effort whose aim is to produce a small stockpile of nuclear explosive weapons. An important class of *national* programs to consider is a clandestine effort to produce, *without nuclear testing,* a first weapon which is *very confidently* expected to have a *substantial nuclear yield.*

At the lower end of the minimal range is a small non-national group (for example, a terrorist or criminal group) whose objective is the crude fabrication of a single nuclear explosive device.

In the discussion which follows, it has been assumed that adequate supplies of fissile material have been made available.

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National Program

A minimal *national* program would call for a group of more than a dozen well-trained and very competent persons, having experience in many fields of science and engineering and access to the open technical literature. They would need a staff of technicians, diverse laboratory facilities, and a field-test facility capable of handling experiments with large high-explosive charges. This group would further need the financial and organizational structures to fabricate or purchase on the open market a variety of items required for the assembly mechanism and for the (non-nuclear) test instrumentation.

If these requirements are met, and the program is efficiently and competently carried out, the objective could be attained approximately 2 years after the start of the program at a cost of a few tens of millions of dollars.

This estimate does not include the time and money to obtain the fissile material or to establish a modest scientific, technical, and organizational infrastructure. The estimate also does not include the cost of a delivery system. It should be realized, however, that in many circumstances the delivery system could be quite crude.

Some details of the effort, including composition of the technical group, would depend on whether a gun-assembly weapon or an implosion weapon were built. However, the expenditures of manpower, money, and time would not differ significantly for the two types of weapons. (See the discussion of low-technology design below.)

The success or failure of the effort described above in producing a militarily effective nuclear explosive is far more dependent on the *competence* of the people involved than on the technological problems themselves. In trying to evaluate the potential of a specific nuclear weapons development program, detailed knowledge of the strengths and weaknesses of personnel is more valuable than details of the technological base of the country.

In the context of the *national* effort discussed above, competence involves more than the proper credentials (i.e., university degrees). For the group to be competent, the members must have a degree of creativity and intuition. However, a high degree of inventiveness is not required. Geniuses are not needed. What is needed is a group that has the ability to do absolutely sound work, both theoretically and experimentally, and independently arrive at correct judgments.

The level of technological effort put forth in the minimal *national* program can be called *low technology*. Low technology encompasses the sort of nuclear device designs that would likely be produced for a first use or first test. This requires techniques which allow high confidence without prior nuclear test experience. This could be characterized as 1945 U.S. technology. A discussion of low-technology design is given below.

Non-National Program

At the low end of the minimal range of effort, a small group of people, none of whom have ever had access to the classified literature, could possibly design and build a crude nuclear explosive device. They would not necessarily require a great deal of technological equipment or have to undertake any experiments. Only modest machine-shop facilities that could be contracted for without arousing suspicion would be required. The financial resources for acquisition of necessary equipment on open markets need not exceed a fraction of a million dollars. The group would have to include, at a minimum, a person capable of searching and understanding the technical literature in several fields and a jack-of-all-trades technician. Again, it is assumed that sufficient quantities of fissile material have been provided,

The actual construction of even a crude nuclear explosive would be at least as difficult as the design itself. The small non-national group described above would probably not be able to develop an accurate prediction of the yield of their device. The device could be a total failure, because of either faulty design or faulty construction. Here again, a great deal depends on the competence of the group; if it is deficient, not only is the chance of producing a total failure increased, but the chance that a member of the group might suffer serious or fatal injury would be quite real. However, there is a clear possibility that a clever and competent group could design and construct a device which would produce a significant nuclear yield (i.e., a yield much greater than the yield of an equal mass of high explosive).

Low-Technology Nuclear Explosives

Low-technology devices can be fabricated from any fissile material that has sufficient concentrations of U^{235}, U^{233}, or plutonium. The different critical masses of these materials require different amounts of fissile material for constructing nuclear explosives of basically similar design. Other significant distinctions of these materials are their radioactivity and their inherent neutron background. These two properties affect their handling and fabrication, the variety of assembly schemes available for use, and, to some extent, the yield potentials of low-technology devices.

With respect to radioactivity and handling characteristics, U^{235} clearly offers the least difficulty. U^{233} is considerably more radioactive, and this problem is compounded by a small impurity content of U^{232}, which decays through a long chain to thallium–208 which emits penetrating and intense gamma radiation. Plutonium presents serious handling problems, principally because intense alpha radiation causes it to be very toxic when inhaled as a dust, Reactor-grade plutonium is several times more radioactive than weapons-grade plutonium but the radiation levels encountered with either are practically the same compared to the much lower radiation levels encountered with U^{235}. 1 Radioactivity problems are manageable for all these substances, especially for anyone with reactor-fuel handling capability.

The impact of neutron background requires discussion. The neutron background can come from many sources. There are neutrons present at all times because of cosmic ray activity, but this background is quite small. The major source in fissile material is from spontaneous fission. For one kilogram of U^{235}, spontaneous fission produces approximately one neutron per second. The spontaneous fission rates of weapons-grade plutonium and typical reactor-grade plutonium are 60,000 and 300,000 times higher, Another source of neutrons is the alpha-n reaction. In this case, radioactive decay of the fissile isotope yields alpha particles, some of which then collide with impurities such as boron, carbon, or oxygen to yield neutrons.

The classic problem presented by background neutrons is that of *prenitiation* of the nuclear-fission chain reaction. In order to assemble fissionable material to produce a nuclear explosion, a subcritical mass (or masses) of material must be rapidly moved into a configuration which has a level of supercriticality sufficient to produce a significant nuclear yield before it blows itself apart. Preinitiation in a nuclear explosive is defined as the initiation of the neutron chain reaction before the desired degree of supercriticality has been achieved. Because the nuclear yield depends upon the degree of supercriticality at the time the chain reaction is initiated, preinitiation will result in a lower yield. However, initiation is a statistical process and can be understood using statistical techniques.

Preinitiation, by itself, does not necessarily make an explosive unreliable. Preinitiation does result in a statistical uncertainty in the yield. Another way to state this is that the probable nuclear yield is statistically distributed between predictable upper and lower limits, which are likely to be more than a factor of 10 apart. For a *well-understood design properly constructed*, however, the most probable yield range could be predicted within much closer limits.

In some low technology assembly designs, preinitiation can cause the nuclear yield to be

[1] The material commonly called weapons-grade plutonium contains primarily plutonium–239 and less than 7 percent of the undesirable isotope plutonium–240. Reactor-grade plutonium has a larger percentage of this isotope and is produced in most commercial power reactors under normal operating conditions.

so low that it is effectively zero. However, there are low-technology assembly designs where the lowest yield because of preinitiation is still militarily significant.

It is widely known that there are two basic methods of assembling fissile material in a nuclear explosive. The first method is to assemble two (or more) subcritical masses by the use of gun propellants. This is commonly referred to as a gun-assembled nuclear weapon.

In a gun-type device, the velocities of assembly that can be obtained in practice, although high in everyday terms, are still so small that unless the neutron background is low, all or most of the nuclear yields realized will be virtually zero.

A second method is to compress a subcritical configuration of fissile material into a supercritical mass by use of a high explosive surrounding the material. This assembly is commonly referred to as an implosion weapon and can be used to assemble the fissile material very rapidly. The velocity of assembly is much higher than can be achieved in gun assemblies, Also, because of the material compression, less fissile material is required to reach any given level of supercriticality. The very rapid assembly allows use of fissile material with higher neutron background than can be used in gun-assembled devices. Said another way, for a given level of neutron background in the fissile material, the probability of preinitiation is reduced by use of the faster implosion assembly.

Highly enriched U^{235} or U^{233} or plutonium can be used to produce effective weapons by use of low-technology implosion designs. A low-technology gun-assembled system would give effectively zero nuclear yield if plutonium were used.

It is widely believed that gun assembly is the simpler way to produce a nuclear explosive. Although the gun assembly may be conceptually simpler, the difficulty of actually constructing a nuclear explosive is roughly equivalent whether a gun or implosion assembly is used. The difficulties of the gun assembly are often not appreciated: a large mass of high density must be accelerated to a high speed in a short distance, putting quite unusual requirements on the gun design.

Yields of Low-Technology Nuclear Explosives

Using low-neutron background materials (i. e., U^{235}, U^{233}, and weapons-grade plutonium), it is possible to design low-technology devices to produce yields reliably up to the equivalent of 10 or 20 kilotons of TNT. For high-neutron background materials (e.g., reactor-grade plutonium), low-technology devices will have probable yields lower than those where low-neutron background materials are used. The probable yields could be lower by a factor of 3 to 10 or more (depending on the design); but yields in the kiloton range could be accomplished.

Thus, militarily useful weapons with reliable nuclear yields in the kiloton range can be constructed with reactor-grade plutonium, using low technology.

The Second Stage of a National Program

After the construction of its first nuclear explosive, a country might follow one of several courses in its weapons-development program. It might merely choose to continue making and stockpiling weapons similar to its first, with no nuclear testing or expansion of its program.

Alternatively, the nation might proceed to develop weapons that are militarily more useful than its first low-technology explosive. From purely technical considerations, this second course is entirely possible.

A likely objective of a second-stage national program would be the development of weapons of similar yield to its first low-technology explosive, but with one or more of the following improvements:

(a) markedly smaller physical size;
(b) composed of significantly less fissile material;
(c) narrower range of uncertainty of yield,

Alternatively, a nation might concentrate on producing weapons with significantly higher yield than its first explosive. These objectives could be achieved using reactor-grade plutonium.

The greater complexity of such designs would require greatly expanded resources of manpower, funds, and equipment. A few nuclear tests would be an essential part of the expanded program.

The expanded program could not be clandestine and would require several years to achieve significant advances.

Thresholds of Fissile Material for Setting Physical Security Requirements

Materials containing U^{235}, U^{233}, and plutonium can be used for making fission explosives only if these isotopes are sufficiently concentrated. For each isotope, a minimum concentration of that isotope in U^{238} can be specified, below which the mixture is not usable in a practical nuclear explosive. The minimum concentration for U^{235} has been specified at 20 percent (i.e., one part U^{235} to four parts U^{238}) for many years. There appears to be no reason to change this.

The bare-sphere critical mass of metallic 20 percent U^{235} and 80 percent U^{238} is about 850 kg (i.e., about 1,900 pounds). This critical mass can be reduced by a factor of two or three by surrounding the sphere of fissile material with some substance, such as iron, uranium, or beryllium, in order to reflect neutrons back into the fissile material. However, the size and weight of the combination of reflector and fissile material will not be substantially less than that of the bare sphere, and may even be greater. Finally, the assembly system, whether gun or implosion, adds substantially to the size and weight of a nuclear explosive.

Thus, if any fissile material is mixed with U238 with such low concentration of the fissile isotope that the bare-sphere metallic critical mass is greater than about 850 kg, the material could not be used to construct a nuclear explosive of practical weight.

Detailed calculations show that the above criterion sets the following thresholds for U^{235}, U^{233}, and plutonium mixed with U^{238}:[2]

U^{235} to U^{238}	1:4	(i.e. 20 percent concentration of U^{235})
U^{233} to U^{238}	1:7	(i.e. about 12 percent concentration of U^{233})
Pu^{239} to U^{238}	1:7	(i.e. about 12 percent concentration of Pu^{239})
reactor-grade plutonium to U^{238}	1:6	(i.e. about 14 percent concentration of reactor-grade plutonium)

Below these concentrations, the total weight of the explosive would be so large as to make it impractical.

The United States currently requires physical security on strategic amounts of uranium enriched to 20 percent or more in U^{235}. The 850 kg bare-sphere metallic critical mass criterion provides a basis for consistent safeguard requirements for U^{233} or U^{235} in U^{238}.

For other materials such as plutonium in U^{238}, and for U235, U233, or plutonium mixed with Th^{232}, the criterion is still applicable for safeguards requirements. s In these cases, however, highly concentrated fissile material could be obtained by chemical rather than isotopic separation. Chemical separation is considerably less difficult than isotopic separation, and is likely to remain so despite potential advances in enrichment technology.

The United States currently requires physical protection for 2 kg or more of plutonium, 2 kg or more of U^{233}, and 5 kg or more of U^{235} (contained in uranium enriched to 20 percent or more). There appears to be no compelling technical reasons to change these mass thresholds for physical security. However, consideration has been given to these thresholds only in the context of use of materials for fission explosives, and not in the

[2] Private communication, Robert W. Selden, Lawrence Livermore Laboratory.

[3] Because uranium is not soluble in thorium, a metal alloy is not possible; the criteria thus should be applied to powder mixtures or mixtures of oxides.

context of use in dispersal weapons. (See "Radiological Weapons," end of this chapter.)

Similar safeguards threshold properties should be formulated for other fissile byproducts of peaceful nuclear operations, notably neptunium–237, when and if they become generally accessible. They probably do not constitute a problem at this time. The isotope P^{238}, which is widely used for isotopic power sources, is also a fissile material (comparable to Pu^{229} in this respect). However, it is so intensely radioactive and generates so much heat that it would be entirely impractical for use in a nuclear-fission explosive weapon,

PEACEFUL NUCLEAR EXPLOSIVES

A nation that has clandestinely developed a nuclear weapon may require a test to confirm its design or to collect data for a more sophisticated weapons program. Because bomb tests larger than 10 10 kt are unlikely to escape detection, the nation might be deterred by the spectre of international repercussions—except for one loophole. The nation could claim that the explosion was for peaceful purposes, exactly as India did. Even existing nuclear states might use peaceful nuclear explosions (PNEs) as a cover for weapons tests because the two are technically indistinguishable. Thus, PNEs have been a major obstacle in arms-control negotiations for a comprehensive test ban treaty (CTBT). Such a treaty could in itself deter proliferation by providing an example of self-restraint on the part of the nuclear powers. A double effect of PNEs, therefore, is to detract from disincentives to proliferation and provide a cover for those who do proliferate.

Only recently have such concerns over the abuses of PNEs begun to outweigh the hopes for benefits from them. Beginning in the late 1950's, the United States actively researched and promoted domestic applications of nuclear explosions under its Plowshare Program. Many non-nuclear weapons states grew so interested in the promises of the technology that a PNE provision in the Non-Proliferation Treaty (NPT) became an important incentive for their signature. In return for their agreement to refrain from developing any kind of nuclear explosion, these nations were guaranteed access to any benefits of PNEs on a nondiscriminatory, low-as-possible-cost basis,

A look at some of these possible beneficial applications of nuclear explosions is warranted to understand if they are fulfilling their original promise and if they are worth preserving or promoting, The technology of PNEs is reviewed in appendix II of volume II. In brief, the applications fall into two categories: excavations and contained explosions. The United States abandoned its plans for excavation projects in 1969 because the technology was immature and inflexible, and the radiation release constituted both a health hazard and a violation of the Limited Test Ban Treaty. The U. S. S. R., however, created a reservoir with a nuclear explosion and is seriously interested in using them to make more reservoirs and to excavate mountainous portions of a canal route, The PNE applications mentioned by non-nuclear weapons states have been mainly excavations. Among these are canal projects studied by Egypt and Thailand.

The applications of contained nuclear explosions include several that would help exploit energy and mineral reserves. Examples are stimulation of gas and oil recovery (including oil shale), creation of storage cavities, and fracture of ore bodies to permit mining by leaching. A comprehensive study of contained PNE applications in the United States was completed in 1975 for the Arms Control and Disarmament Agency (ACDA) by the Gulf Universities Research Consortium, Their charge was to project the use of PNE technology up to the year 1990. Their report indicates that some of the proposed projects might be economically attractive, but not in the next decade and not before a great many technical unknowns and adverse environmental effects are resolved. The only application—albeit a limited one—that does not seem to have non-nuclear alternatives is the use by the U.S.S.R. to seal runaway gas-well fires.

Because of these many difficulties, the United States has ceased its former role of promoting PNEs. After having spent $160 million on the Plowshare Program, the United States currently allots about $1 million per year and has shown a willingness to forgo PNEs altogether. The Soviet interest on the other hand has increased as that of the United States has waned, although they appear to have entered a period of questioning now.

Implementation of the PNE provisions of the NPT has been assigned to the International Atomic Energy Agency (IAEA), which seems to see a limited role for itself. It acts as an information clearinghouse and proposes to assist with feasibility studies. (It recently conducted a preliminary review of the Egyptian canal project.) An ad hoc advisory group has been assembled to consider future activities. Very few requests for information have been received by the IAEA, and this apparent lack of interest in PNEs by non-nuclear weapons states perhaps parallels the slow maturation and diminished promise of the technology. Nevertheless, even an NPT nation with no previous plans to use PNEs might legitimately want to keep open the option or resent the discriminatory approach of the NPT, which allows the development of PNEs only to weapons states.

The slow implementation of the PNE services can also provide justification for a nonsigner to stay outside the NPT and even to develop its own "peaceful nuclear explosion. " This veil is quite transparent, however. The nation would have to make its claim credible by manifesting a carefully planned agenda of potential PNE applications. Interestingly, India has only vague plans and has not requested any IAEA assistance. These PNE plans would have to justify the large and sophisticated development program required for a real PNE: An effective PNE must be inexpensive, physically small, and yield minimal amounts of radiation, in contrast to the "low-technology" nuclear weapon described earlier.

A more indirect but nonetheless substantial effect of PNEs on the NPT results from their impact on arms control negotiations. Since the 1968 signing of the NPT, wherein the nuclear weapons states agreed to move towards disarmament, the only test bans that have been negotiated between the United States and the U.S.S.R, are the 1974 Threshold Test Ban Treaty (TTBT) and its associated 1976 Treaty on Underground Explosions for Peaceful Purposes (PNET, still unratified). The PNET places the same upper limit of 150 kilotons on explosions as the TTBT because both sides admitted that no one can verify that PNEs are not being used for weapons development, even with the unique PNET feature of onsite inspections. This limit places very little restraint on weapons testing. The separate status accorded to PNEs will make further reductions more difficult to achieve and will hinder progress toward a comprehensive test ban. The separation was made at the insistence of the U.S.S.R.

In the face of such technological and political ambivalence, the present U.S. course has been to proceed with a low level of research on major uses of PNEs and move slowly and cautiously toward providing PNE services to NPT signees. This course appears neatly to encompass all three major dangers of PNEs: hindering progress toward a CTB, retarding membership in the NPT, and providing excuses for nations to develop their own nuclear bombs.

An alternative course could be to temporarily ban all testing of PNEs pending a less ambiguous demonstration of a beneficial and viable application. Research could continue on non-nuclear aspects of the applications. International opinion is not conducive to a permanent ban at this time, but that could change if the promise of the technology continues to be limited. Even a temporary ban could ease progress toward a CTB,

A step in the opposite direction would be to establish an international service to provide PNEs to all nations regardless of their membership in the NPT. This action would eliminate the excuse for development of an indigenous PNE. The very existence of such a service, however, would tend to condone nuclear explosions in general.

Until international agreement can be reached on some action, PNEs will remain a difficult problem.

RADIOLOGICAL WEAPONS

Radiological weapons are defined to be devices for dispersal of radioactive materials, produced a substantial time before their dispersal (e.g., not in a nuclear explosion) for any of the following purposes:

a. Killing people within a short time (less than a few weeks).
b. Killing people, or causing severe illness, after a long time (weeks to many years).
c. Damaging property through short-term contamination to levels that require evacuation to prevent severe effects on occupants.
d. Damaging property through long-term contamination, to low levels that would deny access to or use of an area if present occupany or use standards for the general population were enforced.

Targets for dispersal could be:

a. High concentrations of people inside buildings; dispersal as aerosol introduced into air-conditioning or ventilation systems.
b. High concentrations of people outside (e.g., crowded urban streets or sports events),
c. Urban areas as a whole, with high-population density, to affect people and property inside and outside buildings.
d. Large urban, suburban, or rural non-agricultural areas, primarily to deny access and require expensive decontamination. The dispersal might even be designed specifically not to produce any significant acute health effects.
e. Agricultural area, primarily to deny access and use.

In principle, any radioactive substance could be used in a radiological weapon. A number of radioactive isotopes are in widespread use outside the nuclear power industry, in hospitals, universities, research institutions, and industrial research and manufacturing facilities. Most of these applications have nothing to do with nuclear power research or applications. For example, cobalt–60 is widely used in treatment facilities in hospitals; strontium–90 and cesium– 137 are used in measuring gauges in several industrial applications; radioactive sources of all kinds, some of them quite strong, are kept in university laboratories. Several incidents of theft of such sources have occurred in the United States and abroad, and at least one incident of deliberate (although not lethal) dispersal has occurred. (See appendix III of volume II.)

Most theoretical attention, however, has focused on the use of plutonium, spent fuel, or waste from spent fuel in radiological weapons. Such materials could be dispersed either by an aerosol generator (perhaps after dissolution), or by the use of attached chemical explosives, depending on the material, the objective, and the target.

Small quantities of nuclear material not subject to physical security safeguards could be dispersed in ways that would cause many prompt and/or delayed deaths and require expensive decontamination. However, there are also many generally available, publicly described, chemical and biological agents that could be as effective, or more so, than radioactive agents as weapons for killing people and/or contaminating property.

No known cases of deliberate dispersal of plutonium, U^{233}, spent fuel, or waste from spent fuel have occurred in the United States, at least since 1969, when the AEC began compiling complete statistics of such nuclear incidents.

The available records from the rest of the world are less complete; one case of spent-fuel waste dispersal *may* have been plotted, but was not executed.

Radiological weapons could be the subject of a hoax as well as the basis of a real threat. Although threats to detonate a nuclear explosive have proved more popular with hoaxers to date than threats to disperse radioactive material, the latter type of hoax is potentially more troublesome. It would be easier to mount a *technically* credible dispersal hoax than a nuclear explosive hoax. However, hoax identification does not rely on technical assessment alone. (See appendix III, volume II.)

In conclusion, a large number of toxic substances, including plutonium and other radioactive isotopes, could conceivably be used by groups or individuals for effectively attacking large numbers of people or causing considerable property damage by denial of use or expensive decontamination. The question of imposing effective physical security safeguards to prevent theft or diversion of nonradioactive toxic substances in widespread use has apparently not been assessed, but appears on the surface to be extraordinarily difficult and perhaps not feasible. It does not appear reasonable to require safeguards for small quantities of nuclear or other radioactive materials in the absence of consideration of safeguards on nonradioactive toxic substances.

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