LATENT PROLIFERATION

THE INTERNATIONAL SECURITY IMPLICATIONS OF CIVILIAN NUCLEAR POWER

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In Memory of My Father

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PREFACE

This study is addressed both to scientists and to policy-makers and others without extensive technical training. For this reason, I have attempted to set forth the relevant technical background with considerable detail and care. I have tried both to present a coherent and quantitative picture of the nuclear industry for the scientists and to explicate technical matters in a way that will be helpful to the non-technical reader. In this attention to technical detail and in the later systematic analysis of the political implications of civilian nuclear power, I believe this study provides a quite different focus than other works in the field.

I have sought also, through this attempt to combine technical detail and systematic political analysis, to achieve a middle-ground of analysis between the typical policy papers generated within governmental bureaucracies on the one hand and academic research on the other. The chief shortcoming of the government policy paper is usually its extremely narrow focus in which the most significant issues are frequently left out of account especially if they are not relevant to short-term calculations. This is due to the little time available to both the writers and readers of policy memoranda, to the persistent sense of political constraints which often seem to impose a wide gap between the desirable and the feasible, and, above all, to various bureaucratic and institutional factors which restrict the range of arguments that appear appropriate for discussions within a given national administration.

For similar reasons, policy analysis within the government does not always marshal and sift evidence in as thorough a fashion as possible. While considerable segments of academic research relevant to contemporary policy issues suffer similar handicaps, the major shortcomings of such research, I believe, are of a somewhat different kind. Academic analysis is first of all not infrequently out of date, employing data and concerned with policy disputes no longer pertinent. This is due in part to the slowness with which much relevant data, often classified, becomes available to researchers outside the government, and in part to the speed with which policy issues are often raised, argued, and decided (temporarily at least) within the government. Whereas government policy analysis generally suffers from a too rigid regard for political constraints, academic policy analysis frequently pays too little to the limitations that circumscribe the scope of governmental action. I have not I know avoided all these drawbacks but I hope the attempt at least has been of some value.

The idea for the scope and title of the study derives from two of my colleagues at the Arms Control and Disarmament Agency during 1964-1965, Leonard Rodberg and Mason Willrich. At that time, we used the term "incipient proliferation" to describe the concept discussed here. The title "latent proliferation" seemed to me slightly more descriptive of the concept, however.

I am deeply grateful to a large number of persons. I wish first to thank those who made possible the support given me during the study by Princeton's Woodrow Wilson School, Center of International Studies, Center for Environmental Studies. I wish also to express gratitude to my former associates at the United States Arms Control and Disarmament Agency, from whom I learned much that is in this study, and to the several friends and officials in the United States Atomic Energy Commission who helped me see it through.

Among the several scientists who helped me, I am especially grateful to Marvin Goldberger, Michael May, Henry Smyth, and above all to Freeman Dyson, for his constant encouragement as much as for his painstaking review of the first two chapters. Among other colleagues and associates at Princeton, I wish especially to extend appreciation to Robert Gilpin and Richard Ullman, and to the students who participated in my seminar on nuclear energy policy. I am indebted also in many different ways to Marver and Sheva Bernstein, John and Ellen Schrecker, and Robert and Liz Socolow. I owe a debt of gratitude as well to Jean Wiggs, who typed this manuscript with remarkable care and good cheer.

Finally I wish to express a deepfelt thanks and gratitude to Richard Falk.

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INTRODUCTION

The production of an atomic bomb requires but 10 kilograms of plutonium or 25 kilograms of uranium-235. Compared to this, by 1980, over 30,000 kilograms of plutonium will be discharged annually from civilian nuclear power reactors throughout the world. Twenty to twenty-five countries beyond the five present nuclear weapon states will then be producing at least 100 kilograms of plutonium per year in their civilian programs; several will be generating a still larger amount. A substantial fraction of this plutonium will be recycled into power reactors; plutonium reprocessing, fabrication, and trade will become a widespread commercial enterprise. Similarly, by 1980 or soon thereafter, several countries are likely to have a substantial capacity to produce highly enriched uranium, which also will be a ubiquitous element in commerce and international trade. By 1985, annual worldwide plutonium production in civilian programs will have reached 75,000 kilograms. In addition, the introduction of breeder reactors will require initial plutonium and uranium-235 inventories at each reactor of over 3000 kilograms. A single substantial diversion of any of this mass of fissionable material to weapons purposes would have a shattering impact on international relations and on domestic tranquility. Appropriation of the material by a non-nuclear state would severely jolt the fragile system of international safeguards now being established; and once significantly breached, it is questionable that this system could prevent a rapid and widespread diffusion of nuclear weapons. Even more clearly, a single theft of fissionable material (and consequent construction of an atomic device) by sub-national groups, criminals or terrorists, would give rise to blackmail and other perils of an unparalleled character. Despite these dangers, the cost and effort nations appear willing to expend on safeguards are not high. The nuclear industry resists safeguard intrusions, and national atomic energy commissions have been reluctant to impose stringent safeguard conditions on them. Several nations have not signed the Non-Proliferation Treaty and show no willingness to accept the safeguard obligations there set forth. Yet one significant illicit diversion of nuclear material, and nations will be willing to undertake whatever draconian measures necessary to combat the danger and to prevent its recurrence. There is in this discrepancy between danger and response a severe distortion of priorities. This is the theme of this study. The object of the study is to make vivid and detailed the technical and political realities which constitute the dangers inherent in the spread and intensification of civilian nuclear power.

Chapters 1 and 2 describe the manner in which civilian nuclear power programs provide a foundation for the development and production of nuclear weapons. Considerable effort has been made in these chapters to present the relevant information in as concrete a manner as possible. Thus, in Chapter 1 the worldwide nuclear industry is surveyed virtually plant by plant and in quantitative terms. Wherever possible, general categories of activity are described in sufficient detail to permit the reader to form something more than simply an abstract picture of what is happening. Thus, for example, the discussion of plutonium transport in Chapter 1 includes some data on the actual manner of such transport, the types of containers used and the magnitude of the shipments involved. In general, the purpose of these chapters is to provide a realistic picture of the ways in which civilian nuclear power programs can be diverted to weapons development. The basic argument of the first two chapters is that the technology, scientists, and technicians required to produce nuclear warheads are widely diffused; and for the most part nations or sub-national groups wishing to acquire nuclear weapons already possess or could obtain the necessary delivery systems appropriate to their purposes. Acquisition of fissionable material thus provides the salient obstacle to the production of nuclear weapons. But fissionable material is also precisely what is used and accumulated in quantity in any civilian nuclear power program; and the intensification and spread of these programs thereby creates management and control problems of colossal proportions.

Confronted with this conversion potential, the international community has instituted systems of national, regional, and international safeguards, the formal and legal procedures that attempt to ensure that nuclear material is not diverted from civil use to weapons or other illicit purposes. In an effort to assess the effectiveness of these safeguard systems, Chapter 3 undertakes detailed examination of both their legal and technical character. Such examination leads inescapably to the conclusion that inspection and control procedures will not be sufficient in the long term to prevent the diversion of nuclear material to weapons purposes. So long as nations have sovereign control, both legally and practically, over their nuclear programs, safeguards, albeit indispensable, will face an impossible task. A system of inspection superimposed on an otherwise uncontrolled exploitation of atomic energy by national governments will not prove an adequate safeguard.[1]

The situation today is therefore characterized by a continuing intensification of civilian nuclear power programs whereby nations increasingly gain independent and autarkic control over the nuclear fuel cycle and more ever closer to a nuclear weapons capability. Chapter 4 attempts to summarize and classify these trends and to explore some of their probable political consequences. Although such analysis must by necessity be highly speculative, it would appear, in general, that intensification of civil nuclear capabilities unimpeded by new control measures will raise grave threats to international and domestic security, many of them altogether unexampled.

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[1]This is a slight paraphrase of the central conclusion of the "Report on the International Control of Atomic Energy" prepared for the Secretary of State's Committee on Atomic Energy, March 16, 1946. Department of State Publication 2498. The conclusion of the Report is quoted at length at the end of Chapter 3.

The final section of Chapter 4 sets forth a very brief policy sketch of what a strategy of control beyond the present safeguard effort might look like. Whatever the specifics of such a strategy, there is not a great deal of time for the international community to respond to the challenge confronting it. Nuclear power is now burgeoning throughout the world, and the foundations for tens of nuclear weapon programs are already being set.

CHAPTER 1. Civilian Nuclear Power

Worldwide nuclear activities are still remarkably limited. It is indeed practical to survey every significant nuclear facility in the non-Communist countries. In undertaking such a survey in this chapter, we try also to highlight concepts and quantitative relationships not adequately presented in the literature typically available to the non-expert. The chapter is divided into five sections, describing in brief (i) some relevant nuclear physics, (ii) the civilian nuclear power cycle, (iii) the economics of nuclear power, (iv) future sources of nuclear energy: breeder and thermonuclear reactors, and (v) the scope and expected growth of civilian nuclear power.

1. Nuclear Energy[1]

Introduction to Atomic Physics

For purposes of the ensuing discussion, atoms may most simply be viewed as composed of a nucleus and a surrounding shell of (negatively charged) electrons. The nucleus consists of (positively charged) protons and of neutrons, which carry no electrical charge. The number of protons, the "atomic number," determines the chemical properties of the atom, and characterizes its name. Thus, for example, all "uranium" atoms have atomic number 92, all "plutonium" atoms atomic number 94, etc. The sum of the

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[1]The purpose of the subsequent sketch of nuclear physics is principally to introduce in an orderly manner several terms used throughout this study. The sketch, very simplified, is by no means complete or altogether self-contained, and for a deeper understanding of nuclear science the non-expert reader is referred to the following sources: Hans Thirring, Energy for Man, Chs. 14, 15, 16; Samuel Glasstone, Sourcebook on Atomic Energy; John Harte and Robert Socolow, Patient Earth, Ch. 18; and Alvin Glassner, Introduction to Nuclear Science.

neutrons and protons is termed the "atomic weight" or "mass number". Isotopes are atoms with identical atomic number but different atomic weight; they differ only in the number of neutrons. An isotope of an atom may thus be characterized by the name of the atom and its atomic weight: for example, "uranium-238" (U-238) or "plutonium-239" (Pu-239).

Several isotopes are unstable; their nuclei will spontaneously emit "radiation". Such radiation arising from the spontaneous decay of radioactive nuclei may be of several types, including alpha rays (helium nuclei consisting of two neutrons and two protons), beta rays (electrons or positrons), gamma rays (electromagnetic radiation or photons), and neutrons.[2]

The rate of radioactive decay or disintegration of any radioactive isotope is measured by a characteristic time, called the "half-life", which is defined as the length of time in which one-half of a large collection of the nuclei of the isotope will decay. Half-lives of isotopes range from fractions of a second to millions of years. For example, thorium-223 has a half-life of 0.1 second, thorium-232 a half-life of 1.39×10^{10} years; uranium-238 has a half-life of 4.5×10^{9} years and plutonium-239, 24,100 years.

All nuclear reactions conserve mass number and atomic number; thus, in exhibiting reactions it is useful to indicate explicitly both these numbers. If the reaction involves the decay of a radioactive isotope, it is also usual to indicate the mode of decay and the relevant half-life.

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[2]The attentive reader may wonder how it is possible for electrons (and their antiparticles, positrons) to be emitted from the atomic nucleus which presumably consists of protons and neutrons. The answer of course is that the nucleus is more complex than so far indicated. But the simple picture need not be completely abandoned; if an electron is emitted from the nucleus (beta radiation), it is permissible to think of it as arising from a neutron changing to a proton in the nucleus: $n \rightarrow p^{+} + e$. An excellent discussion of radiation may be found in Harte and Socolow, Patient Earth, Ch. 18.

permits a very rapid increase in the neutron density within the material and hence in the number of fissions. Of the fissile nuclei, only U-235 is found in nature; it comprises 0.71% of natural uranium, which consists actually of three isotopes: 99.28% U-238, 0.006% U-234, and 0.71% U-235. U-233 is produced through neutron capture by Th-232. Pu-239 is produced through neutron capture by U-238. In practice, neutron fluxes sufficient to produce substantial quantities of U-233 and Pu-239 can be generated only in nuclear reactors (or in nuclear bombs).[5]

Each fission produces roughly 200 million electron volts of energy (200 MeV). The complete fission of one gram of fissionable material would therefore generate approximately 1 megawatt-day of energy (1 MW-day). The fission of 1 kilogram would be sufficient to provide one day's electric power to a city of 300,000. The explosive release of the energy produced by the fission of 1 kilogram would be equivalent to the explosive energy of 18,000 tons of TNT, or 18 kilotons (18 KT), roughly the yield of the

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[5]Natural thorium (atomic number, 90) consists of only one isotope, Th-232. U-233 is produced by the reaction:

$$ {}^{232}_{90}\mathrm{Th} + {}^{1}_{o}\mathrm{n} \rightarrow {}^{233}_{90}\mathrm{Th} \xrightarrow[23\mathrm{m.}]{\beta} {}^{233}_{91}\mathrm{Pa} \xrightarrow[27.4\mathrm{d}]{\beta} {}^{233}_{92}\mathrm{U}\,. $$

Pu-239 is produced by the reaction:

$$ {}^{238}_{92}\mathrm{U} + {}^{1}_{o}\mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \xrightarrow[23\mathrm{m}]{\beta} {}^{239}_{93}\mathrm{Np} \xrightarrow[2.3\mathrm{d}]{\beta} {}^{239}_{94}\mathrm{Pu}\,. $$

For example, the capture of a neutron by a nucleus of U-238 may be written as follows:

$$ {}_{0}n^{1} + {}_{92}U^{238} \rightarrow {}_{92}U^{239} \xrightarrow[23\ m]{\beta} {}_{93}Np^{239} \xrightarrow[2.3\ d]{\beta} {}_{94}Pu^{239} . $$

That is, a neutron with zero charge and one atomic mass unit captured by a U-238 nuclei produces the unstable nuclei U-239 which decays by a beta ray (electron emission) into neptunium-239. Np-239 in turn decays by another beta ray with half-life 2.3 days to Pu-239.

Nuclear Fission

Energy in a nuclear reactor (or fission bomb) is produced by the fission of isotopes of uranium and plutonium: notably U-233, U-235, and Pu-239, the so-called "fissionable material".[3] Under appropriate circumstances, these nuclei, when struck by a neutron, will split into two or more smaller nuclei (that is, will fission) thereby releasing a considerable amount of energy and a sufficient number of neutrons to cause a chain reaction of fissions in adjacent nuclei.[4] In a power reactor, this chain reaction is controlled, with the number of neutrons in the material mass kept relatively constant after a certain point. A bomb on the other hand

[3] Technically, these isotopes, which are those that can be fissioned by neutrons of any energy, are termed "fissile nuclides". Other isotopes, such as U-238, which will fission only at incident neutron energies of over approximately 1 MeV are said to be "fissionable nuclides". But by common usage, U-233, U-235, and Pu-239 are called fissionable material. It may also be added for completeness that Pu-241 which is produced in reactors in small quantities may also be fissioned by neutrons of low energy.

[4] The energy release is equivalent to the difference in mass between the original heavy nuclei and the combined fission products multiplied by the square of the velocity of light, according to the equation $E = mc^2$.

nuclear bomb dropped on Hiroshima.[6]

Fission of a U-235 or U-233 nucleus by a slow neutron will release on the average 2.5 neutrons per fission event (some fissions release 2 and some 3 or more neutrons; this is why the average is not an integral number); fission of Pu-239 releases 2.9 neutrons on the average. The great majority

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[6]These two equivalences (one gram fission produces 1 MW-day; one kilogram fission produces an explosive yield of 18 KT) are worth remembering, and may be easily calculated. For example:

One gram of U-235 contains $6 \times 10^{23}/235$ atoms (where 6×10^{23} is Avogadro's number). Complete fission of these would produce

$\frac{6 \times 10^{23}}{235} \times 200$ MeV $= 5 \times 10^{23}$MeV. Since 1 MeV $= 4.5 \times 10^{-20}$kw-hrs, the fission energy of one gram is $\frac{5 \times 10^{23} \times 4.5 \times 10^{-20}}{24}$ kw-days = 1 MW-day.

Similarly, given that the explosive yield of 1 ton of TNT is 10^9 calories and that 1 calorie $= 2.6 \times 10^{13}$ MeV, the complete fission of 1 kilogram of fissionable material would produce

$\frac{5 \times 10^{23} \times 10^3}{2.6 \times 10^{13} \times 10^9}$ = 20 KT TNT equivalent. Since, about one-tenth of the fission energy escapes via gamma ray photons, betas, and neutrinos, and is consequently not available to the explosion, the explosive energy equivalence is actually 1 kilogram = 18 KT TNT equivalent.

of fission neutrons have energies in the region 1 to 2 MeV.[7] Each fission neutron will have one of three fates: it may fission another fissionable isotope and thus carry the chain reaction; it may be captured by a nucleus of the material in which the fissionable isotopes are imbedded without producing fission; or it may escape from the material altogether. The utilization of fission energy for power or explosives requires that a chain reaction be sustained; on the average, one or more of the neutrons released by each fission must cause another fission before it is captured or escapes from the material. This is the "critical condition"; a reactor or bomb must become critical before it can release usable amounts of energy. The relative probabilities of fission, capture, and escape and thus the critical condition depend on the configuration and composition of the material and on the average energy of the incident neutron. Clearly the higher the concentration of fissionable nuclei in the material, the higher the probability of fission. Also, the higher the ratio of volume to area of the material, the less the likelihood that neutrons will escape before fission or capture. For a given material composition, criticality will be approached as the mass of the material increases. If a sustained chain reaction in the particulr material is at all possible, there will thus exist some minimum "critical mass", at which the critical condition will have been achieved.

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[7]The number of neutrons released per fission event depends on the incident neutron energy. In the range up to 1 MeV, the change is very slight. But at higher energies, the average number of fission neutrons increases at a rate of about one additional neutron per 7 MeV increase in energy. Fission of U-235 by 14 MeV neutrons will produce an average of 4.5 neutrons per fission event. Similar fission of Pu-239 will produce 4.75 neutrons on the average.

It may also be noted that while most of the fission neutrons are released promptly (within about 10^{-14} seconds), a small fraction, less than one percent (0.65% for U-235, .36% for Pu-239), are delayed from a fraction of a second to a few minutes. This delay provides an important factor in the control of nuclear fission reactors.

Although fission of the fissile nuclei will take place regardless of the energy of the incident neutron, the probability of the fission is highest when the neutron energy is relatively low. By contrast, other nuclei which can fission, such as U-238, will do so only at very high energies, greater than 1 MeV.[8] Non-fission capture of neutrons also depends on the energy of the incident neutron; in U-238, the probability of such capture diminishes as neutron energy decreases. As a consequence, a chain reaction in natural uranium or in uranium only slightly enriched in U-235 may most easily be sustained at low neutron energies, when the fission "cross-section" (probability) of U-235 is highest and the capture cross-section of U-238 low. Since the neutrons released by fission have average energy in the range 1 to 2 MeV, reactors using natural or slightly enriched uranium must employ a "moderator" (material such as carbon or water) to slow down the neutrons before they are captured by the U-238.[9]

Reactors which thus require that the neutrons be slowed to thermal energies (and these include essentially all commercial power reactors built and under construction) are called "thermal" or "slow" reactors.

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[8]Low energy neutrons here mean neutrons which have roughly "thermal velocities", corresponding to the average agitation velocity of atoms in a body at a given temperature. The kinetic energy of these atoms is proportional to the (absolute) temperature of the body. Thermal energies at temperatures found in nuclear reactors are near .1 ev, corresponding to neutron velocities of about 5 kilometers per second. A 1 MeV neutron has velocity about one thousand times greater. It is customary to talk of high energy neutrons as "fast" and low energy neutrons as "slow" or "thermal".

[9]The situation is actually slightly more complicated still. Even without a moderator, a high energy neutron released into a block of uranium will eventually slow down to thermal energies through collisions with the uranium nuclei. (By the same mechanism, it will very quickly slow down to energies below 1 MeV, thus foreclosing the possibility for U-238 fission.) However, on the way down from the high energy the neutron is exposed to a particularly great risk of being captured by a U-238 nuclei, especially in the energy range near 7 eV. The moderator acts to slow down the neutrons below this energy before they are exposed to the U-238 nuclei. This explains incidentally why a mass of natural uranium left alone in the ground or elsewhere will not explode. See especially, Thirring, Energy for Man, 326-329.

Reactors which do not deliberately slow the neutrons are termed "fast" reactors. Such reactors must employ a high fraction of fissionable material, over 20 to 30% in the core; if uranium is the fuel, it must be enriched to at least 20 to 30% in U-235 (or mixed with equivalent amounts of Pu-239).[10] Fast reactors are usually identified with breeder reactors (although, in fact, breeders need not be fast, nor fast reactors, breeders), which are discussed later in Section 4.

Since as earlier indicated, only U-235 of the fissile isotopes is found in nature, all reactors must start with uranium (U-238 and U-235) as the fuel. Eventually, it might be possible to produce sufficient U-233 (if the reactor is surrounded with Th-232) or Pu-239 to fuel the reactor, which is in fact the object of the breeder program discussed later. At the moment, however, all power reactors utilize the fission of U-235, and, to a lesser extent, Pu-239 produced in the fuel by U-238 neutron capture. Not every Pu-239 nuclei exposed to a neutron will fission; occasionally the Pu-239 will capture the neutron to produce Pu-240. If the exposure of the plutonium to a neutron flux is sufficiently long, still higher isotopes of plutonium will be formed in the same manner. Pu-241 is fissionable and thus usable in reactors and weapons, but Pu-240 is not. Moreover Pu-240 is significantly radioactive which, as will be noted in Chapter 2, can complicate weapons development, if the Pu-240 is mixed with the Pu-239 in sufficient concentration.

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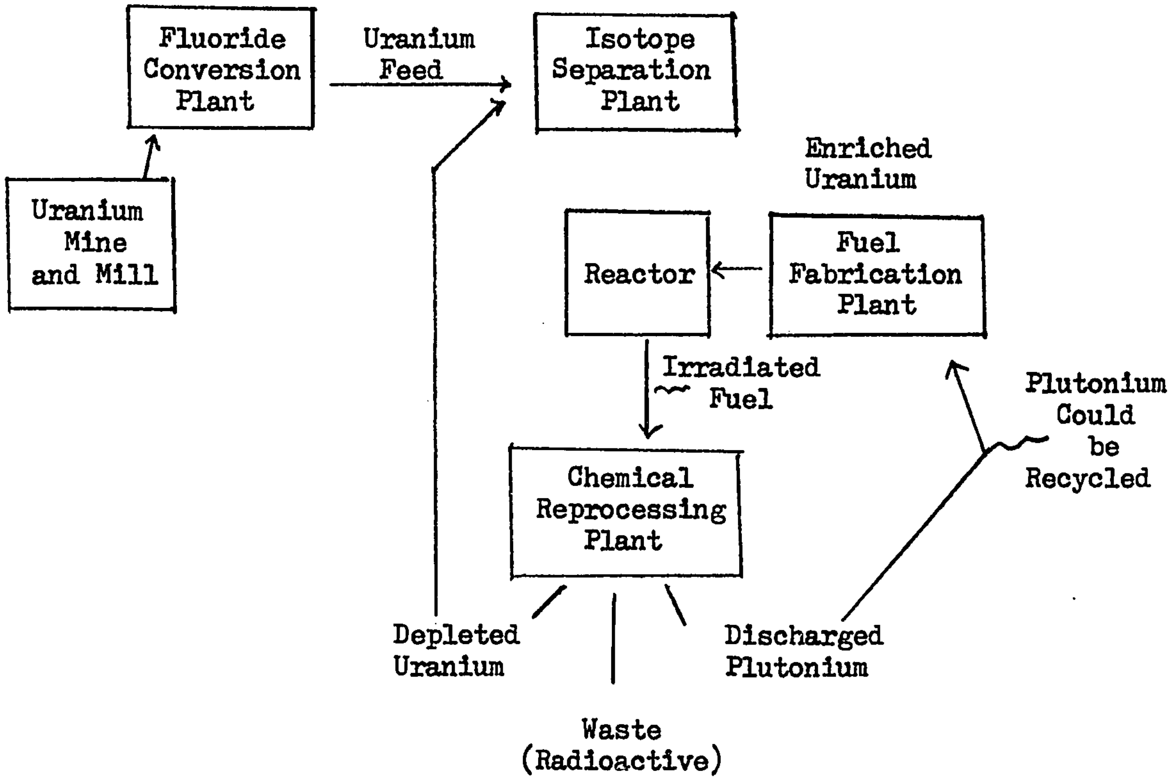
[10]Glasstone, Sourcebook, 15.52.

2. Civilian Nuclear Power Cycle

Overview

Figure 1 presents a simplified sketch of the civilian nuclear power cycle, the key components of which are the uranium mine and mill, the fluoride conversion plant, the isotope separation plant, the fuel fabrication facility, the nuclear reactor, and the reprocessing plant. The central facility is the reactor where the energy is actually produced by a controlled chain reaction of fissions. The uranium mine, fluoride conversion plant, isotope separation plant, fuel fabrication facility, and reprocessing plant merely produce and process the fuel used in the reactor.

Figure 1. Sketch of Nuclear Fuel Cycle



The energy, initially in the form of heat, is usually converted to electrical power. Thus a commercial nuclear reactor in essence is simply a replacement for a conventionally fueled power plant, producing electrical power by use of fissionable material rather than by coal, oil, or falling water. However, instead of ash as the inevitable byproduct, the nuclear reactor typically produces plutonium and highly radioactive waste products.

For the purpose of this study, perhaps the most noteworthy general characteristic of the nuclear fuel cycle is its relative decentralization. For the most part, the industry trend appears to be toward large regional facilities (fabrication plants, reprocessing plants, etc.) which will serve reactors at considerable distances. This tendency may be compared to another possibility: that an integrated fuel cycle be located at a single site, with conversion, fabrication, and reprocessing done continuously at a site co-located with the nuclear reactor. The relative security advantages and disadvantages of these two possibilities are examined in a later chapter.

Uranium (and Thorium) Resources

As shown in Table 1, uranium ore is widely distributed throughout the world, although 85% of the reasonably assured reserves[11] recoverable at less than \$10 per pound U_3O_8 (uranium oxide) in the non-Communist countries are located in Canada, South Africa, and the United States. These assured reserves presently total somewhat more than 900,000 tons of U_3O_8 with an additional one million tons potentially recoverable at less

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[11] Reasonably assured reserves refer to material which occur in known ore deposits and which can be removed from the earth and processed at the given price range with present technology.

than $10 per pound, surmised to exist. Reasonably assured reserves recoverable at between $10-$15 per pound U_3O_8 are estaimted to exceed 750,000 tons, with another 700,000 tons assumed to exist. Uranium in these cost ranges are generally found in ore deposits of .05 to 0.5%, often at shallow depths, mineable by open pit methods. The reserves are typically spread over a very large number of separate deposits, over 1200 deposits in the United States alone.[12]

Still more extensive reserves are now available at the higher cost ranges. For example, in 1968, the AEC estimated as reasonably assured domestic reserves, 5 million tons U_3O_8 in the $30-$50 cost range; 6 million tons U_3O_8 in the $50-$100 range.[13] It is believed that further prospecting will reveal considerably more extensive resources throughout the world at all cost ranges above $10 per pound U_3O_8.[14] It has also been shown that uranium can be extracted from sea water, where it is estimated the uranium content exceeds 4 billion tons. The eventual cost of extraction remains uncertain, with estimates ranging from less than $30 per lb. to over $100 per lb.[15]

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[12] OECD, World Uranium and Thorium Resources.

[13] U.S. Atomic Energy Commission, Cost-Benefit Analysis of the U.S. Breeder Reactor Program, 71.

[14] World Uranium and Thorium Resources, 6-17.

[15] World Uranium and Thorium Resources, 8.

Table 1. World Uranium Resources[16]

(USSR, China, and Eastern Europe Not Included)

Thousands of Tons of U_3O_8

Price Range per lb. U_3O_8	< $10		$10 to $15	
Type of Resource	Reasonably Assured	Estimated Additional	Reasonably Assured	Estimated Additional
Country				
Canada	230	230	130	170
United States	340	600	160	350
South Africa	200	15	65	35
France	45	25	10	15
Sweden	-	-	350	50
Australia	20	10	10	10
Niger	25	40	15	15
Others (including Argentina, Central African Republic, Gabon, India, Italy, Japan, Portugal, Angola, Spain, Brazil, Mexico, Turkey, and Yugoslavia)	65	60	50	70
TOTAL WORLD	930	975	785	710

[16]Adapted from World Uranium and Thorium Resources, 18; and U.S. Atomic Energy Commission, The Nuclear Industry, 1970, 35-42. Estimated additional resources refer to material surmised to occur in unexplored extensions of known deposits, or in undiscovered deposits, in known or postulated uranium regions.

One ton U_3O_8 is equivalent to 770 kgm U metal.

These estimates may be compared to the demand for uranium: A 1000 MW_e enriched uranium plant requires 600-750 tons U_3O_8 for the initial core; 200 tons per year thereafter. A natural uranium reactor of this size requires respectively 300 tons for the initial core and 150 tons per year thereafter. Based on these factors, projected worldwide requirements for uranium are as follows: annual requirements by 1980, 72,000 tons, doubling every 3-5 years; cumulative requirements to 1980, 420,000 tons; to 1985, one million tons. This demand is divided roughly equally between the domestic (U.S.) demand and that from the rest of the non-Communist world.[17]

Among the most important non-nuclear countries, West Germany, Japan, India (probably), and the UAR do not have sufficient stocks of uranium to mount a significant nuclear weapon program or to support their planned peaceful programs without substantial imports. Brazil (possibly), Israel (possibly), East Germany, Sweden, and of course Canada and South Africa do have sufficient reserves. The United Kingdom will be dependent on uranium imports to support both its peaceful and military programs. France and China will have sufficient reserves to pursue both vigorous nuclear weapon and concurrent civilian programs.[18]

There has not been extensive worldwide prospecting for thorium and consequently no firm estimates of global thorium resources exist. As lower limits though the following picture obtains: In the price range \$5-\$10 per pound of $Th\,O_2$, India has 300,000 tons reasonably assured reserves and an

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[17] The Nuclear Industry, 1970, 35.

[18] World Uranium and Thorium Resources. Uranium requirements for weapons are discussed in Chapter 2.

estimated additional 250,000 tons; the U.S. has 100,000 tons reasonably assured and an additional 500,000 estimated; Canada has 80,000 reasonably assured; and there are other scattered resources in Africa, Australia, Southeast Asia, Scandanavia, and Brazil.[19]

Enriched Uranium Cycle

Commercial reactors can utilize either natural uranium (0.7% U-235) or uranium slightly enriched in the isotope U-235. For the natural uranium cycle, the fluoride conversion and isotope separation plant steps, described next, are skipped; the milled uranium goes directly to the fuel fabrication facility.

Fluoride Conversion

The uranium is converted to uranium-fluoride (UF_6), a gas, for feed into the isotope separation plants. The uranium feed is of three types: natural uranium from the mill, in the form usually of U_3O_8, slightly enriched uranium (< 5% U-235) discharged from reactors and now needing re-enrichment for reactor recycling, and intermediate enriched uranium (> 5% U-235) needed for special purposes. The technology and capital investment required to achieve these conversion tasks are not appreciable.[20]

At present, there are two commercial conversion plants in the United States (at Metropolis, Illinois and Sequoyah, Oklahoma) with a combined annual capability of converting 15,000 tons U_3O_8 to UF_6. The AEC-operated Paducah plant is also still operable. In addition, three foreign countries (excluding the USSR and China) have UF_6 conversion capability available for commercial service: Canada in Port Hope, Ontario (2500 tons per year),

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[19] Ibid., 20. One ton Th O_2 contains 795 kgm Th metal.

[20] See section 4, this chapter.

the United Kingdom in Springfields (3200 tons per year), and France at Pierrelatte (3800 tons per year).[21] No domestic or foreign commercial capability for conversion of enriched uranium now exists; the AEC has undertaken such conversion in the United States. However, in the United States, three commercial plants for conversion of slightly enriched uranium and one for conversion of intermediate or highly enriched uranium are planned to be in operation by 1975.[22]

Estimated world-wide annual requirements for conversion are as follows:[23]

Conversion of	1975	1980
ore concentrates	22,000 tons	130,000 tons
slightly enriched uranium	600	1,400
highly enriched uranium	5	5

Isotope Separation Plant

Natural uranium is composed mainly of two isotopes: 0.7% U-235 and 99.3% U-238. The isotope separation plant produces uranium enriched in U-235, that is, uranium with a U-235 content greater than 0.7%. Because isotopes are atoms which exhibit identical chemical behavior and thus cannot be separated by chemical means, the enrichment process must take advantage of the slight mass differences which do affect the physical behavior of the atoms. Several such processes are in principle possible, although only two now appear commercially significant. These are gaseous

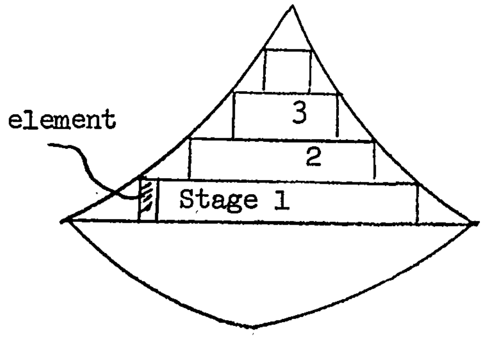
[21]The Nuclear Industry, 1970, 50-52.

[22]Ibid., 57.

[23]Ibid., 53, 57.

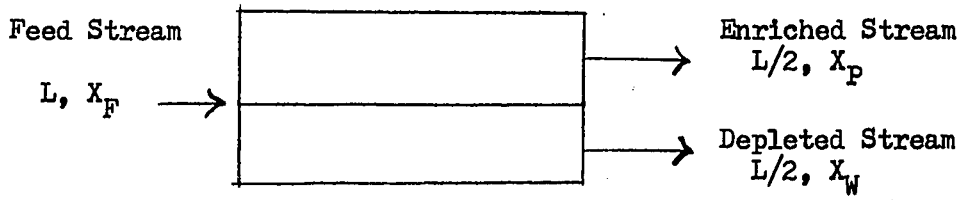
diffusion and centrifugation.[24] The first method uses the fact that lighter molecules in an equilibrium mixture of gas have slightly higher velocities on the average than the heavier molecules and consequently diffuse through the walls of a perforated confining barrier more easily than will the heavier molecules. The gas centrifuge process is based on the fact that the lighter molecules in a rapidly rotating gas become slightly separated from the heavier molecules.

Whatever the process, the separation plant will consist essentially of an array of separative elements (barriers, centrifuges, etc.) connected in series, each element effecting some small degree of separation. The entire array is termed a "cascade". Elements operating in parallel on material of the same U-235 concentration form a "stage".



[24]Conceivable commercial processes include the separation nozzle process, sweep diffusion, thermal diffusion, and electromagnetic separation as well as gaseous diffusion and centrifugation. These processes are admirably explained in Dennis Holliday and Milton Plesset, "Elementary Introduction to Isotope Separation", RM-4938-PR, June 1966. Aside from the two main candidates, the separation nozzle process has recently received considerable attention by Foratom (Forum Atomique European) as one possible basis for a future European enrichment plant. See Foratom, "Report on European Uranium Enrichment", January, 1969.

Each element in the cascade will take a feed stream L of U-235 concentration X_F and split it into two streams, one slightly enriched in U-235 (concentration X_P) and one slightly depleted in U-235 (concentration X_W).[25]



The separation power of an element may be defined as $\alpha = \frac{X_P}{1-X_P} \Big/ \frac{X_W}{1-X_W}$, the relative assays of U-235 and U-238 in the enriched and depleted streams. A more often used quantity is ψ , the separation factor, defined as $\psi = \alpha - 1$. For any given process ψ will be independent of the assay of the feed into the element and of the flow rate, L, of material through the element. For all processes other than the electromagnetic method, ψ is very small; for example, .00429 for gaseous diffusion.[26] The separative work done by the element will depend on the flow, L, and this separation factor. It will not depend on the assay of the feed material, Separative

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[25] U.S. Atomic Energy Commission, <u>AEC Gaseous Diffusion Plant Operations</u>, ORO-658, Appendix 1, contains a clear description of the separation process. Also, see Holliday and Plesset, "Elementary Introduction to Isotope Separation" for discussion of cascades. The diagram here is somewhat simplified in showing the feed stream divided into two equal parts which need not be the case.

[26] This is the ratio of the average velocities of the UF_6 molecules minus one. The ratio of velocities is equal to the square root of the ratio of the masses, or $\sqrt{\frac{352}{349}}$.

work is measured in kilogram separative work units (SWU) or metric ton separative work units, and reflects the actual physical effort expended.[27] That is, the actual separative work accomplished by an element will depend on its size and character, and on the power level at which it is operated (to rotate a centrifuge, to pump gas through a barrier, etc.).

Because the separation factor for an element is so low, a very large number of elements and stages and large quantities of power must be utilized in a cascade to achieve any substantial amount of separative work. The cascade is operated so that materials of different assay are not mixed. This requires elaborate pumping between stages with two flows proceeding simultaneously, one toward stages of higher and higher enrichment and one toward stages of increasingly lower U-235 assay. The material handled by the higher enrichment stages continually diminishes. Since ψ is independent of assay and flow rates, the number of stages required in any cascade is completely determined by ψ and by the enrichments of the initial feed stream and the final product and waste streams. It is easily shown in fact that the number of enrichment stages (N) and depletion stages (D) in an ideal cascade are given by

$$N = \frac{1}{\psi} \ln \frac{R_P}{R_F}$$

$$D = \frac{1}{\psi} \ln \frac{R_F}{R_W}$$

[27]Roughly, one kilogram SWU applied to 2.35 kgm natural uranium will produce 1 kgm 1.4% U-235, and 1.35 kgm 0.2% U-235.

where $R_i = \frac{X_i}{1-X_i}$.[28] Thus, for any separation task, the number of required stages is inversely proportional to the separation factor, ψ. These are lower limits, valid for ideal cascades where materials of different assay are not mixed. Practial cascades would require a somewhat greater number of stages. In a gaseous diffusion cascade, $\psi = .0049$. To go from natural uranium to 93% product would therefore require at least $N = \frac{1}{.0049} \ln \frac{93/7}{.7/99.3} = 1600$ enrichment stages. The number of stages in a centrifuge cascade (with say $\psi = .10$) required to achieve the same result would be $N = \frac{1}{.10} \ln \frac{93/7}{.7/99.3} = 80.$[29]

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[28]Let $R_i = \frac{X_{P_i}}{1-X_{P_i}}$, the relative isotopic assay fed into the ith stage of the cascade. It then follows that $R_i\alpha = R_{i+1}$; and by extension, $R_i\alpha^N = R_{i+N}$. To go from feed of relative isotopic assay R_F to enriched product R_P will therefore require N enrichment stages where $R_F\alpha^N = R$; the cascade if run efficiently will also require D depletion stages where $R_F \alpha^{-D} = R_W$, the relative assay of the tails. From these relations, it immediately follows that

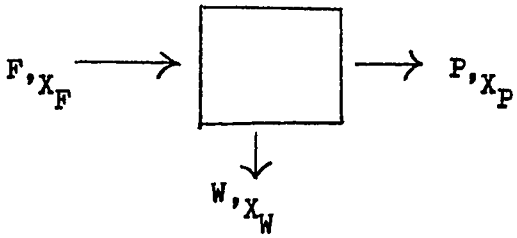
$$N = \ln\frac{R_P}{R_F} / \ln \alpha \approx \frac{1}{\psi} \ln \frac{R_P}{R_F}$$

$$D = \ln \frac{R_F}{R_W} / \ln \alpha \approx \frac{1}{4} \ln \frac{R_F}{R_W}$$

[29]The separation factor, ψ, in the gaseous diffusion process is always the same (.00429). The separation factor for centrifugation will however depend on the velocity at which the centrifuge is rotated. Ultra-centrifuges already had achieved separation factors close to $\psi = 0.10$ a few years ago. They now can probably do much better. See Halliday and Plesset, 13-16.

This suggests an important technical difference between gaseous diffusion and centrifugation. The pumping and stage arrangements for the former are inherently much more inflexible than those for centrifugation. A centrifuge plant designed to produce slightly enriched uranium can be much more easily modified to produce highly enriched, weapons grade, uranium than can a gaseous diffusion plant. This greater flexibility of centrifugation derives from three considerations: a centrifuges cascade requires many fewer stages than a gaseous diffusion plant; it requires, however, many more elements per stage to obtain comparable throughput rates; and all centrifuge elements are roughly of the same size wherever they may be in the cascade. Because of the first factor, less interstage pumping is needed in a centrifuge cascade. The second and third factors permit the cascade to be rearranged more easily. This may be looked at in a somewhat more casual way. The collection of highly enriched product whatever the initial deployment of stages requires eventually a tapered cascade, in which the material flow from stage to stage continually decreases. To construct such a cascade from a truncated cascade of many fewer stages in effect will require transferring elements from the lower stages to the top. In a centrifuge plant, this would be relatively easy because the individual elements are more or less interchangeable and there are many per stage. In a gaseous diffusion cascade by contrast, the elements in the lower stages are very large, much too large to be appropriate for use in the top regions of the cascade.

If one looks at the cascade as a whole, there is a feed (F) into the cascade of material with X_F U-235 concentration; an enriched product stream (P) with U-235 concentration X_P; and a waste or depleted stream (W) with U-235 concentration X_W.



The amount of feed to produce P kilograms of enriched product is simply given by

$$F = \frac{X_P - X_W}{X_F - X_W} P.$$

This may be derived simply from the conservation of mass, $F = P + W$, and the conservation of U-235 isotopes, $X_F F = X_W W + X_P P$:

$$X_F F = X_W (F-P) + X_P P$$

$$F = \frac{X_P - X_W}{X_F - X_W} P .$$

Similarly, the separative work done is given by[30]

$$SW = P V (X_P) + WV (X_W) .$$

It may be observed from these relationships that given a specific assay feed (say, natural uranium) and a specific desired product (say, 100 kgm of 3% U-235), the required amounts of feed and separative work will depend on the assay of the waste stream. If this assay is set at a level near the feed assay, say at 0.6%, the separative work requirement will be relatively low, but the feed requirement in tons of natural uranium will be high. Conversely, at very low waste assays, for example

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[30] V(X) is the so-called "value function", not derived here. It has the form $C_o + C_1 X + (2X-1) \ln \frac{X}{1-X}$, and the property that the change in "value" effected by a separation element is independent of the assay of the feed.

0.1%, the separative work requirements will be high and the feed requirements low. It then follows that given the costs of separative work and uranium feed, there will exist some waste assay that minimizes the total cost of the enrichment process. For operational gaseous diffusion plants this assay is approximately 0.2% U-235, and the waste assay is consequently set at this figure.

Table 2 is a standard table of enriching services based on the preceding equations and a waste assay, $X_W = 0.2\%$. The table is illuminating in that it provides an easy way to calculate the amounts of material and work required to go from any assay feed to any desired product. For example, let us compare the efforts involved in producing first 3% enriched uranium from natural uranium, and then using the 3% enriched uranium to produce weapons-grade uranium (93% U-235).

From Table 2, we will need 181.6 kgm natural uranium fee and 235.5 kgm SWU to produce 1 kgm 93% product. To go from 3% feed to 1 kgm of 93% product requires

$$F = \frac{X_P - X_W}{X_F - X_W} = \frac{93.0 - 0.2}{3.0 - 0.2} = 33 \text{ kgm.}$$

The production of 33 kgm of 3% U from natural U requires (from Table 2) 4.3 x 33 = 143 kgm SWU. Thus we may envision the production of 1 kgm of 93% U-235 in two steps: First, 181.6 kgm of natural U and 143 kgm SWU produce 33 kgm of 3% U-235. Then, using these 33 kgm as feed, 92 kgm SWU additional produce 1 kgm 93% U-235.[31]

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[31]Although not apparent from Table 2, as indicated above, changing the waste assay would change both the feed and separative work requirements. For example, reduction of the waste assay from 0.2% to 0.1% would increase the separative work required to go from natural U to 3% U-235 by about 40%; this reduction would decrease the feed requirement by about 15%. An increase of the waste assay from 0.2% to 0.4% would decrease the required separative by 20% and increase the feed requirement by almost 50%. See, for example, U.S. Atomic Energy Commission, Selected Background Information on Uranium Enriching, ORO 668, 43.

Table 2 Standard Table of Enriching Services[32]

Assay (wt. % U-235)	Feed Component (Normal) (kg U Feed/kg U Product	Separative Work Component (kg SWU/kg U Product)
0.20	0	0
0.30	0.196	- 0.158
0.38	0.352	- 0.197
0.42	0.431	- 0.197
0.46	0.509	- 0.189
0.50	0.587	- 0.173
0.54	0.665	- 0.151
0.58	0.744	- 0.123
0.65	0.881	- 0.062
0.711 (Normal)	1.000	0.000
0.80	1.174	0.104
0.90	1.370	0.236
1.00	1.566	0.380
1.20	1.957	0.698
1.40	2.348	1.045
1.60	2.740	1.413
1.80	3.131	1.797
2.00	3.523	2.194
2.40	4.305	3.018
2.80	5.088	3.871
3.00	5.479	4.306
3.60	6.654	5.638
4.00	7.436	6.544
5.00	9.393	8.851
6.00	11.350	11.203
8.00	15.264	15.995
10.00	19.178	20.863
14.00	27.006	30.737
18.00	34.834	40.724
25.00	48.532	58.369
35.00	68.102	83.816
50.00	97.456	122.344
70.00	136.595	174.302
85.00	165.949	213.892
92.00	179.648	232.796
93.00	181.605	235.550
98.00	191.389	269.982

The kilograms of feed and separative work components for assays not shown may be determined by linear interpolation between the nearest assays listed.

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[32]Copied from ORO-658, 37.

Similarly, a 1000 MW_e enriched uranium reactor may require typically about 30 metric tons of 3.4% U-235 per year, which could be produced by 150 metric ton units of separative work from natural uranium. Modified to produce highly enriched uranium, a plant with such a capacity could produce 640 kgm of 93% U-235 from natural uranium.

All currently operational substantial isotope separation facilities use the gaseous diffusion process.[33] There are three U. S. diffusion plants, in Oak Ridge, Paducah, Ky., and Portsmouth, Ohio with a combined capacity of 17,000 metric ton units. This capacity could be expanded by about 50% without the construction of new plants. The only other gaseous diffusion plants operating in non-Communist countries are the Capenhurst Plant in the United Kingdom (400 metric ton units/year) and the Pierrelatte Plant in France (300 metric ton units/year). In addition, there are gaseous diffusion plants in the USSR and probably in China.[34]

Although there are no firm plans anywhere for additional plants, the AEC has undertaken several studies aimed at the construction of new plants during the late 1970's and the 1980's. Also, several foreign countries have considered future isotope separation plant constructions. For example, the French are contemplating the construction of a plant of 6,000 metric tons/year capacity;[35] various possibilities including joint Euratom sponsorship of the French plant;[36] and the United Kingdom, West

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[33]ORO-668, 13-16. The Nuclear Industry, 1970, 60-71. China presumably.

[34]The Nuclear Industry, 1970, 60-71.

[35]Ibid., 68.

[36]Ibid., 68-71. Foratom, "Report on European Uranium Enrichment."

Germany, and the Netherlands have undertaken to develop a commercial centrifuge plant.[37] The security implications of these several enterprises are examined in Chapter 4 of this study.

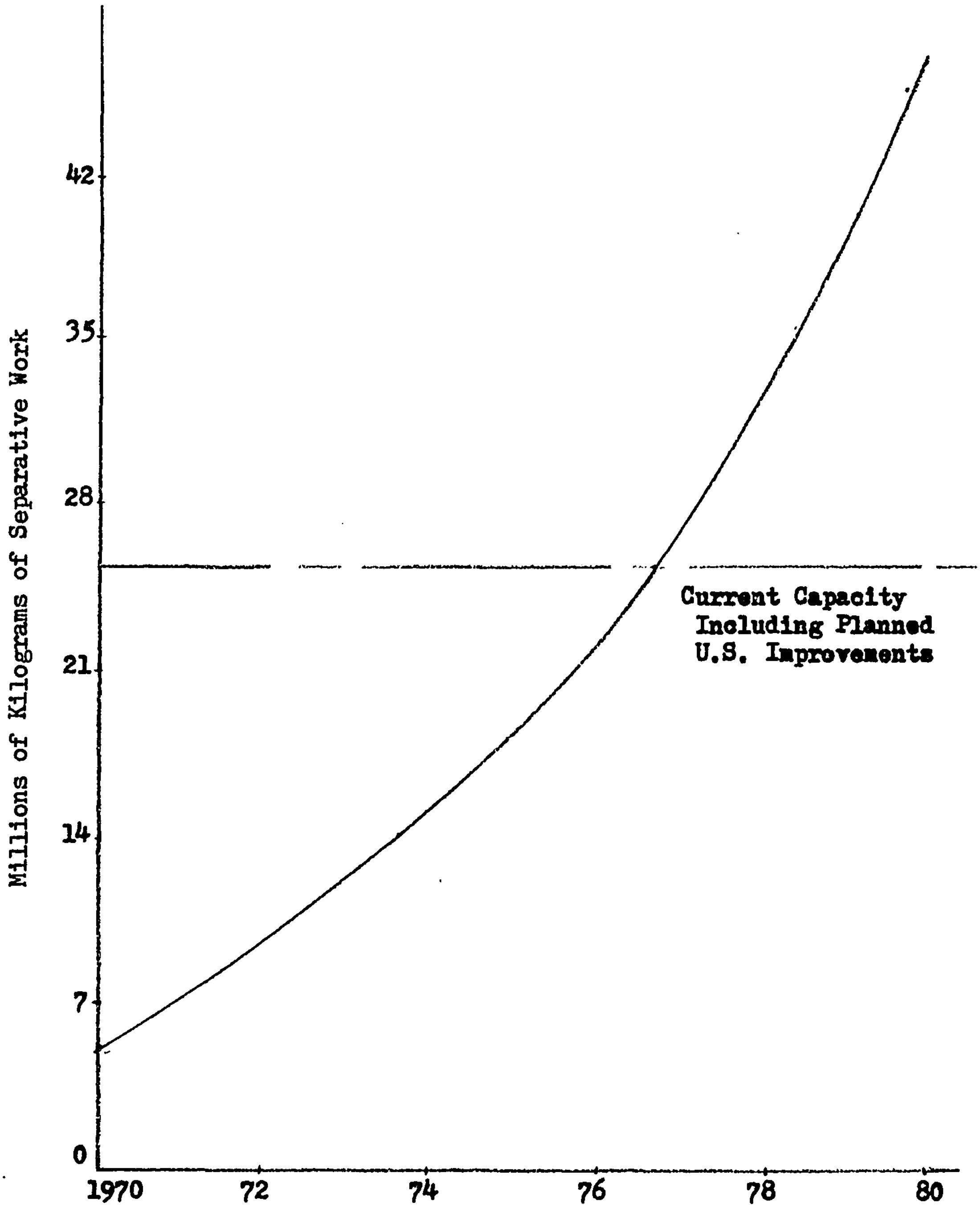
Whatever the fate of these specific enterprises, it is clear that more world enrichment capacity will soon be needed. Annual separative work requirements for the United States are estimated at 10,000 metric ton units in 1975, 21,000 metric ton units in 1980. Foreign requirements will be about half the U.S. total in 1975, almost equal to the U.S. total by 1980.[38] After 1980,annual enrichment demand in the non-Communist countries is expected to grow at 5,000 metric ton units per year.[39] Thus the following figure:

[37] The Nuclear Industry, 1970, 70. Canada, Italy, Japan, and South Africa are also active in separation technology development. Indeed, South Africa has claimed that it has developed a "unique" process, and that a corporation to exploit this breakthrough has been established. It is also of interest that the Soviet Union now appears prepared to enter the commercial enrichment market.

[38] Ibid., 63.

[39] Ibid., 65.

Figure 2. Demand for Uranium Enriching (Non-Communist Countries)[40]



[40]Adapted from The Nuclear Industry, 1970. 63.

Conversion and Fuel Fabrication Plant(s)

The conversion and fuel fabrication plant(s) converts the enriched UF_6 into uranium compounds suitable for processing (usually UO_2),and processes the uranium (natural or enriched) into properly devised compounds, shapes and cladding for insertion into the reactor. This entails several different types of capabilities: notably, conversion of enriched uranium fluoride to uranium oxide powder, production of uranium oxide pellets from the powder, fabrication of fuel elements containing the pellets, and fabrication of carbide fuels. Fabrication of plutonium fuels require similar processing. The specialized technology required for these steps is widely available, and several commercial enterprises in the United States and Europe have already established fabrication facilities of a variety of kinds.[41]

As a rough approximation, a 1000 MW_e light water enriched uranium reactor would require the fabrication of 75 MTU for the initial core and additional annual fabrication of 24 MTU. This leads to estimated annual domestic fabrication requirements of 3,000 metric tons uranium (or uranium plus plutonium) in 1975, 5,000 metric tons in 1980. Foreign fabrication requirements, which will be met for the most part by the involved foreign countries, are about the same.[42]

At present, there are several major fuel fabrication facilities in the United States; the average capacity of these plants is less than one

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[41] Ibid., 74-95.

[42] Ibid., 85.

metric ton uranium per day.[43] There are many additional such plants in the rest of the world including twelve located in the non-nuclear countries. In addition, each nuclear-weapon state possesses at least one facility for the fabrication of highly enriched uranium; there is one such plant also in Italy.

Fuel fabrication plants will become especially critical points in the nuclear fuel cycle when there is substantial plutonium recycle at which times the plants will be processing large quantities of fissionable material.

Nuclear Reactor

The essential requisite of all nuclear reactors is the achievement of a controlled chain reaction involving fissions of U-235 and Pu-239 (or U-233). As stated earlier, in all current commercial power reactors, the chain reaction must be carried by relatively slow or thermal neutrons, much slower than the velocities at which the neutrons are emitted during fission. As a consequence, all "thermal reactors" contain material, called a moderator, to slow-down neutrons. They must also contain a fluid to cool the reactor. Several materials have been used as moderators - including, beryllium, graphite, organic liquids (benzene derivatives), light and heavy water. Coolants have included sodium, fused salts, several gases (carbon dioxide, helium, air, steam), and also organic liquids and light and heavy water.[44] Thermal reactors may be classified by the choice of moderator and coolant among these materials and fluids. The most important commercial types are as follows:

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[43] Ibid., 74-79. U.S. Atomic Energy Commission, Competition in the Nuclear Power Supply Industry, 1968, 183-212.

[44] Robert Loftness, Nuclear Power Plants, 74-76.

Reactor Type	Moderator	Coolant	Fuel	Comment
Boiling Water Reactor (BWR)	Light Water (H_2O)	Light Water	~ 2.5% U-235	Almost all power reactors in U.S., Germany, and Japan (BWR and PWR)
Pressurized Water Reactor (PWR)	Light Water	Light Water	~ 3% U-235	
Advanced Gas-Cooled Reactor (AGR) - at high temperatures (> 1000°F)	Graphite	Carbon Dioxide	~ 2% U-235	United Kingdom
High Temperature Gas-Cooled Reactor (HTGR)	Graphite	Helium	Highly Enriched U	Under construction in U.S.
Gas Cooled Reactor	Graphite	Carbon Dioxide	Natural U	United Kingdom, France. Some types which use magnox cladding are termed "magnox" reactors
Heavy Water Reactor	Heavy Water (D_2O)	Heavy Water	Natural U	France, Canada, India

Reactors may also be classified by the degree to which the burned fissionable material is replaced within the reactor by the production of Pu-239 or U-233 through neutron capture by U-238 and Th-232. Present commercial reactors, which replace about one-half the fissioned nuclei through this process, are termed "converters". The major reactor of this type now under development in the United States is the HTGR, the high temperature gas-cooled reactor, which will be able to utilize either a U-235/plutonium cycle or a U-233/thorium cycle. Part of the fuel for this reactor is highly enriched uranium (> 90% U-235).[45] The third type

[45] The Nuclear Industry, 1970, 181. Nuclear Engineering International, December 1969, 1069.

of reactor, the so-called "breeder", produces more fissile nuclei than it uses up. The breeder will be discussed in section 4.

For at least the next decade most reactors will continue to be converters. Of these, the BWR, PWR, and AGR employ slightly enriched uranium (approximately 1.6% U-235 for the AGR to 3.4% U-235 for the PWR). Because of the greater fraction of fissile isotopes in the lightly enriched reactors, light (ordinary) water can be used as a moderator despite its propensity to absorb neutrons. In natural uranium reactors however, if water is used as the moderator, it must be heavy water, which does not have a high neutron absorption capacity. Thus outside of the United Kingdom where the AGR plays a prominent role, the terms "light water reactor" and "enriched uranium reactor" are often used interchangably.

The performance of a reactor may be roughly described by three parameters:

(a) Installed (Rating) capacity in electrical megawatts (MWe). This gives the total electric power output. Typically, the power converted to electricity is about one-third the total power (heat per unit time) produced by the reactor. Thus the electrical megawatts (MWe) is about one-third the thermal megawatts (MW_t) produced in a reactor. This ratio, which itself may vary some from reactor to reactor is termed the reactor "efficiency". Most commercial reactors built during the next two decades will probably have capacity between 300 to 1200 MWe.[46]

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[46]With emphasis on the high side. Of 23 reactors for which construction contracts were awarded in the U.S. during 1968 and 1969, all but two exceeded 800 MW_e. The Nuclear Industry, 1970. 154-155, 180.

(b) Specific power. This gives the thermal power per unit of fuel of the reactor. A typical value for light water reactors is 25 MW_t/MTU--(25 thermal megawatts per metric ton uranium).

(c) Burn-up. This measures the total (heat) energy produced in a unit of fuel before it is removed from the reactor. The higher the burn-up, the more economical the reactor. Typical burn-up values: for enriched uranium reactors, 25,000 MW_td/MTU; for natural uranium reactors, 4,000-10,000 MW_td/MTU. The burn-up essentially determines the uranium requirements to fuel a given reactor and the composition of the discharged plutonium.

A specific power of 25 MW_t/MTU and burn-up of 25,000 MW_t-days/MTU implies an average dwell time in the reactor for a given fuel element of 1000 days or about 3 years. Three to four years is in fact a reasonably typical figure for both enriched and natural uranium reactors. The size of reactor elements vary between roughly 10 kgm to 50 kgm. The core of a light water enriched uranium 1000 MW_e reactor might typically contain 1500 elements (50 kgm/elements), with a third of these discharged from the reactor each year. Not all the U-235 in the reactor fuel will be fissioned before discharge. For example, in a light water enriched uranium reactor, at charge an element might contain (say) 3% U-235, and at discharge 1% U-235. Approximately one-fourth of the energy produced in the reactor will be due to plutonium fission.

Although reactor technology is unclassified, most non-nuclear states are now dependent on the United States, United Kingdom, West Germany, France, and Canada for reactor construction. They will probably remain so for the forseeable future. Indeed with respect to light water enriched uranium reactors which have now gained a clear economic advantage over the natural uranium reactors, the United States (where the market is divided among 5 companies) is dominant.[47]

The distribution of power reactors throughout the world is described in section 5.

Chemical Reprocessing Plant

The reprocessing plant separates and recovers the plutonium, uranium, and fission products in the irradiated fuel. This is accomplished through a relatively straightforward chemical technology which is completely unclassified and within the technical and economic competence of all countries planning nuclear power programs. Most plants are designed to handle mainly one type of fuel, the variety including fuel from slightly enriched uranium reactors, from natural uranium reactors, and highly enriched uranium fuels. In all cases, the reprocessing and recovery generally occurs one year after discharge of the irradiated fuel from the reactor; the high radioactivity of the fuel immediately upon discharge requires that it be "cooled" in a pool of water for several months prior to reprocessing.

A 1000 MW_e enriched uranium reactor requires a reprocessing capacity of approximately 30 MTU (slightly enriched) per year; a natural uranium reactor, about triple this. Since the average dwell time of a fuel element in the reactor is 3 to 4 years and, as indicated, a year is required from reactor discharge to recovery, these reprocessing requirements lag the installed power by four to five years. Total annual

[47] As reflected in current domestic and foreign contracts for new reactors. The Nuclear Industry, 1970. 154-155, 179.

reprocessing requirements for the United States by 1980 are expected to approximate 3000 MTU per year; total world requirements will be more than double this.[48]

A large number of reprocessing plants throughout the world are now in operation or under construction. In the United States, there are three such commercial plants:

Plant	Planned Eventual Capacity
Nuclear Fuel Services	900 MTU/year
General Electric	300 MTU/year
Allied Chemical	1500 MTU/year

In addition, at least three other commercial plants are now planned, though construction has not yet begun. Also, the AEC operates three reprocessing plants to service its plutonium production reactors.[49]

There is also a burgeoning foreign reprocessing industry as indicated in the following:

[48] Ibid., 251, 262-263. See also U.S. Atomic Energy Commission, Forecast of Growth of Nuclear Power, 1970, WASH-1084, para. 18.

[49] The Nuclear Industry, 1970, 244-250.

Table 3. Chemical Reprocessing Plants Abroad (Constructed and Planned)[50]

	Capacity (MTU/year)	Capability
Eurochemic, Mol Belgium		
(joint effort of 13 countries)	180	Natural U and Enriched U
United Kingdom		
Windscale 1.	2200	Natural U
Windscale 2.	300	Enriched U
Dounreay, Scotland	1	Highly Enriched U and Pu
France		
Cap de la Hague	450	Natural U
Marcoule	450	Natural U
Germany		
Karlsruhe	40	Enriched U
Italy		
Trombay	100	Natural U
Tarapur	150	Natural U and Enriched U
Japan		
Tokai-Mura	200	Natural U and Enriched U
Norway		
Kjeller	40	Enriched U
Spain		
Moncla	1/10	Highly Enriched U
Argentina		
Buenos Aires	1/5	Highly Enriched U

[50]Adapted from The Nuclear Industry, 1970, 264.

The entire world reprocessing requirements by 1980 (about 6000-8000 metric tons per year) could be met by a handful of large plants of 1500 MTU/year capacity plus a few smaller plants to handle specialized material. This possibility that world commercial reprocessing requirements could be handled by a relatively small number of facilities, widely distributed throughout the non-Communist world, suggests a powerful control measure, which will be examined at a later point.

Irradiated (Discharged) Fuel: The Production of Plutonium

The fuel discharged from a reactor and processed contains mainly highly radioactive fission products, plutonium, and uranium. The plutonium is composed of the isotopes Pu-239 and Pu-241 which are fissionable by thermal neutrons, and Pu-240 and Pu-242 which are not. Both the total amount of contained plutonium and the plutonium isotopic composition will depend on the type of reactor and its mode of operation.

For normal economic modes of operation, the plutonium content in the discharge fuel averages 275 grams to 360 grams per MW_e per year for the enriched uranium reactors, with about 30% of this the non-fissile isotopes Pu-240 and Pu-242. Natural uranium reactors produce nearly twice as much plutonium, roughly 500-600 grams per MW_e per year, about 15-20% of which are the non-fissile isotopes. Thus, a 1000 MW_e enriched uranium reactor will produce about 300 kgm of plutonium per year (70% fissile isotopes); a 1000 MW_e natural uranium reactor will produce about 600 kgm plutonium per year (85% fissile isotopes).[51] One hundred kilograms fissile plutonium

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[51]From a variety of data. See for example Russell Stanford and Charles Moore, "Commercial Plutonium" in CONF-660308, 78-85; The Nuclear Industry, 1970, 88, 262. As an example of plutonium production from a natural uranium reactor the U.K. magnox reactor at burn-ups of 3000 MW_td/MTU produce 0.67 grams Pu/MW_{th}d at 17% Pu-240 plus Pu-242; it produces about 500 kgm plutonium per year per 1,000 MW_e.

is sufficient for more than ten weapons.

The plutonium isotopic composition is very strongly dependent on the average burn-up values of the discharged fuel, that is, the length of time the fuel remains in the reactor. This is partly because the rates at which the higher isotopes of plutonium build-up depend on the amount of Pu-239 present in the reactor; if the fuel discharge is frequent, the higher isotopes, which are produced by successive neutron captures of Pu-239, Pu-240, and Pu-241, will have little opportunity to form. Frequent discharge also ensures that the produced Pu-239 will fission much less frequently than the more plentiful U-235. By contrast, under ordinary exposure levels, as more and more Pu-239 relative to U-235 is formed in the fuel, an increasing fraction of the energy is produced by Pu-239 fissions, occurrences which of course reduce the relative amount of Pu-239 in the discharged product. Figure 3 indicates this dependence of isotopic composition on burn-up levels for enriched uranium reactors. Natural uranium reactors exhibit similar dependence.[52] It may be noted that the production of plutonium with greater than 90% Pu-239 by light water reactors would lead to reprocessing requirements and a rate of fuel removal from the reactor five times as great as for normal operation (with burn-up of 25,000 MW_td/MTU). These data are important because the weapons utility of plutonium depends on the isotopic composition, as is discussed in Chapter 2.

The plutonium generated in the reactor may be recycled: that is, it may be fabricated into new fuel elements, possibly blended with natural

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[52]For example, the U.K. magnox reactors show the following dependence: 1000 MW_td/MTU → 13%; 3000 MW_td/MTU → 17%.

or slightly enriched uranium. This has not yet been done on a commercial basis, however, and it is too soon to forecast confidently future recycle requirements for plutonium fabrication. At most, after perhaps 5 years, plutonium might be expected to replace about one-third of the U-235 that would otherwise be required were there no recycling. In such a case, plutonium use would average roughly 200 kgm plutonium per 1000 MW_e per year.[53] Uranium requirements would be correspondingly reduced to two-thirds of the values adduced earlier.

Apart from potential use in light water reactors plutonium will be required during the next several years in connection with various research and development enterprises, notably those aimed at the development of breeder reactors. Eventually, of course, plutonium will also be needed for the initial cores of the breeders themselves. Total R & D plutonium requirements in the United States will average 2000 kilograms per year in the middle 1970's; foreign requirements would be similar. Breeder cores will require about 3 kgm plutonium per installed MW_e; a 1000 MW_e reactor will use 3000 kgm of plutonium in the initial core.[54]

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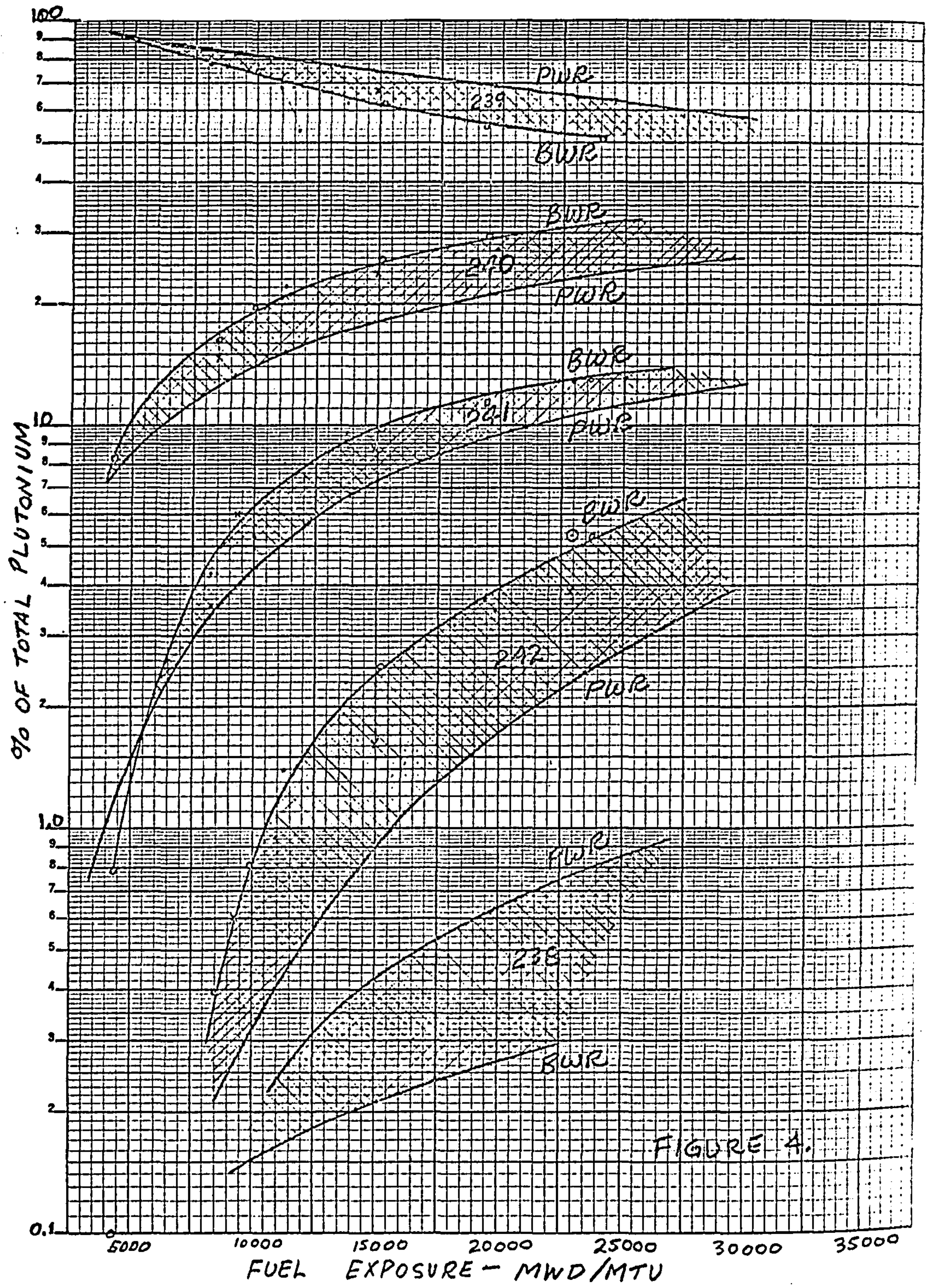
[53]WASH-1084, par. 18. Without recycle, about 150 metric tons natural uranium is required replacement per 1000 MW_e. This corresponds to (.007) x 150 = 1 metric ton U-235. If slightly less than one-third of this, or say 300 kgm, is replaced by plutonium, and we take the fuel value of plutonium as 50% greater than U-235, this gives 200 kgm of plutonium as the required replacement.

Safety considerations will limit the scope of plutonium recycling. The main guarantee of safety is a system in which any sudden rise in temperature causes an instantaneous drop in reactivity. Pu-239 and Pu-241, which have fission resonances just above the thermal range, contribute adversely to such a "negative prompt temperature coefficient of reactivity." Consequently, it will be extremely difficult to use plutonium as a main fuel in thermal power reactors while maintaining present standards of safety.

[54]The Nuclear Industry, 1970, 87-93. See also Section 3, this chapter.

Figure 3 Isotopic Composition of Commercial Pu[55]



[55] Copied from Stanford and Moore, "Commercial Plutonium, in CONF-660308, 84.

Compared to these various demands for plutonium, large quantities of plutonium will be recovered annually from commercial reactors: in the United States, 10,000 kgm/year in 1975; 20,000 kgm/year in 1980, with total world production more than double this.[56] In addition, very large quantities of plutonium produced by the AEC production reactors are apparently available for commercial use if necessary.[57]

Transportation

The scope of transport required by the nuclear industry is suggested by Tables 4 and 5; the data is only for the United States, but foreign programs will require shipments of the same order of magnitude.[58] The import of these data will be made apparent in Chapter 3, where the effectiveness of safeguards is examined. For reasons there explained, the transport system appears highly vulnerable to theft of nuclear material.

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[56] Ibid., 88. See also section 5.

[57] Ibid., 88.

[58] Ibid., 320-329.

Table 4. Transportation in the Nuclear Fuel Cycle[59]

Commodity	Point-to-Point	Tonnage of Shipments 1975	Tonnage of Shipments 1980
U_3O_8	Uranium mill to feed preparation plant	17,000	34,000
Normal UF_6	Feed preparation plant to gaseous diffusion plant	21,000	43,000
Enriched UF_6	Gaseous diffusion plant to fuel fabrication plant/ materials processing	4,200	9,000
UO_2	Material processing plant to fuel fabrication plant	3,200	6,600
Fabricated fuel assemblies	Fuel fabrication plant to reactor	3,700	7,600
Irradiation fuel	Reactor to reprocessing plant	1,500	3,800
Recovered Products	Reprocessing plant to various destinations		
	TOTAL	51,000	104,000
	TOTAL (including weight of containers)	150,000	300,000

[59]Adapted from The Nuclear Industry, 1970, 320.

Table 5. Type of Containers Used for Transportation[60]

U_3O_8	55 gallon steel drums carrying 650 pounds U_3O_8
Normal UF_6	pressurized cylinders, 14 ton UF_6 capacity
Enriched UF_6	pressurized cylinders, 4,800 pounds UF_6
UO_2	drums
New fuel elements	protective packages, up to 8,000 pounds
Irradiated fuel	shielded lead or uranium casks, 30-100 tons, carrying 1-4 tons of spent fuel
Recovered products	tanks, protective packages, shielded casks.

[60] Ibid., 320, 322-326.

Summary: Nuclear Fuel Cycle for a 1000 MW_e plant

In summary, consider the variety of activities required to service a 1000 MW_e reactor, say of the PWR, slightly enriched uranium, type.

Uranium Requirements. The initial core will require 625 tons U_3O_8. This corresponds to 480 metric tons natural uranium or 75 metric tons of uranium enriched to 3.4% in U-235. Average annual replacement requirements are 200 tons U_3O_8, or 150 metric tons natural uranium corresponding to 24 metric tons enriched uranium. Time from procurement of U_3O_8 to production of enriched UF_6 will be about 6 months.[61]

Isotope Separation Requirements. The initial core will require 370 metric ton units of separative work. Annual replacement loadings will require 150 metric ton units. There will elapse approximately 6 months from the procurement of enriched uranium in UF_6 to insertion of elements into the reactor.[62]

Fuel Fabrication. The initial core will require the fabrication of 75 MTU (slightly enriched); average annual fabrication requirements thereafter will be 24 MTU. The elements might each typically weigh 50

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[61]WASH-1084, para. 14 and 18. The conversion of short tons of U_3O_8 to metric tons of enriched uranium is made as follows:

$$U(\text{natural}) = \frac{a_{enr.} - a_{tail}}{a_{feed} - a_{tail}} U(\text{enriched})$$, where a_{enr}, a_{feed}, and a_{tail} represent the U-235 percent content in the enriched product, the natural uranium feed, and the depleted tails.

$$U(\text{enriched}) = U(\text{natural}) / \frac{(3.4 - .22)}{(.71 - .22)}$$

$$U(\text{enriched}) = \frac{U(\text{natural})}{6.5}$$

Given that 1 ton U_3O_8 contains .77 metric tons uranium, this gives:

$$U(\text{enriched}) = \frac{U_3O_8}{6.5} (.77).$$

[62]Ibid., pars. 14 and 18.

kilograms, which would mean a reactor inventory of 1500 elements and an average annual replacement of 500 elements.

In the Reactor. Average burn-up of the fuel is 32,000 MW_tdays/MTU at a specific power of 34 MW_t/MTU. It follows from this that the average dwell time of an element is about 3 years. The composition of the fuel at charge and discharge looks as follows:

Fresh fuel assay	3.4% U-235
Spent fuel assay	0.9% U-235

This means that about one-fourth of the energy produced in the fuel is due to plutonium fission.[63]

Reprocessing Plant. The reprocessing requirement is 24 MTU per year. A given fuel element will go through the reprocessing approximately 4 years after its insertion into the reactor. The plutonium discharged will average about 10 kgm per MTU, or 240 kgm Pu per year. This corresponds to one-fourth kgm Pu per installed electrical megawatt. The fissile component of the plutonium will average about 75%.[64]

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[63]See WASH-1084, para. 15 for PWR data. One MTU at charge contains 34 kgm U-235; at discharge, it contains 9 kgm. This means that 25 kgm U-235 were burned, which would account for 25000 MW_t-days, given that 1 gram fission produces 1 MW_t day energy. Since average burn-up is 32,000 MW_t days, 7,000 MW_t days or 22% of the total energy must be due to plutonium fission.

[64]Ibid., para. 18.

3. Economics of Nuclear Power

Introduction

Although nuclear fuel costs very little to transport, radioactive shielding and criticality requirements assure that very small and dispersed nuclear reactors, as replacements for example of internal combustion engines, will not be practical for the foreseeable future.[65] Thus nuclear power will for the most part be used to generate electricity in central electric power stations, in which nuclear reactors simply replace the furnace of the conventional power plant, with the energy distribution system no different between the two cases. The relative costs of producing electricity in central power stations thus provides the major economic comparison between nuclear and conventional power.

Cost of Nuclear Power

The three major cost components for both nuclear and conventional power plants are:

- Fuel Cycle Cost
- Fixed Charge Costs (essentially the interest charge on the fixed investment)
- Maintenance and Operating Cost

Tables 6 and 7 illustrate typical breakdowns of these costs for a 1000 MW_e light water nuclear power plant, and a 1000 MW_e natural uranium reactor such as might be constructed in the 1970's. The estimates are based on the equivalence 1000 MW_e- year = 72×10^8 KW_e-hours. This assumes the plant will operate over the year at an average capacity of about 80%.

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[65]Nuclear power could however be used to "charge" batteries or other energy storage systems which could be used in small dispersed plants.

The item which perhaps most requires explanation in the Tables are the plutonium credit price. This simply reflects the commercial value of plutonium in a nuclear reactor. (It's value as weapons material would of course be far greater). Assuming the feasibility of recycling plutonium in converter reactors, this value must be roughly comparable to the value of U-235 in a commercial reactor, approximately $8 per gram.[66]

The Tables indicate the cost of electricity at the "bar", before distribution to the consumer. Such distribution over distances typical in the United States would approximately double the total cost of electricity. With this in mind, the Tables present an easy way to calculate the effect on electricity costs of changes in any cost component. In particular, it may be seen that even quadrupling the cost of natural

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[66] Production of 1 kilogram of 3.4% U-235 requires 6.2 kgm U and 5.2 SWu, at a total cost of about $270. The cost per kilogram U-235 is thus $270/.034 or $8/gram U-235. Plutonium, because it emits more neutrons per fission event than U-235, might be expected to have a slightly higher value. The incremental value of plutonium in a breeder reactor would be still higher, but as long as commercial breeders remain over a decade in the future, plutonium for fueling of breeder cores would have to be heavily discounted. At the moment, because of the long breeder lead time and the relative lack of experience with plutonium recycling in converter reactors, there is scarcely any real commercial market for plutonium. See, for example, Paul MacAvoy, Economic Strategy for Developing Nuclear Breeder Reactors,82.

Table 6. Illustrated Cost Figures for a 1000 MW_e Light Water Enriched Uranium Reactor[67]

	Annual Requirements	Average Costs	Cost/Energy (Mills/KW_e-hr.)
Fuel Cycle Cost			1.50
Natural U Feed	160 MTU	\$22/Kgm U (\$8/lb U_3O_8)	0.50
Conversion to UF_6	160 MTU	\$2.5/kgm U	0.06
Enrichment (3.4% U-235)	150 MTSWU	\$26/kgm SWu	0.54
Fabrication	24 MTU_{enr}	\$90/kgm U	0.30
Reprocessing	24 MTU_{enr}	\$33/kgm U	0.11
Transportation	24 MTU_{enr}	\$5/kgm U	0.02
Fuel Inventory	[80 MTU_{enr}]	\$300/kgm U	0.28 *
(Plutonium Credit)	(200 kgm)	(\$10,000/kgm Pu)	(-0.28)
Capital Investment	1000 MW_e	\$260/KW_e	3.60 *
Maintenance and Operation	--	\$3,000,000	0.40
Total Cost	--	--	5.50

* Interest charge taken at 10%/year.

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[67]Devised mainly from data in The Nuclear Industry, 1970, 49-94, 145-158, 241-270; U.S. Atomic Energy Commission, Trends in the Cost of Light Water Reactor Power Plants for Utilities, WASH-1150, esp. iii-vii; Potential Nuclear Power Growth Patterns, WASH-1098, Tables 2.10, 2.11, 5.2, 5.3, 5.4, E-1.

Table 7. Illustrative Cost Figures for a 1000 MW_e Heavy Water Organic Cooled Natural Uranium Reactor[68]

	Annual Requirements	Average Costs	Power Cost (Mills/KW_e-hr)
Fuel Cycle Cost			1.65
Natural U Feed	150 MTU	$22/kgm U	0.45
Fabrication	150 MTU	50/kgm U	1.05
Reprocessing	150 MTU	27/kgm U	0.55
Charge on Fuel Inventory	[300 MTU]	70/kgm U	0.30
(Plutonium Credit)	(350 kgm)	(10,000/kgm)	(-0.50)
Capital Investment	1000 MW_e	$280/$KW_e$	3.90
Maintenance and Operation	--	3,000,000/year	0.40
Total Cost	--	--	5.95

[68]Devised mainly from data in WASH-1083, 18, 86; WASH-1098, Tables 2.10, 2.11, 5.2, 5.3, 5.4, E-2. The capital investment is based on the data in WASH-1083, but with application of the same escalatory factor that occurred for light water reactors as reported in WASH-1150.

uranium would raise the total cost by only a few percent.[69] The cost of nuclear power will vary substantially with the charge rate on fixed investment, load capacity, and with the installed capacity of the plant, there being particularly evident economics of scale associated with larger plants. These dependences are illustrated in the two following Figures:

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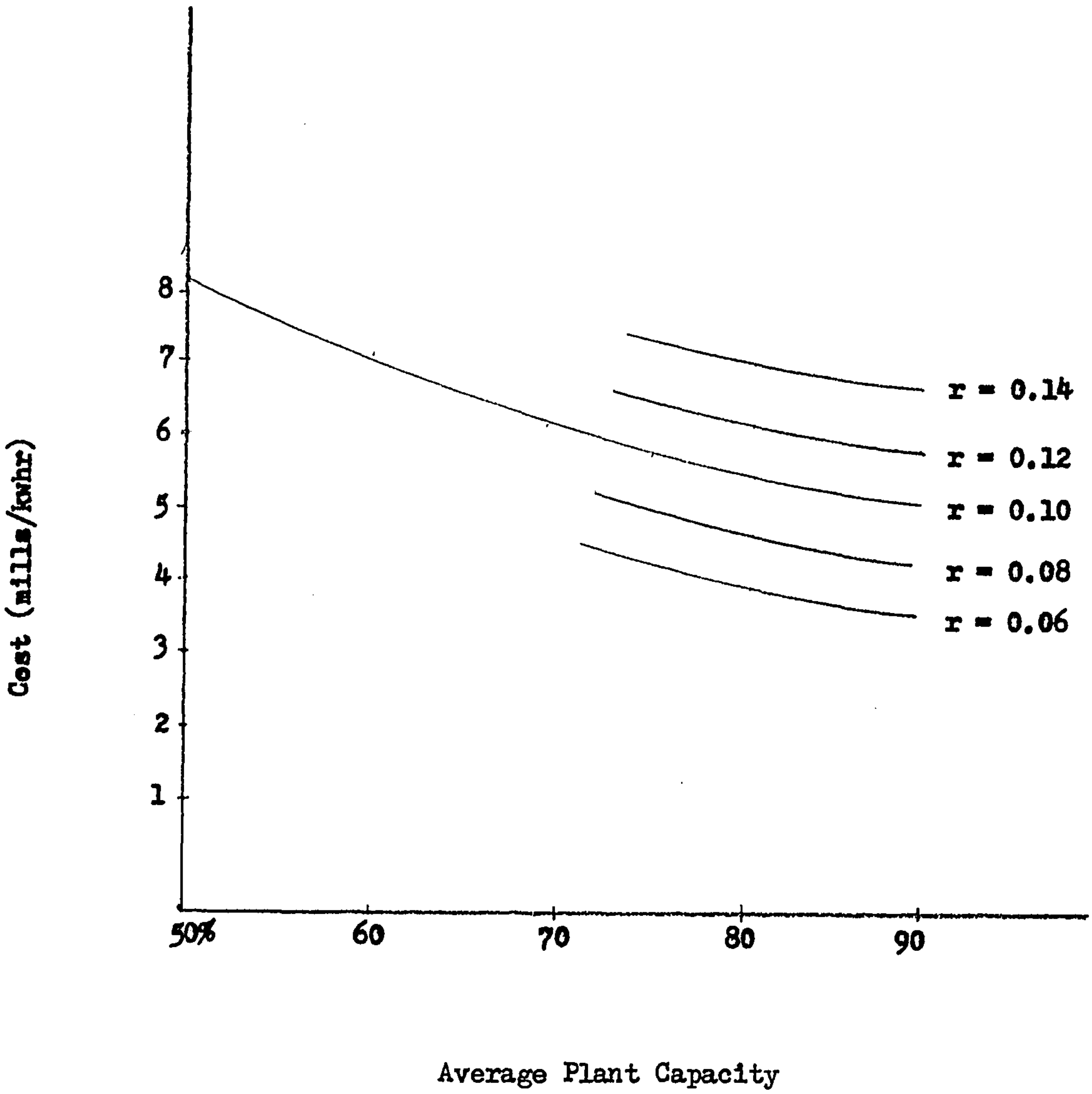
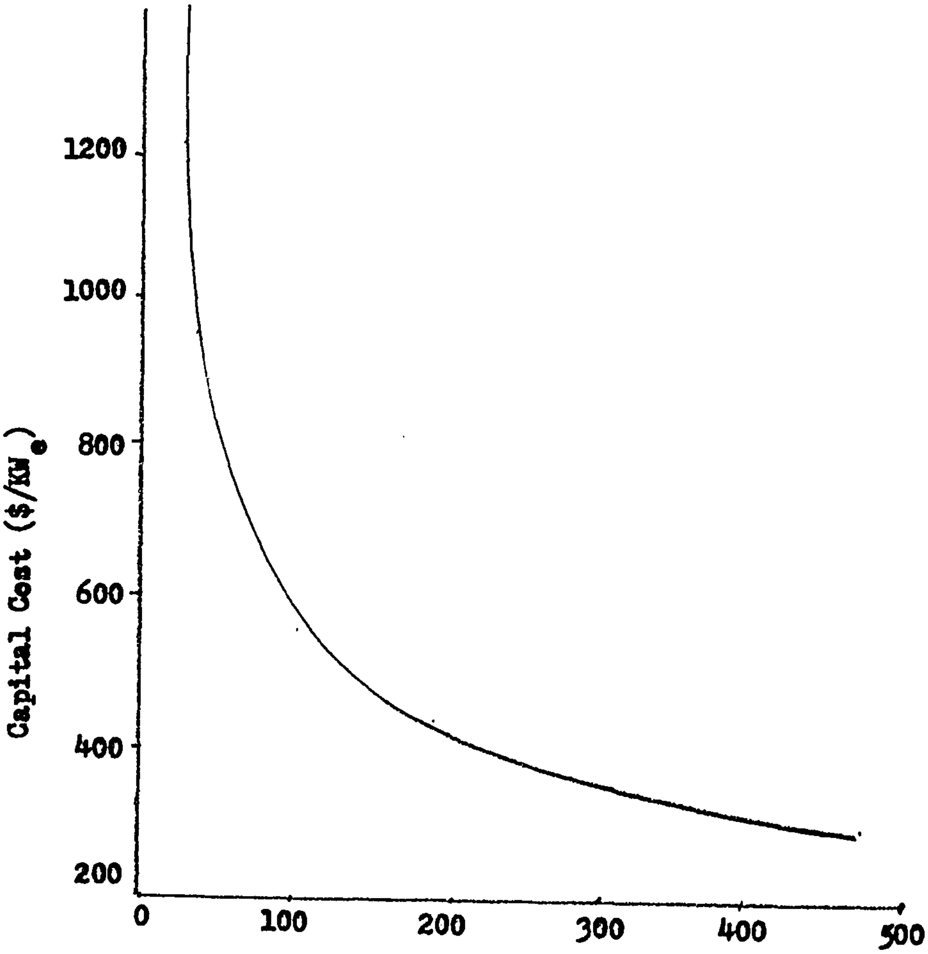
[69]From Table 6, for example, the natural uranium feed contributes 0.50 mills/KW-hr to a total power cost at the bar of 5.50 mills/KW-hr. Quadrupling the uranium cost would raise its contribution by 1.5 mills/KW-hr, and the total bar cost by the same margin (assuming conservatively that the rise in uranium prices did not raise the plutonium credit). Counting distribution costs, the total power cost would thus be raised about 1.5/11.2 = 13%. This conclusion is interesting. For if as seems possible (see section 2), uranium could be extracted from sea-water at costs of not much over \$30/lb U_3O_8 (about quadruple present prices), there need not be a rapid introduction of breeder reactors to conserve uranium resources if a more cautious breeder development program seems otherwise desirable.

Figure 4. Illustrative Dependence of Nuclear Power Cost on Average Capacity Factor and Annual Discount Rate (r): 1000 MW_e Light Water Reactor.[70]



[70] Based on data given in Table 6.

Figure 5. Illustrative Dependence of Nuclear Power Cost on Size of Nuclear Plant: Light Water Reactor[71]



Size Plant (Installed MW_e)

[71]Adapted from U.S. Atomic Energy Commission, "SmallNuclear Power Plants," COO-284. Cost figures given in the report have been arbitrarily doubled in the above figure to reflect the approximate 100% rise between 1960 and 1971 in the fixed cost of constructing a 1000 MW_e plant. Thus the ratios presented in the COO report have been preserved.

Competitive Position of Nuclear Power

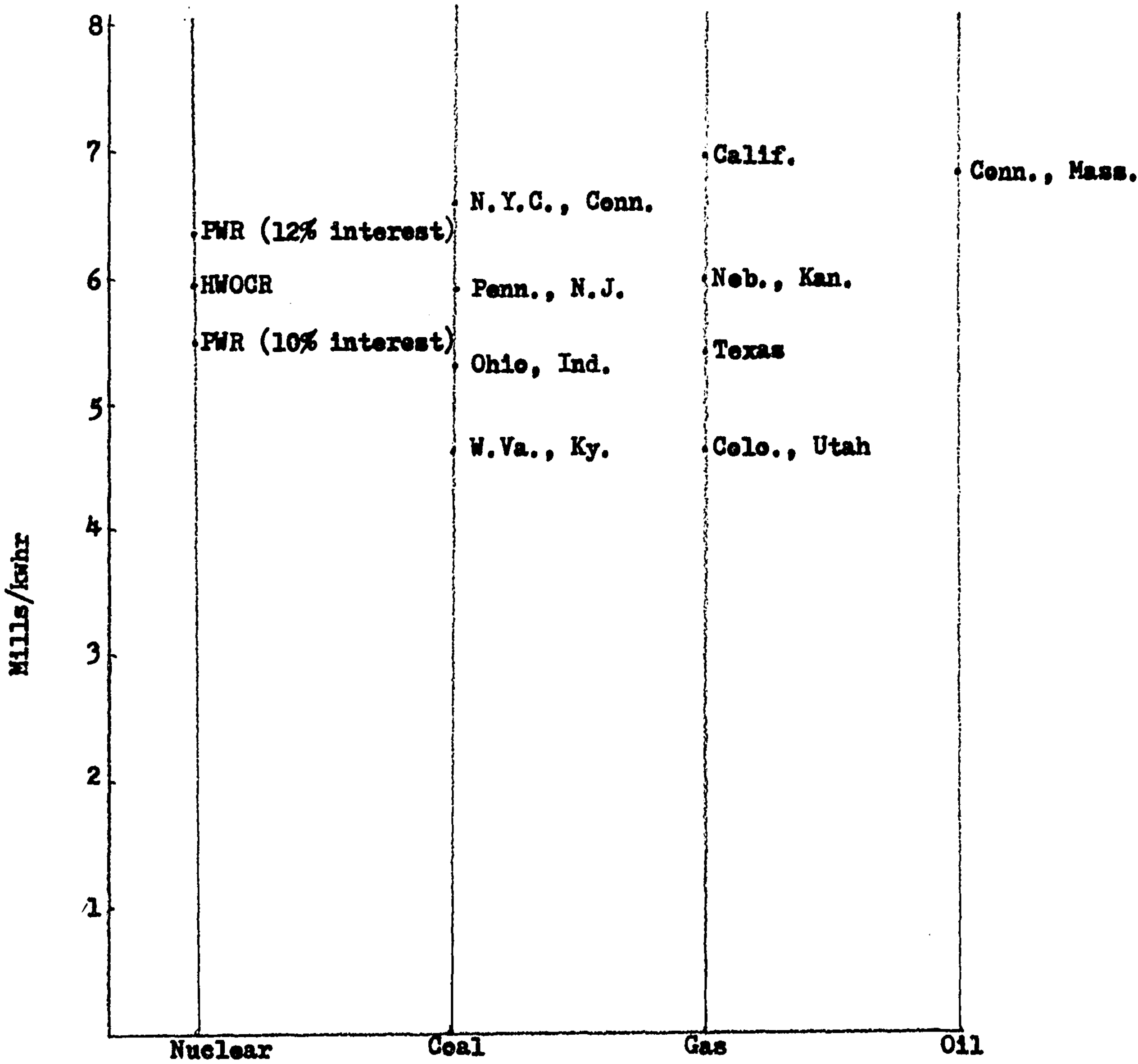
Table 8 presents cost figures for a 1000 MW_e coal-fueled power plant in New England; and Figure 6 illustrates the variance of total power cost for various sources.

Table 8. Costs of Fossil-Fuel Power[72]

	Unit Cost	Total Cost (mills/KW-hr)
Fuel Costs	20-40¢/million BTu	2-4
Capital Investment	$195/$KW_e$	2.7
Maintenance and Operation	$3,000,000/year	0.4
Total	--	5-7

[72]WASH 1098, Tables 2.8, 2.9; WASH-1150, Table 3, 30-42.

Figure 6. Variance of Power Cost



It is immediately noteworthy, that nuclear fuel costs typically comprise a smaller fraction of the total power cost than is the case for fossil fuel plants, whereas the capital costs for nuclear plants are correspondingly higher. Fuel costs for a nuclear plant for example may average about 25% of the total cost, whereas the fuel contribution for coal or oil plants will typically exceed 50%. This asymmetry has three evident consequences. First, nuclear power will look relatively more attractive than fossil fuel in capital-rich nations with reasonably low discount rates. Secondly, because of the high capital costs, it is relatively more important to operate nuclear power plants on high load factors than it is conventional fossil fuel plants. Thirdly, rises in the price of uranium, or in general in the fuel cycle cost, will have only moderate effect on the total nuclear power cost. Since the cost of fossil fuel power varies substantially with the distance of the power station from the fossil-fuel sources, nuclear power would look unevenly attractive in comparison even if nuclear power costs were roughly the same throughout the world, as might be expected from the very low cost of transporting nuclear fuel and equipment. Such unevenness is indeed the case. There is, however, as illustrated in Figure 6 considerable variance also in nuclear power costs, due principally to differences in rated capacity, in discount rates, and in expected base load.

The cost of electric generation in the terms presented above is not the only consideration that will influence the choice between conventional and nuclear power. In the remainder of this section some other relevant factors are briefly discussed.

Energy Security

Nuclear power appeals to many countries as a means of establishing energy security -- an independence from imports of fossil-fuel, and in the long term security against depletion of fossil-fuel resources. The demand for energy throughout the world is certainly impressive. Electric power especially is essential to industrial growth; an increase of one percent in industrial production requires an increase in the production of electric energy of somewhat over one percent. At present, the annual growth rate of installed electric capcity in the industrialized countries is between 5 to 8 percent, in the less developed countries nearly double this, with the world average a bit less than 8 percent per annum.[73] It is reasonable to suppose that at least these growth rates will be sought during the next two decades. Similarly, primary energy consumption, while not so closely tied to increases in industrial production or gross national product as is electric consumption, will have to grow rapidly to support significant increases in national product. The present annual rate of increase typically ranges between 2 and 8 percent, with the less developed countries generally showing the more rapid growth.[74] The ratio of electrical to total primary energy consumption ranges currently between 20 to 30 percent, the developed states possessing the higher ratio.[75]

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[73]U.S. Atomic Energy Commission, Forecast of Growth of Nuclear Power 1971, WASH-1139, Table 5. Fremont Felix, "Electrical Energy, Total Energy, and National Income," Table 1.

[74]Felix, "Electrical Energy" Table 1.

[75]Ibid., Table 1.

Since electric demand is increasing faster than the total energy demand, these ratios will gradually increase -- to perhaps 40 to 45 percent by the 1980's in the industrialized countries.

Given these data, some fairly crude but illuminating implications may be quickly drawn. As a rough approximation, the electric energy demand two decades hence in both the less developed and industrialized countries will be roughly the same as the total energy demand in these countries today. Thus the annual fuel requirements to meet the electric power demand will be comparable to current fuel consumption levels. But most important to the issue of energy security, from one-half to two-thirds of the of the fuel requirements in twenty years will be in sectors in which nuclear power will not be directly applicable -- that is, for uses other than electric power generation. Thus the fossil-fuel requirements for most countries in two decades could be as much as twice current requirements even if the entire electric power production were then generated by nuclear power stations. It is thereby evident that the advent of nuclear power alone will not in the general case provide an energy security for countries unable to obtain such at present.

Nevertheless, nuclear power will appear especially attractive to countries with few other sources of cheap fuel who now import a substantial fraction of the energy resources consumed. On a world basis, about one-third of the total energy consumed derives from imported fuel (mostly oil which accounts for 90% of world trade of energy fuels). In Western Europe, energy imports comprise approximately 60% of consumption; 80% in Japan. About 20% of world energy imports are to underdeveloped countries.[76]

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[76]Joel Darmstadter, "International Flows of Energy Sources," Reprint No. 86, July 1970, Resources for the Future, reprinted from IEEE Spectrum, May 1970, 67-72.

The major fuel importers of course do not include the significant oil producers; Algeria, Libya, Nigeria, Columbia, Venezuela, Iran, Kuwait, Yemen, and Indonesia. Nuclear power will also appear relatively less necessary in countries with large coal reserves, although several of these countries in fact have initiated vigorous nuclear programs. The status of coal and lignite reserves is indicated in Table 9. Finally, most of the underdeveloped regions in Latin America, Africa, and Southeast Asia possess vast undeveloped water power potential, part of which probably could be exploited at costs well below nuclear power costs.

Nuclear Power in the Less Developed Countries

In most of the less developed countries, nuclear power not only is not likely to have dramatic impact, but may well not even effect the cost reductions evident in the developed nations. This pessimism results principally from the large rating capacities and capital intensity imposed by nuclear power technology. As reflected in Figure 5, small nuclear reactors are not for the most part competitive with fossil plants. Nuclear power looks most attractive at rating capacities well above 100 MW_e, with most units now under order exceeding 300 MW_e and the most impressive economies evident above 600 MW_e. Unfortunately plants of these sizes appear much too large for almost all the less developed countries, partly because each unit would represent too large a fraction of the total installed electric capacity in such countries and partly because these countries typically do not possess extensive interconnected grid systems sufficient to distribute electricity from a large central power plant. For example, the total installed electric capacity in 1969 in Algeria was 639 MW_e; Burma, 258 MW_e; Ghana, 631 MW_e; Greece, 2390 MW_e; Indonesia, 912 MW_e (1968 data); Israel, 1012 MW_e; Pakistan, 2062 MW_e;

Peru, 1672 MW_e; Tunisia, 259 MW_e; UAR, 2725 MW_e -- Argentina, Brazil, Mexico, and India are the only underdeveloped countries with total capacity exceeding 6000 MW_e. The capacities of these nations all fall between 6000 MW_e and 16,000 MW_e but each has a relatively limited grid network.[77]

The high capital intensity required by nuclear reactors imposes several other difficulties on developing countries. First, since rational capital discount rates in these countries will tend to be higher than in the developed countries, capital intensive investments will look correspondingly less attractive if less capital intensive alternatives are available. Secondly, power plants with a high fixed investment must have a high average load factor for efficient operation, a stipulation much easier achieved in developed countries with sophisticated grid systems. Thus, for example, the average load factor in the United States is about 60 percent compared to 26 percent in Algeria, 38 percent in Argentina, 50 percent in Brazil, 40 percent in Mexico, and 42 percent in India.[78] Large initial capital investment requirements which must for the foreseeable future be met by imports from the developed countries also impose in many instances severe foreign exchange problems on the developing countries, although these problems must be compared in the long run to the foreign exchange savings due to the relative cheapness of nuclear fuel compared to conventional fuel imports.

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[77]United Nations, Statistical Yearbook, 1970, Table 139.

[78]United Nations, Statistical Yearbook 1970, Tables 139 and 140.

Table 9. Coal and Lignite Resources Compared to Current Energy Consumption Level - by Region and Major Countries*

Region	Coal-Lignite Reserves (Million Metric Tons Coal Equivalent)	Current Consumption** (Million Metric Tons Coal Equivalent)	Reserve Lifetime at Current Consumption Rate (years)
North America			
United States	1,600,000	1,900	850
Canada	95,000	160	600
Total	1,695,000	2,060	800
Latin America			
Mexico	5,300	45	120
Colombia	14,500	10	1,500
Venezuela	3,700	25	170
Other	4,400	110	44
Total	27,900	190	140
Asia (incl. USSR)			
USSR	1,400,000	880	1,600
China	1,250,000	370	3,400
India	75,000	85	900
Japan	12,000	190	60
Other	8,800	75	120
Total	2,745,800	1,600	1,700
Europe			
Germany (FRG & GDR)	330,000	350	940
UK	205,000	280	730
Poland	96,000	115	840
France	15,000	150	100
Other	50,000	570	88
Total	696,000	1,465	480
Africa (incl. UAR)			
South Africa	82,000	55	1,500
Other	2,000	37	55
Total	84,000	93	900
Oceania			
Total	20,000	65	300
Middle East (excl. UAR)			
Total	--	50	--
World	5,400,000	5,500	1,000

*Adapted from Bituminous Coal Facts 1968 (Reserve Data, Published 1960) and Statistical Yearbook 1967 (Consumption Data for 1966).

**Current Consumption includes consumption of liquid fuel and use of water power and nuclear power.

Table 10. World Water Power Capacity[79]

Region	Potential (10^3 MW_e)	Percent Developed
North America	310	20
South America	580	< 1
Western Europe	160	30
Africa	780	< 0.3
Middle East	20	--
Southeast Asia	450	< 0.4
Far East	40	45
Australasia	50	5
USSR, China, and East Europe	470	3
TOTAL	2,860	5

[79]King Hubbert, "Energy Resources," in Resources and Man, Table 8.7.

Notwithstanding these compelling reasons to believe that nuclear power will be introduced into less developed areas much more slowly than into the industrialized countries, it is understandable that the developing countries remain deeply interested in nuclear power. Three factors especially shape the sensibilities of these countries: the hope for external economies, a concern with long-term marginal costs, and a particularly sensitive desire for energy security.

Although it is conceivable that investments in nuclear power plants will create significantly greater "spin-off" advantages in technical personnel, supporting technologies, etc. than would be the case with investments in conventional generating plants, the revolutionary economic effects which have in the past been associated with shifts in energy technology cannot be expected. For one thing, as already indicated, as long as nuclear power remains limited to the production of electricity in large power plants, it will be able to touch at best only a portion of a nation's power requirements since as a world average electric energy comprises less than one-quarter of the total energy expended.[80] Also, even in the crucial industrial areas where electricity is most used, reductions in the cost of power will have limited impact. This is due in the first instance to the high distribution costs of electricity, which would not be affected by reductions in the costs of production. A still more striking reason is the small fraction of the total costs associated with most industrial processes that may be attributed to electric power. This fraction is less than two percent for all major

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[80]This ratio varies only slightly from region to region, averaging in the industrialized countries nearly 30 percent, in the developing areas, between 20 and 25 percent.

manufacturing and agricultural sectors in the United States (as listed by the U.S. Bureau of the Census) with three exceptions, chemical and allied products (2.5%), petroleum and coal products (3.0%), and primary metals (3.5%).[81]

The unlikelihood of revolutionary <u>economic</u> impact (at least in the short term) due to nuclear power may be contrasted to past shifts in energy production:

> The history of energy consumption ... [spans] numerous developments in the energy field that have had a profound economic and social impact ... These include such changes as the transformation of the energy base from wood to coal in the nineteenth century; the development of improved methods of illumination and lubrication in the late nineteenth century; the tremendous growth of liquid fuels after the first World War; and the growth of electrification throughout the twentieth century.
>
> Thus, the change in the energy base from wood, a limited resource, to coal, which was available in apparently endless amount, opened the way to the large-scale, unimpeded growth of iron and steel production. Adequate supplies of iron and steel, in turn, made it possible to revolutionize transportation by building a railroad network which crisscrossed the country. The way was also opened to the ever-expanding production of machines constructed of metal which have provided the foundation for the modern industrial system. Not only did coal support the necessary growth in metals production, it also supplied the large amounts of fuel needed to power locomotives and the machines of industry. The growth of the system of machine production depended, too, on adequate lubrication and illumination, both made available in the latter part of the nineteenth century in sufficient amounts, at low costs, and in greatly improved quality when mineral sources, mainly oil, replaced animal and vegetable products. On another front, adequate illumination based on kerosene and also on gas manufactured from coal multiplied the effects of public education by making it easier to utilize the newly learned skills in reading and study at home in the evening hours.

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[81] U.S. Department of Commerce, <u>Census of Manufacture</u>, 1963, Volume I.

In the twentieth century, the impact of liquid fuels and electricity has been critically important in facilitating further changes. Liquid fuels have been fundamental to the growth of automotive transportation, whose influence on the American way of life is obvious beyond any need for description. As for electricity, its impact is without parallel among energy developments in the present century. By virtue of the unique form in which electric energy is made available, it has made possible numerous developments in the field of communications and automatic controls which otherwise would be inconceivable. Less apparent perhaps, is the impact electricity has had on industrial plants, where the substitution of electric motors mounted on machines for the older system in which mechanical energy was transmitted by belts powered by a single prime mover has made possible a complete reorganization of production practices. The [previous] analysis ... provides a basis for believing that improvements in production practices, resulting from electrification, are an important element in explaining the remarkable acceleration in labor and capital productivity in the period following the first World War, which has been disclosed in historical studies of the efficiency of the American economy.

What are the unique characteristics of these significant changes in energy use? In every instance they have made possible essentially new, or enormously improved, ways of performing important social or economic functions. They have not accomplished this alone, but always in combination with other changes -- railroads, automobiles, electric motors, etc. -- themselves often made feasible by changes in energy sources or their form.

<u>Conceiving of atomic energy only as a cheaper fuel for generating electric energy strips it of any possibility for having an economic impact as significant as these earlier energy innovations have had.</u>[82] (emphasis added)

It is evident, however, despite the above that the less developed countries would look with unease at a situation in which the advanced industrial countries increasingly converted to nuclear power while they maintained their principal power investments in conventional plants, whatever the short-term economic realities. The Cuban delegate to the

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[82]Samuel Schurr and Bruce Netschert, <u>Energy in the American Economy 1850-1975</u>, 27.

United Nations articulated this fear with great passion while speaking against the Non-proliferation Treaty:

> It can be stated, in sum, that in the not too distant future nuclear energy will constitute the principal source of energy for the planet. But what then will be the situation of the under-developed countries that today suffer from an acute power shortage? What prospect will those countries have for reaching the standard of living of the industrialized countries if to that chronic shortage there are now added the effects of a monopoly of the new sources of energy? What sort of relationships will exist between the underdeveloped countries and the great industrialized Powers when the latter hold in their hands the control over the supply of nuclear energy? Who would be so naive, at this stage of the game, as to hope for an attitude, in the business of supplying nuclear energy, more favorable, a spirit of cooperation more disinterested, than at present rule in trade relations between rich and poor countries?[83]

The foregoing comparative marginal cost data assume that the nuclear and fossil fuel plants are imbedded in an economy not significantly altered by the addition of new electric capacity. In the long run, though, a very large expansion of fossil fuel plant capacity will require the construction of new supporting facilities to transport the fuel -- new rail coal cars, new trackbeds, etc. (Nuclear power expansion might require new mining and reprocessing equipment, etc. but would not require additional transportation facilities.) In the industrialized countries, such construction is not likely to change the marginal costs very substantially or very quickly; to a degree, the long term marginal costs associated with such construction are reflected in the fossil plant fuel costs which typically attempt to estimate the fossil fuel costs

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[83]Comments by Cuban delegate Roa, UN General Assembly, First Committee, May 13, 1968: A/C.1/p 1566, 72.

for a twenty to thirty year period. For the less developed countries, however, the long term marginal costs of a large expansion in their coal, gas, and oil plant capacity could be appreciable, and should consequently affect the choice between nuclear and conventional power. Such, however, is likely to be the case only for the very large developing countries, notably India and China, where transportation costs will tend to be comparatively high.

The desire for energy security in the developing countries, not persuaded that they will be recipients of fair, non-interventive trade practices by the industrialized nations, is already apparent in the aforementioned comments by Roa of Cuba. Roa goes on to assert very clearly the fear of the less developed countries of undue reliance on the developed countries.

> The prospect could not be more bleak for the countries of the Third World. They will be forced perpetually to depend on the Powers supplying nuclear energy or else be obliged to renounce the use of such resources for power. Or -- which is the same thing -- they will have to accept permanent subjection to the interests of the great powers or else renounce forever all possibilities for development.[84]

This fear is not entirely illusory, but it is difficult to see how most developing countries can have any real choice but reliance on others.

On the average, the less developed areas will have to increase their per capita energy consumption four-fold to achieve a level comparable to the present levels in Western Europe -- 2000 to 3000 kgm Coal Equivalent.

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[84] *Ibid.*, 73.

If we assume an average population rise of 2 percent per annum, then by the end of the century, such a per capita energy increase would require approximately an eight-fold expansion of total energy consumption. The countries of Latin America, Asia, and perhaps parts of Africa will have great difficulty in becoming energy independent at such levels through reliance on fossil fuels alone. However, much of the earlier analysis of the impact of energy security considerations on national energy plans applies most forcefully to the less developed countries. Despite a strong wish by such countries to maintain an energy independence from the developed countries, such does not appear feasible if they are not now independent, since their fossil fuel requirements will continue to grow markedly even should they increasingly turn to nuclear power to meet electricity demands.

4. Advanced Developments

Introduction

This study is concerned principally with the dispersion and control of current nuclear technology. Nevertheless, since advanced technology now under development will have impact on even short term policy considerations, some discussion appears justified. The two technologies of specific interest are breeder reactors and controlled fusion devices. Breeders are now under very intense development in the United States, Europe, Japan, and the Soviet Union. The American effort is targetted for full-scale commercial introduction of 1000 MW_e **breeders** by 1984-1986 with deployment of smaller demonstration plants by the end of the 1970's.[85] Fusion reactors are probably further off. However, if their scientific feasibility can soon be demonstrated (no certain thing), it is conceivable that they can be introduced on a time scale that does not lag breeders by more than 5-10 years or even less.[86]

Breeders

Nuclear reactors which produce more fissile nuclei[87] than are fissioned are termed breeders. Breeders may employ either a uranium-

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[85] The Nuclear Industry, 1970; 182-188. Glenn Seaborg and Justin Bloom, "Fast Breeder Reactors," in Scientific American, November 1970, 13-21.

[86] William Gough and Bernard Eastlund, "The Prospects of Fusion Power," in Scientific American, February 1971, 64. "depending on one's underlying assumptions on the level of effort and the difficulties ahead, the time it would take to produce a large prototype reactor could range from as much as 50 years to as little as 10 years."

[87] The reader may wonder whether the creation of more fissile nuclei than are used up does not mean that man has somehow tapped an infinite energy source, a sort of perpetual motion machine. This alas is not the case; eventually all the fertile material, where the energy is locked until fission, will be used up. The breeder merely permits energy extraction from the non-fissile nuclei.

plutonium cycle or a thorium-U-233 cycle; and they may utilize either fast or slow neutrons. The uranium-plutonium cycle operates with a plutonium and/or highly enriched uranium core surrounded by a blanket of U-238 (in natural or depleted uranium) which is the fertile material. The U-238 in the blanket captures fission neutrons to produce plutonium. The thorium cycle replaces the U-238 blanket with thorium as the fertile material, and eventually uses U-233 as the core material. (Since U-233 does not exist naturally, the initial cores will have to be either plutonium or U-235). The thorium captures fission neutrons to produce U-233.

In order that breeding occur, the number of neutrons produced (by fission) per neutron absorbed in the fuel must exceed two, one neutron to carry the chain reaction and one to produce a new fissile nuclei. The actual numbers, η , are of the following order:[88]

	Thermal neutrons	Fast neutron
U-235	2.04	2.10
Pu-239	1.79	2.70
U-233	2.29	2.25

For U-235 and Pu-239, η is uncomfortably close to two for thermal neutrons, but much higher for fast neutrons (which produce more neutrons per fission event). Consequently breeder reactors employing the uranium-plutonium cycle use fast neutrons; they are termed fast breeders. A thermal plutonium breeder is impossible; if one wants a thermal breeder only the

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[88] U.S. Atomic Energy Commission, The Use of Thorium in Nuclear Power Reactors, WASH 1097, 17, 104.

thorium cycle is available.[89]

At the moment, two fast breeder options are being pursued in the United States and elsewhere. These are the Liquid Metal Fast Breeder Reactor (LMFBR) which uses liquid sodium as the coolant, and the High Temperature Gas-Cooled Breeder Reactor (HTGBR) which uses pressurized helium as the coolant. Similarly, two thermal breeder concepts using a thorium cycle are being developed: the molten salt reactor and a reactor using light water as the coolant and moderator. However, despite these various options, in the United States and all other countries engaged in breeder development, the LMFBR is the primary and at the moment only serious development candidate.[90] Table 11 provides some typical design parameters for a 1000 MW_e LMFBR.

Table 11. Illustrative Design Parameters for LMFBR[91]

Power	1000 MW_e
Efficiency	40%
Core	PuO_2-UO_2 mixture, ~ 15% fissile material
Fissile Inventory	2.5 kgm/MW_e
Burn-up	80,000 MW_td/MT
Breeding Ratio	1.3
Average Specific Power	175 MW_t/MT fuel
Specific Power	1.0 MW_t/kgm Fissile Material
Doubling Time	12 years

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[89] W. H. Zinn, "Review of Fast Power Reactors," in Reactors Vol. 1, R.A. Charpie, et al. (eds.). Seaborg and Bloom, 13-21.

[90] AEC staff studies (July 1971). Also The Nuclear Industry, 1970, 182-188.

[91] WASH 1098, Table E-5. Recent AEC design studies (July 1971) use target parameters of 100,000 MW_td/MT, core inventories of 10-13% fissile corresponding to 1.6-2.8 kgm/MW_e, breeding ratios of 1.3-1.4, and doubling times of 8-13 years.

A most interesting physical parameter associated with breeder reactors is the "doubling-time", the time it takes the reactor to double the initial inventory of fissile nuclei. This time depends on the breeding ratio, the number of fissile nuclei formed per fissile nucleus used up and on the specific power at which the breeder operates. Specifically, it is easy to show that the doubling time in years is given by $T = \frac{3}{p(R-1)}$ where R is the breeding ratio and P, the specific power measured in MW_t/kgm of fissile material.[92] This assumes that the bred plutonium is not immediately recycled and that no significant amount of uranium fissions. With recycling, the doubling period could be somewhat shortened.[93] Typical values for fast breeders give R = 1.2 and P = 1 MW_t/kgm Pu. These lead to a doubling period of 15 years. An R = 1.5 would reduce the doubling time to about 6 years.

A discharge exposure of 80,000 MW_td/MT and average specific power of 175 MW_t/MT fuel implies a dwell time in the reactor for core elements of about one and a half years. Since the total reactor power is 2200 MW_t, there must be approximately 12.6 MT fuel in the core or 12.6 kgm/MW_e; plutonium comprises less than 20% of the core or about 2.5 kgm/MW_e. Given these data, it may be seen that at the first reprocessing step, the total

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[92]Let the initial inventory be I. Since the breeding ratio is R, the amount of material fissioned to produce a net gain of I is I/R-1. (This doubles the core inventory which is kept constant.) The total amount of energy expended by this fission is $\frac{I}{R-1} \times 10^3$ MW_t days where I is in kilograms and using the fact that 1 kgm of fission produces about 10^3 MW_t days. If the specific power is P MW_t/kgm, then total power is PI thermal megawatts. This means that the production of $\frac{I}{R-1} \times 10^3 MW_t$ days energy requires $\frac{I}{(R-1)IP} \times 10^3$ days or approximately $\frac{3}{(R-1)\ P}$ years.

[93]Victor Gilinsky, Fast Breeder Reactors, Appendix B.

plutonium inventory of the reactor will be approximately 2800 kgm.[94] If the plutonium were removed from the blanket as well as the core or recycled at this point, this figure would also give (roughly) the maximum plutonium inventory of a breeder reactor at any given time. This may be compared to the contained plutonium in a 1000 MW_e light water reactor, after say four years, of about 800 kgm. It is also the case that both breeder and light water converter reactors will produce a net plutonium of approximately 0.2 kgm/MW_e per year.[95] However, whereas the discharged plutonium from light water reactors is only about 8 kgm per metric ton of discharged fuel, it comprises about 200 kgm per metric ton for breeder reactors.

The Pu-240 content of breeder plutonium will also be quite different. As shown earlier, Pu-240 will comprise about 20-25% of the plutonium normally discharged from light water reactors. Plutonium with this isotopic composition can also provide the core fuel of breeder reactors. But the Pu-240 concentration of plutonium produced in the breeder blanket, will be very low, on the order of 5%.[96] The breeder in this sense acts as

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[94] 80,000 MW_td/MT corresponds to the fission of 80 kgm Pu, producing approximately 80 (0.3) = 24 additional kgm Pu. For reactor, total additional is 12.6 x 24 = 300 kgm. The total initial inventory is 2500 kgm.

[95] In one year, the 2200 MW_t breeder will produce 2200 x 300 = 660,000 MW_td energy, corresponding to the fission of 660 kgm. With a breeding ratio of 1.3, this gives a net plutonium production of about 200 kgm per year.

[96] AEC staff studies, (July 1971). The flux in the blanket is very low. See also WASH-1098, Table E-5.

a plutonium cleaner, taking "dirty plutonium" (high Pu-240 content) and producing "clean plutonium" (low Pu-240 content). The significance of Pu-240 for a weapons program is discussed in Chapter 2.

Breeders will save significant amounts of uranium resources. Over the next half century the use of breeders as planned can reduce by over one million tons the amount of uranium that would be consumed without breeders (and without fusion).[97] Breeders are also expected to reduce nuclear power costs by 0.5 to 1 mill per kilowatt-hour initially, and perhaps eventually by as much as 2 mills per kilowatt-hour.[98]

From a safeguards perspective, the dangers of breeders do not derive principally from the amount of plutonium produced which is no more than current reactors, but rather from the necessity in a breeder economy of extensive fabrication and transport of the plutonium in forms suitable for weapons. It is also true as indicated that part of the plutonium produced by breeders will be unusually clean in Pu-240.

Controlled Fusion

At sufficiently high collision velocities, certain light nuclei upon collision will combine (or fuse) with a consequent large release of energy. This process is termed fusion. The high velocities may be obtained in a plasma at quite high temperature; and since under appropriate conditions, the release of energy through fusion will raise the temperature of the plasma, a chain reaction of fusions may thus be ignited. Since in this

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[97]Seaborg and Bloom, "Fast Breeder Reactors," 21.

[98]*Ibid.*, 21.

case the chain is due to the maintenance of high temperatures, the reactions are termed thermo-nuclear.[99]

The specific fusion reactions which appear potentially useful in reactors include the following.[100]

Table 12. Fusion Reactions

1. d + d → He-3 + n + 3.2 MeV
   d + d → t + p + 4.0 MeV

2. d + t → He-4 + n + 17.6 MeV

3. d + He-3 → He-4 + p + 18.3 MeV

4. Li-6 + p → He-3 + He-4 + 4.0 MeV

5. Li-6 + He-3 → He-4 + p + 16.9 MeV

6. Li-6 + d → Li-7 + p + 5.0 MeV
   Li-6 + d → He-3 + He-4 + p + 2.6 MeV

7. Li-6 + d → He-4 + He-4 + 22.4 MeV

8. Li-7 + p → He-4 + He-4 + He-4 + 17.5 MeV

The two d-d reactions occur with roughly equal probability. These reactions plus the d-t reaction which has the largest cross-section are those considered most important for fusion reactors.[101] In all the cases,

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[99] At the temperatures necessary for the fusion reaction, the atoms will have their electrons stripped off, creating thus a gas of charged particles, or a "plasma".

[100] Gough and Eastlund, "The Prospects of Fusion Power," 54. d represents deuterium, the first heavy isotope of hydrogen containing one proton and one neutron; t represents tritium, containing one proton and two neutrons; p represents a proton. All the reactants and products in these reactions with the exception of the neutron are electrically charged, a matter of significance as will be noted below.

[101] R.F. Post, "Controlled Fusion Research and High Temperature Plasmas," in Annual Review of Nuclear Science, Volume 20, 1970, 515.

the energy release is very considerable. For example, the burning of one gram of deuterium would produce 24,000 kwh.

For the practical use of fusion energy in a reactor, the plasma must be raised to a temperature sufficient to ignite the reaction (the ignition temperature) and must be confined for a sufficiently long period at sufficiently high plasma density so that more energy is produced than is needed to heat the plasma. The ignition temperature for the d-t reaction is about 40 million degrees C; for the d-d reaction it is roughly ten times this or 400 million degrees C. At temperature above the ignition temperature, the density and confinement time of the plasma must be such that their product is equal to or greater than 10^{14} seconds/cubic centimeter. (For example, this condition would be met by a plasma of density 10^{14} ions/cc and confinement time of one second; or equally by a density of 10^{16} ions/cc and confinement time of 10^{-2} seconds). No fusion device has yet achieved these conditions.

From Table 12, it may be seen that all the nuclei reactants with the exception of the lithium isotopes and deuterium are also products of fusion reactions. Thus tritium and He-3, for example, could be bred in the fusion reactor itself. This is important because on the one hand tritium and He-3 reactions offer several advantages, and on the other, deuterium and lithium are remarkably plentiful and cheap.

Two factors suggest the attraction of breeding tritium. First, the ignition temperature for the d-t reaction is an order of magnitude below that required for the d-d process. Still more important, the energy production is a hundred times greater in the d-t reaction at all temperatures.[102]

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[102]Thirring, Energy for Man, 376-377. Post, "Controlled Fusion," 518.

The advantages of employing the d-He3 process are more subtle. They derive from the fact that He3 is produced in both branches of the d-d reaction, directly in one instance and indirectly in the second from the decay of tritium. This suggests a reaction cycle where the He3 is internally bred by d-d reactions and consumed by d-He3 processes. The end result of such a cycle would be that 6 deuterons would be consumed yielding 3 protons, 1 neutron, 1 electron, and 2 He4 nuclei + 43.5 MeV. This energy release corresponds to 97,000 kwh/g of deuterium. Most significantly, 93% of this energy would be in charged particles thus permitting the direct conversion of fusion energy to electricity. Such efficiencies imply a reduction in waste heat compared to fission reactors or fossil fuel plants by a factor of ten.[103] The direct conversion cycle also vastly reduces the number of neutrons emitted from the reactor core, thus diminishing any danger that fusion neutrons could be used with fertile material to produce fissionable material.

The crucial fuels, deuterium and lithium, are plentiful and cheap. Deuterium is present in hydrogen in a concentration of one part in 6500. Thus the oceans represent an essentially inexhaustible reservoir of fuel, all the more impressive since the separation of the hydrogen isotopes is simple and inexpensive. Lithium also is relatively abundant, forming about .006% of the earth's crust. Whatever reaction cycle is actually used, the fuel costs associated with the production of fusion energy will be virtually zero. This does not mean that the power will cost nothing. Capital costs will be high, and replacement of vacuum walls will be

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[103] Post, "Controlled Fusion," 511, 516.

frequent. Nonetheless, it appears possible that the overall power costs (if commercial fusion is at all possible) will be considerably below present values.[104]

Unlike fission reactors, a fusion device will not produce fissile material as part of its normal operation. It will produce a high neutron flux, however, which could in principle be used to breed fissile material if the fusion core were surrounded by a fertile blanket, uranium or thorium. Safeguards will have to guard against this, a relatively simple matter since no commercial reason exists for such a blanket. Fusion reactors will also demand safeguards to account for the tritium produced. For reasons adduced in Chapter 2, tritium could potentially be of considerable value in weapons.

[104]See, for example, Post, "Controlled Fusion," 510-516. R. Carruthers, et al., "The Economic Generation of Power from Thermonuclear Fusion."

5. Growth of Nuclear Power

The wide and rapid spread of nuclear power expected after 1970 is reflected in Tables 13 to 18 and Figures 7 to 10. The data through 1975 and to a somewhat lesser extent through 1980 are quite reliable, for the most part based on reactors actually operating, under construction, or ordered. Projections after 1980 become increasingly less certain in detail. The key estimates are those for installed capacity; other relevant data may be derived from these. Installed nuclear capacity will in turn depend upon the rise in electric power generating capacity. In the United States, this rise is expected to average slightly over 7% per year between 1970 and 1985, from 310,000 MW_e to almost one million MW_e at the end of 1985. Nuclear power will usurp an increasingly large share of this increase, with nuclear power plants expected to account for 15% of added generating capacity in the period 1968-1972, 37% in 1973-1977, and 50% in 1978-1987.[105]

Table 13. Electric Generating Capacity and Nuclear Power Growth in United States (MW_e)

	1970	1980	1985
Total Installed Electric Generating Capacity	310,000	690,000	995,000
Nuclear Capacity	5,000	150,000	300,000

[105] WASH-1139, Tables 1, 2. The electric power projections to 1980 are based on plants under construction, ordered, and planned by utilities.

Foreign countries will exhibit a similar growth. As may be seen in Tables 14 and 15, the growth in electrical generating capacity is expected to average between 5 and 15% per year with again nuclear power accounting for an increasingly large fraction of the added capacity. For example, in Western Europe and Japan, this "nuclear fraction" will average between one-third and one-half in the period 1970-1980.[106]

Both in the United States and in foreign countries, the nuclear power growth between 1970 and 1980 will be almost completely dominated by light water enriched uranium reactors. By 1980, it is expected that less than one-eighth of the total world installed nuclear capacity will be in natural uranium reactors.

Given the data on installed nuclear capacity, other pertinent data for individual countries may be derived from the following simple approximate relationships:[107]

Uranium Requirements:

Light Water Reactor:

Initial Core: 0.75 ton U_3O_8 per installed MW_e

Annual Replacement: 0.20 ton U_3O_8 per installed MW_e

Natural Uranium Reactor:

Initial Core: 0.30 ton U_3O_8 per installed MW_e

Annual Replacement: 0.12 metric ton units per installed MW_e

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[106]WASH-1139, Tables 5, 6. Projections in electric generating capacity are based mostly on extrapolation of average annual increases over the past decade.

[107]The global data presented in Table 18 and Figure 8 reflect a somewhat more detailed analysis.

Isotope Separation Requirements -- Light Water Reactors:

Initial Core: 0.40 metric ton units per installed MW_e

Annual Replacement: 0.12 metric ton units per installed MW_e

Fabrication and Reprocessing Requirements:

Light Water Reactor: .03 Metric Tons Uranium per installed MW_e

Natural Uranium Reactor: .10 Metric Tons Uranium per installed MW_e

Fissile plutonium discharged:

Light water, Enriched Uranium Reactor .240 kgm/MW_e

Natural Uranium Reactor .360 kgm/MW_e

(plutonium recovery in a given year derives from the installed capacity at the end of the year four years previous)

Plutonium discharged from Light Water Reactors equals approximately .007 of the uranium discharged.

Table 14. Electrical Generating Capacity in Foreign Countries[108]

Country	Installed at End of 1959[1] (MWe)	Expected at End of Year[2]		Average Percent Increase Per Year[3]	Forecast at End of 1980[4] (MWe)	Forecast at End of 1985[4] (MWe)
		Year	MWe			
Argentina	3,200	1975	6,200	4.3	7,700	9,500
Australia	5,700	1975	19,700	8.0	29,000	42,700
Austria	4,000	1976	7,500	3.7	8,700	10,400
Belgium	4,300	1975	8,600	4.4	10,700	13,200
Brazil	4,100	1975	15,800	8.8	24,000	36,600
Canada	21,100	1974	52,400	6.2	75,500	102,200
China (Taiwan)	700	1975	3,800	11.1[5]	6,600	10,300
Denmark	1,800	1972	4,700	7.7	8,600	12,400
Finland[6]	2,400	1978	5,600	4.6	6,100	7,600
France	20,700	1974	44,300	5.2	60,000	77,300
Germany, West	25,500	1971	48,400	5.5	78,300	102,200
Greece	600	1974	3,500	12.8[5]	6,200	10,000
India	4,700	1974	20,300	10.3[5]	35,900	57,900
Israel	400	1974	1,800	10.5[5]	3,200	5,200
Italy	16,500	1972	35,100	6.0	55,900	74,800
Japan	20,500	1972	63,200	9.0	126,400	194,900
Korea, South	400	1975	6,200	16.5[5]	10,000	16,100
Mexico	2,900	1976	8,500	6.6	11,000	15,100
Netherlands	4,700	1972	10,800	6.6	18,100	24,900
New Zealand	1,500	1977	5,000	7.0	6,100	8,500
Norway	6,100	1971	11,100	5.1	17,300	22,200
Pakistan	300	1976	3,900	15.5[5]	5,700	9,200
Philippines	500	1975	2,400	10.3[5]	3,900	6,300
Portugal	1,300	1972	2,500	5.1	3,700	4,800
South Africa	5,000	1975	15,700	7.4	22,500	32,300
Spain	6,400	1977	27,100	8.4	34,500	51,500
Sweden[7]	8,500	1980	23,400	5.0	23,400	30,500
Switzerland	5,400	1975	10,700	4.3	13,200	16,300
Thailand	200	1975	2,100	16.9[5]	3,300	5,300
Turkey	1,200	1974	3,200	7.0	4,800	6,800
United Arab Rep.	800	1970	3,600	14.3[5]	9,400	15,100
United Kingdom	34,700	1975	88,700	6.0	118,900	159,400

[108] Reprinted from WASH-1139, Table 5. Data are based on information contained in "World Power Data" for 1960 from FPC, in "Statistical Yearbook" for 1968 from U.N., and reports of new plant constructions after 1959.

Table 15. Nuclear Fractions for New Electric Power Capacity in Foreign Countries[109]

Country	Periods for Nuclear Fractions[1]		Nuclear Fraction				
			From Data		Extrapolation		
	Base Year	Years per Period	First Period	Second Period	Third Period	Fourth Period	Fifth Period
Argentina	1967	4	0	0.25	0.40	0.50	0.57
Australia	1968	4	0	0.10	0.17	0.24	0.30
Austria	1968	4	0	0.44	0.61	0.70	0.76
Belgium	1966	5	0.11	0.60	0.75	0.81	0.85
Brazil	1967	5	0	0.08	0.14	0.20	0.25
Canada	1965	5	0.02	0.16	0.26	0.34	0.41
China (Taiwan)	1967	5	0	0.28	0.44	0.54	0.61
Denmark	1970	5	0	0.30	0.46	0.56	0.63
Finland	1970	5	0	0.60	0.75	0.82	0.86
France	1966	5	0.11	0.28	0.40	0.48	0.54
Germany, West	1966	5	0.04	0.42	0.58	0.67	0.73
Greece	1967	5	0	0.29	0.46	0.56	0.63
India	1967	4	0.08	0.08	0.08	0.08	0.08
Israel	1970	5	0	0.24	0.39	0.49	0.56
Italy	1967	5	0	0.13	0.23	0.31	0.38
Japan	1969	7	0.18	0.36	0.47	0.55	0.61
Korea, South	1965	5	0	0.14	0.25	0.33	0.40
Mexico	1968	4	0	0.44	0.61	0.70	0.76
Netherlands	1966	4	0	0.16	0.28	0.37	0.44
New Zealand	1970	5	0	0.35	0.52	0.61	0.68
Norway	1970	5	0	0.13	0.23	0.31	0.38
Pakistan	1964	6	0	0.16	0.27	0.36	0.43
Philippines	1970	5	0	0.54	0.70	0.78	0.83
Portugal	1970	5	0	0.36	0.54	0.63	0.70
South Africa	1970	5	0	0.15	0.26	0.34	0.41
Spain	1967	5	0.07	0.27	0.40	0.49	0.56
Sweden	1965	5	0	0.44	2	2	2
Switzerland	1967	4	0.55	0.95	0.97	0.98	0.99
Thailand	1970	5	0	0.40	0.57	0.66	0.73
Turkey	1970	5	0	0.29	0.44	0.55	0.62
United Arab Republic	1970	5	0	0.08	0.16	0.22	0.27
United Kingdom	1964	6	0.11	0.38	0.52	0.61	0.67

[1] For example, a base year of 1967 and years per period of 4 correspond to a first period of 1968-71, a second period of 1972-75, a third period of 1976-79, a fourth period of 1980-83, and a fifth period of 1984-87, inclusive of first and last years given for each period.

[109] Reprinted from WASH-1139, Table 6.

Table 16. Estimate of Cumulative Capacity of Nuclear Power Plants in Foreign Countries

Country	Fuel Type	Thousands of Electrical Megawatts at End of Calendar Year															
		1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Argentina	Enriched									0.3	0.3	0.6	0.6	1.0	1.0	1.4	1.4
	Natural				0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Australia	Enriched							0.5	0.5	1.1	1.1	1.8	2.4	3.0	3.7	4.4	5.3
Austria	Enriched							0.6	0.6	0.6	0.6	1.3	1.3	1.3	2.0	2.0	2.0
Belgium	Enriched	0.1	0.1	0.1	0.1	0.5	0.9	1.3	1.3	1.9	1.9	2.6	2.6	3.3	3.3	4.2	4.2
Brazil	Enriched								0.5	0.5	1.0	1.0	1.5	1.9	2.3	2.9	3.5
Canada	Natural	0.2	0.8	1.6	2.1	2.6	2.6	2.6	3.4	4.8	6.3	7.8	9.4	11.1	13.0	14.9	17.0
China (Taiwan)	Enriched							0.6	0.6	0.6	1.2	1.2	1.2	1.8	2.2	2.7	3.2
Denmark	Enriched									0.4	0.4	0.8	0.8	1.4	1.8	2.2	2.6
Finland	Enriched								0.4	0.4	1.0	1.0	1.0	1.4	1.4	1.9	1.9
France	Enriched	0.2	0.2	0.2	0.2	0.8	1.2	2.0	3.0	4.0	5.2	6.3	7.6	9.1	10.8	12.5	14.4
	Natural	1.3	1.3	1.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Germany, West	Enriched	0.8	0.8	0.9	2.2	2.2	5.9	7.0	8.9	11.0	13.3	15.6	18.1	21.1	24.3	27.7	31.3
Greece	Enriched							0.4	0.4	0.8	0.8	1.2	1.2	1.7	2.1	2.6	3.1
India	Enriched	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.8	0.8	1.3	1.3	1.9	1.9	2.6	2.6
	Natural			0.2	0.2	0.4	0.6	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Israel	Enriched										0.3	0.3	0.3	0.6	0.6	0.9	0.9
Italy	Enriched	0.4	0.4	0.4	0.4	0.4	0.4	1.2	2.0	2.7	3.4	4.1	4.8	5.6	6.8	8.1	9.4
	Natural	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Table 16 - Continued

Country	Fuel Type	Thousands of Electrical Megawatts at End of Calendar Year															
		1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
Japan	Enriched . . .		1.1	1.1	1.6	2.8	4.9	7.6	10.8	13.9	17.1	20.6	23.7	27.9	34.2	41.2	48.8
	Natural	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Korea, South	Enriched . . .						0.6	0.6	1.1	1.1	1.1	1.6	1.6	2.1	2.6	3.0	3.5
Mexico	Enriched . . .							0.6	0.6	1.3	1.7	2.1	2.6	3.2	3.7	4.3	5.0
Netherlands	Enriched	0.1	0.1	0.1	0.1	0.5	0.5	1.0	1.0	1.5	1.9	2.3	2.8	3.3	3.9	4.5	5.2
New Zealand	Enriched . . .									0.3	0.3	0.6	0.6	1.1	1.1	1.6	1.6
Norway	Enriched . . .										0.5	0.5	0.5	0.5	1.1	1.1	1.6
Pakistan	Enriched . . .							0.2	0.2	0.4	0.4	0.7	0.7	1.0	1.0	1.5	1.5
	Natural		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Philippines	Enriched . . .									0.4	0.4	0.8	0.8	1.2	1.6	2.0	2.5
Portugal	Enriched . . .										0.3	0.3	0.3	0.3	0.6	0.6	0.6
South Africa	Enriched . . .												0.4	0.9	1.4	1.9	2.5
	Natural									0.5	0.5	1.0	1.0	1.0	1.0	1.0	1.0
Spain	Enriched . . .	0.6	0.6	0.6	0.6	0.6	0.6	2.1	2.6	3.6	4.6	5.6	6.8	8.0	9.7	11.5	13.4
	Natural				0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Sweden	Enriched . . .	0.4	0.4	0.4	0.4	1.2	2.7	3.3	4.1	6.3	7.9	9.5	11.1	12.4	13.7	15.1	16.6
Switzerland	Enriched . . .	0.4	0.4	0.7	1.0	1.4	2.0	2.4	2.9	3.4	3.9	4.4	5.0	5.6	6.2	6.8	7.5
Thailand	Enriched . . .											0.5	0.5	0.9	0.9	1.4	1.4
Turkey	Enriched . . .											0.4	0.4	0.7	0.7	1.1	1.1

Table 16 - Continued

Country	Fuel Type	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
		Thousands of Electrical Megawatts at End of Calendar Year															
United Arab Rep. . . .	Enriched . . .										0.3	0.3	0.3	0.6	0.6	1.0	1.0
United Kingdom	Enriched . . .	0.1	0.1	0.8	2.2	4.1	5.4	6.6	9.6	12.7	16.1	19.6	23.4	27.4	32.3	37.6	43.1
	Natural	4.6	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Total (rounded), without U.K.	Enriched . . .	3.4	4.5	4.9	7	11	20	32	42	57	72	89	103	125	147	175	200
Total (rounded), with U.K.	Enriched . . .	3.5	4.6	5.7	9	15	25	38	51	70	88	109	126	152	179	212	243
	Natural	6.5	7.8	9.3	11	12	12	12	13	15	16	18	20	22	24	26	28

[110] Reprinted from WASH-1139, Table 7.

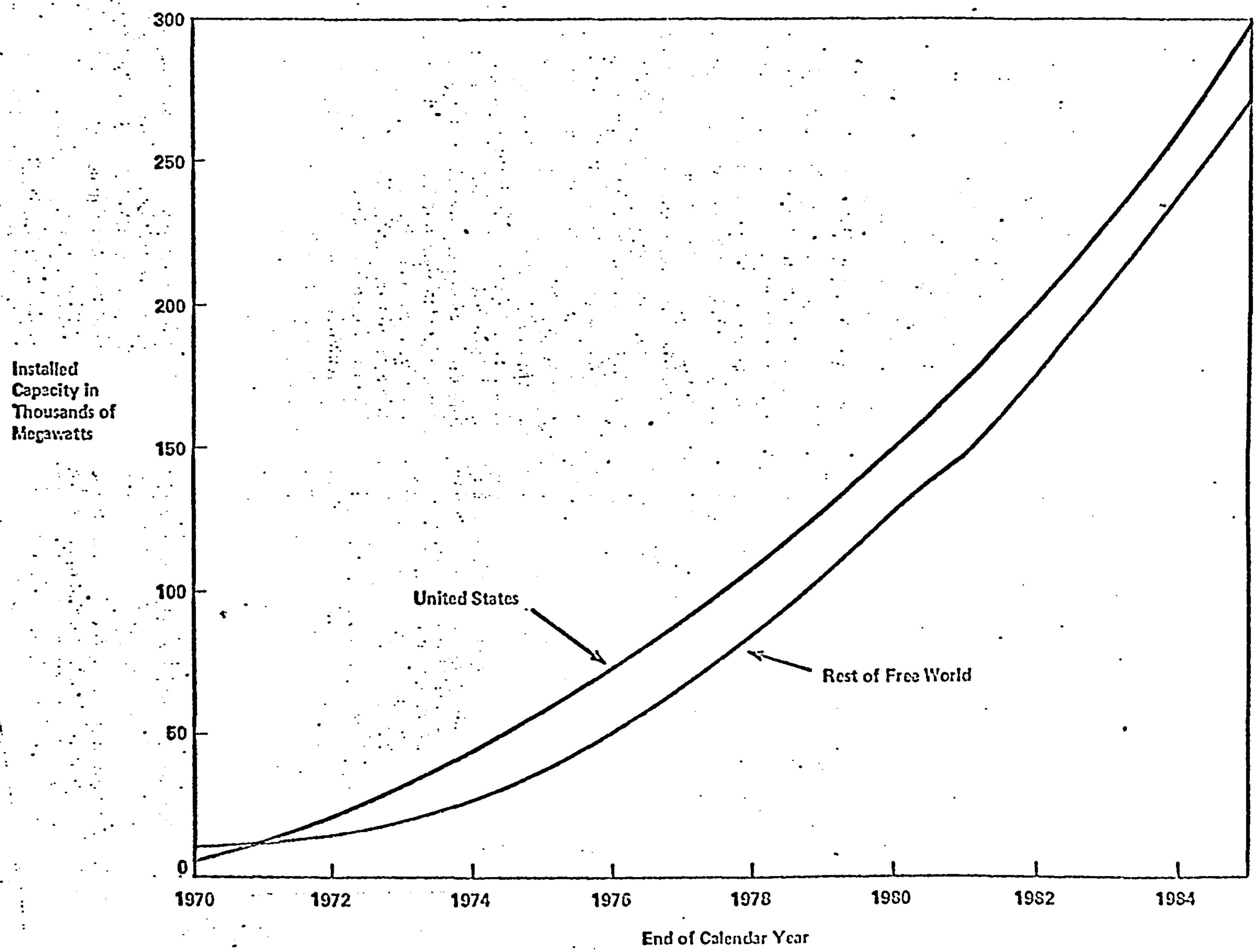
Table 17. Estimated Cumulative Capacity of Nuclear Power Plants in Communist Countries[111]

Electrical Megawatts

	1975	1980
Bulgaria	800	?
Czechoslavakia	150	1100
East Germany	70	> 500
Hungary	1000	?
Poland	200	?
Romania	600	?
U.S.S.R.	> 8000	?

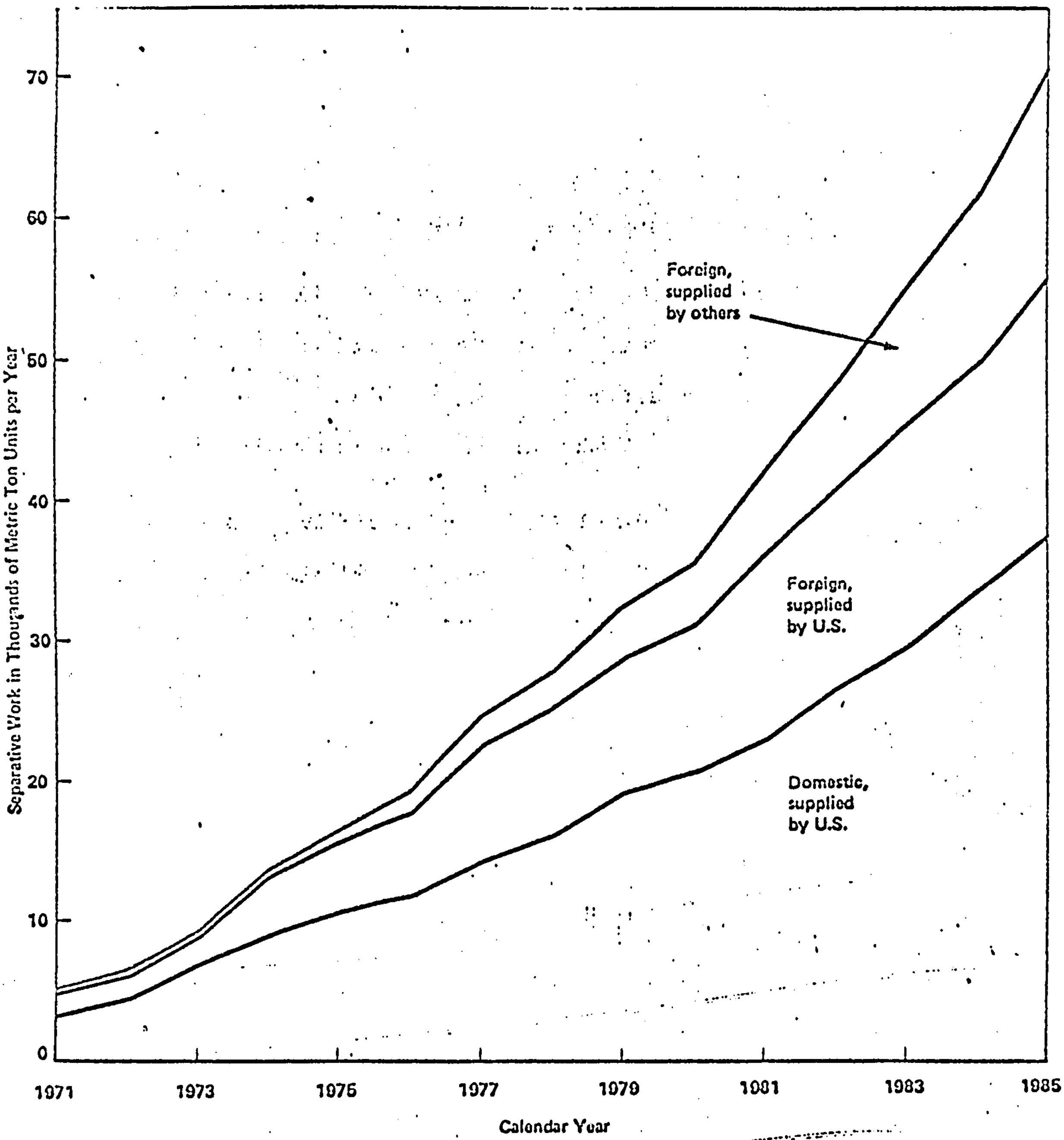
[111] From Foreign Reactor List, July 1970, Reports and Special Projects Branch, Division of International Affairs, U.S. AEC.

Figure 7. Forecast of Growth of Nuclear Power[112]



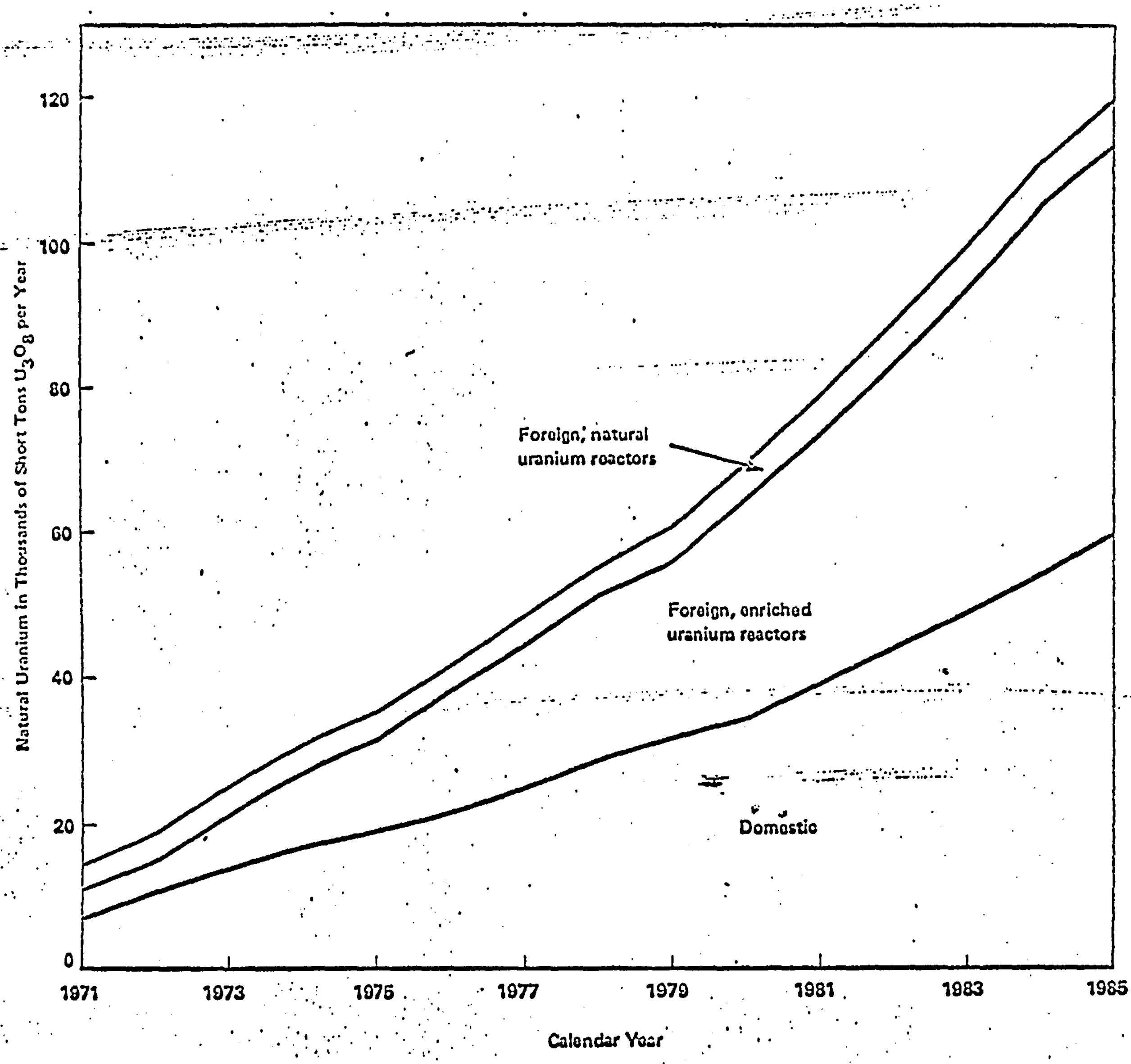
[112] Reprinted from WASH-1139, Figure 1.

Figure 8. Forecast of Separative Work Requirements[113]
(with plutonium recycle and tails assay of 0.2% U-235)



[113] Reprinted from WASH-1139, Figure 2.

Figure 9. Forecast of Natural Uranium Requirements[114]



114 Reprinted from WASH-1139, Figure 3.

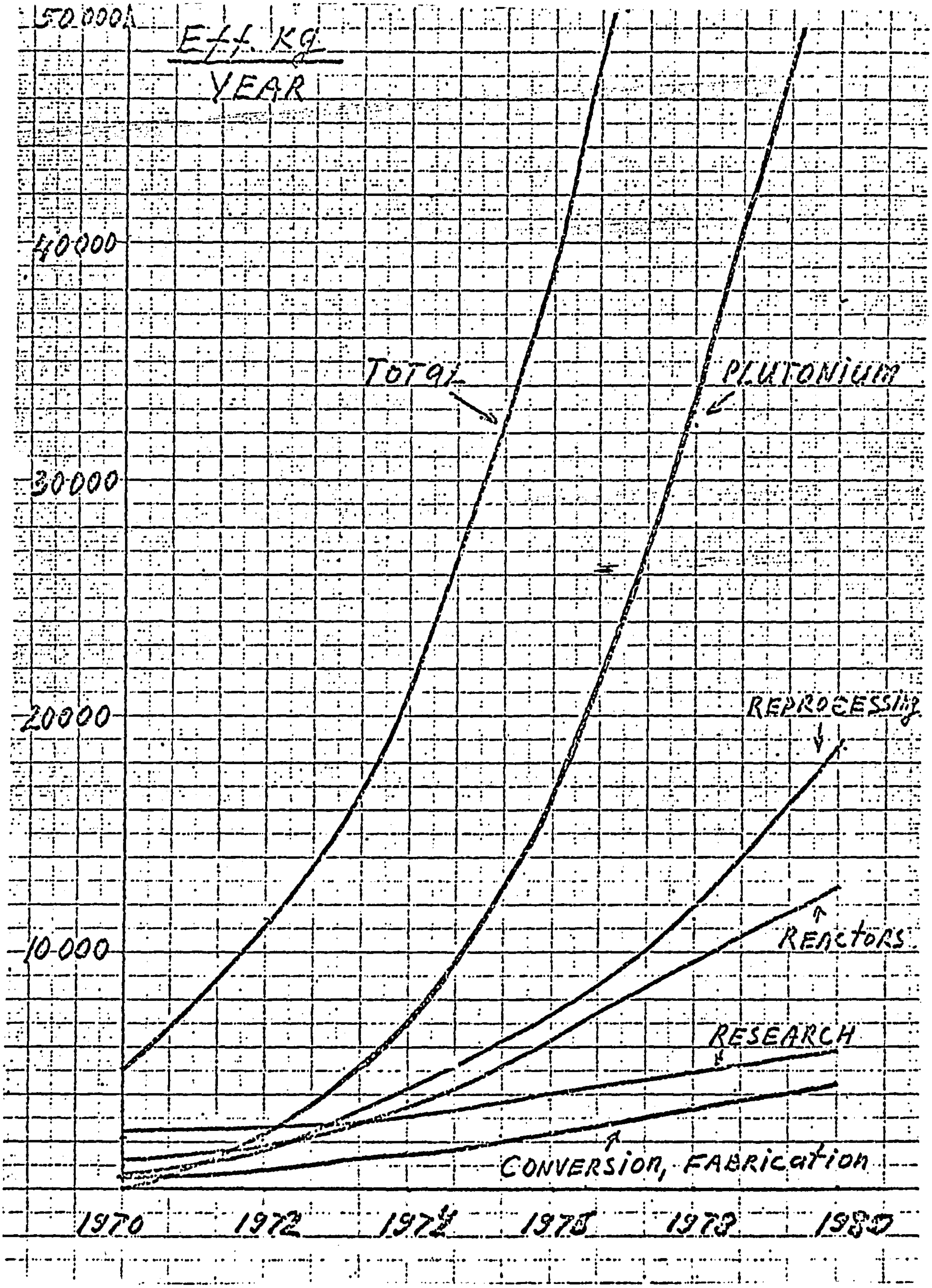
Table 18. Forecasts of Plutonium Discharged from Power Reactors[115]

Kilograms of Fissile Pu Recovered per Year

Year	United States	Foreign
1971	400	3,500
1972	500	3,800
1973	900	4,000
1974	2,100	4,500
1975	4,000	5,500
1976	6,400	6,700
1977	8,900	8,400
1978	10,800	10,600
1979	12,400	12,900
1980	15,600	16,200
1981	19,300	19,800
1982	22,500	23,800
1983	27,400	27,600
1984	32,300	32,200
1985	37,100	37,400

[115] From WASH-1139, 19. Assumes no Pu recycle. Note that U.S. and foreign totals are nearly identical from 1976 onward.

Figure 10. Distribution of Fissionable Material in the Fuel Cycle - Non-Nuclear-Weapon States.
(Total Inventory or Annual Throughput in Effective Kilograms)[116]



[116]See next page.

[116] IAEA, GOV/COM.22/80, "Projections of Safeguards Costs 1971-1975," October 19, 1970, Fig. 5. This Figure is from a staff study by the IAEA, based on a 1980 nuclear power growth projection in the non-nuclear-weapon states of 120,000 MW_e. The terms used refer to the following:

Plutonium - plutonium inventory available in stock, and in utilization.

Reprocessing - reprocessing plants throughput.

Reactors - inventory in power reactors and cooling ponds.

Conversion and Fabrication - throughput.

Research - uranium inventory in research and development activity.

"Effective kilogram" is a unit used to indicate the relative weapons utility of fissionable material. The quantity in effective kilograms of any material is (a) for plutonium, its weight in kilograms, (b) for uranium with an enrichment of 1.0% and above, its weight in kilograms multiplied by the sequare of its enrichment, and (c) for uranium with an enrichment between 0.5% and 1.0%, its weight multiplied by .0001. For example, 1 metric ton of 3.6% uranium would consist of $(1000) \times (.036)^2 = 1$ effective kilogram.

CHAPTER 2. Nuclear Weapon Requirements

1. How to Make an Atomic Bomb

The essential ideas underlying nuclear weapon physics are well known. The very brief discussion following is simply to introduce the concepts and terms used later to discuss the capabilities of non-nuclear countries to develop nuclear explosives. There are two central classes of nuclear weapons: fission weapons and thermonuclear weapons in which a large part of the energy is produced by the fusion of light nuclei, (notably, tritium and deuterium). Since at present, fusion reactions for weapons purposes require extremely high temperatures practically producable only by a prior fission explosion, the latter is of most relevance to the problems of proliferation.

Fission Weapons

The fission of a U-235, Pu-239, or U-233 nuclei by a fast neutron produces from two to several high energy neutrons and approximately 200 million electron volts energy. The neutrons produced by the fission are able under certain circumstances to create a chain reaction of fissions, which if sufficiently rapid will provide an explosive release of energy. Under the conditions that exist in a bomb, the period of each neutron generation (the time for a fission neutron to fission another nucleus) is approximately 10^{-8} seconds; and the total time for the energy to be realeased (virtually regardless of the yield of the explosion) is roughly 10^{-6} seconds.[1] The explosive yield released by this process is usually measured in terms of the explosive power of TNT. Since the explosive energy of one ton of TNT is 10^9 calories, the fission of 1 kilogram of material is equivalent to 18,000 tons of TNT (18 KT).[2] The relevant nuclear parameters of the three fissile nuclides are such that roughly speaking Pu-239 and U-233 possess similar weapons' properties, and for many purposes may be considered interchangeable. In most respects, U-235 is an inferior weapons material.

For a given density and geometry, there will exist a minimum size, the critical mass, below which a chain reaction could not occur. With suitable means to make efficient use of the fission neutrons, nominal spherical critical masses are:

Plutonium	5 kgm
U-235	25 kgm

Without such means, the respective critical masses are roughly 10 kgm

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[1]Glasstone, Sourcebook, paras. 14.22, 14.23. In U-235, for example, 2.5 neutrons per fission event are released on the average. If the number of neutrons lost per fission is roughly 0.5, the neutron population will be given by $N = N_o e^{t/\tau}$ where τ is the generation time, and N_o is number of initial neutrons. If the fission chain starts with one neutron ($N_o = 1$), it follows that 56 generations are required to produce 2.5×10^{24} neutrons, the number of atoms of U-235 in one kilogram. This would take about half a microsecond. Another 10^{-8} seconds would double the number of neutrons, and so on, so that any yield explosion (within reason) would occur certainly within 10^{-6} seconds.

[2]See fn 6, section 1, chapter 1.

for plutonium and 50 kgm for U-235.[3]

Once a critical mass is obtained, there is a rapid release of energy, which at once gives rise to the familiar nuclear explosive effects, and which simultaneously begins to blow apart the assembled mass of fissile material. The essence then of a nuclear weapon is a device to assemble suddenly a supercritical mass of fissionable material and to ensure that this is done in such a way that a significant fraction of the atoms undergo fission before the assembly destroys itself. The efficiency of this process will be defined by the ratio of explosive yield to weight; that is, it will depend, for a given weight of fissile material, chemical

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[3]Theodore Taylor et al., Preliminary Survey of Non-National Nuclear Threats, 14. Suitable means refer to "reflectors" -- material such as U-238, placed around the fissile material, which has the effect of sending neutrons back into the fissile assembly when it receives a neutron flux. The spherical critical masses can be crudely estimated from widely available data, since the "critical radius" must be of the same order of magnitude as the mean free path (λ) of a neutron in the fissile material. Consider for example Pu-239. The fission cross-section (roughly constant between 0.1 and 1.0 MeV) is about 1.8 b (1.8×10^{-24} cm^2). Since there are $\frac{6 \times 10^{23}}{239} \times 19.0 \approx 5.1 \times 10^{22}$ atoms/cc, $\lambda^{-1} \approx 5.1 \times 10^{22} \times 1.8 \times 10^{24} \approx 10^{-1}$ cm (where the density of plutonium is taken as 19 g/cc). Thus $\lambda \approx 10$ cm. The actual critical radius would be less than this because η for Pu-239 in a high energy spectrum is almost 3.0. Arbitrarily taking $R_c = \lambda/2 \approx 5$ cm gives leads to a critical mass of 10 kgm. Other important parameters can be similarly (crudely) estimated. For example, from published data on the energy spectrum in a fast breeder reactor core, an average neutron energy in the core of Pu-239 may be taken as approximately 1.0 MeV, corresponding to a neutron velocity of $V = 12.5 \times 10^8$ cm/sec. The time between fissions in the chain must thus be of the order of $\lambda/V \approx 10^{-8}$ seconds, consistent with published figures.

explosive, and casing, on the fraction of the material which undergoes fission.

There exist two methods of assembly. One, the "gun-type", explodes two separated subcritical masses together by means of chemical explosives much as a piston is fired into a cylindrical ring. The second employs an "implosion" technique. A sub-critical mass is rapidly compressed by a surrounding mass of chemical explosives, with the resultant increase in density and decrease in surface area causing the assembly to become supercritical.[4] For reasonable efficiency, it is important that the chain reaction not start too soon, not, that is, until the assembly has become fully supercritical. Otherwise, the assembly will begin to destroy itself before most of its nuclei will have had a chance to fission. Thus there cannot be tolerated a neutron background that would introduce large numbers of neutrons into the assembly before it becomes fully supercritical. Since the crucial period begins with the onset of criticality, the more rapid the assembly, the higher the neutron background that can be accepted. It turns out in actuality that because Pu-240 is a high neutron emitter (through spontaneous fission), plutonium cannot be used at all in a gun-type device where the assembly is relatively slow. Such devices must use uranium. Implosion weapons, where the assembly is comparatively rapid, utilize either plutonium or uranium.[5] With respect to plutonium, it is reasonable to inquire whether

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[4]Henry Smyth, Atomic Energy for Military Purposes, 212. Richard Hewlett and Oscar Anderson, The New World, 245-249, 347-407. Glasstone, Sourcebook, 14.83 - 14.85. The weapons tested at Almagordo and dropped on Nagasaki employed the implosion device, the Hiroshima bomb, the gun-type.

[5]Hewlett and Anderson, The New World, 245-249.

there might be some degree of Pu-240 concentration which would make even an implosion weapon impossible. This issue is discussed in section 3 of this chapter.

Thermonuclear Weapons

Thermonuclear weapons utilize the fusion reactions:

$$d + d \rightarrow {}^{3}_{2}He + n + 3.3 \text{ MeV}$$

$$d + t \rightarrow {}^{4}_{2}He + n + 17.6 \text{ MeV.}$$

Both reactants, deuterium (${}^{2}_{1}H$) and tritium (${}^{3}_{1}H$), are of course isotopes of hydrogen, and hence the term "Hydrogen Bomb". As earlier stated in chapter 1, the reactions have a threshhold temperature of about 10^8 degrees, so far practically producible only by the prior explosion of a fission weapon. Presumably then, thermonuclear weapons must consist of at least two stages, a fission weapon and a second stage comprising the light nuclei used in the fusion.[6]

The d-t reaction produces energy at a rate about 100 times that of the d-d process, and tritium would thereby appear a highly desireable substance to employ in a weapon. However, tritium is not found in nature (it has a half-life of 12 years), and it can be artificially produced in a reactor only at a very slow rate. If tritium is used in thermonuclear weapons, most of it probably must be made in the bomb itself, although whether this is so has not been revealed. One theoretical possibility would be to surround the fission stage with "light-heavy" lithium hydride (a compound of the light isotope of lithium and deuterium). Upon exposure to a high neutron flux, a large number of tritium nuclei will be

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[6] Glasstone, Sourcebook, 14.115-14.120. Thirring, Energy for Man, 375-378.

produced by the reaction $^{6}_{3}Li + n \rightarrow \alpha + t + 4.7$ MeV; the tritium so generated could then react with the deuterium available.[7]

Despite this possibility, that most of a tritium fuel could be produced in the bomb, an initial supply of tritium is probably highly desireable and perhaps essential for the efficient explosion of a thermonuclear weapon. The temperature threshhold for the d-t reaction is significantly below that for d-d, and the rate of energy production is, as indicated above, more than a hundred times greater. Apart from its probable utility in two stage (fission-fusion) devices, tritium for these reasons would also appear crucial to the achievement of a pure fusion explosion should it in fact ever prove possible to bypass the fission stage through the use of lasers or other methods to produce the required temperatures. Scientists at the June 1970 Pugwash Conference suggested this possibility as one strong reason to safeguard tritium.[8]

Unlike fission weapons which are limited in yield by the constraint that no part of the fissile material assembly can be critical before detonation, thermonuclear explosives confront no such limitation; as much thermonuclear material as one wishes could be assembled with no danger of a spontaneous explosion. Thus the yields possible with thermonuclear weapons seem limited only by weight and volume constraints imposed by the delivery system.

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[7]This possibility is pointed out for example by Thirring, Energy for Man, 377.

[8]P. L. Ølgaard, in F. A. Long and J. J. Mackenzie, eds., Impact of New Technologies on the Arms Race, 260-263.

2. Technical Constraints

Nuclear Weapons

Development of nuclear weapons requires the confluence of technical knowledge, skilled personnel, some industrial-assembly facilities, certain non-nuclear material, nuclear material, and some degree of testing. It appears that these requirements with the potential exception of nuclear materials are within the province of a large number of countries. Taylor, Van Cleave, and others in unclassified (albeit unpublished) studies for the U.S. Army Research Office have reached pessimistic conclusions after careful searches of the unclassified literature on nuclear physics:

> The knowledge required for the construction of relatively crude fission explosives having yields equivalent to thousands of tons of high explosives, and light enough to be carried in any automobile, is readily available in unclassified books and documents and is known to thousands of people throughout the world. Given the required amounts of sufficiently enriched uranium or plutonium, such explosives could be designed and built in six months or less by a dozen or fewer people without extraordinary technical experience, using materials and facilities that are commonplace, at costs that many private individuals could afford.[9]

In a slightly earlier study for the Office of Research, Van Cleave and associates at Stanford Research Institute reached these central conclusions:

> (1) The difficulty and cost of making nuclear weapons is often greatly exaggerated in the case of many countries. For an increasing number of countries, the production of even advanced nuclear weapons (compared with the first few generations of weapons in the United States) is neither difficult nor particularly costly. For others, the more advanced and costly systems are not required.

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[9] Taylor, Survey of Nuclear Threats, 3.

(2) Future nuclear weapons powers enjoy certain important advantages over states that elected to produce nuclear weapons in the past. These include: availability of information; availability of nuclear facilities and materials; experience either actual or vicarious in relevant technological processes; advanced auxiliary technologies (compare the "Los Alamos Computer" room full of girls with desk adding machines -- with computers available today); and changes in the state of the art of nuclear weapons.

(3) There is an erroneous assumption, implicit or explicit, in most analyses of the Nth country threat that the United States experience must be essentially duplicated. A conclusion that follows as a corallary of the above and from an examination of Nth country capabilities and requirements is that neither in the extensive research and development facilities, nor the laborious and costly testing, nor in the stages of weapons development is this so. With much less effort and cost, based on previously developed knowledge and resources, an Nth country may be able to start with, or go directly to, advanced, even sophisticated and versatile, nuclear weapons.[10]

Similar conclusions cannot be reached in regard to thermonuclear weapons. Here the relevant published data have been very scarce, and the intrinsic technical difficulty very formidable. Nonetheless, with time, it is highly likely that thermonuclear design knowledge will spread widely as has fission data. Even, at present, the large, industrialized non-nuclear states, notably West Germany and Japan, probably possess much of the required technology and could produce the remainder.

The foundation for these grim assessments may be specified in more detail.

Technical knowledge. In large part, because of studies used in nuclear reactor design, significant data relevant to fission weapon designhave been widely disseminated. These include detailed information concerning the nuclear properties of fissile isotopes, the theory of chain reacting systems,

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[10] William Van Cleave, Nth Country Threat Analysis, Summary.

extensive critical mass data, the theory of hydrodynamics, data on the phases of a nuclear assembly, details of conversion of plutonium and uranium compounds into metallic forms suitable for fission explosives, high explosive technology, techniques for measurement of shock waves, fusing and firing system design information, etc.[11] In sum:

> Very little basic physics knowledge is needed if detailed drawings of the device are available along with some instructions on how to proceed. If, on the other hand, efficient and light fission explosives are required, and drawings or detailed recipes are not available, it is necessary to know or learn a great deal. In either case, all the necessary basic physics knowledge is already distributed throughout the world.[12]

Personnel. Taylor divides the kinds of people useful to a nuclear weapon development effort into three kinds:

Direct experience designing, building, or testing nuclear explosives	Thousands (mostly in nuclear weapon states)
Highly developed technical skills and basic knowledge of the specific required technical fields	Tens of thousands (concentrated in countries with substantial programs in civilian nuclear technology)
Required basic skills, but without specific knowledge or experience in specific required fields.	Millions

Taylor believes that at least a crude fission device could be produced by tens of scientists and engineers who were capable but by no means distinguished. The competence to design nuclear weapons would thus be in

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[11] Taylor, Survey of Nuclear Threats, 10-13.

[12] Ibid., 10-11.

the province of scores of countries including essentially all now with civilian nuclear programs.[13]

Industrial Base. The development and production of relatively unsophisticated fission weapons do not seem to require a large or sophisticated industrial base -- extensive use of large computers, excessively fine machine tolerances, etc. In general, it is probably fair to state that the kinds of sophistication nations (or organizations) will tend to seek will be well within their industrial capability. Estimates made below in section 3 and earlier UN estimates indicate that the resource and financial requirements to produce a few nuclear weapons per year (sans delivery vehicles) would not be large.[14]

Nuclear Material. These include the fissionable material, natural, depleted, or slightly enriched uranium, thorium, tritium, deuterium, and lithium, all potential sources of nuclear energy by fission or thermonuclear reaction, either directly or following neutron bombardment.

The detailed use of the non-fissionable nuclear material in nuclear explosives and in the instances of tritium and lithium-6 (light isotope of lithium) the precise modes and rates of production, have not been published. Deuterium (heavy water) and natural lithium can be easily purchased in large quantity throughout the world.

Testing. Various kinds of design and confirmation testing, perhaps but not necessarily including full-scale "nuclear tests," would be required whatever the scope of the development program. It is very doubtful that

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[13] Ibid., 13-14.

[14] United Nations, Effects of the Possible Use of Nuclear Weapons, October 1967, UN A/6858.

a sophisticated country would have to undertake a full scale test to develop reasonable confidence in the reasonable confidence in the reliability of moderately efficient warheads especially if the yield of the weapon did not have to be predicted precisely. Were full-scale tests necessary, their cost would be moderate. A U.N. study has estimated that one underground test of a 20 KT device would cost $12 million, and that four such tests would cost $15 million. This study assumed that no more than one test would be necessary to support a small nuclear weapon program.[15]

In the earlier test stages, in investigations of the stages of assembly of the nuclear material (the implosion and consequent compression of a subcritical mass to supercriticality), the development of a U-235 weapon would appear significantly easier than of a plutonium device. For in the former case, the developers could use, as a surrogate for the U-235, natural uranium which while not capable of undergoing a chain reaction would retain many of the hydrodynamic properties of the enriched uranium. This is one reason to fear the development of an inexpensive centrifuge method to separate uranium isotopes.

Development Time. The time to develop a nuclear weapon required by a nation starting with no explicit weapons experience but from a base founded in civilian nuclear power would vary from country to country. But as a rough guide, we may guess the following:[16]

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[15]United Nations, Effects of the Possible Use of Nuclear Weapons, Annex 4.

[16]These are simply estimates derived from several conversations with scientists. They must be considered only very rough guidelines.

	Time	Tests
Primitive Weapon	2 years	0
Advanced Fission	> 5 years	> 10
Thermonuclear	< 10 years	tens

3. Nuclear Material Constraints

The crucial material required for the production of fission weapons are U-235, Pu-239, or U-233.

U-235

It is generally believed that weapons grade uranium must contain over ninety percent U-235.[17] The attainment of one critical mass (about 25 kgm) of oralloy (93.5 percent U-235) by isotope separation of natural uranium would require about 4.5 metric tons of natural uranium. The separation requirements would be approximately six metric ton swu. At a uranium price of $22 per kilogram and a separative work charge of $26 per kilogram swu, the total cost of producing one critical mass of oralloy would come to about $250,000 or $10,000 per kilogram U-235. If slightly enriched uranium (say, 3%), such as would be used in a light water reactor, were available as feed, the separative work requirements would be reduced by almost two-thirds. Were still more highly enriched uranium available, the separative work requirements would be further diminished, ramatically so. These data are shown in Table 1, where the cost of natural uranium is taken as $22/kgm and the cost of separative work as $26/kgm swu.

[17] This does not mean, however, that lower grade uranium could not be used to obtain an inefficient nuclear explosion. Probably enrichments as low as 25% or so could be sufficient; the enrichment required for a fast breeder reactor is about this order.

Table 1. Effort and Cost to Produce 25 kgm of 93% U-235[18]

Feed	SWu	Natl. U (kgm)	Cost ($)
Natural U	5875	4580	253,500
3%	2320	830	60,300 *
10%	925	240	24,000 *
20%	530	115	14,000 *

*The cost here is taken simply as the cost of the extra separative work required; there is no charge assessed for the U feed.

These estimates of course assume that an isotopic separation complex is already available; the separation cost used is essentially the operating cost associated with the American gaseous diffusion plants. The effort and cost required to produce weapons grade uranium were such a separation complex not initially available would be substantially increased. Estimates by the AEC and Foratom indicate that specific investment costs for a new gaseous diffusion plant constructed outside Europe would be no less than $150/kgm swu for a plant with capacity in the vicinity of 2,000,000 swu/year. Smaller plants would have significantly greater specific investment costs.[19] Furthermore, this estimate does not

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[18] These data may be obtained from Table 2, Chapter 1 as follows: Take the instance where the feed is 20% enriched. Then the feed required to produce 1 kgm of 93% product is $\frac{93.0 - 0.2}{20.0 - 0.2} = 4.68$ kgm. The separative work to produce 4.68 kgm of 20% product may be found from the Table; it is 4.68 x 45.747 = 214.06 kgm swu. Also from the Table, 235.55 kgm swu are required to produce 1 kgm 93% product. Thus the work required to go from 20% feed to 1 kgm 93% product is given by 235.55 - 214.06 = 21.49. This may be multiplied by 25 to obtain the number presented in the Table.

[19] Foratom, "Report on European Uranium Enrichment," Annex 1.

include the higher specific costs due to production of high enrichment stages or to the requirement for an associated large power reactor to supply power to the separation plant. Taking these factors into account, the specific investment cost of a 2,000,000 kgm swu/yr plant would probably be at least $250, or $500,000,000.[20] At a discount rate of 10% and power charge of 7.5 mills/KWhr, the separation charge of such a plant would be about $40/kgm swu, or 50% higher than current U.S. charges. The cost/kgm to produce 93% U-235 at this charge would be nearly $15,000/kgm.

A separation plant of 2,000,000 kgm swu/yr capacity is however extremely large, well beyond the commercial or weapons needs of any non-nuclear nation. A potentially more attractive route to an enrichment capability would be through the construction of a relatively small centrifuge plant. Dutch and German studies for Foratom have suggested that such plants of capacity as low as 100,000 kgm swu could possibly be constructed at investment costs of $200/kgm swu/yr.[21] At such a specific investment cost, a small plant of 100,000 kgm swu/yr capacity would cost $20,000,000 to construct. Even using very low interest rates (7.5%), low specific electric consumption rates (438 KWh/kgm swu), and low power costs (7.5 mills/KWh), the costs of separation work of such a

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[20] Ibid., 5-6.

[21] Ibid., Tables 7,8,9. This figure is based on a cascade designed to produce only 3% U-235. A high enrichment cascade would cost much more.

plant would also be roughly $40/kgm swu.[22] A plant of capacity 100,000 kgm swu/yr could produce approximately 20 critical masses of U-235 per year from natural uranium feed. Still smaller plants would cost correspondingly more per critical mass; a U.N. study has estimated that a separation capacity of 2 critical masses per year would cost about $500,000/kgm U-235.[23]

Plutonium

Plutonium is produced at a rate of about 120 to 225 grams fissile plutonium per year per installed thermal megawatt in natural uranium reactors; the rate of production in enriched uranium reactors is approximately two-thirds this, 80 to 150 grams per year per thermal megawatt. The rate depends on the burn-up level of the reactor, since at higher burn-ups, relatively more of the energy output in the reactor is produced by fission of the bred Pu-239. At normal civilian reactor burn-up rates, the fissile plutonium production rates are at the low end of the above spectrums, 120 grams/MW_t-year and 80 grams/MW_t-year for the natural and light water reactors. At very low burn-ups, the comparable production rates would be somewhat less than 225 grams/MW_t-year and 150 grams/MW_t-year respectively.[24]

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[22] Ibid., Tables 7, 8, 9.

[23] United Nations, Effects of the Possible Use of Nuclear Weapons, 54-55.

[24] Typical figures for commercially operated reactors may be found in WASH 1098, Table 5.3; also Tables E-1 and E-2. For low burn-up levels, maximum plutonium production rates may be calculated from the reactor conversion ratio - the ratio of fissile nuclei produced to fissile nuclei consumed. Typical conversion ratios for light water and natural U reactors may be taken as .50 and .75 respectively (WASH 1098, Tables E-1, E-2. WASH-1097, Table 5.2.4). Thus at low burn-up levels, each gram of material fissioned will produce .50 and .75 grams of fissile plutonium. Since 1 gram fission is equivalent to 1 MW_t day, fissile plutonium is produced at the respective rates of .50 and .75 grams/MW_t day. This comes to about 150 grams and 225 grams per MW_t year for the two types of reactors.

The isotopic composition of the plutonium will also depend on the burn-up (or fuel exposure time) as shown in Figure 3, chapter 1, and in footnote 52, Chapter 1. At burn-up levels characteristic of commercial natural and enriched uranium reactors (say, 5000-8000 $MW_t d/MTU$ for natural and 25,000-35,000 $MW_t d/MTU$ for enriched reactors) the Pu-239 content of the discharged plutonium will average about 80% and 60 to 70% respectively. Should higher concentrations of Pu-239 be desired, the frequency of fuel discharge will have to be increased, with consequent increases in fuel, isotopic separation, and chemical reprocessing requirements.

Consider now, for illustration, the effort and cost required to produce plutonium of varying isotopic composition, first by generating the plutonium in an already constructed commercial power reactor, and second, through the construction de novo of a "production" reactor whose sole function is to produce plutonium. These two cases will bracket the actual requisite costs of plutonium production.

In a power reactor, where plutonium is produced merely as an inevitable by-product, the relevant costs ought to include only the additional expenses required to produce unusually high concentrations of Pu-239. These costs for an enriched uranium reactor of the PWR type are shown in Figure 1. By these data, it may be seen that the annual production of 420 kgm fissile plutonium (90% concentration would cost $60,000,000 or about $150,000/kgm, even if all capital and normal operating costs were charged to the production of power.

Figure 1. Effort and Cost Required to Produce Plutonium of Varying Isotopic Composition: 1,000 MW_e PWR Used as Illustration.

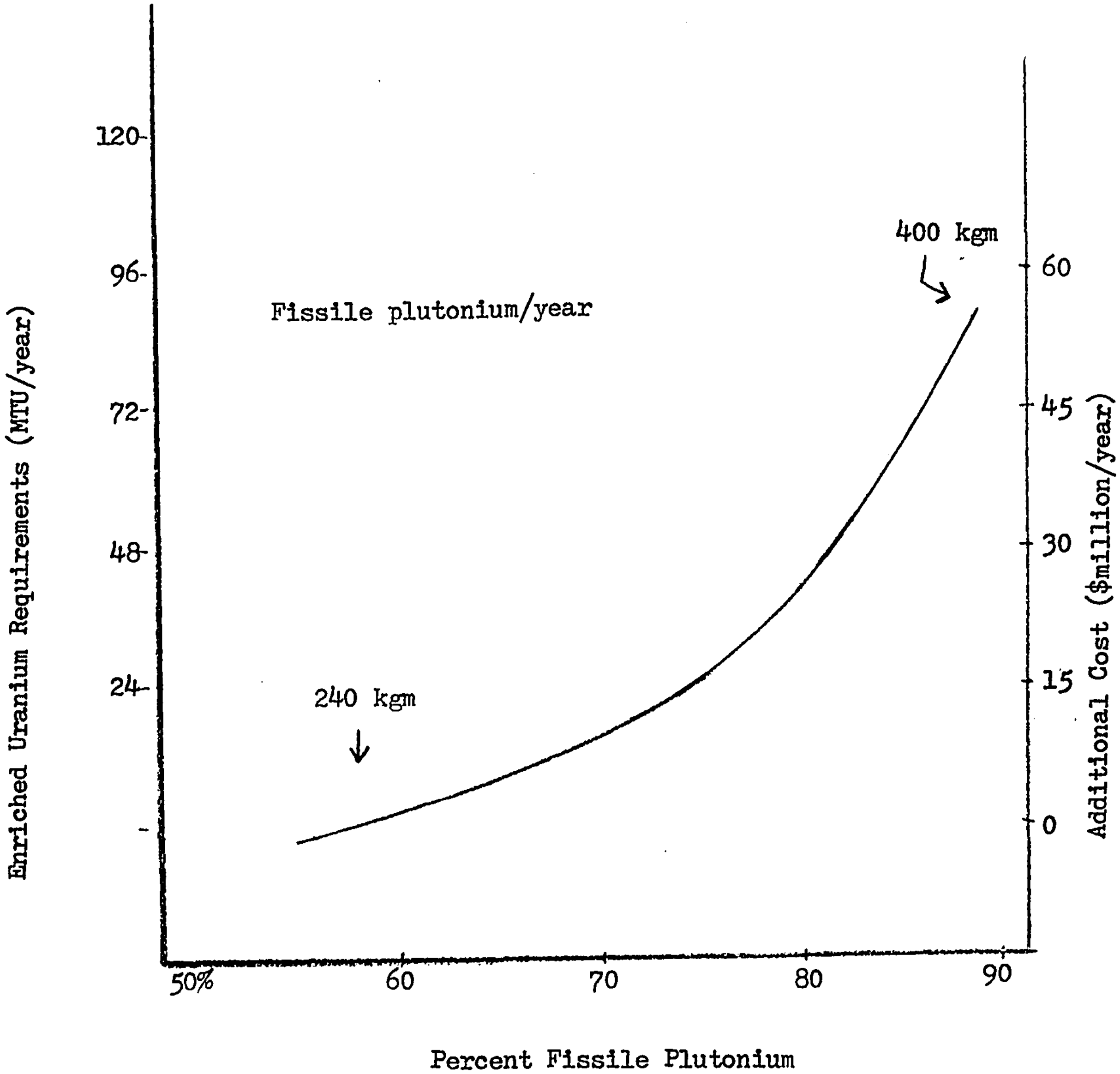
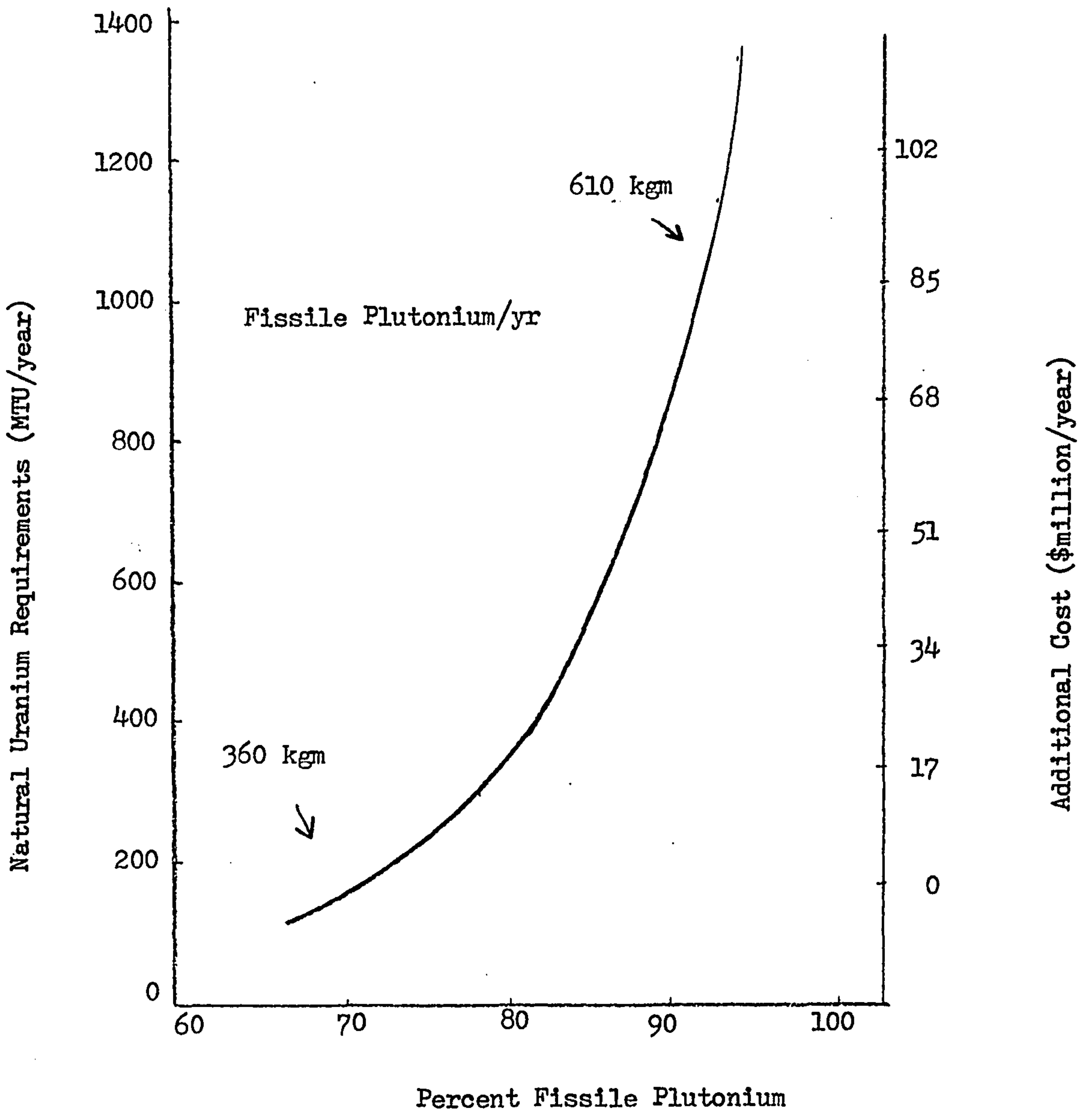


Figure 2. Effort and Cost Required to Produce Plutonium of Varying Isotopic Composition: 1000 MW_e HWOCR Used as Illustration.



Similar results obtain for natural uranium reactors as shown in Figure 4. Again the average cost per kilogram fissile plutonium (90% concentration) is about $150,000.

Rather than utilize commercial power reactors, where the entire capital investment and much of the operating expense may be written off to the generation of power when one calculates the plutonium cost, a country may instead construct an operate a reactor specifically to produce plutonium and nothing else. In such a case, electric generation equipment would not be needed and the capital cost of the reactor would be correspondingly reduced. Taking this cost as two-thirds the cost for construction of a power reactor and employing the data in Figures 3 and 4, the following Table of costs may be devised. In these calculations it is assumed throughout that high-grade plutonium

(> 90% Pu-239) is sought.[27]

Table 2. Cost of Producing 90% Plutonium Through Construction of Production Reactors

Type Reactor	Capacity (Thermal megawatts)	Fissile Pu/yr (kgm)	Cost/kgm Fissile Pu (Dollars)
Natural U (Heavy water moderated, organic cooled)	3,000	600	200,000
	300	60	240,000
Enriched U (PWR)	3,000	400	225,000
	300	40	280,000

Another conceivable way to produce high Pu-239 content would be to operate a reactor in its normal commercial mode, producing thereby (say) 70% Pu-239; and then enriching this plutonium in Pu-239 through the use of isotope separation methods. Such a procedure in fact appears comparatively

[27]Table 2 is based on the following:

	PWR 3000	PWR 300	HWOCR 3000	HWOCR 300
Fuel Cycle	$\$75 \times 10^6$/yr	$\$7.5 \times 10^6$/yr	$\$100 \times 10^6$/yr	$\$10 \times 10^6$/yr
Capital	$\$170/KW_e$	$\$370/KW_e$	$\$190/KW_e$	$\$410/KW_e$

These data are derived from Figures 3 and 4 (90% Pu-239), and the following simplifying assumptions: the capital costs are taken as 2/3 of the capital costs of a power plant with electrical generating equipment (see WASH 1150). The fuel cycle (plus O & M) costs for the 300 MW_t plants are simply taken as 1/10 the comparable costs for the 3000 MW_t (1000 MW_e) plants. The fixed capital interest rate is taken as 10% for all cases. The PWR and HWOCR costs data are taken from WASH 1150, v, Table 2; WASH 1098, Table 5.2; WASH-1083, 17-18, Table 5.4.

cheap, even allowing for the increased difficulty compared to uranium isotope separation of separating Pu-239 and Pu-240 which are only one mass unit apart. At the very low mass flows which would be involved in the plutonium separation effort, centrifugation appears the best process to utilize; it at least would be far preferable to gaseous diffusion. Since the separation factor in centrifugation is proportional to the mass difference between the isotopes and since the separative work capacity of an element is proportional to the square of the separation factor, the capacity per element for the separation of Pu-239 and Pu-240 (1 mass unit apart) will be 1/9 of the capacity for the separation of U-235 and U-238 (3 mass units apart). However, the relevant separative work requirements are extremely low, less than 1 SWu per kilogram of product to produce 90% Pu-239 from 70% Pu-239. The cost of a separation effort of this magnitude would be negligible.

These cost estimates have so far assumed that the necessary supporting nuclear services (conversion and fabrication, isotopic enrichment, reprocessing, etc.) may be purchased either from domestic or foreign sources. If this is not the case, and a country embarking on weapons program had to construct its own indigenous nuclear industry, the requisite effort to produce plutonium would be increased substantially. For illustration, consider the capital costs associated with required fuel services for a 300 MW_t and 3000 MW_t reactor.

Table 3. Capital Costs Required to Support a 300 MW_t and a 3000 MW_t Light Water Reactor[28]

	Cost ($million)	
	300 MW_t	3000 MW_t
Isotope Separation Plant	15	30
Fuel Fabrication	2	3
Reprocessing Plant and Plutonium Conversion to Metal	2	8

The 300 MW_t reactor could produce about 20 kgm high-grade plutonium per year; the 3000 MW_t reactor, ten times this. Although interest on capital investment has been included in above cost estimates, if new construction is required, the cost of producing the plutonium would be higher because of a loss of economy of scale and (perhaps) also substantially higher interest charges. If for illustration we assume an interest rate differential of 5 percentage points, and the data of Table 3, the cost of plutonium would be raised only roughly $25,000/kgm for the 300 MW_t light water reactor , $5,000/kgm for the 3000 MW_t light water reactor.

Thus, we may conclude that high grade plutonium produced in commercial reactors will cost approximately $150,000 per kilogram. Plutonium produced in production reactors would cost between $200,000 to $300,000 per kilogram.

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[28]The isotope separation data are very speculative; they are based on optimistic forecasts of ultra centrifuge performance.

U-233

U-233 is produced in thorium reactors by the process $Th\text{-}232 + n \rightarrow Pu\text{-}233 \xrightarrow{\beta} U\text{-}233$. The only commercial reactor utilizing thorium now under construction, is an advanced converter employing highly enriched U-235 as the initial fuel and necessary makeup. It consequently does not produce more weapons grade fissionable material than it consumes.

Although not now commercially competitive with the uranium cycle, a thorium cycle can also be employed in light water reactors.[30] Design studies indicate that under normal operating procedures, the net production of U-233 in such a cycle for a 1000 MW_e PWR would be about 25 kgm/year (compared to approximately 250 kgm Pu/year if operated on a uranium cycle). The fuel cycle cost for the thorium cycle is estimated to be roughly 30% higher than the uranium cycle under the usual assumption of \$8/lb U_3O_8. The thorium cycle becomes competitive with uranium at an ore cost of \$16/lb U_3O_8.[31] The low rate of U-233 production reflects the large contribution of U-233 fission to the power output. The rate can be increased by more frequent core changes so that the proportion of U-235 to U-233 remains high. But if significant amounts of uranium fuel are thus available, there appears no special attraction to the thorium cycle for a nation wishing to acquire a weapons capability.

Thorium may also in principle be used in a havey water organic cooled reactor (HWOCR) employing either highly or slightly enriched uranium or

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[30] The thorium cycle is here taken to mean U-235 (Th-232) U-233. The usual uranium cycle is U-235 (U-238) Pu-239.

[31] WASH-1097, 81-84, Table 5.4.2.

(possibly) natural uranium. Such a reactor (1000 MW_e) could produce 80-100 kgm U-233 per year.[32] Again the fuel cycle costs appear to be at least 30% higher than the case if a uranium cycle is employed.

As indicated in Chapter 1, section 4, U-233 can also be bred in a molten salt thermal breeder reactor. Here design studies indicate a potential breeding ratio of 1.07 and doubling time of 15 years for a 1000 MW_e reactor. With a fuel inventory of 1 kgm/MW_e, this means that roughly 70 kgm U-233 net will be produced each year.[33]

Significance of Isotopic Composition

Dirty, Denatured Plutonium:

Upon neutron bombardment, Pu-239 will sometimes fission and sometimes capture a neutron to form Pu-240. Pu-240, though not fissile, is a fertile isotope; it captures neutrons to form the fissile Pu-241. Pu-241 in turn will also sometimes capture a neutron to produce Pu-242, a "parasitic" isotope, neither fissile nor fertile. The question has often been asked whether a suitable concentration of Pu-240 (and Pu-242) could in effect "denature" a plutonium mass, that is, make it harmless (non-fissionable). There are two principal reasons why Pu-240 might have such effect. First, although it is a fertile isotope, upon neutron capture, it does not emit neutrons; consequently if present in sufficient quantity, it could prevent or delay the chain reaction. Secondly, because it emits neutrons through spontaneous fission, Pu-240 could lead to a predetonation fizzle. This latter effect is discussed in the next subsection. As to the first

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[32] WASH-1098, Table 5.3; WASH-1097, 86-90.

[33] WASH-1097, 75.

effect, there are now strong experimental and theoretical reasons to doubt its importance. For example, from published data, we know that the core of a fast reactor can consist of as little as 10-15% fissile material, with the plutonium part of the core over 35% Pu-240. Thus a chain reaction can certainly be sustained in plutonium that is quite "dirty" (having high Pu-240, Pu-241, and Pu-242) concentration. The mass of plutonium would however have to be larger than were the plutonium relatively pure in fissile isotopes. A similar conclusion may be drawn from relatively simple theoretical calculations based on published cross-sections in a fast neutron spectrum for the plutonium isotopes.

Spontaneous fission and predetonation:

Aside from diluting the Pu-239, Pu-240 will have still another deleterious effect due to its proclivity to fission spontaneously, that is without prior collision with a neutron. Such spontaneous fission will release neutrons into the plutonium assembly, possibly causing a "predetonation" of the assembly at a non-optimum time, with a consequent fizzle of the explosion.[34] The precise relevant data governing this predetonation effect are not easily found in the unclassified literature; but some rough guesses can be ventured.

Presumably, predetonation cannot occur before the assembly becomes critical; in the pre-critical period, a stray neutron would not cause a chain reaction. The problem must arise as the plutonium is being

[34]Hewlett and Anderson, The New World, 234-235, 251.

imploded, moving from a sub-critical to a super-critical state.[35] This period should be on the order of 10^{-6} to 10^{-5} seconds. The build-up of neutrons sufficient to fission a kilogram of material will require on the order of 10^{-6} seconds.[36] Compared to these times, the spontaneous fission rate of Pu-240 is about 1 fission per 10^{-6} seconds per kilogram, corresponding to a half-life of approximately 10^{11} years.[37]

This suggests that the Pu-240 neutron background could on the average prove somewhat of an obstacle to the achievement of a nuclear explosion; it could with some probability reduce the efficiency of the explosion. That is, the introduction of an unwanted neutron into the assembly is a random occurrence with an average expectancy of one per 10^{-6} seconds per kgm Pu-240; and there will consequently be a probability distribution of fission yield reduction due to predetonation. In most cases, this reduction would be expected to be relatively minor, though possibly very drastic in a few instances (depending of course on the ratio of Pu-239 and Pu-240). Beyond these considerations, it is also conceivable that ways are available to absorb stray neutrons, during the implosion period in a manner that would not affect the neutron build-up at the desired moment. It might also be possible in some manner to flood

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[35] Ibid., 234-235, 251. In this discussion, it is assumed that the implosion technique is used. In fact, precisely because of predetonation dangers, a gun-type device utilizing plutonium is not practical; it assembles too slowly.

[36] Glasstone, Sourcebook, para. 14.22. Freeman Dyson, private communication.

[37] The comparable half-life for Pu-239 is 5×10^{15} years and can be ignored.

the supercritical assembly with neutrons, thus constricting the time required to fission the assembly material. Also, it is noteworthy that the AEC and the International Atomic Energy Agency (IAEA) have not made distinctions between clean and dirty plutonium. The past AEC price for fissile plutonium has been the same regardless of the Pu-240 content. Similarly, IAEA safeguards do not distinguish among plutonium of varying isotopic composition.[38]

All these considerations suggest that high Pu-240 content would not prevent insuperable obstacles to the construction of an implosion device. It is certain that plutonium of isotopic composition found in discharge from commercial reactors is potentially useable in weapons and must consequently be safeguarded. Nevertheless, the foregoing also suggests that high Pu-240 content will increase the difficulties of weapon fabrication; high purity Pu-239 is a more attractive weapons material than dirty plutonium. According to James Schlesinger (now chairman of the AEC); "Let me categorically assert that under these circumstances [Pu-240 contents up to 30%]the weapons design and gesting problems are awesome, especially for a nation with a limited technological base."[39]

Radioactivity - Predetonation

Aside from the spontaneous fission of Pu-240, the isotopes of plutonium are also significantly radioactive, as shown in the following Table.

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[38]See, for example, IAEA, <u>INFCIRC</u> 66.

[39]James Schlesinger, "Nuclear Spread: The Setting of the Problem," RAND P-3557.

Table 5. The Radioactive Decay of Plutonium Isotopes.[40]

Isotope	Type Decay (average energy in MeV)	Half-Life (years)	Disintegration Rate (curies/gram)
Plutonium			
-238	α 5.50	86	16.5
-239	α 5.15	24,360	.07
-240	α 5.16	6,760	.20
-241*	β .02	13	110
-242	α 4.88	3.79×10^5	3×10^{-3}
(Pu-241 $\xrightarrow{\beta}$ Am-241)			
Americium			
-241	α 5.48	458	3.2

*α - decay branch, .002%, 4.90 MeV.

The presence of the higher plutonium isotopes could have three types of adverse impacts on the development of an atomic weapon: first, radioactive emissions can also cause predetonation problems; second, substantial amounts of radioactivity would complicate handling of the fissionable material; and thirdly, the emission of highly penetrating radiation would increase the difficulty of concealing weapons or material, or transporting them clandestinely.

Predetonation can be initiated by alpha particles if there are impurities present in the assembly which emit neutrons upon alpha bombardment. The contribution of the plutonium isotopes to this problem may be viewed as follows: As shown in the Table, the rate of alpha particle emission

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[40] Adapted from Table of Isotopes, Sixth Edition, by Lederer, Hollander, and Perlman. 1 curie = 3×10^{10} disintegrations/second.

from Pu-239 is about .07 curies/gram. The comparable rate for Pu-240 is .20 curies/gram. Thus the requisite level of purity in a plutonium mass of one-fourth Pu-240 must be about twice what it could be in a 100% Pu-239 assembly. Calculation of the contribution of Pu-241 is more complicated. Pu-241 is not an alpha-emitter, but it beta-decays with a relatively short half-life to Am-241 which is. Am-241 has a half-life of 458 years; it is about 12 times as active as Pu-240, and 50 times as active per gram as Pu-239. Upon release from a reactor, the plutonium will contain some Am-241 and some Pu-241, the relative concentrations dependent on the fuel exposure time in the reactor. After discharge from the reactor, the Pu-241 will decay into Am-241 at the rate of 110 curies/gram; in just over thirteen years, half the original Pu-241 will have decayed to Am-241. So long as the Am-241 is removed from the material by chemical means, it of course plays no role in the predetonation problem. Once the plutonium is assembled into a weapon, however, it may not be convenient to remove continually the constantly produced Am-241. In this case, the alpha background due to the Am-241 will grow with time. For typical reactor burn-up times, the Pu-241 content at discharge could be as high as or higher than 12% of the contained plutonium, with the Pu-240 concentration 30%. With these concentrations as benchmarks, the Am-241 concentration after one year would be about 5% of the Pu-241 or 0.6% of the total contained plutonium. In such instance, the alpha contributions of the Pu-239, Pu-240, and Am-241 would be in the ratio 1.5 to 3.6 to 1. The Pu-240 would provide the largest number of alpha particles, Pu-239 the next largest, and Am-241 the least. One year later, however, were the Am-241 not separated its alpha contribution would have doubled.[41]

On balance, it would appear that the presence of Pu-240 and Pu-241 will cause some increase in purification efforts, but not a prohibitive increase.

Radioactivity - Hazard

All the isotopes of plutonium are highly toxic. The maximum permissible body burden for Pu-239 is 0.04 μc, and the maximum permissible concentration in air is 2×10^{-12} $\mu c/cm^3$.[42] Thus regardless of the isotopic composition, essentially complete physical containment of plutonium is necessary in any processing or fabrication facility. Any plutonium work must be performed in "glove boxes" through remote handling techniques. Such boxes may typically be constructed of steel, with 1 cm thick plastic viewing panels.[43] Primary physical containment of the plutonium is thereby provided whatever the isotopic composition; there still remains a potential radiation hazard which as discussed below will depend somewhat on the isotope concentrations.

Four types of radiation are emitted from the plutonium isotopes: alpha-rays, beta-rays, gamma-rays, and neutrons. The first may be disregarded as a significant radiation hazard. The range of an alpha particle,

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[41] Pu-241 will also emit alpha-rays directly, but with a half-life of 4×10^5 years. Such direct emission can thus safely be ignored in comparison with Pu-240 or Pu-239 alpha-radiation; it can also be ignored in comparison to Am-241 radiation if Am-241 is present in the Pu-241 in concentrations greater than (say) 1/100.

[42] R. L. Gulley, "Plutonium Handling," in CONF-660308, 149.

[43] Ibid., 150.

which is relatively heavy and charged, is very small indeed. Most alpha particles emitted by the radioactive decay of the isotopes here at issue range between 4-6 MeV. At these energies, they could penetrate 1/200 centimeter in water (or tissue), much less in heavier material; they could be completely stopped by a piece of paper or an outer layer of dead skin. Furthermore, the vast majority of the particles will be stopped within the plutonium mass itself where they originate. Finally, from the data presented earlier, it may be noted that the higher isotopes of plutonium given their usual concentrations are not significantly greater alpha-radiation contributors than Pu-239.[44]

Pu-241 is the only beta-emitter among the plutonium isotopes. It has a half-life of 13 years with the maximum beta energy approximately 20 kev. This is a relatively low energy electron; such radiation can be easily stopped, for example by the glove box; it is difficult to see any serious problem arising from this radiation.[45]

As indicated above the two initial sources of neutrons will be the spontaneous fission of Pu-240 and the interaction of alpha particles with light metal impurities. In addition, these neutrons could cause a rapidly decaying chain of fissions releasing a few more neutrons. The neutron yield due to the spontaneous fission is very low:

Pu-238	3.4×10^3 n/g-sec
Pu-240	1.0×10^3
Pu-242	1.7×10^3

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[44] Harte and Socolow, Ch. 18. Gregory Choppin, Nuclei and Radioactivity, 42-44.

[45] Harte and Socolow, Ch. 18. Choppin, Nuclei and Radioactivity, 44-46.

An activity of 10^3 n/g-sec corresponds to a surface dose rate of approximately .003 rem/hr/g.[46] This may be compared to occupational exposure limits typically set at 5 rem/yr for the whole body. Neutron shielding would thus be required for any prolonged exposure to plutonium containing gram concentrations of Pu-238, Pu-240, or Pu-242. Such shielding could be provided by the glove box, if it is specifically designed for that purpose. Were the plutonium in a compound with low atomic weight material, the neutron radiation (due to alpha, neutron reactions) would be (slightly) greater. The emission rate from $Pu^{240}F_4$ for example is 1.6×10^4 n/g-sec.[47]

Gamma Radiation, Neutrons, and Signatures

Oftentimes upon alpha decay, gamma radiation will also be emitted.[48] This radiation is highly penetrating and presents a radiation hazard. In addition, since the energies of these rays are characteristic of particular decay modes, their observation in general would permit identification of the radioactive source. In this sense each of the plutonium isotopes has an identifiable and unique gamma ray signature.

Although gamma radiation is more penetrating than other types, the energies of the plutonium gammas are relatively low. The most energetic

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[46]Gulley, "Plutonium Handling," 156.

[47]Ibid., 151, 157.

[48]Sometimes, the alpha decay leaves the daughter nucleus in an excited state; that is, in a state not at its lowest or ground-state energy. The daughter nucleus in these instances de-excite almost immediately by emission of gamma rays. The radioactive decay of any specific nucleus will be to the ground or to any of several possible excited states according to a definite random probability distribution.

gamma associated with Pu-239 decay is 770 kev but this occurs with a frequency of only 2 x 10^{-5}%; the most probable gamma emission is 52 kev which occurs 0.02% of the time. Pu-240 decays with a 650 kev gamma, 2 x 10^{-5}% of the time. Pu-241 has an alpha decay branch and an associated gamma of 145 kev, 1.6 x 10^{-4}% frequency. Am-241 possesses the most gamma activity with a 60 kev radiation emitted 36% of the time, and higher energy gammas up to 722 kev emitted with frequencies on the order of 10^{-3} to 10^{-4}%.[49]

The ensuing radiation health hazard is significant and partially dependent on the isotopic composition. The surface dose rate from an infinite slab of pure Pu-239, for example, has been calculated as about 1 rad/hr. For equivalent concentrations, Pu-240 produces about six times the gamma radiation of Pu-239. Pu-241, after 60 days of decay into Am-241 produces about double the Pu-240 contribution, and this about doubles again after another 120 days.[50] This radiation will impose somewhat greater shielding requirements than otherwise required, although installation of 0.64 cm thick lead-glass panels to glove box exteriors and lead impregnated gloves are sufficient to reduce the radiation to acceptable safety levels. Complete concealment of this and neutron radiation, however, would require more elaborate shielding.[51]

For the highest energy ray given off by the plutonium isotope decay, about 0.6 cm of lead is required to reduce the intensity by one-half; over 2 cm of lead would be needed to cut the intensity of the gammas to one-tenth the original intensity. However, for the lower energy and more

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[49]Table of Isotopes. The percentages refer to the fraction of decays in which the particular gamma is emitted.

[50]Gulley, "Plutonium Handling," 156.

[51]*Ibid.*, 150-152.

prevalent gammas of less than 100 kev, less than 1 mm of lead would be required to halve the gamma intensity.[52]

Radioactive Decay of Uranium Isotopes

Neither U-235, U-238, nor U-234 possess troublesome radioactive properties; as a consequence, there appears no significant issues of the sort discussed earlier associated with the fabrication of U-235 into weapons material. The same cannot be said of U-233, which in general will be found mixed with very small albeit significant quantities of U-232.

[52]Gamma ray intensity is attenuated exponentially in any material: if I_o is the initial intensity (number of photons per area per time), then the intensity I of the radiation after passing through a thickness χ is given by $I = I_o e^{-\mu x}$. The absorption coefficient will depend on the material and the energy of the gamma ray photon. Actually, since the gamma ray beams in question would seldom be mono-energetic, the actual intensity fall-off will in these cases appear more complex.

Table 6 The Radioactive Decay of Uranium Isotopes[53]

Isotope	Decay Mode (Energy in MeV)	Half-Life (years)
U-234	α 4.76	2.47×10^5
U-235	α 4.42	7.1×10^8
U-238	α 4.18	4.51×10^9
U-232	α 5.31	72
U-233	α 4.81	1.62×10^5

U-232 is produced in a thorium reactor by the three processes shown below. In each case, the reaction-chain includes an (n, 2n) reaction that will occur only at high neutron energy. Consequently, the U-232 build-up will be more marked the higher the neutron energy spectrum in the reactor.[54]

Production of U-232[55]

1. Th-232 $\xrightarrow{(n,2n)}$ Th-231 $\xrightarrow{\beta}$ Pa-231 $\xrightarrow{(n,\gamma)}$ Pa-232 $\xrightarrow{\beta}$ U-232

2. Th-232 $\xrightarrow{(n,\gamma)}$ Th-233 $\xrightarrow{\beta}$ Pa-233 $\xrightarrow{(n,2n)}$ Pa-232 $\xrightarrow{\beta}$ U-232

3. Th-232 $\xrightarrow{(n,\gamma)}$ Th-233 $\xrightarrow{\beta}$ Pa-233 $\xrightarrow{\beta}$ U-233
   Pa-233 $\xrightarrow{(n,2n)}$ U-232

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[53]Table of Isotopes

[54]WASH 1097, 108-109.

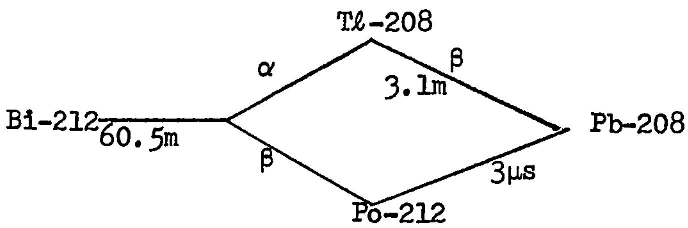
[55]WASH 1097, 108

Both U-233 and U-232 are alpha emitters. Their half-lives are 1.6 x 10^5 years and 74 years respectively. Thus U-232 decays at a rate 2200 times that of U-233, and thus if present in ratios on the order of one part per 1000 compared to U-233, will contribute significantly to neutron background due to alpha reaction with light metal impurities.

The most significant radiation due to U-232 however does not come from the decay of U-232 directly, but rather from the decay of two of its daughter products, Bismuth-212 (Bi-212) and Thallium-208 (Ti-208) which emit highly penetrating gamma radiation. These isotopes are produced in the following decay chain:[56]

$$\text{U-232} \xrightarrow[74\ y]{\alpha} \text{Th-228} \xrightarrow[1.9\ y]{\alpha} \text{Ra-224} \xrightarrow[3.6\ d]{\alpha}$$

$$\text{Rn-220} \xrightarrow[55\ s]{\alpha} \text{Po-216} \xrightarrow[0.16s]{\alpha} \text{Pb-212} \xrightarrow[10.6h]{\beta}$$



Bi-212 emits high-energy gammas (0.4 to 2.1 MeV); Tl-208 emits a gamma of 2.6 MeV. As the Bi-212 is formed the gamma activity of a sample of uranium containing U-232 rises markedly. At typical concentrations of U-232 encountered upon discharge of fuel from thorium reactors, remote handling procedures are necessary. It has even been contemplated that the discharged product would be stored for 10-15 years before any recycling into the reactor to allow decay of Th-228, the first daughter of U-232.[57]

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[56] WASH 1097, 108-109.

[57] *Ibid.*, 96-97. Freeman Dyson, private communication. The U-232 fraction in U-233 is likely to be between 10^{-3} and 10^{-2}.

More interesting still, the gamma radiation provides a signature difficult to conceal. This may be seen by the following:

Table 7. Absorber Thickness Required to Reduce Intensity of 2.1 MeV Gamma -rays to One-half the Original Intensity[58]

Lead	1.5 cm
Iron	2.5
Concrete	6.0
Water	15.0

Even with use of lead, a shielding thickness of over 10 cm would be required to reduce the intensity of 2.1 MeV gamma-rays to less than 1/100 of its initial value.

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[58]Choppin, Nuclei and Radioactivity, 47. See also fn 53, this section.

4. Size and Yield of Nuclear Weapons

The United States can evidently produce fission weapons as small as six inches in diameter and as light as 50 pounds. For example, one weapon design of six inches in diameter and 34 inches in length weighs 120 pounds; another design of 11 inches in diameter and 16 inches length weighs slightly over 50 pounds. These are fission weapons. Thermonuclear weapons can be made as small as 11 inches or so in diameter and 150 pounds in weight.[59] The yields of these weapons have not been published. If we assume roughly that the fissionable material comprises one quarter the weight of the lighter (fission) weapon and that the weapon efficiency is 20 per cent, the expected yield would be on the order of 20 KT. The design and such yield efficiency doubtless reflect considerable sophistication, which less advanced states or terrorist groups could not hope to match. However, given roughly the same size weapon but an efficiency of say 5 per cent, the weapon yield would still be a substantial 5 KT.[60] Still more conservatively, we might consider weapons say four times the size of those indicated with an efficiency also of 5 per cent. Such a weapon might weigh from 200 to 500 pounds and produce an explosion in the ten KT range. Weapons of even

[59]These data are based on a letter from the Director of the USAEC Division of Classification to Dr. Michael May, Director of the Lawrence Radiation Laboratories, November 16, 1971, and Dr. May's subsequent transmittal of the letter to the author. The information is of course unclassified. The two fission designs described probably refer to gun-type (uranium) and implosion (plutonium) weapons respectively, although this is not indicated in the letter. Nor is there any data on the yields of the weapons described. Some information on the size of nuclear weapons was also given in an unclassified description of fission weapons supplied to the FBI in 1955. According to this description, gun-barrel devices will probably be made of steel, with inner and outer bore diameters ranging from 2 to 10 inches and 5 to 12 inches respectively; the length of the entire device need not exceed about $2\frac{1}{2}$ feet.

[60]In private verbal communications, physicists with experience in weapons design have stated that the achievement of 5% efficiency is relatively easy, 20% quite difficult.

this size could be transported clandestinely; they certainly could be delivered easily by almost any type of vehicle.[61]

5. Delivery Vehicle Constraints

Five types of delivery capabilities span the major possibilities:

(1) A capability to deliver clandestinely and detonate nuclear weapons in situ within a country, such as might be sought by terrorist, revolutionary, or counter-revolutionary groups.

(2) A force sufficient to deliver one to a few weapons against the cities of an unsophisticated, partly underdeveloped national adversary, such as might be sought by certain African nations.

(3) A force sufficient to deliver a few to several nuclear weapons against the cities or massed forces of a moderately sophisticated opponent. India would probably seek a force at the high end of this spectrum, Israel perhaps at the low end.

(4) A small but sophisticated capability to deliver nuclear weapons against military targets -- such as might be desired by Sweden or Switzerland.

(5) A force sufficient to match the forces of the current nuclear powers, in some respects at least: for example, a for ce that could survive a U.S. or Soviet first strike and breach the great power defenses in a retaliatory strike, or simply a force that could match the British and French nuclear forces in prestige. Such a capability would probably be sought by West Germany and Japan, but no other nation, should they strive for nuclear weapons. It would require hardened and dispersed missiles and/or sophisticated bombers.

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[61] See below.

The size of possible nuclear weapons clearly permits clandestine transportation, even by individuals not in vehicles. At least three factors will complicate the task of the concealer, however. First, plutonium and uranium are extraordinarily dense, weighing over half again as much as lead of the same volume.[62] Objects extremely heavy for their size ought thus to excite suspicion. Secondly, a gun-type device (perhaps the easier to produce) does have a characteristic shape and considerable length; it could be concealed but with difficulty. Finally, and most importantly, weapons, especially those fabricated from plutonium or U-233 will be significantly radioactive. If they are to be concealed from a vigorous detection effort (say at airports or docks) extra shielding would be required, the amount depending on the scope of the detection effort assumed. Referring to section 3 this chapter, we note that about 0.6 cm of lead would be required to reduce the high energy gamma-ray intensity from plutonium by one-half; about 4 cm of lead would thus be needed to reduce the intensity one-hundred-fold. Such shielding about a sphere of 5 inches (12.7 cm) in diameter (corresponding to 50 pounds of plutonium) would weigh almost 80 pounds; this would constitute a substantial fraction of the total weight of the weapon, but would not necessarily make its delivery unmanageable.[63]

It seems clear then that for forces of types (1) or (2), delivery will not prove a serious obstacle. Conventional airplanes, small boats, small missiles, trucks,automobiles could all be used. The great variety

[62] Uranium weighs 18.7 g/cc (1167 lbs/cf); plutonium weighs approximately the same. Lead, by comparison, 11 g/cc (687 lbs/cf).

[63] See the unclassified description of fission weapons supplied to the FBI in 1955 (fn. 59).

of ways to deliver a fairly crude nuclear weapon against an undefended urban population assure that the security of any nation will become irreversibly precarious once groups willing to use nuclear weapons against it obtain the nuclear warheads. Even the most powerful nations would be vulnerable to unsophisticated delivery, especially by internal terrorist groups or anonymous international adversaries.[64]

For forces of type (3), somewhat more elaborate delivery capabilities would be required. Of the countries that fall into this category, India would face the severest challenge if it sought a force that could survive a Chinese first strike and attack Chinese cities over a thousand miles distant. The United Nations Report to the Secretary-General on Nuclear Weapons estimated the costs of a force that might minimally meet such requirements.[65]

-- purchase of thirty to fifty Canberra, B-57, or similar bombers

   $180 million acquisition cost, $25 million annual operating cost

-- development of fifty 1500 n. mi range soft-sited missiles of modest accuracy and reliability

   $850 million acquisition cost, $10 million annual operating cost

The missile component of such a program might take an industrialized country eight to ten years. It also seems highly probable that the costs of such a missile development program to India, or other developing nations, would be higher even than indicated by the UN study based as this

[64]See Chapter 4, section 3.

[65]United Nations, Effects of the Possible Use of Nuclear Weapons, Annex 4.

was on the capabilities of industrialized nations with good experience in aircraft and space technology. The costs, even so escalated, would not be prohibitive, however. A high quality force comprising 100 IRBMS, thermonuclear warheads, and a couple of missile-launching submarines which might cost 5-6 billion dollars over a ten year period (somewhat over one-half the cost of the French nuclear program), would imply an annual cost of 500 million dollars per year - or roughly one-quarter the current Indian defense budget.[66]

For other countries seeking capabilities of type (3), the problems appear still more tractable. The phantom jets would provide Israel with a very excellent potential means of nuclear delivery, and Israel is in addition already developing a short-range missile capacity probably capable of delivering nuclear warheads.[67] The Arab nations could not match the Israeli sophistication, but would confront a very small and vulnerable nation. By the time they could develop nuclear weapons, the Arab states would certainly pose a reasonably strong threat of being able to deliver a few crude weapons against the few major Israeli cities, directly or clandestinely. Most of the other states that may eventually be placed in category (3) also already possess substantial delivery capabilities. For

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[66]See Dilip Mukerjee, "Itching for the Bomb" in Far Eastern Economic Review, July 9, 1970; A.B. Shah, ed. India's Defense and Foreign Policies, esp. articles by M.R. Masani, M.R. Dandavate, and Roj Krishna. It should be noted that these authors do not entirely agree on either the probable costs of a nuclear program or on the impact of such a program on the Indian economy. The author is also indebted to the analysis of Chandra Varma in a seminar paper "India and the Bomb," October 18, 1971 (unpublished).

[67]The Phantom Jet (F-4M produced by McDonnell-Douglas in the United States) can carry alternatige loads of up to 16,000 lbs. of nuclear or conventional bombs. It has a combat radius of approximately 1000 miles. (Jane's All World Aircraft, 394). The surface-to-surface missile (the so-called Jericho) is apparently now under manufacture in Israel; it was developed jointly by Israel and France. The Jericho has a reported range of 300 miles or more and payload capability of 1000 to 1500 lbs. The cost of the missile has been estimated at roughly one million dollars, which may be compared to the five million dollar cost of a Phantom Jet. New York Times, October 5, 1971, 1).

example, several Latin American countries (including Bolivia, Brazil, Chile, Peru, Uraguay, and Venezuela) now use the American-built B-25J light bomber capable of delivering 4000 lb. payloads at ranges of over 1000 miles. Peru also possesses the relatively advanced Mirage 5, French-built fighter-bomber, and Argentina, the Italian-built Aermacchi fighter-bomber. A few Latin American air forces also use the advanced American-built F-470 Thunderbolt which has a range of over 1000 miles. Elsewhere, the Soviet-built IL-28 Ilyushia tactical bomber, with a capability to deliver 4500 lbs. of bombs at ranges of 1500 miles, is in service in Poland, Czechoslavakia, Romania, Hungary, East Germany, Indonesia, Taiwan, and Egypt. The sophisticated American-built fighter-bombers, the F-100D Super Sabre and F-84F Thunderstreak are used by several NATO air forces, notably Denmark, Turkey, Belgium, and Germany. Mirage fighter-bombers are in use in South Africa, Pakistan, Lebanon, and Iraq.[68]

Delivery systems adequate to support programs of type (2), short range high performance aircraft, short-range high accuracy missile systems, nuclear mines, etc. seem well within the capabilities of the countries which might reasonably seek them; and to some extent they are already available: for example, Sweden possesses advanced aircraft capable of nuclear delivery in the J35F Draken and 105, both produced by Saab. The latter has a ragne of 1000 miles and bomb payload of over 1000 lbs. Sweden has also deployed the RB08A cruise missile with payload capacity of several hundred pounds.[69]

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[68] Janes, Military Aircraft, 311, 314-322. Institute for Strategic Studies, The Military Balance 1969-1970.

[69] Jane's, Military Aircraft, 321-322.

Type (1) forces will demand moderately large and sophisticated bomber and missile systems. The UN study estimates the costs of some plausible elements of such a force as follows:

Table Costs of Delivery Vehicles[70]

	Acquisition Cost ($ millions)	Annual Operating Cost ($ millions)
50 French Mirage IV bombers	940	100
300 British V-bombers	1800	120
50 Minuteman I, in hard emplacements	1250	5
25 French ballistic missiles in hard emplacements	700	?
210 US FB-111 with air-to-surface missiles	2200	340
3 French missile-launching nuclear submarines each with 16 missiles of 1500 n mi range	1000	20

West Germany and Japan have sufficient technology and industry to implement programs of such scope. They also already have a significant capacity to deliver nuclear weapons. German NATO forces, for instance, employ the Pershing 1A surface-to-surface nuclear-capable missile as well as the previously mentioned F-84F Thunderstreak fighter-bomber which has a designed nuclear delivery capability.[71]

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[70] United Nations, Effects of the Possible Uses of Nuclear Weapons, Annex 4.

[71] Jane's Military Aircraft, 36, 320.

Aside from these explicit weapons systems, scientific and space rockets in general provide an immediate missile technology-base to countries which possess them: these include Japan which has developed a 4-stage rocket capable of placing 220 lbs. in terrestrial orbit; Germany, which has developed highly sophisticated upper stages for the ELDO (European Launcher Development Organization) rocket; the other states of the ELDO group, Italy, Belgium, the Netherlands, Australia, and France; and Italy, Sweden, Argentina, Australia, Brazil, and Canada, which have produced research sounding rockets capable of sending small payloads (on the order of 100 lbs.) to altitudes of roughly 100 miles.[72]

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[72] Jane's All the Worlds Aircraft 1970-71, 642-655. The weapon capabilities of these rockets (and others) may be crudely estimated from the following:

Roughly speaking, the relationship between deliverable payload and range for distances over 500 n. mi. is given by the two sets of equations:

$$(1)\quad V_{ex} \ln \frac{M_o}{M_p} = u$$

$$\begin{aligned}(2)\quad & u \text{ (orbit)} = 26{,}000 \text{ fps}\\ & \mu \text{ (5500 n. mi)} = 23{,}700 \text{ fps}\\ & \mu \text{ (2000 n. mi)} = 16{,}000 \text{ fps}\\ & \mu \text{ (< 500 n. mi)} = \text{flat earth approximation}\end{aligned}$$

where V_{ex} is the rocket exhaust velocity, M_o is the initial mass of the rocket including fuel, M_p is the final mass or payload, and μ is the velocity required for the given ranges noted.

Equation (1) ignores gravitational and air resistance effects, but gives a relatively accurate figure for the mass ratio, M_o/M_p, especially for purposes of comparison. It may be derived from a simple integration of the differentialform for the conservation of momentum of a rocket: $M\,du + V_e\,dM = 0$, where M = mass of the rocket. Equation (2) may be derived from basic dynamics as well, though the equations for the intermediate ranges are somewhat more complicated. The required velocity for near earth orbit follows from the familiar laws of circular motion:

$\frac{Mu^2}{R} = Mg$; with $R \approx 4000$ miles and $g = 32$ feet per second, this gives $u = 26000$ fps.

(The author is indebted to Harold Hornby of NASA for the parts of the above and following information which are not evident from basic physics; and for the assurance that the basic physics provide reasonable approximations for the purposes of this section.)

(continued on next page)

Footnote 72 continued:

For a given class of rockets, V_{ex} varies little:

V_{ex} for different classes of rockets	
cryogenic (liquid oxygen)	14,000 fps
conventional liquid rockets (kerosene)	10,000 fps
solid fuel rockets	8,000 fps

These equations imply most importantly the following (for conventional liquid rockets):

(1) If a nation can launch a payload Mp into earth orbit, it can deliver a payload 1.25 times as great at intercontinental ranges.

(2) It could deliver 4 times the payload at 2000 n. mi. than could be delivered to intercontinental ranges. (In practice, this means alternatively that the saem payload could be delivered by one less stage).

(3) For short ranges ($<$ 500 n. mi), the maximum lateral range of a rocket would be approximately twice its maximum altitude. This (plus the payload trade-offs of equation (1)) permits a quick estimate of the potential weapon carrying capabilities of high altitude sounding rockets.

6. Summary - Weapons Foundation Provided by Civilian Nuclear Power

The technology, scientists, and technicians required to produce nuclear warheads are widely diffused; and for the most part nations wishing to acquire nuclear weapons already possess or could obtain the necessary delivery systems appropriate to their purposes. Acquisition of fissionable material thus provides the salient obstacle to the production of nuclear weapons. Fissionable material is also precisely what is used and accumulated in quantity in any civilian nuclear power program. Roughly speaking, this nuclear material may be diverted to weapons purposes in one of three ways: (1) the gradual clandestine diversion of nuclear material over a relatively long period; (2) the sudden appropriation of reactors and associated facilities for subsequent production of weapons material; and (3) the appropriation of a plutonium (or enriched uranium) stockpile orignally accumulated through the civilian program.

Any of these approaches would save considerable resources and time, compared to that which must be expended in a de novo effort. The first method would of course be the slowest with the actual rate of accumulation depending on the size of the nuclear program and the amount of diversion. If we assume a 5 per cent diversion to be the outside maximum possible to conceal, (See Chapter 3), the maximum rate of accumulation would be roughly 10 kgm plutonium per year per 1000 MW_e reactor, about sufficient for one bomb. This is not very much and such clandestine accumulation probably will not appear attractive to most countries, particulary in view of the substantial weapon requirements of most countries with large civilian programs and the small civlian programs of most countries with small weapon requirements (See Chapter 4).

The appropriation of an already operating reactor and support system would provide much quicker access to large stocks of fissionable material, on the order of 200 kgm of separated plutonium within one to two years of the reactor take-over. Appropriation of a plutonium stock-pile would of course constitute the most direct way for a nation to secure plutonium, and as indicated in Chapter 3 is not even clearly prohibited legally.[73]

[73]Chapter 3, section 4.

CHAPTER 3. Safeguards

1. Introduction

The formal and legal procedures applied by national governments and international organizations to ensure that nuclear material is not diverted from civil use to weapon's or other illicit purposes are termed safeguards. Their objective, more precisely, is to detect removal of significant quantities of nuclear material from civil programs for the manufacture of explosive devices or for purposes unknown, and to deter such removal by the risk of early detection and sanction.[1] The purpose of this section will be to assess how successfully current and projected safeguard procedures are likely to meet this objective.

Safeguards are now administered on four distincet levels:

(1) by national governments on nuclear facilities and material within their own borders. (domestic safeguards)

(2) by national governments on nuclear facilities and material in another country to whom they have provided nuclear assistance. (bilateral safeguards)

(3) by regional organizations on nuclear facilities and material in the member states. The only significant such safeguards now in effect are those applied by Euratom of the European Economic Community. (Euratom safeguards)

(4) by the International Atomic Energy Agency (IAEA) on the nuclear facilities and material in states with whom the IAEA has concluded safeguard agreements. (IAEA safeguards)

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[1]Paraphrased from IAEA GOV/COM.22/164, Model Agreement, paragraph 27.

The last three categories of safeguards, with objective to prevent the illicit acquisition of nuclear material by states, may be termed "international safeguards."

Diversion of nuclear material from civil programs under safeguards may occur in one of three essential ways:

--within a given country, diversion by individuals or small groups either for illicit domestic use or for offer to a foreign agent.

--evasion of international safeguards through clandestine diversion of nuclear material by a country.

--straightforward abrogation by a country of an international safeguards agreement.

Of these, domestic safeguards attempt to guard against the first, and international safeguards against the latter two. But domestic and international safeguards are by no means unrelated. Without effective domestic safeguards, a nation could plausibly claim that the first type of evasion above had occurred when in reality it had kept the nuclear material for itself.[2] More directly, international safeguard procedures are substantially simpler if they supplement rather than completely supplant domestic controls and accounts.

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[2]F. Morgan, Report to the Director General of the IAEA (Topic 1, Part 1), 13.

2. Types of Safeguards

The four levels of safeguards--domestic, bilateral, regional (Euratom), and IAEA--have different legal foundations, use somewhat different safeguard procedures, and lead to different degrees of effectiveness. For reasons to be indicated, however, bilateral and Euratom safeguards are diminishing in importance, and the significance of safeguards to the control of nuclear power will depend increasingly on the effectiveness and durability of domestic safeguards and of the IAEA safeguards system.

Domestic Safeguards

All states with nuclear power programs have imposed special domestic legislation to control nuclear material. Although the legal framework of the ensuing safeguard systems differs slightly from country to country, the domestic safeguard program of the United States may be taken as fairly representative of the systems adopted by at least the major Western nuclear power states.[3] Under American legislation, the ownership of facilities and material is divided between the Atomic Energy Commission (AEC) and private industry or persons. The legislation provides that the AEC shall be the sole owner of all significant production facilities, although it is also empowered under license conditions described below to enter into contracts with private persons to use and operate the facilities. Special nuclear material (U-233, U-235, Plutonium) may be owned either by the AEC or privately. For a short period, until December 31, 1970, the AEC was permitted to distribute special nuclear

[3] European Nuclear Energy Agency, OECD, Nuclear Legislation, passim.

material by way of sale, lease, or grant, or production or enrichment services to any licensee for commercial or scientific ends. After that date, the AEC has been unable to supply special nuclear material on lease for use in licensed reactors. After June 30, 1973, reactor licensees who hold special nuclear material on lease must either return it to the AEC or purchase it outright.[4] Regardless of the ownership, all persons or contractors constructing or operating nuclear facilities, possessing or using nuclear material, or importing or exporting nuclear material require prior licenses from the AEC.[5] These licenses can impose any safeguard conditions the AEC believes appropriate. In general, the AEC requires specified accounting procedures, measurements and statistical controls, and certain minimum physical security standards.

Bilateral Safeguards

Several countries have agreements with countries to whom they have transferred nuclear material or otherwise given nuclear assistance which provide for the application of safeguards. In these cases, the safeguards apply specifically to the material supplied to the recipient nation, not to the parts of the recipients nuclear fuel cycle which were established independently of such foreign assistance. The stringency of the safeguard requirement imposed by the bilateral agreements differs somewhat from supplier to supplier. Under U.S. bilateral agreements pursuant to the supply by the U.S. of nuclear material and assistance,

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[4] Nuclear Legislation, 225-227. Also Ralph Lumb, Report to the Atomic Energy Commission, March 1967, 83 ff.

[5] Lumb, 83 ff.

the U.S. has maintained the right to review design of facilities and accounting procedures, to demand accountability and operating records of the cooperating government, and to undertake independent inspections and measurements when it deems it appropriate. The cooperating government in addition undertakes to facilitate the application of safeguards and to guarantee that the nuclear material and assistance provided will not be used for weapons or other military purposes.[6] Other supplier countries, such as Canada or France, have on occasion in the past evidently imposed less stringent safeguard conditions.[7]

Several countries have supplied nuclear material or assistance to other states under bilateral agreements. These include, for example, the United Kingdom, Belgium, Sweden, and South Africa in addition to the aforementioned Canada, France, and United States.[8] The United States has entered by far the most bilateral agreements, many of them still in force. These latter include Australia, Brazil, Benmark, Greece, Iran, Israel, Japan, Korea, the Philippines, South Africa, Spain, and Thailand.[9] However, the safeguard functions of these bilaterals have for the most part been transferred to the IAEA safeguards system under trilateral agreements among the IAEA, the United States, and the recipient foreign state.[10] By the middle of 1971, there were only four bilateral safeguard arrangements that had not been transferred

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[6]Wayland Young, Existing Mechanisms of Arms Control, 20.

[7]Canada, for example, has no inspection privileges in connection with the Indian CANDU reactor, although India has undertaken not to use the reactor for non-peaceful purposes.

[8]Nuclear Legislation, passim.

[9]Ibid., 228.

[10]Ibid., 227-228. Including all those listed above.

to the IAEA and these will apparently be transferred eventually.[11] A similar shift to the IAEA has been made by most other supplier countries, and under the Non-Proliferation Treaty (NPT) provisions, signatories will be obliged to demand or accept IAEA safeguards on nuclear material transferred to non-nuclear countries.

Because of this shift of bilateral safeguards to the IAEA, it is scarcely necessary to evaluate the effectiveness of bilaterals. On balance, however, it is probably safe to conclude that the shift away from bilaterals will increase the effectiveness of international safeguards. For while certain features of bilaterals improve on the IAEA safeguards system (in ways mentioned later), reliance on bilaterals rather than a single international system would inevitably encourage supplier states to compete for markets and political favor through the gradual removal of safeguard restrictions on their transfers of material.[12]

Euratom Safeguards

The Treaty signed in Rome on March 25, 1957 (by France, the Federal Republic of Germany, Italy, Belgium, Luxembourg, and the Netherlands)

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[11]AEC, Office of Safeguards and Material Management, private communication, August 1971. The four are with Italy, Norway, Switzerland, and Sweden. The U.S. also has a mutual defense agreement relating to nuclear matters with France. Thirty-five bilaterals have been transferred to trilaterals.

[12]Bilateral safeguards have in principle one singular advantage over IAEA safeguards: they are the quid pro quo result of assistance from the state imposing the safeguards. As a consequence, states cannot simply withdraw unilaterally from the safeguard obligations, and even after withdrawal from the NPT a state's bilateral obligations would remain. Similarly, sanctions for bilateral safeguard violations typically may be more easily and effectively applied: only one state need act and it could do so by withdrawing equipment and material supplied under the bilateral agreement.

establishing the European Atomic Energy Community (Euratom) contained various security provisions. Notably, the Treaty required that the Euratom Commission satisfy itself that in the territories of the member states (i) nuclear material is not diverted from its intended use as declared by the users and (ii) provision relating to special obligations assumed by the Community in an agreement with an outside party be observed.[13] Within this specified scope, the safeguards apply to all nuclear facilities in the member states. That is, whereas IAEA or bilateral safeguards (apart from NPT provisions) now apply only to facilities and material covered by explicit agreement between the involved parties, Euratom safeguards apply to all nuclear activities in the member states declared as peaceful and in the territories of the states. The Treaty also permits Euratom to deal directly with any pertinent person or group involved with the nuclear activities; Euratom need not deal only with member governments. The scope is, however, severely limited, as indicated, to peaceful uses. Safeguards cannot be extended to material intended to meet defense requirements.[14] Apart from safeguards on material and facilities indigenous to Euratom territory, Euratom undertakes to safeguard material transferred to it by external states, notably the United States under formal Agreements for Cooperation.[15] Under the terms of the cooperation agreements, material

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[13] Nuclear Legislation, 239.

[14] Lumb, 92 ff., 96 ff.

[15] Ibid., 25. Nuclear Legislation, 231. The Agreements came into force on February 18, 1959 and July 25, 1960; termination dates are December 21, 1985 and December 21, 1995.

supplied by the United States, unlike indigenous material and facilities, cannot be diverted to weapons. However, unlike the United States, the Euratom system does not require the application of safeguards to nuclear material exported by member countries to non-members, thus permitting member countries upon receipt of U.S. material to export equivalent quantities free of safeguards.[16]

Nonetheless, apart from the above mentioned significant limitations, Euratom safeguards are reasonably compatible with those of the IAEA. Indeed, under the U.S.-Euratom Agreements for Cooperation, the Community is obliged to establish such a system. It is also obliged to satisfy the United States that it is adequately safeguarding nuclear material supplied to it by the United States, which in effect imposes a safeguard system similar to that of IAEA's.[17] Despite this similarity, the desire of the Euratom member states to use the Euratom safeguard system as an alternative to IAEA inspection considerably complicated the NPT negotiations.[18] However, as discussed in the next section, this matter has now apparently been resolved. In effect, the IAEA, while maintaining the right to independent verification procedures, will use and rely upon Euratom inspections and accounts to the extent possible.

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[16] Lumb, 25.

[17] Ibid., 24.

[18] See, for example, Elizabeth Young, "The Control of Proliferation," Adelphi Papers, 56; Mason Willrich, Non-Proliferation Treaty, 108-116.

IAEA Safeguards

The International Atomic Energy Agency (IAEA), established by treaty in 1957 (entry into force, July 29, 1957) is an autonomous body linked to the United Nations and a number of its Specialized Agencies by relationship agreements. It has 98 member states, a Board of Governors consisting of 25 member states, and a large staff located principally in Vienna.[19] Among other tasks, the Agency has been authorized by its Statute to establish and administer a system of safeguards to help ensure that nuclear materials, facilities, and equipment intended for peaceful

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[19] Descriptions of the IAEA may be found in several places, among them Allan McKnight, The Safeguards System of the International Atomic Energy Agency; and John Hall, "The International Atomic Energy Agency," in Young, Existing Methods of Arms Control. The Board of Governors, suffice it to say now, has a partly revolving membership but with the major civilian nuclear states always represented. In the following, several IAEA documents are referred to, and three formal such documents especially must be distinguished:

(1) The Statute. (Approved 23 October 1956 by the Conference on the Statute of the International Atomic Energy Agency. Opened for signature on 26 October 1956 and into force on 29 July 1957. Amended 31 January 1963.) The Statute establishes the Agency, sets out its formal structure, and provides it various and broad functions.

(2) The Safeguards Document. ("The Agency's Safeguards System, 1965, as provisionally extended in 1966 and 1968, " INFCIRC/66/Rev. 2, 16 September 1968.) Pursuant to the Statute, the Safeguards Document sets forth general guidelines as to the circumstances requiring safeguards and safeguards procedures. The Document provides the essential basis for safeguards agreements between the IAEA and individual states, but in no way preempts the necessity for the conclusion of such specific agreements.

(3) The Model Agreement. ("Agreements between States and the Agency Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," IAEA Document, INFCIRC/153, May 1971) This document sets forth the basic guidelines for state-agency agreements pursuant to Article III of the NPT.

use are not diverted to military purposes. As evident from the preceding discussion of bilateral and Euratom safeguards, this safeguard system has become by far the most important element of international safeguards. Its significance has been considerably heightened by the Treaty for the Denuclearization of Latin American and the Non-Proliferation Treaty (NPT), both of which designated the IAEA to execute their control provisions.[20]

The nuclear activities in any state cannot become subject to Agency safeguards until there exists a legal agreement between the IAEA and that state. Such agreement has in the past generally been concluded to ensure that direct IAEA assistance to a state not be subverted, or as part of a trilateral agreement among the IAEA, a supplier, and a recipient state. In these cases, the safeguards apply only to the specific material or facilities supplied to the state. Agreement can also derive from obligations undertaken by states in connection with an international treaty to submit all its nuclear activities to IAEA safeguards. Such, for example, is the case with the Latin American Denuclearization Treaty and the NPT. In these latter instances it is important to note that the state's entire nuclear fuel cycle becomes subject to safeguards upon conclusion of the agreement between the state and the IAEA.

The NPT is likely to be the decisive determinant of how widespread safeguards become during the next several years. Article III of the Treaty states in part:

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[20]Latin American Denuclearization: U.N. Document A/C.1/946 (1967); Documents on Disarmament, 1967, 69-83. NPT: UN A/C.1/L.421/Rev.2/Add.1; Documents on Disarmament, 1968, 461-465.

> Each non-nuclear-weapon state party to the Treaty undertakes to accept safeguards, as set forth in an agreement to be negotiated and concluded with the IAEA in accordance with the statute of the IAEA and the Agency's safeguards system, for the exclusive purpose of verification of the fulfillment of its obligations assumed under this treaty, with a view to preventing the diversion of nuclear energy from peaceful uses to nuclear weapons or other explosive devices.

Note that only non-nuclear-weapon states signatory to the treaty are obliged by this article to accept safeguards on all significant peaceful nuclear activities. However, both the United States and the United Kingdom have voluntarily agreed to place all (or most) of their peaceful nuclear activites under the IAEA safeguard system.[21]

At present, approximately one hundred states have signed the NPT and about two-thirds of these have also ratified the Treaty. Among the states who have not even signed are included these important countries: Argentina, Brazil, France, India, Israel, South Africa, and Spain. Several other states have signed but not ratified pending the satisfactory resolution of discussions with the IAEA regarding the implementation of Article III. These include Japan and the Euratom states of Belgium, the Federal Republic of Germany, Italy, Luxembourg, and the Netherlands. The Euratom countries have in particular withheld ratification until some satisfactory relationship between Euratom and IAEA safeguards could be worked out.

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[21]Statement by President Johnson, 2 December 1967; Documents on Disarmament, 1967, 613-615. Statement by British Disarmament Minister Mulley to the House of Commons, 4 December 1967; Documents on Disarmament, 1967, 616. The American statement by President Johnson declared that when IAEA safeguards are applied under the NPT, "the United States will permit the IAEA to apply its safeguards to all nuclear activities in the United States -- excluding only those with direct national security significance."

No state has yet concluded an agreement with the IAEA pursuant to Article III. However, the IAEA staff and Board of Governors have worked out and approved a "Model Agreement" which is to be the pattern for agreements between the IAEA and NPT signatories in accordance with Article III.[22] Since, the Model Agreement has been approved by virtually all major delegations to the IAEA, including the Euratom states; it is expected that IAEA agreement with states which otherwise accept the NPT will be forthcoming at an early date. In particular, the Euratom states appear now to accept the fundamental right of the IAEA to verify compliance with the NPT.

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[22]See footnote 19.

3. The Safeguard Challenge

Whatever the level of safeguards, whether they be international or domestic, the character of the technical problem remains roughly the same. It is also true that although the detailed safeguard procedures must depend somewhat on the specific type nuclear fuel cycle under observation, discussion of safeguard requirements[23] and effectiveness may focus usefully on one typical "model" fuel cycle. Studies by the IAEA have shown that inspection requirements for any type of facility are similar "irrespective of the particular fuel cycle of which the facility formed a part."[24] For example, inspection requirements for fuel fabrication plants do not appreciably depend on whether the fuel is natural uranium metal, uranium oxide, low enriched fuels, or something else, or whether it is in the form of rods, pellets, grains, billets, etc.[25]

The elements of the fuel cycle are as described in Chapter 1. They include the following:

Uranium mines, mills, and conversion plants

Isotope Separation Plants

Fuel Fabrication Plants

Reactors

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[23]Safeguard or inspection "requirements" simply refer to the level of effort required to achieve a specific degree of effectiveness.

[24]P. Frederiksen, et al., Report to the Director-General of the IAEA (Topic 2), para. 14.

[25]Ibid.

Chemical Reprocessing Plants

Plutonium Finishing Plants

Stores of Nuclear Material

Discards of nuclear material due to isotope separation, fabrication, and reprocessing

Transportation of nuclear material

The quantities of nuclear material flowing through the fuel cycle have been indicated in Chapter 1. However, as illustration of the challenge to safeguard systems, some reprise and reworking of the data there presented will be helpful.

For purposes of illustration, consider the flow of material necessary to support a single 600 MW_e reactor, let us say of the AGR-type used in the United Kingdom. Such a reactor requires an inventory of approximately 3,000 elements, each element weighing 50 kgm and composed of uranium oxide enriched to about 2 to 2.5% U-235. The mean life of an element will be from five to eight years, corresponding to burn-ups of roughly 15000 to 25000 MWD/MT.[26] Upon discharge from the reactor, each element will typically contain between 100 to over 300 grams of plutonium.[27]

Under steady-state conditions, this AGR reactor will necessitate the fabrication of 600 elements per year. This involves the annual handling of approximately 30 MT slightly enriched uranium, or less than 18 effective kilograms of U-235. A given gram of uranium would typically be in fabrication from 10 to 40 days, but might be in fuel store or

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[26] Morgan, Report to the Director-General of the IAEA (Topic 1, Part 2), para. D.

[27] Ibid., Table 1, para. D.

transit for as much as one year before placement into the reactor.[28] The fuel movements to and from the reactor would of course also be 600 elements per year, with dwell time of an element in the reactor being about 5 years. The consequent annual reprocessing requirement will be 30 te slightly enriched and irradiated uranium with a plutonium throughput of about 150 kgm per year. After discharge from the reactor, an irradiated element would normally spend about 120 days in a cooling pond. The actual time in preprocessing would be less than five days.[29] The plutonium discharged from the reprocessing plants will, most of it, be sent to stores where it may be kept for several years.

A typical fast reactor (taking the United Kingdom civil fast reactor -- CFR -- as illustration) would require a fissionable material inventory of approximately 3 kgm/MW_e, with about one-third of this inventory outside the reactor: a given subassembly would be in-pile for, say, 400 days, in cooling ponds, 120 days, and 80 days in refabrication. Thus, a 1000 MW_e CFR would require an inventory of 3000 kgm of plutonium and enriched uranium. These would be incorporated in roughly 300 fifty kgm UO_2 - PuO_2 subassemblies, each one containing 10 kgm of fissionable material.

A very rough picture then of the scope of the safeguard task may be formed by simply multiplying these nominal figures for one 600 MW_e thermal reactor and one 1000 MW_e CFR by the number of equivalent such reactors in the power program. Naturally, with the mix of reactor-types,

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[28]<u>Ibid.</u>, Figure 1.

[29]<u>Ibid.</u>, Figure 1.

all on-line at different times, the real picture for a given country will be much more complex. For example, the planned United Kingdom program for thermal reactors (500 MW_e in Magnox-Natural Uranium reactors and 8000 MW_e in AGR on-line by 1980) would give rise to roughly the following plutonium inventories by 1981:

Table 1. Plutonium Inventory Distribution[30]

In Stores and Fabrication	17000 kgm Pu
In Cooling Ponds	1000 kgm Pu
In Reprocessing	100 kgm Pu

The planned CFR program of fifteen 1000 MW_e reactors would give rise eventually to an additional in-pile inventory of 45000 kgm plutonium (and enriched uranium), and a steady-state amount of 22000 kgm plutonium in fabrication at any given moment.[31]

The safeguard task will depend not only on the quantities of nuclear material moving through the fuel cycle but also on the times during which a diversion should be observed. These "critical times" depend on two factors: (i) the time to process the diverted material into a weapon, and (ii) the time after which the source of the diversion of the material would become difficult to trace. Put another way, diversions need not be observed immediately upon the violation, but neither should they be observed only very long after it, the maximum preferred period given by the critical time. Nominal critical times (based mainly on [i]) for diversions at various points of the fuel cycle are as follows:

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[30] Ibid., para. C.

[31] Ibid., paras. 3-4.

Table 2. Critical Times[32]

Fuel Fabrication	20 days
Fuel Stores and Transit	20 days
Reactor	120 days
Cooling Pond	120 days
Reprocessing	20 days
Store	20 days

The above thus describes the scope of the safeguard task. It is a task that requires three basic types of functions or components:

Accounting

The measurement of material flows and inventories at various points in the fuel cycle, often through sampling techniques. Such measurement must in any case be accomplished simply as part of a rational materials management policy.

Containment

The imposition and investigation of seals and stamps which could indicate with virtual certainty whether they had been broken, tampered with, or forged.

Surveillance

The imposition of inspectors or electronic surveillance which could by their physical presence observe (and therefore deter) unauthorized diversions of nuclear material.

The essential idea of all accounting schemes is to divide these elements of the fuel cycle into "material balance areas" (MBA's), which

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[32] Ibid., Figure 1.

are defined as clearly demarked areas that permit (1) a physical inventory of nuclear material within the area whenever desired, and (2) the measurement of the flow of material across the area's boundaries. In general, MBA's will be chosen as coincident with a given nuclear facility or substantial distinguishable part of such facility. In all cases, one would expect that the boundaries of any principal nuclear facility would be coincident with the boundaries of the appropriate MBA's.[33]

The measurements or estimates then required by (2) above provide the "book inventory" and the difference between this and (1), the physical inventory, becomes the "material unaccounted for" (MUF).[34] Thus, for a given MBA, the MUF is simply determined by:

MUF = Change in physical inventory -- Net flow into MBA

More precisely,

$$MUF = (I_E - I_B) - (R - S - L), \text{ where}$$

I_E and I_B = physical inventory at end and beginning of inventory period

R = receipts of material into MBA

S = shipments of material from MBA

L = quantity of material, measured or estimated, discarded during inventory period as normal operating loss.[35]

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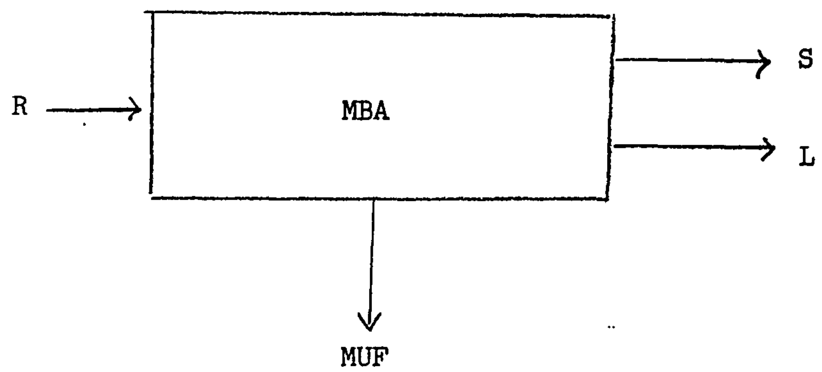
[33]Frederiksen, Report to the Director-General of the IAEA, paras. 8 and 11.

[34]The MUF can, of course, be positive or negative.

[35]Fredericksen, Report to the Director-General of the IAEA, Para. 8. Proceedings of the AEC Symposium on Safeguard Research and Development, WASH-1147, p. 8.



A central task of any safeguard system is to detect any significant MUF in timely fashion.[36] To do so, the safeguard system must be able to monitor and measure flows of material into and out of the MBA at its borders, and to measure physical inventories when necessary. Under reasonable precautions, in which the physical inventory remains sealed, the MUF can be kept to a minimum simply by accurate measure of boundary flows. When this is the case, safeguard inspection can be concentrated at a very small number of places in the fuel cycle, namely the boundaries of the MBA's (the input and output of reprocessing plants, of fabrication facilities, etc.). These places may be termed "salient points."[37] The first limit then on the effectiveness of a safeguard system is the precision with which material flowing through MBA's can be accounted for through measurement and statistical techniques alone. In general, this precision will not depend sensitively on the amount of the material flow, and consequently the MUF will be proportional to the total throughput of the system. Typically, as will be discussed

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[36]The hazard of any violation will be decided by the suitability of the material taken for weapons and by the time for which a loss can remain undetected.

[37]Frederiksen, Report to the Director-General of the IAEA, para. 14.

forthwith, the MUF will at least turn out to be anywhere from 1/10 of a percent up to 1 percent of the material put through. In fractional terms this is very small, but in absolute quantities can be very large.[38]

The second safeguard technique is containment. It is based on two presumptions: (i) that locks and seals can be devised which will indicate with certainty over any period whether they have been tampered with, and (ii) that stamps may be imposed on a piece of material (say, the end of a fuel element) in a way to establish its unique identity.[39] There seems little doubt that these techniques can indeed be accomplished. The drawback to containment procedures is rather that they cannot easily be used in facilities such as fabrication and reprocessing plants where the safeguarded material is constantly undergoing change in composition and shape. In reactors, in cooling ponds, and in transit, however, containment procedures appear highly useful. In these instances, it should be noted that the effectiveness of containment will not typically depend on the amount of material under safeguards or being diverted. That is, containment techniques possess a "go-/no-go" character; they work or they don't.[40] The effectiveness of surveillance and physical security procedures also does not depend sensitively on the quantity of material an evader may be trying to divert. Consequently, as with containment, it is not possible to characterize quantitatively the effectiveness of surveillance. All one can say is

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[38]WASH-1147, 12.

[39]Morgan, Report to the Director-General of the IAEA (Topic 1, Part 1), para. 22.

[40]Ibid., para. 25.

that the greater the surveillance and security, the greater the deterrent to a would-be evader, and the greater the cost to him.

4. The Effectiveness of Safeguards

The effectiveness of safeguards depends on (i) their technical efficacy -- how well they guard activities which are under safeguard jurisdictions, and on (ii) their legal scope -- how many activities fall within the safeguard jurisdictions. In general, domestic safeguards in principle extend to all activities, and their effectiveness is limited mostly by (i). The IAEA safeguard system, on the other hand, is severely limited in scope. Some fuel cycles remain altogether outside its jurisdiction; and, as will be seen, the rights of the IAEA, even in countries which accept the safeguards, remain rigorously proscribed. This subsection first describes (i), the effectiveness of safeguards over declared activities, and then (ii) the legal limitations of the IAEA system.

Effectiveness of Safeguards on Declared Facilities

Safeguards will be applied to the following parts of the fuel cycle:

--conversion and fabrication plants

--reactors

--reprocessing and finishing plants

--stores (stockpiles) of nuclear material

--research and development facilities

--transportation networks (for transport of nuclear material)

Two components of the fuel cycle are missing from this list: uranium (and thorium) mines and mills and isotope separation plants. It is not expected that international safeguards at least will be attached to uranium mining and milling operations. The Model Agreement explicitly provides "that safeguards shll not apply . . . to material in mining or ore processing activities."[41] However, under the Model Agreement, states are obligated to report exports (to non-nuclear weapon states) or uranium or thorium and imports of these material. Also quantities of natural uranium in excess of ten tonnes, and of throium in excess of 20 tonnes will be subject to safeguards once they enter the fuel cycle. In effect, this simply means[42] that natural uranium and thorium will be safeguarded as the material moves through safeguarded facilities and during transport.

Isotope separation plants, of course, form an important part of the fuel cycle, one of the two places (with reactors) where fissionable material is created. However, these plants at the moment only exist in countries which already possess nuclear weapons, and the IAEA has had no occasion to work out detailed safeguard procedures for them. Nor have the countries with separation plants published detailed information which would permit safeguard effectiveness evaluations. Moreover, perhaps the most attractive separation technology to the non-nuclear-weapon states, centrifuge plants, have not yet been constructed on large scale anywhere in the world. Thus the omission of separation plants from the following discussion.

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[41] Model Agreement, para. 32.

[42] Ibid., para. 3

There are as yet no completely adequate studies of safeguard effectiveness based on detailed plant records and systematic investigations of various diversion strategies. The studies which have been performed concentrate almost entirely on the effectiveness of accounting procedures to detect diversions under the assumption that the diverter does not frustrate or try to doctor the independent measurements of the inspectorate. Such studies seek to determine the largest diversion possible before the MUF becomes sufficiently high to alert the inspectorate. This manner of analysis thus ignores altogether surveillance and containment; on the other hand, it also does not deal with specific diversion strategies to trick the inspectorate. The accounting effectiveness so determined depends then only on the accuracy of the various independent measurements of the inspectorate and the normal probability distribution of the MUF.

The measure of such accounting effectiveness may be put in the form, "a diversion of x per cent of the throughput will signal the need for an investigation by the inspectorate y per cent of the time." If, for example, x is large compared to the normal MUF of the plant, y will be close to 100%; if x is small compared to the normal MUF, y may be very small. The statement of effectiveness put in this way requires the inspectorate to choose first an acceptable level of false alarms. This may be seen as follows: Two types of errors are possible: the accounting system could fail to detect a diversion, or conversely it could falsely alert the inspectorate when no diversion had in fact occurred. Both type errors cannot be minimized simultaneously. For example, say the inspectorate chooses a 5 per cent level of false alarms. This means that the alarm will place under suspicion all

MUF values which normally fall in the lower 5 percentile region of the MUF probability distribution. If this level were raised to 10 per cent, the probability of a real diversion being ignored would be reduced but the false alarm rate would double (from 5% to 10%).[43]

Conversion and Fabrication Plants

These facilities pose the worst control problem of any in the fuel cycle. The factories are large and complex and the material is not highly radioactive and is often in ill-defined states. There appear numerous opportunities for theft.[44] Surveillance procedures would thus be useful but expensive; if the scope of inspection is to be limited, the burden of the inspection system would have to be on measurement and accounting, notably on measurement of inputs to the facilities and on non-destructive testing of the produced elements.

Under the assumption of a false alarm rate of 5 per cent, a throughput of 1 ton uranium per day, and a nominal U-235 enrichment of 3%, such procedures applied to conversion and fabrication plants producing UO_2 pellets could achieve the following degrees of effectiveness:

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[43] L. F. Wirfs, in U.S. Atomic Energy Commission, Safeguards Systems Analysis of Nuclear Fuel Cycles, WASH-1140, 152-153.

[44] Morgan, Report to the Director-General of the IAEA (Topic 1, Part 2.) 1-2, para. 92.

Table 3. Threshholds for Detecting Uranium Losses in Conversion and Fabrication Losses[45]

- Probability Level of 80 Per Cent -

	Uranium (pounds)	U-235 (kgm)
3 months	900	16
6 months	1000	21
12 months	1400	34

For example, a diversion of 900 lbs. UO_2 or 16 kgm U-235 after 3 months would produce an MUF sufficient to alert the inspectorate 80% of the time. The threshhold levels after a year of 1400 lbs. UO_2 and 34 kgm of U-235 correspond to undetected diversions of 0.2% and 0.3% of the respective throughputs.

These data, based on ideal extrapolations from plant experience, represent the best performance that the measurement system is capable of achieving in a normal operating environment. The actual performance of conversion and fabrication plant accounting procedures falls considerably below this ideal performance. Threshholds corresponding to actual plant performance are three to four times higher than the ideal levels set forth in Table 3.[46]

However, even at yearly diversions as high as 102 kgm of U-235 (corresponding to 1% of throughput), the 80% threshhold level for actual plants would not be too alarming unless the diverter had access to isotope enrichment facilities. This is true as long as the diverted

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[45]Wirfs, 160

[46]Ibid., 160

material is low enriched uranium. Diversions on the order of 100 kgm of plutonium would on the contrary be very serious. Once plutonium recycling and fabrication become part of the normal fuel cycle, safeguards on conversion and fabrication processes will have to be extraordinarily stringent.

Reactors

Inspection of reactors will have to rely mainly on surveillance and containment. Measurement and accounting procedures alone cannot determine the critical data on the plutonium content of discharged elements with precision. This content depends on four factors: the total weight of uranium passed through the reactor, the average fuel burn-up, the total reactor energy output, and the moderator temperature (and distribution of irradiation in the reactor core). Even if the inspector has access to these operating data and to the reactor codes (systematic histories of irradiation distributions based on moderator temperatures, etc.), total plutonium content could be calculated only to a precision of 2-3%. If the reactor operator were able to produce false records, especially of total power output, independent computations of plutonium by the inspectorate could not produce precisions better than 10%.[47] That is, although the reactor operator would not have total freedom to juggle records of power level (since they must be consistent with other data available to the inspectorate), he could produce a false record that underestimated plutonium production by 10% or more.

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[47]Morgan, Report to the Director-General of the IAEA (Topic 1, Part 2), para. 13-17.

The security against plutonium diversion at the reactor must thus depend on prevention of the clandestine removal of irradiated reactor elements. The divertor could attempt this through substitution of an irradiated element by either an unirradiated element or one which was only lightly irradiated. Such diversion could be discouraged through physical surveillance, element containment procedures, and non-destructive irradiation checks of discharged elements.[48]

Reprocessing Plant

The material flowing through reprocessing plants is highly radioactive, not easily stolen. The main diversion hazard would be the construction of clandestine pipework that could gradually siphon off part of the throughput during a normal run. Confronted with this possibility, the main inspection task is to measure plant inputs and outputs with sufficient precision to detect any significant such diversion. As with fabrication plants, the inspection must rely on measurement and accounting procedures; and studies of reprocessing plant safeguards parallel those for fabrication plants. Investigation of the probability distribution of MUF's in actual plant operation suggests the following Table of effectiveness. The Table assumes a false alarm rate of 5 per cent and a throughput campaign of 40 metric tons of irradiated low enriched uranium containing 10,000 grams/metric ton of plutonium (400 kgm).

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[48] Ibid., para. 19-20.

Table 4. Threshholds for Detecting Material Losses in a Chemical Reprocessing Plant[49]

- Probability Level of 80 per cent -

Diversion (% of Input)

	Capability Model	Performance Model
Plutonium	0.77	1.54
Uranium	0.62	1.30

A diversion of 0.77% of 400 kgm plutonium corresponds to 3 kgm plutonium per campaign. Over a year a relatively small reprocessing plant of capacity one metric ton per day might run 5 or 6 forty metric ton campaigns.

Effectiveness on Principal Facilities - Summary

Safeguards will probably be sufficient in the 1970's to detect diversions of more than 1 to 5 per cent of fissile material throughput per year in any part of the fuel cycle; and they may do even better.[50] More accurately, safeguards should be sufficient to raise alarms of such magnitude diversions. But proof of diversion will no doubt be difficult to establish; states would probably frustrate attempts by the inspectorate to gather relevant evidence even through clear safeguards violations rather than risk exposure. Moreover, the safeguards systems now contemplated do not appear entirely adequate to prevent diversions even if detection is possible.

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[49]Adapted from R.A. Schneider and D.P. Grandquist in WASH 1140, 83. The capability model represents the best performance that the measurement system is capable of achieving in an operating environment. The performance model represents what might be expected in practice from a high quality measurement system.

[50]It should be emphasized, however, that no serious systems study of safeguards effectiveness based on actual operating MUF's has yet been accomplished. A great deal more data is needed. Summary of Three Reports by Safeguards Consultants, June 1969, 4-5. Also AEC, OSMM, August 1971, private communication.

Sealed Stockpile

As indicated in earlier sections, the supply of plutonium (discharged from civilian reactors) will probably greatly exceed the demand during the next two decades, until breeders become widely installed. There will thus be a requirement to store plutonium, possibly for several years. Such storage might typically be in the form of two kgm metal "buttons" placed in cans or as plutonium nitrate solution (2.5 kgm Pu) in ten litre polyethylene bottles. In such forms storage of one tonne Pu would require a floor area of perhaps 200 m^2, the size of a large room.[51] Seals and other containment procedures should be adequate to ensure that the stores could not be tampered with without eventual detection. The essential remaining safeguard requirement would then be to establish the inventory of the store initially (and after evidence of tampering) as accurately as possible.

One way to do this would be through non-destructive methods involving the transmission of gammas or neutrons (to determine the chemical content). Both theoretical considerations (based on recent changes in technology) and American experience with the radiometric techniques suggest that precisions of 0.3% to 1% are attainable; precisions of 0.1% do not seem probable. Destructive methods, measuring bottled solutions by weight, for example, could have precisions of 0.1% or better.[52] Thus the inventory of one tonne of plutonium should be ascertainable to within one to a few kilograms.

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[51] Morgan, Report to the Director-General of the IAEA, (Topic 1, Part 2), paras. 58-66.

[52] Ibid., paras. 62-66, 84.

Working Inventories: Research and Development

Reactor physics experimentation typically requires a rather large working inventory of fissionable material, which must be safeguarded. The following table, taken from British experience, illustrates the amounts and character of material nominally involved in such experimentation:

Table 5[53]

Material	Number of Units	Total Weight
Plutonium Coupons	10^4	500 kgm
Highly Enriched U Coupons (93% U-235)	10^4	460 kgm
Medium Enriched U Coupons (40% U-235)	10^4	625 kgm

If one assumes that each coupon is individually identifiable, the material could be abstracted essentially in one of three ways: downgrade enrichment of a coupon by substituting a coupon with a lower enrichment, remove coupons without replacement, or remove coupons and replace them by dummies. If the inspectorate initially knew neither the correct number of coupons, the mean quantity of fissionable material, nor the exact isotopic composition of the plutonium coupons, it would have to select and identify coupons, measure their chemical content, and, in the case of the plutonium coupons, measure the Pu-240 levels -- in order to determine the inventory. As long as the coupons were individually identifiable, this could always be done with considerable accuracy, though the effort of inspection (number of coupons sampled) would depend on the accuracy desired. For example, to be 95% confident that the inventory

[53] Ibid., para. 67.

of the preceding table (about one tonne of fissionable material is within 1% of the book value would require perhaps two-inspector-days. Reasonable inspection efforts and strategies should ensure the diversions from such coupon inventories of more than about 0.3% will be detected; and it may be possible for the inspectorate to do even better.[54]

Transportation and the Problem of Physical Security

Transportation safeguards have often been cited as among the weakest components in a safeguard system. For example, the chief of the AEC Headquarters Transportation Management Branch has concluded that "transportation provides the weakest link in the entire safeguards chain. It is most vulnerable insofar as diverting material to unauthorized receivers."[55] Actually, the risks of diversion from the transportation network represent simply the most visible and worrisome aspect of a wider problem -- the overt theft of nuclear material by criminal elements or agents of a foreign government. Whereas much safeguards effort has gone into the development of accounting and containment procedures, comparatively less attention has been given to physical security. Safeguard systems can probably now <u>detect</u> diversions more surely than they can <u>prevent</u> them. This vulnerability of material to theft has been especially stressed by the Lumb Panel. Much of the ensuing discussion, while focusing particularly on the transport of nuclear material, will nevertheless be relevant also to the broader issue of physical security of material at any point in the fuel cycle where outright theft is conceivable.

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[54] *Ibid.*, paras. 67-84.

[55] R. A. Kaye, in WASH-1147, 33.

The three most troubling transportation links are probably from the fuel fabrication facility to the reactor, from the chemical reprocessing plant to storage, and eventually from storage to whatever destination. The link from the reactor to the reprocessing plant also provides some opportunity for diversion, but here, because the material is radioactive and unseparated, the difficulties presented to the diverter appear significantly greater. The safeguard problem rises from the relative smallness of the material transported, its enormous value, and the always present dangers of hijacking. To ship 35 kgm of plutonium as an oxide required ten small packages with a total gross shipping weight of 1100 lbs. Twenty-five kilograms of plutonium as a nitrate also required ten packages with gross weight of 4000 lbs. This may be compared to the 43,000 lbs. of freight carried by a standard highway trailer. Moreover, each of these packages is really small, about 1/10 of a cubic foot for the plutonium oxide, with two packages roughly sufficient for one nuclear weapon. Thirty-five kilograms of plutonium would value over $350,000, even at the commerical price of $10,000 per kgm. At the "weapons price" for plutonium (roughly the cost of producing plutonium from scratch), the total value would easily exceed $3.5 million. Eleven hundred pounds of gold (the total shipping weight for the 35 kgm of plutonium) would, for comparison, value about $600,000.

The hijacking risk appears serious. The aforementioned chief of the AEC transportation management estimates that about $720 million annually is lost or stolen from all combined modes of transportation (including air freight).[56] Transportation industry representatives appear to believe that "anything that organized crime wants to lay his (sic) hands on, while it's in the transportation cycle, it's going to get."[57] Although the presumably limited market for stolen fissionable material doubtless now somewhat deters would-be hijackers, this limitation alone probably cannot be relied upon for any long period. The Lumb Panel argued that world black markets in nuclear material were a real danger, and that in at least one recent instance of attempted theft (from the Bradwell Reactor in England), a fence was involved.[58] It is also likely that the theft of material would itself create a market. Thus, Commissioner Larson of the AEC asserts that "once special nuclear material is successfully stolen in small and possibly economically acceptable quantities, a supply-stimulated market for such illicit materials is bound to develop. And such a market can surely be expected to grow once a source of supply has been identified. As the market grows, the number and size of thefts can be expected to grow with it."[59] The AEC now claims that within the United States alone, there exist "at least 37 radical [extremist] organizations which . . . could mount a coordinated attack for the purposes of stealing

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[56] Kaye, in WASH-1147, 34.

[57] S. Edlow, in WASH-1147, 37.

[58] Lumb, 17, 39.

[59] C. Larson, in WASH-1147, 179.

unclassified nuclear material," either for its financial value or as "an anti-establishment measure" (sic).[60] Later in this study, we further consider potential uses for illicit nuclear material.

Confronted with these risks of hijacking, neither international nor domestic safeguards appear fully adequate. Under international safeguards, although each nation is required to guarantee that the nuclear materials will not be transferred to unauthorized parties, there is no requirement for physical protection of the materials. That is, the IAEA does not apply physical surveillance to transported material, nor does it require such surveillance by the host nation. Thus, while IAEA containment and accounting procedures could eventually detect a diversion; they can do little to prevent them. Apart from the consequent risks of criminal diversion, this situation permits a government with inadequate domestic safeguards against hijacking or other overt theft to undertake a diversion while claiming it was perpetrated by criminal elements.[61]

The burden of providing physical protection to the transported material thus falls on the domestic safeguard systems. In the United States, with probably the most sophisticated such system, there appear nonetheless substantial vulnerabilities. Most significantly, the transportation of nuclear material is predominantly handled by private firms under license from the AEC. Although the AEC could in principle

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[60] E. D. Hightower, in WASH-1147, 40.

[61] Lumb, 77.

impose essentially whatever security conditions it chose, the AEC fears that too severe (and costly) a set of regulations would lose the interest of the transportation industry altogether, given the relatively small quantity of business involved. Thus, the transportation safeguard procedures are now determined in significant part by financial considerations.[62]

At all points in the transportation cycle, responsibility for the enforcement of safeguard procedures is diffuse or limited or both. For example, at the moment, carriers are exempt from licensing requirements and the AEC control must be through licensed shippers and consignees.[63] But these licensees have little authority to enforce and check safeguard standards on the shippers. The responsibilities of the carrier to the shipper are quite limited. Moreover, the penalties[64] to the carriers, shippers, and consignees of loss (and even theft!) of material are not severe. Under the Atomic Energy Act of 1954, drastic penalties (including death) are applicable only to diversions intended to injure the United States or to provide advantage to a foreign power. Where the intent is simple personal gain, the penalty is merely five years and/or $10,000. The penalties for innocent loss of material, even if through carelessness or negligence, are still less severe (though there may be substantial economic loss).[65] The Lumb Panel recommendations to increase these penalties have not yet been implemented.

[62] L. M. Brenner, in WASH-1147, 22.

[63] Ibid., 22.

[64] Edlow, in WASH-1147, 31.

[65] Lumb, 34 ff., 80.

Partly as reflection of this legal situation, the physical security imposed on shipments of nuclear material is not elaborate. There are typically no armed guards, nor armed escorts. Certain safeguard procedures are, however, being effected which will improve security. These will probably include, continuous operation from point of origin to destination, driver security clearances, driver training programs, attendance of lading at all times during transit, alarm systems, numbers on top of equipment so that it is easily identifiable from the air, pre-routing of shipments over specific highways, etc.[66]

Related to the imposition of physical security measures, the AEC has not yet developed firm ideas on several key issues: Where should armed guards be provided?[67] Should parcels containing fissionable material be conspicuously marked?[68] Should material be shipped in large or small quantities?[69] What procedures can be devised to determine quickly whether material has been actually stolen rather than lost?[70] It should be noted finally that these problems and questions raised

[66] G. F. Boyd, in WASH-1147, 28. These are actually features now used in programs for transporting high explosives and other dangerous commodities.

[67] Hightower, in WASH-1147, 41.

[68] Brenner, WASH-1147, 37.

[69] J. E. Wilkins, in WASH-1147, 37.

[70] Brenner, in WASH-1147, 22-23.

above are realized by the AEC, and are under investigation. For example, the AEC has contracted a study with the public accounting firm of Wright, Long, and Company to assess and analyze the threat to materials in transportation.[71]

Scope and Costs of Safeguards

The level of effort required to achieve the safeguards' effectiveness indicated in the foregoing is considerable. Technical studies by the IAEA and AEC indicate inspection levels of the following order:

Table 6. Inspection Requirements[72]

Facility	Number of Inspectors and Analysts (all shifts)
Power or High Power Research Reactor	1
Reprocessing Plant (1 to 10 tonnes per day)	7-19
Sealed Store	1 visit per month
Conversion or Fabrication Plant (1 to 10 tonnes per day)	10-16
Headquarters	50 + 10% of number of inspectors

Given the expected growth of civilian nuclear power, these data lead to the following estimates of total IAEA staff and cost requirements pursuant to implementation of Article III.

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[71] Ibid., 24. An excellent discussion of the transportation problem may be found in Deborah Shapley, "Plutonium: Reactor Proliferation Threatens a Nuclear Black Market," in Science, Vol. 72, 143-146.

[72] Brookhaven National Laboratory, "IAEA Cost and Manpower Requirements Under the NPT-Alternative Levels of Inspection," in Hearings Before the Joint Committee on Atomic Energy, on AEC Authorizing Legislation FY 1970, 91st Congress, 1st Session, 1969, 2135.

Table 7. IAEA Staff Requirements[73]

Year	All Non-Nuclear Weapon States		All Parties to NPT including U.S., U.K., USSR	
	Staff	Cost	Staff	Cost
1975	549	$20.4 mil	755	$35.9 mil
1980	758	34.1	1112	61.3
1985	1033	52.7	1531	101.6
1990	1378	69.5	2162	169.1

Other estimates have been made which are markedly higher than these for the period after 1975, notably those by Theodore Taylor. Taylor estimates total staff requirements (all NPT Parties) as approximately 3000 in 1980; 7000 in 1985; and 12,000 in 1990; Taylor's estimate of the total annual safeguard cost by 1990 is $518 million. These higher estimates are due mostly to higher estimates of nuclear power growth (1,500,000 MW_e for 1985 instead of 620,000 MW_e), slightly higher estimates of staff requirements per reactor, and of cost per inspector ($40,000 per year instead of $25,000 per year).[74]

It is important to note that even the high estimates indicate safeguard costs less than 1% of the cost of the total electric power produced. Both the cost and manpower requirements, while considerable,

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[73] Ibid., 2134. The cost estimate is based on $25,000 per inspector, $35,000 per headquarter's staff, and various equipment costs.

[74] Raymond R. Edwards, "Comparison of Assumptions on IAEA costs of administering safeguards," in Hearings before the JCAE on AEC Authorizing Legislation 1970, 91st Cong., 1st Session (1969), 2129-2130.

ought not prove significant impediments to the establishment of the IAEA inspection system.[75]

Vulnerabilities in the IAEA System

Apart from the limitations described above, the IAEA safeguard system suffers several additional vulnerabilities relating to (i) country coverage, (ii) undeclared facilities, (iii) non-weapon military activities, (iv) physical security, (v) abrogation, (vi) residual stockpile rights, (vii) sanctions, and (viii) exports to non-parties.

Country Coverage

As earlier indicated, many important states have either ratified or indicated they will ratify the NPT, with its provision requiring non-nuclear signatories to accept IAEA safeguards over all peaceful nuclear activities. However, a few significant non-nuclear states have not yet even signed the Treaty and may not do so in the near future. These include Argentina, Brazil, India, Israel, Pakistan, South Africa, and Spain. In addition, some countries who have signed may withhold ratification for a variety of reasons. Most notably, the United Arab Republic conceivably may not ratify until Israel does. The non-adherence of these countries to the NPT does not, of course, mean that all nuclear activities therein will be unsafeguarded. On the contrary, in the short term, all such activities in these countries will be under either bilateral or IAEA safeguards. In the longer term, however, as the states

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[75]IAEA staff studies indicate still lower costs and manpower requirements. These studies estimate that only 167 inspectors will be required to safeguard all non-nuclear-weapon-state-facilities by 1975, at an annual cost of $5.7 million. This would comprise about one-fourth of the total IAEA budget at that time. GOV/COM.22/80, "Projections of Safeguard Costs 1971-75," October 19, 1970.

develop indigenous capabilities, some material will become free from safeguards unless the states can be persuaded to join the NPT.[76]

Undeclared Facilities

The IAEA possesses no right to inspect for undeclared clandestine facilities. It cannot look routinely for such facilities; nor can it send inspectors to the site of some suspect undeclared plant. This probably is not too serious a limitation, if, as is sensible, the IAEA could rely to an extent on various national intelligence capabilities. Clandestine construction and operation of an isotope separation plant or nuclear reactor within a particular country would appear extremely difficult, given normal political and intelligence operations by other nations in that country. This appears especially true for non-nuclear weapon states which are, of course, the chief places of interest.

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[76]Of the major countries who have not signed the NPT, Argentina, Brazil, Pakistan, and Spain have no indigenous capability to develop power reactors, nor any plans to develop such reactors through unsafeguarded foreign assistance. India and Israel represent the two most interesting cases. India now has two power reactors producing substantial amounts of plutonium. One, the Canada-India reactor (Rajasthan), although not formally subject to safeguards, was acquired on an Indian undertaking that it would be used for peaceful purposes only. Most observers believe that India will honor this commitment. The second reactor (Tarapur) is subject to U.S. bilateral safeguards. India is, however, developing an indigenous reactor which may be ready by 1977. Israel has only the French-built research reactor at Dimona which went critical at the end of 1964. With a power rating of only about 24 MW_t, this reactor could produce at most a few kilograms of plutonium per year. As far as is known, Israel has no reprocessing capability, and the plutonium produced in Dimona presumably remains unseparated. The reactor is not subject to formal safeguards, but the United States has sought and apparently received assurances from the Israelis that the plutonium produced is not being diverted to weapons. At present, nine power reactors are under Agency safeguards: one in India, three in Japan, one in Pakistan, two in Spain, and one each in the United Kingdom and United States.

Isotope separation plants, certainly those employing the gaseous diffusion technique, are massive constructions and use enormous amounts of power. Reactors are not as large, but produce considerable amounts of radioactive products and waste, difficult entirely to conceal. While fuel fabrication and reprocessing plants may be somewhat easier to hide, especially the latter if they are small, these facilities do not actually produce fissionable material; their concealment would exacerbate the safeguard problem in other parts of the fuel cycle, but would not in itself be decisive. In sum it seems unlikely that a country could conceal an entire undeclared fuel cycle. How the IAEA would react to the discovery of clandestine facilities is, however, an altogether different problem. It is one considered below under "sanctions."

Military Activities

Under the NPT, non-nuclear states cannot manufacture nuclear weapons or nuclear explosives. The Treaty safeguard provisions are to prevent these specific uses. Other military (albeit non-weapon) uses of nuclear material are permitted, and need not be placed under safeguards. The Model Agreement simply requires a state which wishes to exercise its option to use nuclear material for military purposes to so inform the Agency, and to make arrangements with the Agency to ensure that safeguards shall again apply as soon as the nuclear material is reintroduced into a peaceful nuclear activity.[77] This "loophole" will probably not prove very serious for the near future. Military but non-weapon uses of nuclear

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[77] Model Agreement, para. 14.

energy by non-nuclear countries will remain severely limited during this time. At the moment, no non-nuclear state has made public definite plans for such use, the most relevant example of which is probably nuclear propulsion units for military submarines. Equally important, it is just material applied to a specific activity which is exempted from safeguards; while the material is being processed through the ordinary fuel cycle, it is effectively under safeguards as are the facilities it passes through.[78]

Physical Security

The IAEA has neither the authority nor the responsibility to secure nuclear material through physical protection measures, such as armed guards. Nor even does the IAEA have the authority or responsibility to establish physical protection standards, much less to impose them on the inspected country. Thus the effectiveness of international safeguards will depend in part on the degree to which states are willing to impose strong domestic measures of physical protection, something over which the IAEA has no direct control.[79] Effective safeguard security should therefore ideally require to the extent practicable a division of principal nuclear facilities among the non-nuclear states so that no one state can accede to a completely independent capacity to produce weapons material through simple physical possession of the safeguarded facilities. This is a matter to which we return in later sections.

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[78]Allan McKnight, The Safeguards System of the IAEA (to be published), Ch. IV. Mason Willrich, Non-Proliferation Treaty, 119-121.

[79]Douglas E. George and Ralph F. Lumb, "International Safeguards," in Willrich, ed., Civilian Nuclear Power and International Security, 55.

Abrogation

The NPT safeguard obligations of states under Article III are likely to be coterminous with the state's adherence to the Treaty itself. This last can be ended by any party "if it decides that extraordinary events, related to the subject matter of [the] Treaty, have jeopardized the supreme interests of its country," and if it gives "notice of such withdrawal to all other Parties to the Treaty and to the United Nations Security Council three months in advance."[80] Thus may be seen an inevitable weakness in the Treaty and its imposed safeguards: facilities established during the time the Treaty remains in force, possibly through the assistance of other countries, will become unsafeguarded three months after withdrawal notice unless safeguards are still required under other agreements undertaken by the withdrawing state. And once one important state withdraws, other parties to the Treaty are likely to consider such action as an "extraordinary event" sufficient to impel their own withdrawal.[81]

Residual Stockpile Rights

The status of stockpiles of fissionable material produced during a safeguard period after abrogation of the safeguards agreement is somewhat unclear. From Table 18 of Chapter 1, it is evident how important this issue is. If countries can simply and legally appropriate all

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[80]Non-Proliferation Treaty, Article X.

[81]It is, however, true that safeguards agreements suspended during the time a state adheres to the NPT, typically will again be effected once the NPT obligations lapse. Such will be the case with U.S. bilaterals and with IAEA agreements. It is important that other states also impose this condition of persistence of safeguard rights before providing assistance to states, even those party to the Treaty.

plutonium produced in safeguarded reactors whenever they wish (after appropriate notice of abrogation) the entire purpose of safeguards is undercut. Nevertheless, the Safeguards Document simply asserts:

> In the light of Article XII.A.5 of the statute, it is desirable that safeguards agreements should provide for the continuation of safeguards, subject to the provisions of this document, with respect to produced special fissionable material, and to any materials substituted there for.[82]

The Model Agreement nowhere makes mandatory this desired provision. By contrast, the Mexico-IAEA safeguards agreement pursuant to the Latin American Nuclear Free Zone Treaty does make the provision explicit.

> Any notice of termination shall be given to the other Party three months in advance and any notice shall also indicate the reasons for termination. However, this Agreement shall remain in force with regard to any produced nuclear material listed in the Inventory until the Agency has notified the [Mexican] Government that it has terminated safeguards on such material . . . .[83]

Thus, the absence of explicit statement in the Model Agreement in light of the Mexico-IAEA precedent is troubling and potential cause for serious dispute in the future.

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[82] Safeguards Document, Para. 16. Emphasis added.

[83] Mexico-IAEA Agreement, INFCIRC/118, 23 September 1968, 31 (c).

Sanctions

Domestic safeguard systems could (and do) impose severe criminal penalties for unauthorized diversions. These penalties could be strengthened in various ways already indicated, but in general they provide a significant deterrent to safeguard violations. Opposed to this, IAEA sanctions are both limited and ill-defined. Article XII.C. of the IAEA Statute as referred to in the Model Agreement gives the Agency Board of Governors power to "call upon" recipient states "to remedy forthwith any non-compliance which it finds to have occurred." The Board must report the non-compliance to the U.N. Security Council and General Assembly. In the event of continuing non-compliance, the Board is authorized to suspend assistance being provided by the Agency or a member of the Agency, recall material and equipment made available to the offending party, and to suspend the non-complying member from the exercise of privileges and rights of membership. The IAEA itself, however, can do little to enforce compliance.

In any case, it is clear that the IAEA cannot actually prevent diversion; it can at best detect it. Still more accurately, the IAEA system is more apt to determine non-compliance by a state with its safeguards' obligations than actually to detect a diversion. A state, rather than permit itself to be caught in a guilty act, will more typically simply frustrate the IAEA inspection. If such is the case, the IAEA, with no explicit evidence of a diversion (but rather merely of non-compliance), will probably tend to tread warily before instituting U.N. action and other sanctions. The Agency and the international community both will be reluctant to organize measures in response to diversions that were merely suspected.[84]

Exports

Article III.2 of the NPT is somewhat ambiguous regarding whether parties to the Treaty can provide nuclear assistance to non-parties who refuse to accept international safeguards on all their nuclear material and activities. For example, could the United States under the NPT properly provide assistance to India as long as India refuses to accept safeguards on all its activities? Article III.2 declares the following:

> Each State Party to the Treaty undertakes not to provide: (a) source of special fissionable material, or (b) equipment or material . . . to any non-nuclear-weapon State for peaceful purposes, unless the source or fissionable material shall be subject to the safeguards required by this article.[85]

There now seems general agreement that such assistance is indeed permitted, although the wisdom of this interpretation appears open to question. The strong argument[86] against this liberal interpretation is that it in effect discriminates against NPT parties who have accepted comprehensive safeguards; it does not provide an inducement for states, such as India, to join the Treaty. On the other hand, it may be argued that attempts to apply the harsher interpretation would merely drive countries more quickly to develop an independent nuclear capability not

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[84] R. Lumb, 70; V. Gilinsky, 71; M. Kratzer, 72; in Willrich, ed., Civil Nuclear Power and International Security.

[85] Emphasis added.

[86] See, for example, Kratzer, 68-69, in Willrich, ed., Civil Nuclear Power and International Security.

under any safeguards whatsoever.[87] Whatever the merits of these respective arguments, the situation remains that non-parties to the Treaty will still be able to receive considerable assistance in their development of a civil nuclear capability.

5. Summary

The effectiveness of safeguards will depend (1) on various technical constraints, (2) on the scope of effort nations are willing to undertake and to finance, (3) on the legal range of safeguards agreements, and (4) on the sanctions that the international community will be willing to invoke.

To the extent that the purpose of safeguards is taken to be reassurance that illicit diversion is not occurring, they can be highly effective. Under practicable safeguard systems, states, much less sub-national groups, could not divert more than one or so per cent of throughput in any facility without raising considerable suspicions of diversion. However, eventually, as the magnitude of throughput mounts, even a one per cent or less diversion over periods of months could be significant.

As significant as this caveat, it is not clear that states will be willing to exercise the maximum degree of control and surveillance open to them. Resident inspectors at all critical points of the fuel cycle, destructive and active non-destructive testing of material, surveillance equipment,and security precautions all are expensive and perhaps frequently intrusive on plant operation. Although the extra cost

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[87] See, for example, M. Vellodi, 68; Kratzer, 68-69 in Willrich, ed., Civil Nuclear Power and International Security.

involved appears low compared to total power costs (on the order of 1%), states seem reluctant to bear them. Long term financing for safeguards has not yet been settled, whether the major costs will be borne by the inspected facilities, the nations with the largest civilian nuclear power programs, or by the total IAEA membership.[88] This reluctance has been confirmed by a recent study on safeguards attitudes undertaken by a group at Kansas State University. The study indicates considerable opposition on the part of industry in the developed countries and governments in the developing areas to safeguard systems which provide regular and deep access to all parts of the fuel cycle and which are otherwise costly.[89]

As already indicated, international safeguard systems are severely limited in legal scope. Even to those parts of the fuel cycle covered by safeguards, rights of access by the inspectorate, rights of design review, rights of the inspectorate to demand various reporting and operating procedures, and their rights to undertake active testing have by no means been fully established for all parts of the fuel cycle. In addition, there are the various "loopholes" adduced above, by which parts of the fuel cycle may remain altogether outside the safeguard's jurisdiction.

The long run effectiveness of safeguards is also in doubt because of the present shaky understanding of sanctions. Since it is unlikely

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[88]With respect to IAEA inspections pursuant to the NPT, the IAEA Board of Governors has temporarily agreed to a formula which assesses the entire IAEA membership but weighs the assessment toward states with large nuclear programs.

[89]Robert Leachman, Kansas State University, private communication.

that nations will permit themselves to be caught red-handed in any actual diversion, safeguards will in general never provide proof of diversion. They may point to suspicious occurrences or even to violations of the safeguards agreement, but not to actual diversion. As a consequence, the imposition of sanctions will be no sure or routine thing, and a nation may come to believe there is little real risk in diversion activity. In this sense safeguards will not be able to prevent the diversion and may not even prove a substantial discouragement.

Thus several factors which will influence the effectiveness and durability of safeguards remain unsettled: the degree of access and testing which will be permitted, the manner and extent to which safeguards will be financed, and the violation reporting and sanction procedures. Because of opposition from industry and non-nuclear states, it seems likely that the determination of the safeguards procedures will be through compromise, neither as stringent as safeguards adherents would wish nor as permissive and non-intrusive as industry would want.

For all the reasons adduced above, investigation of international safeguards leads one inescapably to the conclusion that such inspection and control procedures will not be sufficient in the long term to prevent the diversion of fissionable material to weapons purposes. So long as nations have sovereign control, both legally and practically, over their nuclear programs, safeguards (albeit indispensable) will face an impossible task. This critical conclusion dominates this study as it dominated for a flickering instant U.S. policy in 1946. It is a perspective which has since been lost; and it is now worth quoting again the central conclusion of the "Acheson-Lilienthal Report" on which the postwar American position toward international control of atomic energy was based:

> Such considerations have led to a preoccupation with systems of inspection by an international agency to forestall and detect violations and evasions of international agreements not to use atomic weapons. For it was apparent that without international enforcement no system of security holds any real hope at all.
>
> In our own inquiry into possibilities of a plan for security we began at this point, and studied in some detail the factors which would be involved in an international inspection system supposed to determine whether the activities of individual nations constituted evasions or violations of international outlawry of atomic weapons.
>
> We have concluded unanimously that there is no prospect of security against atomic warfare in a system of international agreements to outlaw such weapons controlled <u>only</u> by a system which relies on inspection and similar police-like methods. The reasons supporting this conclusion are <u>not merely technical</u>, but primarily the inseparable political, social, and organizational problems involved in enforcing agreements between nations each free to develop atomic energy but only pledged not to use for bombs. National rivalries in the development of atomic energy readily convertible to destructive purposes are the heart of the difficulty. So long as intrinsically dangerous activities may be carried on by nations, rivalries are inevitable and fears are engendered that place so great a pressure upon a system of international enforcement by police methods that no degree of ingenuity or technical competence could possibly hope to cope with them. We emphasize this fact of national rivalry in respect to intrinsically dangerous aspects of atomic energy because it was this fatal defect in the commonly advanced proposals for outlawry of atomic weapons coupled with a system of inspection that furnished an important clue to us in the development of the plan that we recommend later in this report.
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> We are convinced that if the production of fissionable materials by national governments (or by private organizations under their control) is permitted, systems of inspection cannot by themselves be made "effective safeguards . . . . to protect complying states against the hazards of violations and evasions."

It should be emphasized at this point that we do not under-estimate the need for inspection as a component, and a vital one, in any system of safeguards -- in any system of effective international controls. In reading the remainder of this section it is essential to bear in mind that throughout the succeeding sections of this report we have been concerned with discovering what other measures are required in order that inspection might be so limited and so simplified that it would be practical and could aid in accomplishing the purposes of security.

The remainder of this section, however, is concerned with outlining the reasons for our conclusion that a system of inspection superimposed on an otherwise uncontrolled exploitation of atomic energy by national governments will not be an adequate safeguard.[90]

[90] "A Report on the International Control of Atomic Energy," prepared for the Secretary of State's Committee on Atomic Energy, March 16, 1946. Department of State Publication 2498.

CHAPTER 4. Latent Proliferation and International Security

1. Introduction

Every past shift in the way men produced energy, from animals to wood, from wood to coal, from coal to gasoline and oil, has generated accompanying deep changes in economics and politics.[1] The present rapid shift to nuclear energy will prove no exception. Indeed, nuclear power with its uniquely dangerous component, fissionable material, may prove the most drastic energy development of all. Its double-edged character has no comparable precedent.[2] To divine the character of the changes in politics, especially international politics, that will surely occur as a consequence of the global shift to civilian nuclear power is no easy task, however. There is little real experience or precedent to point to; any sustained analysis will per force be highly speculative.

In undertaking such speculation, two styles of analysis are possible. On the one hand, it is tempting to proceed immediately to abstractions, with stress on types of collective entities rather than their variation;

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[1]See Chapter 1, section 3. This statement needs little elaboration. Coal made possible the iron and steel industries and the railroad; the form and distribution of energy sources determined the location and growth of great cities; liquid fuels were essential to the growth of the automobile industry. The shift to electricity as the preferred form of energy has had still greater impact.

[2]This is not to say, however, that many past technologies have not had as well an ambivalent character. Dynamite and TNT afford perhaps the clearest example recognized as such at the time; but, of course, automobiles, airplanes, computers, the microscope, almost any modern technology has a Frankenstein aspect!

to talk, that is, of nuclear super-powers, of spheres-of-influence, etc., rather than of the real components these types describe. Thus a "typologist" will talk of nuclear super-powers behaving so and so, rather than about the behavior of the United States and Soviet Union. For the typologist, the type is real and the variation an illusion.[3] This mode of procedure is not necessarily objectionable. If the behavior of the United States and Soviet Union in many instances depends rather more on the peculiar status of their nuclear arsenals than on the economic systems of the two nations, or their ideology,

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[3]This sentence is taken from Ernst Mayr, Populations, Species, and Evolution, 4. In this work, Mayr makes the same distinction for biology that is made here for international studies. Mayr's fuller statement is as follows:

> The assumption of population thinking are diametrically opposed to those of the typologist. The populationist stresses the uniqueness of everything in the organic world. What is true for the human species, that no two individuals are alike is equally true for all other species of animals and plants . . . All organisms and organic phenomena are composed of unique features and can be described collectively only in statistical terms. Individuals, or any kind of organic entities, form populations of which we can determine the arithmetic mean and the statistics of variation. Averages are merely statistical abstractions; only the individuals of which the populations are composed have reality. The ultimate conclusions of the population thinker and of the typologist are precisely the opposite. For the typologist, the type (eidos) is real and the variation an illusion, while for the populationist the type (average) is an abstraction and only the variation is real. No two ways of looking at nature could be more different.

The biology analogy is useful to keep in mind for those who believe a typological stress is the only true scientific way.

or their specific leadership, etc., then characterizing the behavior as that of nuclear super-powers makes good sense. But the explanation of the behavior in these instances must precede the definition. It is no use to adduce as evidence in support of some proposition about nuclear super-power behavior simply information on what our two super-powers did on some occasion.[4] Opposed to the typologist view, the "variationist" viewpoint lays stress on the variability of nations and events and national histories. To understand how India might use an incipient nuclear capability requires an understanding of India's position in the world, not a proposition about the behavior of large Asian countries with incipient capabilities, etc. etc. That is, the variationist will place India and Japan and China in the foreground, not the appropriate collective type.[5]

The viewpoint adopted here is mostly, though not exclusively, that of the variationist; and the analysis is forwarded in three inter-connected and somewhat overlapping parts:

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[4] This problem is discussed at greater length in section 3 of this chapter.

[5] Nations too are abstractions. For many purposes, it also makes little sense to invoke "India", "Japan", etc.; nonetheless, most (though not all) of the crucial decisions relevant to international security are made today by national governments acting in the name of their nation. That the "true" national interest may often not be served by these decisions is of no matter.

(1) The Dynamics of Latent Proliferation: the patterns in which we might expect latent proliferation to proceed, and the relationship of the spread of latent capabilities to explicit proliferation of nuclear weapons.

(2) Threats to International Peace: conventional and novel threats to international security as a consequence of the dispersion of civilian nuclear power programs.

(3) Impact on the International System: the effects of latent proliferation on international law, international institutions, and the modes of international politics.

In (1) and (2), specific states and specific contingencies of war outbreak are considered. This discussion is very much in the variationist spirit. Under (3), a more abstract approach is followed. The final part of this chapter sketches several factors that will shape efforts to control the spread and intensification of nuclear capabilities.

2. Classification and Dynamics

From the earlier chapters, it is possible to identify the critical characteristics that will determine a nation's latent capacity to develop a nuclear weapon force. The two crucial measures of such a capacity will be the "potential scope" of the nation's weapon program and its "intensity of latency": That is, the size of the weapons program a nation may reasonably wish or be able to mount, and the quickness with which such a program could be achieved.

The first measure, the reasonable potential scope of the weapons program, depends on relatively stable or slowly-changing factors: the size of the nation's civilian nuclear power complex, the overall economic capacity of the nation, and quite generally, on the nation's political and strategic objectives. The civilian nuclear power program will determine in part the amount of fissile material the nation could produce and its degree of independence should other states wish to prevent it from developing a nuclear weapon force. The economic strength of the country will primarily affect its capacity to produce sophisticated delivery systems. Political and strategic objectives will determine the amount of effort the nation will willingly expend on a weapons program and the minimum level of forces at which the acquisition of nuclear weapons would appear worth the cost. There is of course a very strong and obvious, though not complete, correlation between these three factors, the countries with the strongest economics will tend to have themost substantial peaceful nuclear program and most ambitious strategic force objectives.

The intensity of a latent nuclear weapon program is here taken to refer to two related but nonetheless different capabilities: the "nearness" of a nation to a minimal nuclear weapon force (the acceptable minimum varying from nation to nation and depending on each nation's specific strategic requirements), and its nearness to a substantial weapon's effort fully commensurate with its strategic objectives. The intensity of a nuclear program will rise as various (not necessarily consecutive) threshholds are passed. Four such threshholds or decision-points especially may be identified.

(1) The decision to direct research and development toward the production of nuclear weapons. Unlike the following types, this decision may be implemented to a large degree in secret. Were the material available, a fission weapon probably could be produced by an industrialized country within two to three years from the time of such a decision.

(2) Various steps toward an independent capability to deploy nuclear delivery vehicles. Such steps would be visible and a matter for international concern, but for the most part would tend to be ambigrous and not likely to provoke serious response or censure. To be sure, if a country suddenly asserted a determination to produce hardened dispersed intercontinental ballistic missiles or sophisticated long range bombers, that is weapon systems which would make little strategic sense were they not to be armed with nuclear weapons, this would constitute a strong and threatening signal indeed. But, even here, the (probable) absence of any international agreement on strategic delivery vehicles and the lack of sharp distinctions among delivery vehicles comparable to that between nuclear and conventional warheads, will diminish the prospects for strong international reprisal. More

pertinently, the delivery system developments undertaken by non-nuclear countries are likely to be ambiguous in intent, useable in conventional military modes, in conjunction with the nuclear weapons of an ally, or as part of a civilian aviation program, or as part of a space exploration effort.

The alleged Israeli deployment of medium range surface-to-surface ballistic missiles affords an instructive illustration.

(3) Steps toward independent control of nuclear material. Three general actions of this type may be distinguished: the exploitation of safeguard loopholes, the renunciation of safeguard obligations, and the development of relevant indigenous capabilities.

a. Even within the context of safeguard agreements, states may in various ways move toward more independent positions. Several safeguard loopholes were considered in chapter 3, and all these may be exploited. For example, under the model safeguards agreement pursuant to the NPT, states may remove nuclear facilities involved in military missions from safeguards jurisdiction. The most striking opportunity for states to acquire nuclear material even under safeguards agreements derives from the ambiguous legal status of stockpile material. At present, there is no question that the safeguarded country can keep discharged plutonium in stockpile if it so wishes (albeit under safeguards). But as explained in chapter 3, there is doubt about the status of this material if the safeguard agreement is ended.[6] The first and quite legal step for a country wishing to acquire nuclear weapons would be to place discharged plutonium in stockpile in its own territory, neither sending it to the supplier country or IAEA, nor using it in its peaceful program.

b. States may attempt to remove themselves from safeguard obligations altogether either quite directly or through obfuscation. Such removal need not imply a decision to acquire nuclear weapons. For example, a state may simply withdraw from the NPT giving proper notice and explanation without at the same time announcing a weapons program. More drastically, a state may claim an intention to develop "peaceful" nuclear explosives as reason for withdrawal.

c. States may take steps to develop a self-sufficient nuclear fuel cycle, preferably but not necessarily, free of safeguards. Long-term sufficiency would require possession of all components of the cycle: uranium, an isotope separation plant, conversion and fabrication plants, and a reprocessing, and metal finishing facility, as well as the reactor. However, forward purchases or uranium and fabricated fuel elements could diminish the immediate need to construct the first three of these; only the reprocessing and metal finishing plant would appear absolutely necessary.

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[6]See Chapter 3, section 4.

(4) An overt weapons test. In a sense, such an action is now tacitly recognized as the demarcation between incipient and actual nuclear capability; a nuclear test signals the introduction of a new nuclear-weapon state. Such need not be the case. It has already been argued that a nuclear test may not be necessary to the development of at least crude nuclear weapons. The obverse may also be true; a nuclear test, surrounded by a declaratory policy against the production of deliverable nuclear warheads, would not necessarily signal the initiation of a full nuclear weapons development effort. Nevertheless, a nuclear test would in most cases provide the clearest threshhold beyond which a nation could develop a nuclear force unimpeded if no sanctions were imposed at once.

Latent Capabilities: A Country Survey

In this section, we wish to apply the preceding framework to the actual spread of nuclear power capabilities. In particular, we will want to investigate the time frames at which the various intensity threshholds could in principle be passed.

As indicated, the scope of a latent capability will be relatively slow-changing and roughly correlated with the economic power of the nation; and the seemingly most important non-nuclear states may initially be classified in this manner, as is done in the following chart. The classification closely follows the ranking of civilian nuclear power programs, with a few exceptions. Thus, Japan and Germany have by far the largest projected nuclear power programs among the non-nuclear states: Canada, Sweden, Switzerland, Italy, and Spain have projected programs exceeding 4,000 MW_e installed by 1980; etc. However, because of strategic imperatives, India and possibly Australia will probably want to develop a medium-size force should they decide to develop nuclear weapons at all. The "sophisticated" label simply refers to the nation's general technical and scientific level and its ability (and strategic demand) to develop fairly sophisticated weapons and delivery systems.[7]

The countries in this list which seem of particular interest are Japan and Germany; India, Australia, and Sweden; and Israel. These have variously been considered the closest to a nuclear decision; they will be looked at more closely below along with a general survey of the small-unsophisticated nations, one of which it is well to remember could well become the sixth nuclear state.

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[7]The reader is referred especially to chapter 1, Table 16, and to Chapter 2, section 4.

Nations Classed by

Scope of Latent Nuclear Capability

Large - sophisticated	Japan
	W. Germany
Medium - sophisticated	Canada
	Sweden
	Switzerland
	Italy
	India
	Australia
	Spain
	Pakistan
Small - sophisticated	Israel
	South Africa
	Belgium
	Netherlands
Small - unsophisticated	Argentina
	Brazil
	Mexico
	Greece
	Turkey
	S. Korea
	Portugal
	Taiwan
	United Arab Republic

Japan

Under the basic Japanese atomic energy act the research, development, and utilization of atomic energy are limited to peaceful purposes; both large power reactors now in operation are under IAEA safeguards under trilateral transfer from the United States and Great Britain. All reactors now under construction will have IAEA safeguards attached under the Japanese-American-IAEA trilateral agreement; these reactors all use enriched uranium. In addition, it is expected that Japan will eventually ratify the NPT thus subjecting all future power reactors to IAEA safeguard in any event.[8]

However, the Chugoku #1 reactor now under construction is being Japanese-built; and there is no question that Japan is now capable of building its own reactors without American or other foreign assistance. Several reactors now planned for construction with operation targets between 1974-76 could be developed by the Japanese alone. Safeguards attached directly to these reactors would derive only from direct agreements between Japan and the IAEA, not from obligations to the United States or other suppliers. In some respects, these agreements may in consequence be easier to break; they might also leave ambiguous the status of stockpiled plutonium.[9] Even with these reactors, the United States would have residual safeguard rights as long as the reactors were fueled

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[8]Foreign Reactor List, 18-19; Nuclear Legislation, 117-131.

[9]See Chapter 3, section 4.

with U.S. supplied enriched uranium. These safeguards would not, however, persist on the reactor if the fuel were ultimately derived from another source, indigenous or from another supplier, such as the Soviet Union.[10]

Aside from reactors, Japan possesses other key elements of an independent nuclear fuel cycle - notably a plutonium separation facility. Japan on the other hand does not possess an indigenous source of uranium or an isotope separation capability. However, given the very rapid growth of Japan's nuclear power program which is founded almost entirely on enriched uranium reactors, an enrichment capability might make economic sense sometime during the next few years, and the Japanese nuclear industry is unquestionably interested in such an eventuality.[11]

The picture that emerges from this is that Japan could not have unsafeguarded plutonium any time before 1977, which is three years after the earliest possible criticality date of planned power reactors not yet under construction.[12] Since it seems unlikely that Japan would begin construction of an isotope separation capability before 1973-75, and assuming a 3-4 year construction period, Japan could also not have an indigenous enriching capability much before 1977. To achieve an independent control over plutonium even at this date, Japan would have to assert immediately that reactors about to enter the construction phase

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[10] The Soviet Union has entered the commercial market with an agreement with Sweden. Nuclear Industry, 1970, 71.

[11] See for example comments by R. Imai in Civilian Nuclear Power and International Security, 37.

[12] That is, they could not have such plutonium without breaking safeguard agreements with the United States and Great Britain.

would not be safeguarded, a very unlikely eventuality; or it would have to break or withdraw from a safeguards agreement with the IAEA.

Germany

Germany has several operating power reactors, all of which are under Euratom safeguards and all but one employing enriched uranium supplied by the United States.[13] In addition to the reactors in operation, Germany has several reactors under construction and several more planned. These will all employ enriched uranium. Both currently operating and new reactors will be under Euratom and IAEA safeguards as well if Germany ratifies the NPT as expected. Germany is obliged by the Western European Union and Euratom Treaties to attach safeguards to all its nuclear facilities.

West Germany does not possess an independent source of uranium. (East Germany does have uranium.) Nor does it now have an enrichment capability. Here, however, it is actively pursuing a centrifuge technology in collaboration with Great Britain and the Netherlands. In connection with this tripartite effort, there are as yet no definite plans for the construction of actual centrifuge facilities in Europe. But such construction will probably begin within the next few years in which case the specific location of the facilities will become a matter of controversy. It is probable that the Soviet Union and perhaps the West European countries as well would not look kindly on an enrichment facility on German soil even if it were under safeguards and under the control of a

[13] Foreign Reactor List, 11. The MZFR reactor at Karlsruhe uses natural uranium and heavy water. This reactor has a 50 MW_e power rating, and went critical in 1965.

three-nation consortium.[14] Apart from the uranium and enrichment facilities, Germany has all other necessary components of a self-sufficient nuclear industry: reprocessing plants, uranium and plutonium conversion and fabrication facilities, and a highly articulated research and development program, including extensive facilities engaged in the development of fast breeder reactors.

India

India now possesses three operating power and large research reactors: the CIR (Canadian-Indian Reactor) at Trombay, with power output of 40 MW_t; and the TAPP I and TAPP II slightly enriched uranium reactors at Tarapur, with combined power output of 380 MW_e. In addition, two reactors, RAPP-I and RAPP-II, each 200 MW_e, are under construction in Rajasthan; the first is due to become critical in 1972, the second in 1974.[15] TAPP I and TAPP II were U.S. built, and are covered by IAEA safeguard under a U.S.-India-IAEA trilateral; the United States maintains residual safeguard rights. The United States also supplies fuel for the reactor. It seems highly unlikely that India would attempt to use plutonium from this reactor for weapons purposes, all the more because enriched uranium reactors are relatively inefficient plutonium producers.[16] The RAPP-I and RAPP-II reactors are being built by the Canadians. Both reactors are of the "CANDU-type," employing natural uranium fuel and heavy water as the moderator and coolant. The reactors will be covered by IAEA safeguards under a Canada-India-IAEA trilateral.

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[14] See Chapter 1, 17-18.

[15] Foreign Reactor List, 14.

[16] Ibid., 14. Also see Chapter 2, 13-19.

This leaves the CIR, a large research reactor (40 MW_t) which uses natural uranium and is heavy water moderated and light water cooled; the reactor became critical in 1960. Assuming a possible plutonium production of 200 grams per MW_t per year, the CIR reactor could have produced perhaps 80 kgm over the past decade, enough for a few weapons. The CIR is under no formal safeguard agreement, and the Indians are not obliged to submit it to Canadian or international inspection; nor have they done so. Nonetheless, India has promised the Canadian government on several occasions that it would use the CIR for peaceful purposes only, a promise which was recently reemphasized by Madam Ghandi in quite striking terms. If India does not use the CIR plutonium, it is not likely to acquire any plutonium at all for weapons purposes (from indigenous sources) until the late 1970's at the earliest. The two other power reactors now planned, one of which has just begun construction, are of the CANDU-type and will fall under the Canada-India-IAEA trilateral agreement requiring IAEA safeguards. Neither of these reactors is expected to become operable before 1976-78.[17]

Apart from the safeguard constraints, India has an impressive capability to develop nuclear weapons. Atomic research has been pursued vigorously for several years with a quite excellent scientific establishment; it would be surprising if there has not been substantial explorations of nuclear weaponry. In addition, India has its own plutonium separation capability, and enough uranium to support a moderate weapons and power program. India of course also has enormous amounts of thorium which could support a very large nuclear program based on a thorium cycle.

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[17] Ibid., 14.

Australia

Although Australia has no power reactor now in operation or under construction, nor any reprocessing plant or significant fabrication capability, it does plan to construct a 500 MW_e reactor sometime in the late 1970's, and has requested tenders for its construction.[18] The specifications in these requests by the Australian government impose a requirement of independence. Tenderers have had to show how Australia could avoid undue dependence on foreign suppliers. Several solutions are being offered. The United States, which in proposing the construction of an enriched uranium reactor, has offered fuel supply contracts covering 30 years with 5 years future consumption to be maintained in Australia at all times. Great Britain and Germany are also offering enriched uranium reactors and combining this with a willingness to construct a centrifuge isotope separation facility in Australia. Canada is offering a natural uranium reactor which would permit Australia to bypass the isotope separation process altogether. Australia has sufficient supplies of its own natural uranium.[19]

Sweden

Sweden has both a very impressive civilian nuclear power program and a sophisticated aircraft capability. At the moment, Sweden has two operating power reactors, a natural uranium reactor of 65 MW_t which became critical at the end of 1963, and an enriched uranium reactor of 440 MW_e

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[18] Foreign Reactor List, 2. Leonard Beaton, "The International Political Context," in Civilian Nuclear Power and International Security, 75-76.

[19] Beaton, "International Political Context," 75-76.

which has just become critical. A third reactor is under construction and due to begin operation in 1974-75; it is an enriched uranium reactor of 580 MW_e. In addition, three other power reactors are planned to be completed by 1975-76. Beyond these, the Swedish government has proposed the construction of 6 other large (750 MW_e) reactors before 1980.[20]

The small 65 MW_t reactor in operation since 1963 could have produced perhaps 60 kgm of plutonium. This represents the only indigenously produced plutonium that could now be available to Sweden. The 440 MW_e reactor which has just entered operation could produce about 100 kgm of plutonium per year, the first recoveries of the plutonium occurring during 1972-73. Both of these reactors are under IAEA safeguards, however. Sweden has also ratified the NPT and is now obliged to submit its entire nuclear power program to international safeguards.

Sweden does not now have a plutonium separation plant, but given the size of its program may soon wish to construct one. Sweden does have vast quantities of uranium extractable at prices about double the current world price.

Israel

Israel's only operating reactor capable of generating significant amounts of plutonium is the Dimona reactor near Beersheba. This French-built reactor employs natural uranium, and is heavy-water moderated. Its power rating is 26 MW_t; it became critical in 1963. Given a plutonium production rate of 200 grams per MW_t per year, Dimona could have produced about 30-40 kgm plutonium up to the present. The annual rate of

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[20] Foreign Reactor List, 24.

production is about 5 kgm per year. There is little public information available on what has been happening to this plutonium. So far as is known, there is no plutonium separation facility in Israel. The plutonium may have been separated in France and conceivably then returned to Israel, although this is not known either. Dimona is not under international or bilateral safeguards; however, for the past few years, the United States has been permitted to conduct annual inspections of the facility. These inspections have evidently reassured the United States that the Dimona reactor plutonium has not been diverted to weapons purposes.[21] If it has not, then Israel could not have any fissionable material unless it were supplied by France or the United States.

Other than Dimona, Israel plans to construct some sort of power reactor in the late 1970's, and a couple thereafter. Evidently, Israel would have sufficient uranium to fuel these reactors; it expects to be able to produce 50 tons of uranium per year from indigenous phosphates.[22]

Many observers believe that Israel may already be prepared to construct nuclear weapons in a few weeks from a go-ahead, if it somehow has obtained the fissile material. Israel certainly has the technical ability to develop quite sophisticated nuclear weapons without testing, and must have already undertaken considerable research to this end. In addition, the Israeli development of the Jericho missile has raised

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[21]See, for example, Beaton, "International Political Context," 78.

[22]Z. Ketzinel (Israel Atomic Energy Commission), "Uranium Sources, Production, and Demand in Israel," A/CONF. 49/P/013, Fourth United Nations International Conference on the Peaceful Uses of Atomic Energy, 6-16 September 1971.

speculation about Israel's nuclear capability on the grounds that the missile could scarcely be useful without a nuclear warhead. This assumption, however, is by no means compelling; Israel has evinced considerable imagination in the deployment and use of modern conventional weapons, and a highly accurate surface-to-surface missile even equipped with a non-nuclear payload could conceivably fulfill a significant purpose.[23]

Non-Threshold States

With respect to other countries of particular interest, the situation may be reviewed more briefly. Pakistan is constructing a natural uranium reactor of the CANDU-type (125 MW_e) to become critical in 1971. This reactor will be covered by IAEA safeguards under a trilateral Canada-Pakistan-IAEA agreement.[24] Argentina is deploying a German-built enriched uranium reactor to become critical in 1972. This reactor will be subject to a U.S. bilateral agreement and to IAEA safeguards under German insistence.[25] Taiwan has an enriched uranium reactor under construction to be completed by 1975. This reactor has a power rating of 604 MW_e and will be safeguarded by the IAEA under a U.S. bilateral agreement.[26] The Pakistan, Argentine, and Taiwanese power reactors are the only three actually under construction in the developing countries (aside from India).

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[23]See New York Times, October 4, 1971, 1.

[24]Foreign Reactor List, 21.

[25]Foreign Reactor List, 1; U.S. A.E.C., OSMM, private communication.

[26]Ibid., 5.

Among other states outside of Europe, Chile and Brazil each plan to construct a reactor sometime after 1975. Greece and Turkey propose construction of reactors by the mid-1970's; neither could have access to indigenously produced plutonium until about 1978-80. Korea and Thailand in Asia propose construction of reactors in the mid to late 1970's. The UAR has rather vague plans for the construction of a power reactor; no target date has been set and it is unlikely that a reactor could be completed before 1978-80 at the earliest. Until completion, the UAR will not have access to any indigenously produced plutonium. South Africa has no current plans to construct a power reactor but does possess considerable technical competence, a substantial research reactor, and of course extensive supplies of uranium. Among the countries of East Europe, only Czechoslavakia and East Germany have power reactors in operation. The Soviet-built Czech reactor employs natural uranium and has a power-rating of 150 MW_e. The East German reactor, also Soviet-built is a 70 MW_e enriched uranium reactor. These two countries and Hungary and Poland as well plan construction of other reactors between 1975-1980. All these reactors will presumably be under Soviet and IAEA safeguards.[27]

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[27] *Ibid.*, 1-45.

Table 1. Intensity of Nuclear Power Programs

	Probable Adherent to NPT?*	Uranium**	Reprocessing***	First Pu Stockpile ****	First Indigenous Pu *****
West Germany	yes	no	yes	now	1978
Japan	yes	no	yes	now	1978
Canada	yes	yes	yes	now	now
Sweden	yes	yes	no	now	1978
Switzerland	yes	no	no	now	1978
Italy	yes	no	yes	now	1977
India	no	yes	yes	?	1980
Australia	yes	yes	no	1978	1980
Spain	yes	yes	yes	now	1975
Pakistan	no	no	no	1972	1980
Israel	no	yes	no	?	1980
South Africa	yes	yes	no	1980	1978
Belgium	yes	no	yes	now	1977
Netherlands	yes	no	no	now	1977
Argentina	no	yes	yes	1975	1980
Brazil	no	?	no	1979	1980
Mexico	yes	no	no	1978	1980
Greece	yes	no	no	1978	1980
Turkey	yes	no	no	1982	1980
South Korea	yes	no	no	1976	1980
Portugal	no	yes	no	1981	1980
Taiwan	yes	no	no	1978	1980
UAR	no	no	no	1981	1980

Notes:

*Based on State Department Memorandum, March 1971, on "Status of Treaties Curbing Nuclear Weapon Proliferation," subsequently updated to December 1971. The following important countries have neither signed nor ratified: India, Pakistan, Israel, Cuba, Argentina, Brazil, Chile, Portugal, Algeria.

**Are there sufficient reserves? See Chapter 1.

***Operating and Planned.

****However safeguarded.

*****Earliest date at which plutonium could be recovered from reactors built essentially indigenously; such reactors may have IAEA safeguards attached under NPT agreements.

Summary

The general picture that emerges may best be described in reference to the four thresholds adduced at the beginning of this section: weapon's research and development, delivery vehicle acquisition, nuclear testing, and independent control of nuclear material. First, it may prudently be assumed that one threshold has already been passed by most of the sophisticated countries, the decision to devote research and development effort to the development of nuclear weapons. This would be partly inevitable for states undertaking research on fast plutonium reactors. In any event, fast reactor research ensures that these states have large quantities of plutonium available and facilities appropriate for weapons research should they have made the decision to proceed with such research. It is entirely possible that Israel and possibly India are merely weeks away from the construction of a weapon could they obtain the fissionable material. The status of countries with respect to the second threshold, the acquisition of appropriate delivery vehicles, seems more ambiguous. Furthermore, steps to intensify this capability also tend to have an ambiguous character, and it appears difficult to say much about this dimension of intensification. The third threshold, the actual test of a nuclear weapon, has been passed by none of the countries here considered. This leaves the various degrees by which nations can secure an independent disposition of nuclear material as the decisive and visible steps toward an increasingly intense latent capability.

The situation in this respect is much clearer. Unless the important non-nuclear countries are willing to break a clear bilateral agreement with the United States, United Kingdom, or Canada (and, in most cases, the IAEA as well, though this might be easier), they could not acquire fissile material useable for weapons before 1977-78 at the earliest.[28] The crucial thresholds toward independent control are thus not likely to take place for another 5 to 10 years if the supplier states, the United States above all, maintain a strong insistence on the continued adherence of the affected states to their safeguard obligations. By 1980, however, several states will have reactors safeguarded only under agreements pursuant to the NPT voluntarily entered by the host country.

Prior to this time, several countries will begin to accumulate a plutonium stockpile (albeit under safeguards). They will also develop an increasingly independent nuclear fuel cycle.

There is indeed now little inclination within the international community to restrain the growth of the nuclear power industry or to hamper any state's quest for an independent nuclear power program. For example, because of the current very marked preference for enriched uranium reactors, several nations have become keenly interested in the construction of new enrichment facilities, partly to serve (with profit) the growing demand for enriched uranium and partly to provide an independent source for their own fuel. There is no concerted international effort to discourage such development. Nor does it appear practical to constrain the new facilities to the production of only low enriched uranium. First, if the new facilities employ centrifuge technology, they will probably be intrinsically sufficiently flexible to produce highly enriched (weapons grade) product whatever the initial design goal. Secondly, there may be

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[28] Possibly excepting the Israeli Dimona reactor and the Indian CIR reactor.

legitimate commercial reason to produce highly enriched product, to serve for example high temperature gas-cooled reactors or breeders. Plutonium enrichment (in Pu-239) would also appear a potentially useful commercial activity. Similarly, national nuclear industries will see commercial merit in the construction domestically of other key nuclear facilities: reprocessing plants, fabrication and conversion plants, metal finishing factories, etc. This is already happening.[29]

Apart from the intensification of latent capability being achieved in this manner, nations have become increasingly able to secure a more independent position through the forward purchase of enriched and natural uranium. Such contracts, perhaps most often attached to a specific reactor purchase, would require the supplier to provide at all times uranium sufficient to fuel a specified reactor or reactors for several years. That is, fuel to maintain several years future consumption would be stockpiled in the purchasing country at all times.

This then sketches the capabilities of states to intensify their nuclear power program and eventually to acquire nuclear weapons. But will they actually do so? What is the calculus of benefits and costs, and the locus of political power within the states which will determine this issue? Section 5 of this chapter will address these questions in a peripheral fashion, but for the most part this study concentrates on capability of development, not utility of possession. It does seem important, however, to emphasize the critical importance of the intensity of latency to the internal debate within countries whether to acquire

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[29]See Chapter 1, section 2.

nuclear weapons. That is, one should not think that the national decision to embark on a nuclear weapons program is independent of the status of the civilian program at the time of decision. Thus even if it were true (as it may not be!) that any nation determined to acquire nuclear weapons could eventually do so despite international safeguards and sanctions, safeguards and sanctions would remain important as a discouragement to the initial determination. A nation with large amounts of unsafeguarded plutonium lying about would be more likely to stumble onto a nuclear weapon decision than were the political and economic costs of acquisition high and uncertain.

The instance of the French nuclear program provides a suggestive illustration. Whereas the American, Soviet, and (probably) Chinese decisions to acquire nuclear weapons clearly preceded any latent capability, the same was not true for the French, and in a sense was not true for the British either. Great Britain, however, occupied a unique position after the War, and France affords the only example that seems clearly relevant to the decisions confronting the non-nuclear states today. The striking characteristic of the French situation was that France drifted to the bomb. An independent and highly intensified latent capability developed prior to any clear government decision to embark on a weapon's program. In the early stages, the scientific community, and civilian and military leaders were divided on the desirability of a weapons program but all could support the development of a strong peaceful nuclear program.[30] But once this foundation was established, itimmediately

[30] Lawrence Scheinman, Atomic Energy Policy in France Under the Fourth Republic, 109-111.

became easier for those who wanted the bomb to prevail. It is one thing for a government to launch an expensive and uncertain weapons program that could not reach fruition until well after the expected life of the government itself, and another to make the crucial decision at a time when the critical material is at hand and much of the necessary resources already expended. At this point, it could be difficult for a government to withstand pressure to proceed to a weapon's program. This drift is captured well in Scheinman's study of French atomic policy during the 1950's:

> What was the major import of the first Five Year Plan for French atomic development? In the first place, it may be termed an "industrial production decision" as opposed to a "research decision." It involved a shift of emphasis from research reactors to high-power reactors designed to produce the fissionable material necessary to fuel secondary reactors from which energy could be recuperated. Secondly, the decision to produce plutonium had the long-range probability of relieving France of its reliance on foreign sources for fissionable material. With this independent source of fissionable material, France would then be free of restrictions and limitations on the use of such material as may have been imposed by supplier-nations. Finally, the production of fissionable material meant that the seeds from which a nuclear arsenal could grow were being sown -- a situation which, in the long run, could have profound effects on France's role in the international community and on the weight of her authority as a world power. Despite the public protestations that plutonium was to be produced solely for peaceful purposes, there is no doubt that at least some of the individuals responsible for this decision intended that the plan would blossom into a weapons program. There is adequate support for this conclusion in a recent publication by one of the highest officials in the French Commissariat and a member of that organization since its inception, Bertrand Goldschmidt. In discussing the Five Year Plan, Goldschmidt notes that "the five year plan of 1952 mentioned no eventual use of plutonium for military ends, a decision on this subject not having been taken for several years. It is certain, however, that this aspect of the atomic problem was present, <u>and undoubtedly predominant</u> in the mind of those who inspired and were responsible for the plan."

French interest in the possession of a nuclear weapon is readily comprehensible. What is less easily understood is the manner in which France decided to produce the bomb. For it was not a single decision, a clear-cut long-range policy rationally planned and executed, but rather a series of events and decisions -- or, perhaps, lack of decisions -- which led to the Sahara test in 1960. The most candid statement to the effect that France drifted toward the possession of an atomic bomb without the project ever receiving official sanction at the cabinet level, is found in the following statement which issued from a ranking member of the Quai d'Orsay and of the Atomic Energy Committee: 'On the political level there had been no doctrine of French nuclear armament. In fact the manufacture of an atomic bomb, on which the work began well in advance of the decision which was not finally taken by the Government until very recently, wedged itself into our public life as a sort of by-product of an officially peaceful effort, there existing no overview of the problems involved, nor of the means necessary to solve them, nor of the results to be expected. Until a very recent date we found ourselves in the paradoxical situation of a country which already spent by virtue of ... accords ... between the Commissariat and National Defense important sums in view of a program of nuclear armament without the Government having taken the decision to make the weapons and also without a debate ... in Parliament to approve such a decision.

The question which arises, then, is how and why France developed a military atomic program. The argument which will be advanced in Part II of this study is that in the face of vacillation and indecisiveness by the government, and unawareness and abdication of responsibility by Parliament, policy issues were debated and resolved at another level, and that the elaboration of a military atomic program was guided by a small group of persons from the CEA, the military and the Government.[31]

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[31] Ibid., 85-86, 94-95. Perhaps better than "drift," the French atomic program could be characterized by a persistent effort to keep military options open. See for example Robert Gilpin, France in the Atomic Age, 282-288; Bertrand Goldschmidt, The Atomic Adventure, 97-101. As Gilpin puts it, "the French nuclear program was not the result of a systematic and rational calculation but it evolved step by step in a logical progression from scientific to industrial to military stages ..." (Gilpin, 282-282).

3. Threats to International Peace

Conventional Dangers - Causes of War

Intensification of a latent capability by a nation could provoke armed attacks by two types of international actors: non-nuclear adversaries or nuclear-weapon states, acting either in their own interest or as agents of a wider international consensus.

(1) non-nuclear regional adversary.

A non-nuclear state, persuaded that a regional adversary was about to intensify its nuclear capability, could be provoked to try to dismantle its opponent's nuclear weapon base, a course which would probably include, inter alia, attacks on civilian nuclear facilities. Supremely dangerous, regardless of the specific attack object, attacks on civilian power plants would be especially likely to lead to severe retaliation. The two most evident prospects for such a confrontation rise out of the Arab-Israeli and Indian-Pakistani conflicts. But ultimately there may exist such dangers in parts of Africa, in the Middle East (between Arab States), in Latin America, and in the divided countries, Vietnam and Korea.

Consider, for example, the Middle East situation. Should the United Arab Republic (together with the Soviet Union) become convinced that the Israelis were constructing an indigenous and independent nuclear capability, it may well try to dismantle the key facilities through overt strike or sabotage. This is perhaps not a plausible prospect today but it may become one. The Arab states would in any event incur large risk in such an undertaking, but might hope to limit Israeli retaliation if the attacks were carefully restricted to Israeli nuclear facilities, the Soviets were willing to extend guarantees of some sort to the involved Arab states, and the United States did not approve of an independent Israeli nuclear force. Particularly if part of the Israeli capability derived from an ostensibly peaceful power reactor supplying electricity to Israeli industry and people, the first restrictive condition could not be achieved; and in this case, any attack on the power plant would certainly be met by a severe retaliation. This prospect would make the initial attack less likely but more dangerous should it occur.

Let us turn the situation around. Should the UAR appear to be on the verge of an indigenous weapon capability, the Israelis might be tempted to attack the key facilities. Again such action becomes more plausible to the extent to which the nuclear ally of the target country opposes the country's attempt to obtain its own nuclear force. In any case, extreme vulnerability of Israel to nuclear attack would lead Israel to take extreme risks to prevent the introduction of nuclear weapons into the Middle East.

Whichever country moves first toward a nuclear force, the adversary may fear that the possession of nuclear weapons, first by one and then by both, would cement an undesirable status-quo; this perspective might then lead it to attack either the nuclear facilities or the adversary's country itself before its enemy's nuclear weapons could be brought into play.

Similar dangers are present in other cases as well. For the forseeable future, the nuclear powers will probably oppose the acquisition of nuclear weapons by India or Pakistan. Thus whichever of these two countries moves toward nuclear weapons first, it will risk attack by its adversary with perhaps minimum prospect that the adversary will be deterred by fear of nuclear power censure. Also, as in the Middle East, fear of a premature freeze on still open political issues (notably over Kashmir), could in itself provoke a preemptive strike or ground assault.

Many other instances of these sort might be noted. In Africa, the imminent acquisition of nuclear weapons (or simply unsafeguarded plutonium) by South Africa or Rhodesia could encourage preemptive attack. Similarly, in the Somali-Ethiopia dispute, the unilateral acquisition of nuclear weapons by one country would be deeply provocative to the other. In the South African and Rhodesian cases, the acquisition of nuclear weapons by these status-quo powers might appear intolerable to revolutionary states even if the latter could acquire their own weapons or were protected by reasonably firm security assurances.

(2) nuclear weapon states

A nuclear weapon state, in an effort to maintain the present five power monopoly of nuclear weapons, would be under some persuasion to initiate preemptive attacks against a non-nuclear state that visibly moved to intensify its latent capabilities. The motive for such action by a nuclear power would not be quite that of the non-nuclear regional adversary that feared its opponent would gain some decisive advantage -- that once the non-nuclear state achieved even a minimum weapon capability, the risks and political costs of trying then to dismantle its nuclear facilities would be too high to prevent the opponent from developing at will a large nuclear weapon force. Moreover, as is apparent from the discussions of Chapter 2, the technical difficulty of destroying a nation's capacity to produce nuclear weapons and the scope of targets required to do so would increase alarmingly once the nation gathered a sufficient stockpile of fissile material. For this reason, any move by a non-nuclear state to unlock safeguards on nuclear material even were such movement not accompanied by an explicit initiation of a weapons program would be bound to appear provocative to an unfriendly nuclear power. Such a move, or any other significant intensification of latent capabilities by a non-nuclear nation, could also encourage a nuclear actor to take preemptive action as an agent of a status-quo world order even were the offending nation not of direct concern to the nuclear state. For, it would be widely apprehended that were one non-nuclear nation to strive for weapons status, others would be tempted to follow.

The Cuban missile crisis lends vivid support to the dangers described above. Although the transfer of nuclear-armed missiles to Cuba by the Soviet Union was a different type of action than the kinds being considered here, it did include the essential elements of a non-nuclear country reaching a position in which it could soon deploy nuclear weapons and of a nuclear power determined to strike before such deployment were effected. The Cuban crisis also illustrated the special dangers inherent in situations in which the time from latent to actual capability is very short, and thus in which military solutions come to appear more attractive than the more ponderous diplomatic and economic measures.[32]

For the future, the most dangerous provocation of the kind under review here would be a dramatic intensification of West Germany's latent capabilities. Several such steps may be imagined, both of a technical and legal character. In the first category, Germany could heighten an already impressive latent capacity to produce nuclear weapons by the construction on German soil of an isotope separation facility, especially

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[32]See, for example, Theodore Sorenson, Kennedy, 667-718. Arthur Schlesinger, A Thousand Days, 794-819.

one based on a centrifuge technology in which Germany is preeminent. As argued earlier, centrifuge plants are more flexible than gaseous diffusion complexes, allowing a much easier conversion to weapons purposes.[33] Less significant, but also potentially troublesome to the Soviet Union, would be German participation in a centrifuge consortium such as the contemplated tripartite arrangement with the Netherlands and United Kingdom.[34] It may be expected that the Soviet Union will strongly oppose any attempt to place any of the arrangement's plants in Germany. A second type of technical step toward an independent nuclear capability would be any German effort to develop a full missile or rocket system. At the moment, Germany is cooperating with ELDO in the development of a satellite launching system by producing the upper stage of the proposed rocket.[35]

If either of these actions were taken with the approval of the NATO allies, it is quite unlikely that the actions would be intolerable to the Soviet Union; in themselves, the steps would not constitute an irrevocable threshold. By comparison, any dismantling of legal obligations by Germany relevant to nuclear independence would probably provide a severe provocation. Should, for example, Germany renounce the NPT or even merely its safeguard clause (Article III), the intensification of latent

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[33]See Chapter 1, section 2.

[34]See Chapter 1, section 2.

[35]Janes World Aircraft 1970-71, 650.

capability thereby effected would no doubt cause strong reaction, including possibly strikes against Germany by the Soviet Union or conceivably others. Such reaction would be the less likely the more ambiguous the action.

The Soviet Union will in addition very strongly oppose any European development, which could eventually help provide Germany with an independent nuclear capacity. Thus, it must be expected that any significant degree of independence from the Soviets by East Germany or Czechoslavakia will be combatted, for a variety of reasons of course, but also because the two countries have large uranium reserves which West Germany does not. A Soviet spectre that the Federal Republic, whose chief lack as an independent nuclear power is uranium, may gain access to the reasonably rich uranium deposits of East Germany and Czechoslavakia might thus partially explain the Soviet invasion of Czechoslavakia. (It is certainly clear that the Soviet Union values Czech uranium for which the Soviets have been paying a price fixed far below the world market. The Soviets had reputedly ordered Czechoslavakia as early as 1967 to stop negotiations with Canadian private interests on possible cooperation in Czech uranium mining.)[36]

Japan provides another illustration similar to the German example in several respects. Japan will soon be operating a very large civilian nuclear power program with large stocks of plutonium potentially available; it could also in the near future possess a rather large rocket force.

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[36]State Department, private communication.

Significant intensification of this latent capability would require (in roughly ascending order of seriousness), the production of large numbers of suitable rockets (which possibly could be accomplished under cover of a space and scientific program), construction of indigenous reactors and/or isotope separation plants, an accumulation of a plutonium stockpile, a withdrawal from safeguard obligations, and an explicit rejection of safeguards on the plutonium stockpile. Japan has already staked out a greater degree of nuclear independence by contracting for enriched uranium from the Soviet Union as well as the United States.

China has looked at the burgeoning Japanese nuclear capability with considerable alarm as evidenced by the released transcripts of Chou-en-Lai's recent conversation with James Reston.[37] Although, it is not easy to trace out plausible ways Japan could employ a nuclear force against China or others, China, itself, may have less trouble imagining such employment and take considerable risk to prevent the development of such a force in the first place. Such risk would be the more likely if the American position were ambiguous, neither clearly in favor nor opposed to the Japanese effort.

Elsewhere in Asia, movements to acquire nuclear weapons, whether in India, Indonesia, Japan, or Korea, could also well provoke a Chinese response, again an unlikely event but possible, especially if the United States and Soviet Union do not provide clear security assurances to the victimized countries.

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[37] See New York Times, August 10, 1971, 14:1.

While the German and Japanese situations present the clearest dangers should these countries seek nuclear weapons, confrontations involving less powerful countries may actually be more probable. Just because of the clearly unsettling dangers of a German or Japanese move to acquire nuclear weapons, the allies of these countries will probably strongly discourage such movement. Situations more marginal to the security interests of the nuclear weapon states may thus ironically be more plausibly explosive. Several such situations may be imagined. Should South Africa or Rhodesia, for example, suddenly appear on the verge of acquiring nuclear weapons, one or several nuclear powers might be tempted to undertake a preemptive attack even if no international approval of such action were forthcoming. In the case of Rhodesia, the nuclear actor could well be the United Kingdom, one of the few instances one can imagine them acting unilaterally in such a situation. The Middle East also could be the scene of direct nuclear power intervention to prevent significant enhancements of the latent capabilities of the nations of the area. Although America and the Soviet Union are the most likely candidates for such a role, it is not difficult to imagine contingencies in which France, the United Kingdom, or even China might wish to intervene. The United States also, especially if it could persuade itself it were acting as an international agent, would strongly oppose any dramatic improvement in the latent capacity of Latin American countries, as in a sense was done in Cuba, even if the countries involved were not Communist or particularly hostile. Were this last not the case, the pressures for U.S. intervention would be correspondingly increased, as would the possibilities of a Soviet or Chinese counter-response.

Unconventional Threats

The acquisition of nuclear weapons by criminal or terroristic groups presents the most vivid spectre raised by the proliferation of latent nuclear capabilities. Such a threat is very real. The knowledge and non-nuclear material required to produce a crude nuclear device will probably be available to large numbers of individuals in many countries by 1980 when both the production of plutonium and the international traffic of nuclear material will reach staggering proportions.[38] Although able scientists may be difficult to recruit for such illicit ventures, sufficient numbers probably could be gathered; it would in any case not be prudent to think otherwise. Impressive technical competence is apparently required, for example, to operate illegal narcotics operations.[39] It also appears reasonable that some scientists could be recruited into political terroristic groups either of the left or right. This means that as with states the fissionable material will be the significant obstacle to the development of a weapon by non-governmental groups. But as indicated in Chapter 3, safeguards as now conceived do not provide adequate security against illicit acquisition of nuclear material by such groups.

Similarly once a nuclear device is produced, delivery would not appear a significant problem.[40] Indeed, for many purposes, delivery might not

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[38]See Chapter 1, section 5.

[39]See, for example, U.S. Bureau of Narcotics, Traffic in Opium and Other Dangerous Drugs.

[40]See Chapter 2, section 4.

even be necessary at all if the device were detonated at the site of its construction. Also, of course, as with national arsenals, the threat of use may serve the party's political purpose far better than actual use. It is also important to recognize that because of the admitted dispersion of nuclear know-how, the mere diversion of material, with the consequent threat that it could in principle be fabricated into a weapon, could in itself provide a foundation for criminal and political blackmail.

Three types of non-governmental actors would find purpose in the acquisition of nuclear weapons, even of a crude variety. Most obviously, nuclear weapons provide a source of criminal blackmail of an unprecedented magnitude. A few recent attempts to extort money from governments and airlines under threat of destroying a passenger aircraft provide perhaps the clearest analog of such a blackmail scheme.[41] There is also precedent for high risk, high gain thefts, for example, complex hijacking operations.[42]

Political groups determined on terror and threat as a means of political persuasion comprise a second type of non-governmental actor

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[41]The nuclear blackmail idea has recently also crept into detective and adventure fiction, which in fact provides a rich source of diversion and blackmail scenarios: For example, this theme is treated in one way or the other in Martin Caidin, Almost Midnight; Walter Wager, Viper Three; William Green, Spencer's Bag; and Desmond Cory's, Sunburst. It is probably well to keep in mind Ross MacDonald's assertion that "the detective novel ... may at this moment have within it secrets of what we are and shall be."

[42]See Chapter 3, section 4.

that may find nuclear weapons useful. The U.S. A.E.C. has claimed to have discovered 37 such groups in the United States alone.[43] While this number probably need not be taken seriously, certain domestic extremist groups of both the right and left may be willing to consider at least the threat of nuclear use for political purpose, although no group has apparently yet entertained a deliberate policy of violence designed to kill innocent people. The threat may be still more serious outside the United States, where there have been examples of political violence directed against people. The tactics of the OAS in France during the end of the Algerian struggle affords such an example, as does the use of violence by Arab terrorists in Palestine. One might also imagine desperate political blackmail in South Africa, Rhodesia, Angola, Nigeria, and several other countries as well where oppressed groups may see no other recourse against a perceived repressive government.

The groups just considered would use the threat of nuclear weapons to jostle society; they might or might not wish to identify themselves. The third type of non-governmental actor that may be identified is the group with purpose not so much political persuasion, but rather political power. Military or para-military groups in certain Latin American or African countries might someday wish to employ nuclear weapons for such purpose. Conceivably, revolutionary or anti-colonialist groups seeking power would as well seek to use nuclear threats in an attempt to gain power.

Aside from these three "rational" purposes - criminal blackmail, political persuasion, and political power - all of which depend on the

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[43]See Chapter 3, section 4.

threat of nuclear use rather than the actual detonation of devices, irrational purposes and actors may also be imagined. As a means to wreak vengeance on a society or to otherwise inflict violence, nuclear weapons have few peers, and one cannot altogether rule out the use of nuclear weapons by persons who could expect no rational gain from such action at all. Such use need not be against one's own country. There is considerable concern by the current nuclear weapon states that deployed nuclear weapons could be launched by unauthorized personnel, for example, a small group on a nuclear submarine. The spread of latent nuclear capabilities raises a similar sort of danger rising from similar psychological impulses; a person or group may decide to deliver a nuclear weapon on an adversary nation in the name of its own state. Terrorist and guerilla groups in the Middle East provide a ready illustration of this danger.

Two other unconventional threats closely relate to those posed by the acquisition of nuclear weapons by non-governmental groups. These flow from the acquisition and use of nuclear devices by "pseudo non-governmental" groups and from the employment of "anonymous warfare."

In the first case, a government might well try to mask its own diversion of nuclear material and conceivably the threat or use of weapons under the guise of a criminal diversion or activity. If successful, the government could perhaps be accused of negligence but not of overt violation of safeguard or other similar agreements. This is one reason that domestic safeguards systems must be highly effective and supplemented at key points by international safeguards including if at all feasible physical security of the fissionable material.[44] Once in possession of the material, the

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[44]See Chapter 3, section 4.

government in question could proceed to develop a weapon, later to be made public; or it could deploy the weapon, again under cover of a non-governmental group, thus hoping in this manner to avoid retaliation or international censure. This would be a risky venture of course for any state, but not one altogether out of the question; again, the Middle East provides the most plausible setting for such adventures.[45]

The possibility of clandestine diversion of nuclear material may also encourage the employment of anonymous warfare, where the source of attack is neither acknowledged nor known. Not only would a widespread distribution of unsafeguarded material permit the anonymous use of nuclear weapons, the danger of such use would itself provide a rationale for anonymous attack on an adversary's nuclear facilities. Among the cases considered in the preceding section, it is evident that several could involve unacknowledged attacks on the opponent's nuclear plants.[46]

Finally, small countries may value the possession of crude, and perhaps initially unacknowledged, nuclear weapons as a means to deter a powerful adversary in some desperate contigency. Even were these

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[45]The use by a government of criminal agents to achieve an apparent theft of plutonium as a way of securing the material for an eventual national effort has been colorfully portrayed by Green in the detective novel, Spencer's Bag. The trick employed by the government points to the kinds of vulnerabilities which exist under the present system of international safeguards: A small African country apparently proposes to return lent plutonium to the United States. But since the nation arranges for the transportation itself, it is privy to the date of return, packaging details, etc., and finds it relatively easy to contract for the material's "theft."

[46]Anonymous attack is not unknown. Something of the sort may or may not have been considered by Israeli agents in the so-called "Lavon-Affair."

countries without a delivery system, the power to be deterred could not be sure that a weapon had not been clandestinely smuggled into one of its cities. This type of desperate action could only deter the most drastic threats to a nation's viability, for only in these instances would the threat against the more powerful adversary have any credibility at all. But such instances may be imagined: for example, a U.S. invasion of Cuba, a Soviet invasion of Czeckoslavakia, a South African attack on a neighbor, or conceivably an attack launched against South Africa from elsewhere in Southern Africa.

The dangers inherent in the acquisition of illicitly obtained nuclear material are greatly heightened by the "contamination effect" of any single illicit diversion. Such a diversion would have three immediate consequences, one good, but two bad. On the favorable side, any clear diversion (let alone any ensuing blackmail or use) would certainly lead to substantial additional safeguard precautions and an increased willingness by the international community to impose stringent safeguard conditions on any lax government. This will be discussed later. But among the criminal and extremist communities, successful diversion would provide a considerably different perspective. In the first instance, it would provide an exemplar; it would demonstrate that successful diversion and blackmail were possible. The criminal imagination is improverished and example is important, as the recent outbreak of air piracy has revealed. More directly, a successful diversion could immediately lead to the establishment of a sort of black market - or, more plainly, a set of expectations that stolen material could find buyers. That is, to those with motive and ability to fabricate nuclear devices would be added groups who will undertake large risks simply to steal the material, knowing that markets for their wares exist.[47]

Impact on Stability - Select Critical Review of Literature

As a further step toward an analysis of how the spread of latent capabilities could affect international stability, it is well to examine how scholars have treated a related problem, the consequences of the actual proliferation of nuclear weapons. The relevant literature is substantial, and, as will be noted, for the most part not helpful, although a few useful themes may be discerned.

For expository purposes, it is convenient to divide the authors of the literature into four groups: "the scientists," "the traditionalists," "the systemists," and "the scenarists." The scientists are characterised by an unusual degree of allegiance to more or less explicit models of the "international system" and by an equally unusual alertness to the extent to which their statements can be verified. Every political analyst of course uses models (that is, abstractions) in some form or another. The scientists however attempt (ideally) to postulate some explicit abstraction of reality and then to draw inferences from this abstraction before again bringing the complexity of reality back into the analysis. In this group, we may place Morton Kaplan, Karl Deutsch,

[47]See Chapter 3, section 4.

David Singer, George Liska, Norman Masters, and Cyril Zoppo.[48] The systemists, as the scientists, tend to use models of the international system in their analyses. But unlike the scientists, they generally use the models as a descriptive aid rather than as an explicit abstraction from which one can deduce particular theorems. In this category, we may include Stanley Hoffmann, John Herz, Raymond Aron, Morton Halperin, Bernard Brodie, Kenneth Waltz, Richard Rosecrance, and Ali Mazroui.[49]

The traditionalists tend to examine the international scene bit by bit, looking at it now from the point of view of the United States, at another moment in terms of regional conflicts, and still other times in terms of the "German problem" the "Indian problem," etc. The traditionalists shy away from discussion of proliferation in terms of specific abstractions of the international system, the last indeed a term which they do not typically use. This group does not believe in the utility

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[48]Karl Deutsch and J. David Singer, "Multipolar Power Systems and International Stability" in World Politics, XVI (April 1964), 390. Morton Kaplan, System and Process in International Politics, 50-52; also "Bipolarity in a Revolutionary Age" in Kaplan (ed.) The Revolution in World Politics. Roger Masters "A Multi-Bloc Model of the International System" in American Political Science Review, LV (Dec. 1961), 780-798. C. E. Zoppo, "Nuclear Technology, Multipolarity, and International Stability" in World Politics, XVIII (July 1966), 579-606. George Liska, Nations in Alliance, 255-283.

[49]Raymond Aron, The Great Debate. Bernard Brodie, Escalation and the Nuclear Option. Morton Halperin, China and Nuclear Proliferation. John Herz, International Politics in the Nuclear Age. Stanley Hoffmann, "Nuclear Proliferation and World Politics" in A World of Nuclear Powers, The American Assembly. Ali A. Mazrui, "Numerical Strength and Nuclear Status in the Third World" Journal of Polities, 29, 791-820. Richard Rosecrance, "Problems of Nuclear Proliferation: Technology and Politics;" (UCLA: Security Studies Paper No. 7); The Dispersion of Nuclear Weapons, 1-28. Kenneth Waltz, "The Stability of a Bipolar World" in Daldalus, XCIII (Summer 1964), 881-909.

of seeking verifiable propositions or highly abstract models of international relations. In this cluster of attitudes, the traditionalists resemble the statesmen and bureaucrats responsible for the articulation of national policies. They include William Bader, Hedly Bull, Leonard Beaton, James Schlesinger, Albert Wohlstetter, and the editors of the Peking Review.[50] The scenarist school, of which Herman Kahn is the leading figure, has a special emphasis difficult to characterize. The central feature of this school perhaps is the imaginative projection of future scenarios (coherent sequences of events initiating from some arbitrary starting point) and future worlds coupled with very minimal attempt to weigh their relative likelihood and equally minimal concern with any serious research. The practitioners are also quite careless in their presentation of these future scenarios, it almost never being clear whether significant scenarios have been left out of consideration or not.[51]

This categorization is crude and the classification of writers somewhat over-articulated; their identification in a given category is simply an expository convenience. Most of the scholars mentioned above range over more than one category and some over all four, their perspectives

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[50]William Bader, Nuclear Proliferation and United States Foreign Policy. Leonard Beaton, Must the Bomb Spread, Pelican Original (1966). Hedley Bull, "On Non-proliferation" in Interplay, December 1968. James Schlesinger, "Nuclear Spread" Yale Review 57, 66-84. Albert Wohlstetter, "Perspective on Nuclear Energy" in Bulletin of the Atomic Scientists, April 1968, 2-5.

[51]Herman Kahn, "Nuclear Proliferation and Rules of Retaliation" Yale Law Journal 76, 77-91.

frequently changing, sometimes explicitly and sometimes not. Moreover, the classifications refer only to the nuclear proliferation literature. The authors may understandably adopt different styles at different times.

The central problem addressed by the scientists' approach to nuclear proliferation is the comparative stability[52] of bipolar and multipolar systems, a problem which necessarily involves the corollary issue of how nuclear proliferation affects the polarity of the international system. Unfortunately, the literature sheds no real light on this issue, and abounds with truisms, circularities, commonplaces, and fallacies, faults discussed very pertinently in essays elsewhere.[53] Of these shortcomings, three seem especially to inform the literature here discussed. We may term these the faults of unfulfilled abstractions, of

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[52]The term "stability" requires definition, and in fact is used quite differently by the different authors. For the purposes of this summary, however, the definition supplied by Deutsch and Singer will be generally appropriate. Their definition: "The probability that the system retains all of its essential characteristics; that no single nation becomes dominant; that most of its members continue to survive; and that large-scale war does not occur."

[53]Marion Levy, Jr., "'Does It Matter If He's Naked?' Bawled the Child," 87-109, and "International Theory: The case for a Classical Approach," 20-38, in Klaus Knorr and James Rosenau (eds.), Contending Approaches to International Politics.

irrelevancy, and of undue abstraction.[54]

Ideally, one would like to develop a simplified abstraction or model of reality, deduce consequences from it, and compare these with empirical observation. Models of international conflict however are typically so impoverished that no interesting conclusions can be derived from them unless reality is reintroduced into the model in very arbitrary, haphazard, and faulty ways. Such impoverished models are what we call here, unfulfilled abstractions. A fine example may be found in the work of Roger Master. Master's urbane analysis of the implications of nuclear diffusion is founded on an extended analogy between nuclear power rivalry and oligopolistic competition. Master's method is to note some structural similarities between these two competitive systems, to state some result from oligopolistic theory, to suggest that the result applies as well to international politics, and then to bolster this conclusion by a

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[54] These are different categories than those used by Levy and Bull, but include several of the characteristics pointed out by these authors. It may be helpful to think of the latter two faults in more colorful terms: irrelevancy as the "lamp-post syndrome" in reference to those who seek a lost quarter under a lamp-post where it is light rather than down the street where the quarter was lost -- but where it is very dark; undue abstraction as the "method of German philosophy," a phrase due to Karl Marx and described by Marx thus:

> First of all, an abstraction is made from a fact, then it is declared that the fact is based upon the abstraction. That is how to proceed if you want to appear German, profound, and speculative.
> For example: Fact: The cat eats the mouse.
> Reflection: Cat=nature, mouse=nature; consumption of mouse by cat=consumption of nature by nature=self-consumption of nature.
> Philosophic presentation of the fact: The devouring of the mouse by the cat is based upon the self-consumption of nature.
> Having thus obscured man's struggle with nature, the writer goes on to obscure man's conscious activity in relation to nature; he conceives it as the manifestation of this mere abstraction from the real conflict....

proposition based on the reality of the international system. Master's main contention appears to be that a world of a small number of roughly equal nuclear powers (some or all of which might be regional rather than national actors) could be more stable than the current bipolar system. This conclusion however is so tenuously related to the analysis as to be virtually a non-sequitur. There are to be sure various structural similarities between an oligopolistic system and a system of competing nuclear rivals. But the analysis then falters on two basic grounds. First, it is not at all clear from economic theory that oligopolies of several firms are more stable than duopolies, as Master contends. Secondly and more seriously, the underlying dynamics which allegedly makes oligopolies stable is never persuasively shown as analogous to the dynamics of nuclear power interaction. Consequently, Master's analysis adds no insight or evidence to the problem at issue; the oligopoly analogy must at best be considered a colorful illustration to make more plausible a result otherwise obtained -- although this is not the way in which it is presented.[55]

The charge of irrelevancy may be laid to virtually all the scientific literature. In efforts to quantify and to develop objective measures, the scientists typically tend to avoid the real issues. This tendency is well-illustrated (and, in fairness, recognized by the authors themselves) in a much quoted article by Deutsch and Singer.[56] The body

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[55]Masters, APSR LV, 780-798.

[56]Deutsch and Singer, World Politics XVI, 390.

of this article explores some quantitative relations (notably, the number of possible bilateral interaction opportunities in an international system as a function of the number of actors in the system) which may help explain why, ceteris paribus, multipolar international systems could be more stable than bipolar systems. However, when the authors turn to "some implications of the model for the diffusion of nuclear weapons" they correctly conclude that "the bare and abstract arguments pursued thus far become quite insufficient.... In our analysis of alternative international power systems we have abstracted from all other qualities of the states, governments, and national political systems within them. At the point of policy choice, however, these hitherto neglected aspects may be the decisive ones...a stable general system could be wrecked by the introduction of unstable components." Indeed, the authors ultimately conclude that the spread of nuclear weapons and the consequent creation of a multipolar world would probably be harmful and destabilizing -- and they conclude thus with no serious attempt to show how the factors that they had previously discussed might moderate or affect this conclusion.

Undue abstraction refers to the habit of several authors to thrust some evident characteristic of international relations into more abstract language, and then to "explain" the characteristic in terms of the abstraction. Thus the post-war confrontation between the United States and the Soviet Union becomes a special case of a conflict of two nuclear superpowers, and the relative restraint of the two antagonists becomes a manifestation of the stability attributed to bipolar systems.[57] The

[57] Such stability is counter to Master's notion.

systemist as well as the scientific literature abounds in such unhelpful abstractions as may be seen in the works of Stanley Hoffmann and Raymond Aron. For example, Hoffmann's otherwise interesting essay, "Nuclear Proliferation and World Politics," would be virtually unchanged in substance and greatly enhanced in clarity and concision if every idealization of the international system ("bipolar," "polycentric," "multipolar," etc.) were altogether excised. Undue abstraction is indeed probably the single most prevalent and pernicious shortcoming of the systemists. The central characteristic of the systemist literature is the development of typologies and classifications which will permit various kinds of generalizations. This procedure differs from that of the scientists by a greater reluctance among the systemists to suppress their knowledge of reality at any point during the analysis. Thus they create not models so much as hierarchies of generalizations about international conflict. This leads quite frequently to identities, truisms, and commonplaces as well as to the undue abstractions noted above. For example, one of the central conclusions of one of the more well-known proliferation studies contains (not untypically) both an identity and a truism: "If additionally, great power countermeasures were nil or perhaps even aggravative the probability of some form of nuclear war would increase.[58]

As has already been indicated the traditionalists share many of the shortcomings of government policy makers with the added disadvantage of not having the access to the material and expertise usually available to

[58]It is slightly unfair to take statements such as this out of context. But, in fact, the context in these cases seldom improves the truism.

the bureaucrat. Thus, the traditionalists are not so much unpersuasive as they are irrelevant or out-of-date. Precisely because they have not ventured the typologies and abstractions which the scientists and systemists seek, they do not seem likely to break new ground or to develop a cumulative discipline -- and as with the other groups, they have not done so. Nonetheless, of the groups here discussed, they have probably contributed most to our understanding of the probable impacts of nuclear proliferation. The scenarist's approach appears to some degree in almost all of the analyses, and suffers the drawback already mentioned: very little effort is taken to explain why a given scenario is chosen; and since it is almost always possible to choose relatively plausible scenarios on both sides of any serious issue, the scenario mode of analysis can never be ultimately persuasive.

In general, three overarching characteristics of the entire literature stand out. First, it is striking that there has been virtually no serious analysis of the consequences of nuclear proliferation. To the extent this question has been looked at, most of the academicians seem to agree that proliferation of most any kind would be unfortunate but not so unfortunate as American officials typically assert. But there is virtually no discussion in the literature of more detailed issues such as, for example, the impact of proliferation on regional and international institutions, the character of alliances, or the modes of international intercourse. Second, it is notable that one finds very little enthusiasm in the literature for the Non-Proliferation Treaty, even among those most strongly opposing proliferation. As to other possible remedial or preventive measures, the writers have essentially ignored the Comprehensive Test Ban, Fissionable Material Production Cutoff, and No-Nuclear-Use proposals, perhaps believing these too technical and too wrapped in military security to discuss. In general, the writers tend to believe that technical barriers to proliferation will not be as effective as security assurances and specific defense arrangements between the nuclear powers and major non-nuclear countries. However, despite this view there has been surprisingly little analysis of the kinds and potency of such security arrangements. Finally, somewhat corollary to the above, there is to be found little concern in the literature with the relation between the status and legitimacy of nuclear weapons, especially as these are reflected in the behavior of the great powers, and the prospects of nuclear proliferation. Overall, the literature surveyed possesses very little cumulative value. If one wishes to project and to analyze the potential consequences of nuclear diffusion and to shape policies to cope with them, there is virtually nothing in the literature which seems an indispensable prerequisite to such endeavor, and very little more which seems even useful. This harsh judgement applies more or less equally to all four schools. The scientists have given us few, if any, propositions of potentially cumulative impact; it is difficult to find more than a handful of significant propositions potentially verifiable even in principle. The systemists, traditionalists, and scenarists (and the scientists qua traditionalists) have perhaps enriched our ability to imagine future contingencies. But the systemists have left no legacy of systematic inquiry, nor have they forged a well-defined conceptual framework which others could build upon. The traditionalists, most in tune with the perspectives of governments, have set forth virtually nothing that has been useful to policy formulation, the scenarists even less.

With respect to the substance of the crucial inquiry, the investigation of the effects of proliferation on stability, several authors point out specific and new dangers inherent in a proliferated world. These arguments are mostly familar; In essence, they insist that the greater the number of nuclear weapon states the greater the chance that nuclear weapons will fall into the hands of irresponsible governments or will otherwise be used.[59] In addition, the anti-proliferation arguments (mostly out of the traditionalist literature) are founded on a presentation of specific plausible projected dangers and complexities associated with the spread of nuclear weapons. In large measure, the preceding two sections of this study sketching conventional and unconventional dangers associated with latent proliferation parallel these earlier arguments. In general, most of the analysts examined believe that rapid proliferation would be more dangerous than a slower-paced spread of nuclear weapons.[60] If this is so, it tells us something about the dangers of latent proliferation. This is a point examined in the following section.

The literature also adduces two sorts of arguments in support of the notion that nuclear proliferation could in fact be stabilizing. First there exist several variations on the theme that the consequences of nuclear use are so awesome that regional adversaries would be reluctant to engage in any hostilities or confrontation in fear of escalation to

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[59]The claim of irresponsibility is usually made by western analysts who when they do so are usually thinking of Latin American, Asian, or African States. Representation of the Third World find this part of the anti-proliferation argument less persuasive. See, for example, Mazrui, "Nuclear Status in Third World," 791-820.

[60]Rosecrance, Dispersion of Nuclear Weapons, 1-28.

nuclear conflict. Second, some authors forward a somewhat vague theoretical argument patterned in part on balance-of-power concepts that a global dispersal of power would lead to a more stable world. These arguments are investigated in the following section, although the second will not be fully pursued until part 4 of this chapter.

Stability and the Dynamics of Latent Proliferation

In this section we want to invesigate the "dynamics" of latent proliferation, the probable international pattern in which it will develop. Will there be pressures toward increased intensity, and in what manner will the intensity of one state's nuclear power program affect another's? Central to this investigation is the concept of "stability," a property which measures the vulnerability of a system to perturbations. For it will be nations' perceptions of stability which will determine their responses to changes in the intensity of other state's nuclear capacities. The more stable the system, the less effect will a jolt have on the crucial characteristics of the system. Conversely, the greater the probable effect, the more unstable may one term the system. For the purposes of this analysis, three kinds of instabilities (jolt-effect relations) may be identified:

(1) Competition instability. This type of instability refers to situations in which the intensification of one nation's latent capability encourages similar intensification by other states. This is analogous to so-called arms race instabilities where weapons deployments by one state lead its adversaries to like deployments regardless of whether the initial actions were in fact dangerous.

(2) Crisis instability. A situation may be said to be unstable if an intensification of one country's nuclear capacity leads that country or

others to contemplate armed attack.[61] Such situations have been considered above under the heading of "conventional dangers."

(3) Diffusion instability. A situation of high intensity may be termed unstable if one state's breakthrough to an overt nuclear weapons capability encourages other such decisions and an eventual rapid diffusion of nuclear weapon programs. If one wishes, it is possible to think of this instability as a special case of competition instability; however, it seems generally more convenient to label it separately as done here.

We may ponder each of these instabilities in turn. Consider first the competition or system instability. We wish to examine the probable pattern of latent proliferation which at a given moment may be characterized by the latent intensities of various national nuclear programs. These will in turn depend upon the number of critical thresholds passed by the nation and (inversely) on the time required to display an operational weapons capability. The first and most striking observation we may make is that without drastic changes in international safeguard efforts, the system will probably drift to states of higher and higher intensity. That is, nations will increasingly develop a nuclear independence and will use this independence to draw ever closer to a weapon's capability; the lead times to the display of nuclear weapons will shorten. This is because the system is competitively unstable in several respects.

In the first instance, intensification of nuclear capabilities has a ratchet-like character - the movement is (almost) entirely in one direction.

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[61] Strictly speaking, the relevant jolt need not be an intensification of a state's latent capability; it could be any change in latency or any perturbation whose perception by the involved actors depends on the latent states of the parties' nuclear capacities.

States, once in possession of independently controlled nuclear fuel and nuclear facilities, are not likely to give them up; and regardless of safeguards as currently conceived, plutonium stockpiles will continue to grow. In addition, technology is becoming still more widely diffused with the imminent advent of centrifuges, especially, providing a new intensifying element. Thus even apart from interactions among the latent nuclear powers, one should expect a gradual drift toward shorter lead-time potentials. However, this process will be heightened by the interactions of nuclear power programs. Quite apart from national security concerns, competition among civilian nuclear power programs will in general lead to higher intensity capabilities in several countries. That is, in a race to stake out a portion of a burgeoning world market for nuclear material and services, several states are now developing or contemplating the development of fabrication facilities, reprocessing plants, and isotope separation capabilities. This competitive impulse is reinforced by a more conservative and defensive attitude; not only will countries wish to develop a strong competitive position in a growing market, they will want to remain independent to the extent practicable. If only for purely economic reasons, states will not wish to rely on other's nuclear servides. This autarkic impulse might be balanced if the advantages of a division of labor and of international trade were more striking than appears to be the case. Compared to the total costs of electric power, the extra costs involved in the indigenous construction of independent facilities for fabrication, reprocessing, plutonium finishing, and perhaps even isotope separation are not high, perhaps a few percent of the total. (This is not to say, however, that economic incentives could not influence a nation's policy toward safeguards, independence, and intensification; some suggestions are discussed in section 5 of this chapter).

Nonetheless, despite these strong economic and autarkic pressures toward nuclear independence, national security perspectives probably provide the more significant impulses toward competitive instability. As a few states move noticeably nearer to a nuclear weapon capacity, others will feel pressured to move in the same direction. This is most evident in the case of hostile neighbors. This already may be seen in the groupings of states who have not ratified the NPT: China, India, Pakistan, Burma, Cambodia, and Thailand; Israel, Saudi Arabia, UAR, and Libya; Cuba, Argentina, Brazil, and Chile; Portugal, Zambia, and Uganda. Similarly, states could not long tolerate regional adversaries unilaterally intensifying (legally and actually) their nuclear capabilities. Thus, for example, it is not surprising that Pakistan is constructing a natural uranium reactor similar to the one built in India; and should India manage to shrug-off safeguards obligations, Pakistan will surely attempt to follow. The interaction between countries who are not potential adversaries is less strong and certainly less direct. In the short term, an intensification of (say) India's nuclear program will probably not greatly affect (say) Germany's, or Sweden's, or possibly even Japan's. Countries far apart will not perceive any substantial danger in the other obtaining nuclear weapons before they do. This weak interaction would be particularly evident for states of different potential scope. Where a few bombs might be sufficient for Israel or Pakistan, they would not be so for Germany or Sweden. It would hardly be sensible for Germany, say, to manufacture a "bomb-in-the-basement." In the long run, however, the ramifications of an intensification in one region will have a global impact. Such intensification will affect the structure of the internal debates within potential nuclear weapon states and will weaken the strength of international sanctions.

With respect to national debates over nuclear policy, any intensification of the system will weaken most precedential and moral arguments against a movement to a more independent nuclear position. At the moment, domestic groups opposing nuclear weapons within a specific country can argue that any unshackling of safeguards would lead to a worldwide abandonment of safeguard obligations with consequent long term harm to the country whatever the short term advantages which may be perceived. Similarly, it may be claimed that a country's moral leadership against the acquisition of nuclear weapons is necessary to stem what would otherwise be an irresistible tide toward independent national nuclear forces. Such arguments would obviously lose their persuasive force once other nations began to intensify their own nuclear programs. Under these conditions, national initiatives to secure greater nuclear independence would also be technically more practical; the more national programs not under strict international safeguards nor dependent on assistance from the nuclear weapon states, the easier it would be generally for other nations to secure unsafeguarded material.

Just as internal constraints against an intensification strategy in a given country would be weakened by a general system intensification, so also would the willingness of the international community to invoke sanctions against such a country. In such a situation, the legal justification for an international response could be severely undercut. For example, under the NPT, a nation may withdraw from the safeguard and other Treaty obligations if it decides that "extraordinary events" related to the subject matter of the Treaty jeopardizes its supreme interests. The acquisition of an independent nuclear capability by other states, even those quite distant, may plausibly be adduced as such an extraordinary event. Apart from such legal impact, a general intensification will certainly diminish the willingness of nations, acting unilaterally or in formal or informal international groupings, to impose sanctions on a new country apparently striving merely for some kind of equity. Any general proliferation of independent nuclear capabilities would also make such sanctions more difficult to achieve; a multiplicity of possible sources of fuel, technical help, etc. would severely hinder any attempts to strangle a nation's nuclear power program through embargoes and other export restrictions.

Crisis instability depends critically on the intensity of the system and especially on the characteristic lead-times to the actual deployment of nuclear weapons. In general, the less this time, the more dangerous would appear the occasion. This effect of telescoped time has been illustrated in the preceding section; it has most vividly been observed in the Cuban missile crisis. There are two separate reasons to believe the validity of this effect. Most obviously, in a regional confrontation, if one nation is seen to be moving quickly to a nuclear capability, its adversaries may feel they have to act quickly before the opponent's nuclear weapons are actually deployed and ready to be used. Such was the Cuban missile crisis example. But threat of imminent use is not the only danger requiring rapid response. In several instances, where it may be sensible for states to seek a very small number of nuclear weapons, a rapid international or adversary response to a drastic intensification of a nation's capability would be required simply to prevent its possession of weapons. That is, even when the nation about to acquire nuclear weapons had no evident and immediate plans to use them, a rapid enforcement strategy (such as destruction of reprocessing facilities) might be required to prevent the fabrication (for example) of illicitly obtained material into weapons. Such an enforcement strategy recognizes the impossibility of finding already fabricated nuclear weapons which the possessing nation wishes to conceal.

In a situation in which adversaries had already deployed nuclear weapons, the potential impact of nuclear weapons on crisis instability has a somewhat ambiguous character. On the one hand, depending on the deployment modes of each side's weapons, there may be significant advantage to a first nuclear strike. However, opposed to this destabilizing effect, nations may be deterred even from conventional confrontations by their fear of escalation to a devastating nuclear war. Whatever the merits of this latter perspective with respect to the consequences of actual proliferation, it has less persuasive force in regard to latent proliferation. For in this case, the factors leading to conflict are similarly strong while the stabilizing factors for actual proliferation have no exact parallel. Thus, in a crisis, the existence of very high intensity latent nuclear capabilities would appear to have little beneficial or ameliorating impact and could have a marked harmful one.

<u>Diffusion</u> <u>instability</u> presents a more ambivalent case. On the one hand, actual proliferation could proceed more quickly the more intense the system in general. If a significant number of states are very near a weapons capability, then the move over the line to an overt weapons capacity by one or two countries could trigger a rapid and confused nuclear diffusion before the international community was able to react. Some states may indeed believe that this period would represent the ideal time to display their nuclear weapons. This is what could happen; in terms of capabilities, the more intense the system, the more unstable it would be with respect to diffusion. However, if one examines intentions rather than capabilities, the situation is less clear. For some states, the alternative to an overt, explicit nuclear weapon deployment may well be a highly intense latent capability. In this sense, diffusion instability may be diminished as countries intensify their programs or perceive ways in which they may be intensified.

4. The International System

The preceding sections focused upon specific nations and specific causi belli as a means of trying to grasp the significance of latent proliferation. In this section, the goal is the same, but the emphasis is on the "international system," or as defined here, the complex of ways in which nations (governments), international institutions, and other actors influence the ways nations interact. The international system is taken thus as simply "the ways things are done." We ask the question: how will the spread and intensification of peaceful nuclear power affect (1) the modes of international politics (the means by which nations communicate and try to influence each other); and (2) the global distribution of power and influence? Pertinent to this inquiry will be investigation not only of the direct impacts of peaceful nuclear power but also of the control measures it will demand; thus, in part, this section will occasionally anticipate the next

Modes of International Political Behavior

At the most tangible level, nations and intra-national groups impinge upon other states and extra-national groups in three fundamental ways.[62] (1) They may through economic policy affect other states' economies and environment. Tariffs, surcharges, embargoes, import quotas, non-renewable resource consumption, economic aid, and like measures and activities do this more or less directly. Money supply policies, fiscal

[62] Decisions by governments can affect the citizens of other states directly; and conversely, citizens of one state can affect governments of other countries directly. However, in much of the following, it will be convenient to refer simply to the influence of nations upon nations, with the wider possibilities not meant to be excluded from this short-hand formulation. Also the evident but important fact that government policies and actions are decided by people will not always be reflected in the language except when it becomes the essence of the argument.

measures, river basin management, dam construction, etc. could have more indirect though still potent impact; (2) They may apply military force outside national borders; (3) They may "communicate" with other nationals, via radio propaganda, through music and films, by cultural exchanges, etc.; national policies can encourage or discourage such communication.

This is not to say that nations do not exert influence in other ways, for example, through simply the example of their own political system (one reason some Soviet leaders no doubt feared the Czech government under Dubcek). But for such an example to be made manifest to other countries, it must be communicated in some tangible manner, economic, military, or through other direct communication or transfer. Indeed, the most important way in which nations do exert influence and try to achieve their national interest and some stable world order is not through the actual application of economic, military, or propaganda measures. Rather, it is through threat of such measures. More accurately, it is through the achievement of a system of sanctions conguent with the national interest. This perspective requires elaboration for it is central to an understanding of the true impact of nuclear power.

A system of sanctions is taken here to mean coordinated expectations of indulgences and deprivations meted out in authoritatively expected procedures with the ostensible objective of maintaining public order.[63] These expectations - communicated, reinforced, developed in a variety of ways - provide the central constraint to action by national decision-makers.

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[63]This definition is from W. Michael Riesman's essay, "Sanctions and Enforcement," in The Future of the International Legal Order, III, 274. The following discussion relies at several crucial points on Riesman's analysis, though sanctions here are permitted to include a wider set of factors than is true for Riesman.

The task of any international actor furthering his own interest then is to establish a system of sanctions that will confront those he is trying to influence which are as compatible with his true interests as possible. Thus he will want to develop a "strategy of sanctions." He will want to shape the system of sanctions as he finds it in ways to his liking. A sanction system is not fixed once and for all, but rather is constantly being rearticulated by a myriad of government and non-government decisions. The system in this sense has an existential character; there is no unchanging essence or ideal type and the state of sanctions at any given time is the product of preceding acts and statements.

A given international actor will try to shape the system of sanctions perceived by other decision-makers. The full set of influence on these decision-makers is of course broader than this, and would include the following:

(1) sanctions: the system of sanctions perceived by the decision-maker at a given moment.

(2) economic, military, communication capabilities: these will constrain what the nation can get away with; they underly the efficacy of sanctions.

(3) ability of nation to forge alliances, persuade other states to undertake actions, etc.

(4) internal factors: the impact of foreign policy on the domestic policy provides a significant constraint on the national decision-maker.

(5) perceived benefits of the action contemplated.

(6) strategy of sanctions: the international actors to be influenced will be constrained by <u>their own</u> conception of an appropriate sanction strategy and associated view of public order.

However important all those influences, it is nonetheless more fruitful for the present inquiry to concentrate on the factors which can be most readily affected, the system of sanctions. The components of this system as conceived by Riesman include all the factors by which the "coordinated expectations of indulgencies and deprivations" derive. First there may be adduced all the influence on conceptions of an international public order (or adversely on conceptions of international delicts).[64] These may be explicitly recognized by international treaty or convention and in international legal writings, or they may be implicitly shared by most international actors. For example, there is widespread (verbal) agreement on an individual's right to own property and to be protected against willful destruction of his assets; on certain (obvious) aspects of national sovereignty; on the intrinsic dignity of all humans; etc.[65] A second set of influences derives from expectations of enforcement, or, more generally, of authoritative response to deviant behavior: perceptions of the enforcement capabilities and intentions of various international actors.[66] In general, the Riesman categories

[64] See full definition of sanctions given above.

[65] Riesman, "Sanctions and Enforcement," 282-286.

[66] <u>Ibid.</u>, 292.

include all contributory influences to sanction expectations including those which have become internalized within the individual and those which derive from perceptions of peer group approval, etc. And all of these factors may potentially be influenced in one way or other by latent proliferation. But for present purposes, it is convenient to regroup the Riesman categories into two large components:

(1) International Law. Generally perceived catalogues of illicit behavior and norms of acceptable conduct.

(2) International Enforcement Capacities. These do not exhaust the Riesman taxonomy, but do capture many of the factors most likely to be influenced by intensification of nuclear capabilities.

(1) Law

Traditionally, international law has not dealt with internal acts, that is acts within a country by its non-governmental residents, although in certain instances, international conventions have slightly eroded this concept - for example, conventions dealing with narcotics and health.[67]

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[67]See, for example, Ian Brownlie, Principles of Public International Law, 52-64, 466-486; Hersh Lauterpacht, Oppenheims International Law, Volume I, (Lauterpacht/Oppenheim), 981-983: The World Health Organization has been authorized to adopt regulations concerning sanitary and quarantine requirements and other procedures designed to prevent the international spread of disease. In addition there exist newly articulated conventions and practices concerning the criminal responsibility of individuals, especially with respect to crimes against humanity; there has been a gradual evolution of the principle that states have a right to punish foreign nationals for crimes against humanity. Brownlie 466-486, Lauterpacht/Oppenheim, para. 340q.

Also, laws of piracy are aimed at individuals although here the illicit actions are not generally assumed to occur within national boundaries.[68] By and large, however, internal acts are not covered by international law. This will have to change drastically as the spread of nuclear power continues.

With the exception of certain aspects of biological research and development, no internal actions could be as directly unsettling to the entire international community as the illicit acquisition of nuclear weapons by non-governmental groups. Every organized society will have a deep stake in the discouragement of such acquisition, far greater for comparison than its stake in narcotics control. This underlying reality, once it is fully perceived, will almost certainly become recognized in international law and convention. That is, individual acts of diversion must become characterized as international crimes (such as piracy). Their suppression is thus a duty of all states, and a state negligence in such suppression could consequently be considered an international delict, perhaps justifying intervention by other states.[69]

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[68] Piracy refers to unauthorized acts of violence committed by private vessels on the open seas. It is a so-called "international crime"; the pirate is considered the enemy of every state and can be brought to justice anywhere. Every state has the duty to prevent such acts of individuals: Lanterpacht/Oppenheim, para. 272, para. 151. Conventions against slave trade afford still another similar example: Lanterpacht/Oppenheim, para. 340h.

[69] Some writers even categorise toleration of activities by a state upon its territory of the acts of private persons which endanger the safety of other states as a form of "intervention". Lanterpacht/Oppenheim, para. 134.

Just as international law has traditionally not covered acts of individuals within their own countries, it also has not generally been applied to the internal acts of governments.[70] Thus international law has had virtually no impact on domestic legislation covering purely domestic activities. Again, recognition of the potential dangers of latent proliferation will expand the net of activities appropriately covered by international law and convention. The first dramatic manifestation of this widened scope may be perceived in the safeguards clause of the Non-Proliferation Treaty. This clause and pursuant national agreements with the IAEA present a more striking departure from normal international paractice than has generally been realized. They not only give international inspectors certain rights of observation and measurement at various points in the nuclear fuel cycle; they also require states to submit designs for domestic nuclear facilities for international approval.[71] Presumably also the State-IAEA agreement will require the state to submit its entire domestic safeguard system for IAEA approval. The recourse available to the IAEA and others should this approval not be forthcoming is unclear; but the safeguards agreement will clearly lend support to those who will want to place certain domestic actions or negligences under international legal scrutiny. The question of possible enforcement will be considered presently.

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[70]Even with respect to organized violence. See for example Rosalyn Higgins, "Internal War and International Law" in The Future of the International Legal Order, III., especially 81, fn.

[71]The extent to which safeguards agreements pursuant to Article 3 will actually require such submission is not yet completely clear. But the Model Agreement (See Ch. 3, section 2) seems to incorporate this provision.

Latent proliferation is likely to have one other considerable impact on the scope of international law and how this law is perceived by various international actors. This impact derives from the telescoped time frames for decision imposed by the use and development of nuclear weapons. Although no more momentous decision by a democracy can be imagined that its first commitment of nuclear weapons, such decision will in practice have to be made almost entirely by the highest executive officials - in the United States, essentially by the President alone. There exists insufficient time for wider consultation should a crisis arise. Nor does it seem practicable for legislatures through wider discussion prior to any crisis to lay down explicit contingency guidelines as to when nuclear weapons may be used and when they may not; it would not be possible to envision all the multiple contexts conceivable. Thus nuclear weapons vitiate one of the historic democratic goals, to erode the executive prerogatives to undertake foreign wars. The consequent dilemma will be increasingly perceived as nuclear capabilities intensify; indeed, at very high intensities (very short lead-times to weapons) the decision to display nuclear weapons will in some ways parallel the more drastic decision to use them; that is, crucial decisions will have to be made in a brief period, in secrecy, and under pressure.

The democratic dilemma thus stated has only two possible resolutions. The first, and less satisfactory, would be the establishment of small standing committees of the Legislatures (Congress in the American case) who could be called into deliberation immediately upon the onset of a crisis, such as the Cuban missile adventure. In this manner, a wider and more democratic sensitivity might be directed at the crucial decision to display or to employ nuclear weapons. This resolution, however, has drawbacks. Most pertinently, it still does not permit a wide public discussion; it would merely expand the immediate circle of advisors by a small number. Also, in several countries (the United States probably included), the selection of the committee would have to be made largely on a narrow political basis, with the most analytic members of the Legislature excluded in large measure.

An alternative resolution of the dilemma would be through explicit international agreement on when nuclear weapons could be used. Since the conceivable contingencies of such use are numerous and complicated, the only basis for such international agreement would have to be a relatively simple prohibition, the simplest being never to use nuclear weapons (first) under any circumstances.[72] Such an agreement would require considerable public

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[72]Other variants, also relatively simple in form, may be imagined: (1) A prohibition on the first use of nuclear weapons against non-nuclear states (or against non-nuclear weapon states signatory to the Non-Proliferation Treaty); (2) A prohibition on the use of nuclear weapons against non-nuclear weapon states that do not have nuclear weapons on their soil; (3) A prohibition on the use of nuclear weapons against non-nuclear weapon states that are not engaged in an armed attack assisted by a nuclear weapon state. These three kinds of prohibitions, distinguished by the nature or actions of the states exempt from nuclear attack, essentially dover the no-nuclear-use variants presently under international consideration. The complete prohibition remains the most striking and controversial and is the only one that directly relates to rules of combat between nuclear weapon states. For obvious reasons, variant (1) is the one most frequently forwarded by the non-nuclear weapon states. The second variant, known as the "Kosygin Proposal," has been suggested by the Soviet Union probably because it excludes West Germany from the compass of the no-use commitment. (Documents on Disarmament, 1966, 11) Variant (3), similar to the formula adopted by the United States in connection with the Latin American Nuclear Free Zone Treaty, appears to be the version most palatable to the United States; it clearly permits wide discretion by parties to the agreement on when the use of nuclear weapons would be permitted. (See statement accompanying signature by the United States to Protocol II to the Treaty for the Prohibition of Nuclear Weapons in Latin America, April 1, 1968. Dept. of State Bulletin, LVIII, No. 1505, April 29, 1968.) Still other variants, based on different distinctions, are conceivable. Formulas that have on occasion been considered include (a) prohibitions on the use of nuclear weapons against cities, (Statement by Secretary of Defense McNamara at Ann Arbor, June 16, 1962, found in Documents on Disarmament 1962, 622-629). (b) prohibitions on the first use of nuclear weapons outside one's own territory (Thornton Read, "A Proposal to Neutralize Nuclear Weapons," Policy Memorandum No. 22, Center of International Studies, Princeton University, December 1960) and (c) prohibitions on the use of "high"-yield nuclear weapons.

debate prior to its acceptance, a process which would permit a wide discussion of the kinds of contingencies that might require first use. Thus even if the adopted prohibition is absolute, the leadership bound by the prohibition legally would have an enhanced sense of the type of extreme situation in which it might be broken. More important, however, such leadership would have an increased sensitivity to the kinds of situations in which the employment of nuclear weapons would not be justified. The guiding norm in any crisis would be not to use nuclear weapons; the guiding assumption would be that the adversary would not use them either. In sum, a no-nuclear-use convention would clarify the occasions when nuclear use might be contemplated; and it would encourage the widest possible debate on this issue at the only time such a debate would be possible, before any crisis. Such a convention would have the additional impact of discouraging the overt display of nuclear weapons by states with highly intense nuclear programs, for it would present their leadership with a view of the limited utility of nuclear weapons. From the perspective of this section, the most important point to stress is the increased likelihood of a no-nuclear-use convention, with its dramatic impact on the discretion of nations to employ nuclear weapons, due to the spread and intensification of nuclear capabilities.[73]

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[73]The purpose here is not to undertake an analysis of no-first-use policies. For the beginnings of such analysis, the reader is referred to Richard A. Falk, "On Minimizing the Use of Nuclear Weapons: A Comparison of Revolutionary and Reformist Perspectives" in On Minimizing the Use of Nuclear Weapons, Center of International Studies Monograph No. 23, March 1966, and "Thoughts in Support of a No-First-Use Proposal" in Legal Order in a Violent World, 425-440. Proposal for No First Use of Nuclear Weapons, Center of International Studies Policy Memorandum 28, September 1963. Morton Halperin, "A Proposal for a Ban on the Use of Nuclear Weapons," Institute for Defense Analyses, Study Memorandum Number 4, October 6, 1961.

Along with this heightened concern about the internal policies of governments, the international community will be forced to consider ways to achieve universally binding agreements. As radical in some ways as is the NPT, it is also traditional in imposing obligations only on states that explicitly accept them.[74] International safeguard rights must be secured through explicit agreement by the safeguarded state.[75] But since the existence of even a few maverick states with poor internal safeguards controls could endanger the entire international community,

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[74]This isn't quite true; see below.

[75]See Chapter 3, section 2.

states may be willing to entertain draconian enforcement strategies to secure universal compliance. There is little precedent for such a development, but the prospective dangers have never been so marked.[76]

(2) Enforcement

We can view international enforcement as "collaborative transnational policing of events which a plurality or majority of states commonly characterize as delictual."[77] This need not mean the operation of an international sheriff, but rather "its functional equivalents such that stable patterns of expectations are sustained, holding that certain types of behavior will be enjoined."[78] It is crucial to understand that the transnational enforcement need not be accomplished by states acting in concert or by international institutions. Quasi-public or private groups, whether in formal organizations or amorphous communities

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[76]There exist already several departures from the general rule that treaties cannot validly impose obligations upon states which are not parties to them (Lauterpacht/Oppenheim, para. 522a; Brownlie, 500). For example, the United Nations Charter asserts that the Organization shall ensure that even states which are not members of the UN act in accordance with the Charter principles insofar as this is necessary for the maintenance of peace and security (Article 2(6)). The Opium Convention of 1931 (Treaty Series, 31, 1933) affords another such example; Article 14 of this Convention imposes obligations upon states which are not parties to the Convention inasmuch as the parties are under obligation to stop imports of certain drugs by non-parties who have exceeded the maximum quantity of drugs allotted to them (Lauterpacht/Oppenheim, para. 522a). See also the political analysis of universally-binding agreements by S. Yuter, "Maintaining Nuclear Peace Through International Law," January 1968 (unpublished).

[77]Riesman, "Sanctions and Enforcement," 282.

[78]*Ibid.*, 282.

(such as "scientists") could and frequently do serve important enforcement functions. Intensification of nuclear capabilities could affect international enforcement in several respects including in particular through (i) an increased enforcement role for certain non-governmental groups; (ii) an altered international concept of intervention; and (iii) an increased willingness by nations to force universally binding treaties on recalcitrant states.

As the realization spreads that the national security is threatened as much by a common vulnerability to internal acts of violence and a general diffusion of weapons of mass destruction as it is by more traditional threats, non-governmental organizations and communities will doubtless become increasingly willing to participate in enforcement procedures. The recent air hijacking events provide an instructive illustration; while nations and international institutions appeared frozen in indecision and debate on how to handle the political hijackings, one of the strongest impulses to drastic action came from the international Air Pilot's Association and from the airlines. The sanction (here expectation of penalty) was imposed on the hijacker indirectly by the airline associations, whose direct impact was on the national governments who might have tended to be hospitable to the hijackers.[79] The Associations were able to act quickly; they asserted the dominance of the interests of all world travellers (and the airline industry) over the interests of particular states. In this sense, the functional interests overcame the purely diplomatic.

[79]See Riesman, "Sanctions and Enforcement," 283-284; New York Times, February 15, 1969, May 25, 1969.

With respect to the diffusion of nuclear power, the international nuclear industry and the scientific community in general could in principle play an important role in the development of an effective system of sanctions. Industry could apply sanctions in many ways, most notably by providing severe economic penalties to groups and states who do not cooperate with an international safeguard effort; a community goal ought to be to give economic stake to powerful groups within each country in the maintenance of strong safeguards. Some such possibilities are raised in section 5. The point of emphasis here is the increased opportunities and prospects for "amateur" transnational sanctioning because of latent proliferation. Similarly, for scientists and other essential technologists. The simple theft or diversion of nuclear material will require scientific advice of high quality; and the fabrication of such material into weapons will require still more high quality technical input. Neither criminal groups nor governments could engage in substantial clandestine nuclear activities (reprocessing, metal fabrication, isotope separation, testing, etc.) without alerting significant numbers of national scientists. The vigilance of these scientists would be especially valuable in discouraging criminal activity. And this vigilance would strongly discourage the kind of trick discussed in Chapter 3 where a national diversion is masked as a criminal theft.[80] Unless large numbers of persons are let in on the secret, states will find scientists who might cooperate if they knew what was going on instead of revealing information to an international inspectorate. Put

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[80]Chapter 3, section 1.

another way, states will genuinely want to encourage scientists to detect and report any unauthorized uses of nuclear energy. But once they do this, their own flexibility becomes inevitably diminished. The scientific community could more generally induce expectations of censure in members who violate international convention even at the beck of the state. That is, the community may apply sanctions to its individual members.

As has been repeatedly stressed here, the international community could scarcely permit even a single state, whether through carelessness or deliberation, to allow plutonium to come into the possession of terrorist groups, especially those based outside the particular nation. There can likewise be little toleration for an arbitrary unshackling of international safeguards by some state if such action were likely to precipitate a chain reaction of safeguard renunciations. This implies an increased willingness by the international community to organize multilateral intervention or to countenance and authorize unilateral intervention. International Law already recognizes the right of unilateral or collective intervention in instances when states tolerate certain types of illicit activity harmful to other states.[81] Dereliction of safeguards obligations must eventually prove grounds for such intervention.

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[81]Lanterpacht/Oppenheim, paras. 127, 127a, 134-140. "States are under a duty to prevent and suppress such subversive activity against foreign Governments as assumes the form of armed hostile expeditions or attempts to commit common crimes against life or property." (para. 127a). It may even be held that failure in this duty itself constitutes a form of illegal intervention (para. 134). 'Intervention' is taken throughout this discussion to mean "dictatorial by force or threat of force interference by a state in the affairs of another state for the purpose of maintaining or altering the actual condition of things." (para. 134)

Distribution of Power

Discussion of the impact of latent proliferation on the international distribution of power has in large measure already been anticipated. However, it seems worthwhile to reprieve some of the earlier ideas in a more concentrated manner by focusing on particular aspects or idealizations of the international system: the role of international institutions, the viability of the nation-state, spheres-of-influence and polarity.[82]

With respect to international institutions, the most dramatic impact will be less from the spread of nuclear power directly than from the implementation of measures to control the spread. One class of such measures would include international ownership and management of some of the key elements of the nuclear fuel cycle, for example, reprocessing plants. Such "internationalization" whether under the auspices of the IAEA or under a newly-created organization created subsequent to an international agreement, would if actually implemented constitute an unprecedented development in international relations. A significant part of a state's power capacity would be entrusted to an international body; no country would be able to devise its own energy policy independent of other states.[83]

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[82]By "power" we mean here simply the ability to influence the actions of individuals (singly, in groups, as governments, etc.).

[83]See section 5 this chapter for a discussion of the kinds of international institutional changes that may be envisioned.

More specifically, the dangers of latent proliferation will almost certainly alter the workings of the IAEA and the United Nations Security Council. The enforcement procedures to be followed after a safeguards obligation are currently unclear, and will eventually have to be made explicit. This will probably require some new executive committee attached either to the Council or to the IAEA Board of Governors which could react rapidly upon suspicion of a safeguard violation; the pace of the Security Council at present, not excepting situations (such as the six-day war) when speed seemed absolutely necessary, appears hardly capable of a rapid response that requires action rather than resolution. The security guarantees attached to the Non-Proliferation Treaty also suggests a prospective evolution in Council procedures. One may recall the relevant Security Council Resolution in which the Council "welcomed the intention expressed by certain states that they will provide or support immediate assistance, in accordance with the Charter, to any non-nuclear-weapon state party to the NPT that is a victim of an act or an object of a threat of aggression in which nuclear weapons are used."[84] Although implementation of this resolution apparently need not require further action by the Council as a whole, the Council or a special committee of it would doubtless want to take at least verbal action prior to any actual implementation. This will require new procedures.

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[84] S/RES/255, 1968. Adopted by the Security Council at the 1433rd meeting, June 19, 1968.

Aside from its role in safeguards enforcement, the IAEA will increasingly have to develop an active role in the direct control of nuclear power. This may be accomplished through the international management or ownership of nuclear facilities as already suggested, or, for example, through the institution of a plutonium brokerage at the IAEA.[85] The original IAEA charter permitted the evolution of the Agency in this manner, a development so far aborted, but certain to be encouraged again under the influence of latent proliferation, and the inexorable accumulation of plutonium stockpiles.[86] It is interesting to note in this connection that in the fields of narcotics control and health regulations, a few specialized UN agencies, notably the World Health Organization, have assumed remarkable regulatory powers; indeed the World Health Assembly has been given the authority to adopt directly regulations concerning sanitary and quarantine requirements and other procedures designed to prevent the international spread of disease, without effecting these regulations through international conventions and treaties.[87]

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[85] See section 5.

[86] The IAEA Charter states in part that the Agency shall "require deposit with the Agency of any excess of any fissionable materials recovered or produced as a by-product over what is needed for stated-peaceful uses in order to prevent stockpiling of these materials, provided that thereafter at the request of the member or members concerned special fissionable materials so deposited with the Agency shall be returned promptly to the member or members concerned." IAEA Statute, Article XII, 5.

[87] Lauterpacht/Oppenheim, 981. See also fn 67 above.

The nuclear age has already eroded any pristine notion of national sovereignty. This is manifested most fundamentally in the inability of governments, even of the most powerful nations, to protect their populations from the most grievous attacks (except by threat of retaliation). But the availability of plutonium derived from peaceful nuclear programs renders old conceptions of sovereignty altogether inappropriate. Modern urbanized states are extraordinarily vulnerable to terror and disruption; they cannot tolerate intimidation by nuclear threat, a danger which will be created by any significant lapse of safeguard effectiveness virtually anywhere in the world. The most dramatic impact of latent proliferation will probably thus be to quicken people's perceptions that nations can no longer guarantee their security and peace-of-mind; they will have to look elsewhere for such guarantors - to international and regional institutions and to transnational actors. As suggested earlier, individuals will increasingly have to act as international actors, with their primary allegiance to an international polity. This is all the more true given current conceptions of national leadership, which hold that the governmental representatives of the citizenry owe primary allegiance to that citizenry, not to a wider community. Of course, in principle the two perspectives need not diverge: what's good for the world may be good for the nation. But, in practice, a national leader will often have to choose between some short term and clear advantage to his own nation and a wider and possibly vaguer interest in world order.[88] Thus national leaders must be expected to dispose their countries' nuclear weapons and capabilities in a narrow and selfish fashion, advancing national influence and power over interests of domestic tranquility.

Nuclear weapons ought in theory to have vastly altered national perceptions of spheres-of-influence, which may be taken here as zones or regions in which powerful states try to exercise special influence

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[88] The American decision to drop the atomic bomb on Hiroshima affords an interesting illustration. First, did President Truman even have the "right", given his charge by the American people, to decide that Japanese civilian lives were to be saved in preference to American combat casualties? That is, did Truman have a moral obligation to protect American lives at virtually whatever cost to the enemy (assuming of course that this was the manner in which the issue presented itself)? Secondly, could the President reasonably decide that the adverse precedential impact of the bomb in the long run outweighed its (perceived) short term utility? However, one may now wish to answer these questions, in the abstract, it is clear that national leaders believe their moral responsibility requires their pursuing a fairly narrow national interest. On the atomic bomb controversy, see G. Alperovitz, Atomic Diplomacy; R. Batchelder, The Irreversible Decision; H. Feis, The Atomic Bomb and the End of WWII; H. Stimson, "The Decision to Use the Atomic Bomb," in Grodzins and Rabino itch, eds., The Atomic Age; R. Wasserstrom, ed., War and Morality.

over other state's domestic and foreign policies.[89] Before the advent of nuclear power, a nation's security depended (or appeared to depend) both on the economic resources it commanded and on the degree to which it controlled its border regions and beyond. But the current realities of the nuclear age it may have been thought would have changed this perception. The security of the United States and Soviet Union would no longer appear to depend very much on the rest of the world or on the wealth or terrirotу these states command outside their national borders. Rather, the security of the two superpowers now derives predominantly from their own national nuclear arsenals and perhaps more importantly from their relative ability to avoid any direct confrontations. If valid, this perspective would suggest for example that a growing Soviet influence in the Middle East would provide a threat to Soviet security, not a reassurance. Moreover, as the large nations have increasingly

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[89]Today, the powerful states of significance are only the United States, Soviet Union, and (perhaps) China. In general, the special influence is deployed jealously; a principal objective is to minimize to the extent practical other powerful states' influence. From this perspective, the main targets of influence are the foreign policies of the States within the given sphere. But, as with the United States in Latin America and the Soviet Union in Eastern Europe, the domestic policies of nations within the sphere are also of concern. Foreign and domestic policies are in any case related, directly in many instances or indirectly through the examplar influence of a domestic system (one reason the Soviet Union doubtless opposed the liberal Czech regime). Spheres-of-influence has also a more narrow legal definition, describing, (1) territory exclusively reserved for future occupation by a power which had effectively occupied adjoining territories, (2) territory in a weak state enjoyed by two stronger states by agreement between themselves, or (3) territory in a weak state enjoyed by a strong state by virtue of agreement between the two. Lanterpacht/Oppenheim, para. 227.

learned to exploit their own wealth and have responded to the rising welfare demands of their populaces, the economic value of spheres-of-influence would have been expected to wane.[90] Thus for all these reasons one might have expected that "near" places would have become as irrelevant as "distant" ones to the nuclear powers.[91] But such does not appear altogether to have been the case.

The Soviet invasion of Czechoslovakia and the Cuban missile crisis provide merely the two most dramatic manifestations of the endurance of spheres-of-influence. Other evidence is provided by Soviet incursions in the Middle East, continued oppressive Soviet influence in Eastern Europe, the Dominican landings, and the special watchfulness of the United States elsewhere in Latin America. Why this endurance of what should be an outmoded concept? One reason derives from the polarising American-Soviet ideological conflict after WWII. Any advance in influence by one of the two powers was viewed as a grievous loss by the other. Any Communist gain in Latin America, for example, would inevitably be deplored by the United States whatever the actual ensuing security implications. Similarly,

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[90]Certainly a controversial issue, however. Lee R. Cooper, The Economics of Interdependence; K. Deutsch, et al., France, Germany and the Western Alliance; and especially, E. Morse, "The Politics of Interdependence," in International Organization, XXIII, No. 2 (1969).

[91]An inversion of Wohlstetter's idea that distant places are now as relevant as near ones. See Albert Wohlstetter, "The Illusion of Distance," Foreign Affairs, Volume 46, Number 2, January 1968.

the Soviet Union has opposed any turn toward the West by the countries of Eastern Europe. A bipolar view of the world strongly bolsters the validity of spheres-of-influence.[92] Another argument for the endurance of spheres-of-influence has been advanced by some American "revisionist" historians, such as G. Kolko. Kolko, for example, argues that a crucial determinant of American foreign policy has been the conscious quest by government decision-makers for assured sources for raw materials and for foreign markets.[93] There seems, however, no persuasive evidence to support this contention.[94] Whatever its degree of truth, however, the most important contribution to the endurance of spheres-of-influence may simply be a kind of bureaucratic inertia, an inability of bureaucrats and national security managers to turn away from old national goals.

Whatver the force of these arguments in the past, it is likely that latent proliferation will further support the idea of spheres-of-influence. First, the great powers will see increasing importance to the control of certain resources outside their borders, notably

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[92] More accurately, a concept of zones of influence which encompass not only traditional spheres-of-influence but more distant regions as well. See Richard Falk, "The Legitimacy of Zone II as a Structure of Political Domination," The Center for Advanced Study in Behavioral Science, August 1969 (unpublished).

[93] Gabriel Kolko, The Roots of American Foreign Policy.

[94] See, for example, Richard Barnet, Intervention and Revolution.

uranium. This will not be because either the United States, Soviet Union, (or China) needs such uranium, but rather to preclude other states from obtaining it. In particular, it must be expected that the Soviet Union will oppose any developments in Central or Eastern Europe which might eventually provide West Germany with an independent supply of uranium. Aside from uranium, however, there are various materials needed for a flourishing nuclear industry which are not found in high abundance within the territories of the nuclear powers.[95] In these cases, the important nuclear powers will seek assured sources of the critical raw materials. Far more important to spheres-of-influence than these considerations, though, is the powerful interest of the nuclear powers in discouraging intensification of nuclear capabilities in countries within their own geographic region. The chief reasons for this have been emphasized above: the dangers associated with actual nuclear proliferation within the region, the risks that the nuclear powers will become engaged in interventions to prevent proliferation, and the dangers that sub-national terroristic groups with target goals within the territory of the nuclear power will be able to acquire nuclear material in adjoining territories.

Associated with spheres-of-influence is the concept of polarity - the degree to which power is distributed evenly throughout the world. As suggested in section 3, several analysts have made much of the

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[95]For example, a recent study at the Oak Ridge National Laboratory (M. J. Bell, "Availability of Natural Resources for Molten-Salt Breeder Reactors," ORNL-TM-3563) has identified several materials which would be needed for a widespread deployment of molten salt breeder reactors and which are not plentiful within the United States.

impact of proliferation on polarity and consequently on stability. Their arguments suggest that (actual) nuclear proliferation will produce a multipolar world (more than two states will be able to exert significant influence outside their own borders) and that this would be either stabilising (Masters) or destabilising (Hoffman).[96] Latent proliferation pushes the ambiguity to an earlier stage. That is, it is not clear even that it would erode bipolarity. Indeed, on balance, it appears probable that the spread of civilian nuclear power will reinforce a bipolar system (or tripolar, with China) and eventually even lead to a kind of American-Soviet hegemony. This for the same fundamental reason that latent proliferation is likely to increase the validity of spheres-of-influence: the great powers cannot tolerate the dangers inherent in an uncontrolled expansion of nuclear power capabilities; it will be in the interest of all current nuclear powers that any such threatened uncontrolled expansion be quashed, by almost whatever means.

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[96] See section 3, this chapter, especially the discussion of stability.

5. Toward a Strategy of Control

Introduction - General Objectives and Characteristics of a Control Regime

The central conclusions of the preceding analyses are these:

(1) Under current trends, civilian nuclear power programs will become increasingly intense; that is, they will be ever more readily convertible to weapons purposes. This intensity will be characterized predominantly by an increasing national independence over the nuclear fuel cycle. International safeguards alone will not prove sufficient to prevent this intensification nor the consequent conversions to weapon programs.

(2) Such conversions will be the more probable, the more intense the civilian nuclear programs; and in general, the instabilities introduced by latent nuclear weapon capabilities will become more pronounced as the intensity of the capabilities increase.

The crux of the problem is that safeguards are following technology rather than the reverse. Civilian nuclear power is developing more or less on its own terms with its own economic rationalization. Those wishing to institute controls do the best they can consonant with the already determined technology.[97] A proper control effort will reverse

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[97] For example: "Whatever the outcome regarding isotope separation in Japan may be . . . I cannot agree that people looking at the problem from the international security point of view should regulate the oncentives and actions of industry. Whatever comes out of enrichment technology development for an inudstrial application must be looked at as reality. The means to cope with this reality, be it safeguards or otherwise, must be found." (R. Imai in Civilian Nuclear Power and International Security, 37).

this idea; nuclear power programs cannot be permitted to develop under simply economic and technical guidelines without the safeguard interest being recognized early and persistently. Moreover this interest must be internationally manifested. As Leonard Beaton has observed, statesmen do not now possess any convincing world image for the longer term making it difficult for them to construct policies whose "point and purpose is to defend the character of the longer term."[98]

A strategy to control latent proliferation must have as object a dimunition in the intensity of the system through the discouragement of any significant degree of independent national control of nuclear material. Key nuclear facilities ought to be distributed in such a way that no single non-nuclear country be able to produce nuclear material independently on a substantial basis, and so that any nation wishing to subvert the agreed system would pay grievous economic penalty. In terms of the preceding section, this goal may be sought by the inculcation of an appropriate sanction system - a set of expectations and enforcement procedures combining both political and technical constraints on national behavior. The technical factors will be those which physically deny a nation complete access to all requisite parts of the fuel cycle. The political factors will be ones which discourage nations from even seeking such access. The two types of factors interact. The technical measures described below will have little chance to be implemented if nations are not simultaneously persuaded of the folly and disutility of

[98]Beaton, in Civilian Nuclear Power and International Security, 81.

nuclear weaponry. Thus although political measures such as no-first-use agreements, test bans, strategic arms limitations, etc. are not discussed here, it should be emphasized that any control strategy must eventually encompass such elements.

Whatever specific and detailed schemes are considered, a control strategy must give the non-nuclear states strong political and economic incentive to cooperate, a requirement which demands various degrees of participation by the nuclear weapon states in any international control arrangements that might be agreed upon. The central political imposition on such arrangements would be a fairness or equality of obligation among the participants -- an acceptance by both nuclear and non-nuclear states of similar international obligations, and of comparable access to the authority overseeing the creation and implementation of these obligations. This is not an obvious or immediately compelling proposition, since control of peaceful nuclear programs quite clearly has distinctly different purpose and impact in nuclear weapon states than in non-nuclear countries. Nevertheless, despite such asymmetries, non-nuclear countries have insisted on equality of obligation in regard to safeguards in connection with the Non-proliferation Treaty and may be expected to continue to do so in the future.

The concern of the non-nuclear states is not imaginary; they have a legitimate reason to fear that were they excluded from various commercial nuclear activities and the nuclear weapon states not similarly constricted, a severe asymmetry in industrial development, paralleling the current asymmetry in weapons development, would arise between the nuclear and non-nuclear states. Moreover, were there such an asymmetry, the non-nuclear participants in any international control arrangements would possess little protection against increasingly stringent interpretations by an international control authority which would inevitably be heavily represented by the nuclear states; that is, by the states which would not feel the brunt of severer control mechanisms. Whatever the strength of such direct (though imprecise) economic concerns, it is also evident that habits of sovereignty will lead non-nuclear states to demand reciprocal limitations on the sovereign prerogatives of the nuclear states, if they themselves are forced to accept such restrictions, even if the limitations imposed on the nuclear countries are essentially meaningless at least with respect to proliferation concerns. Thus, in sum, the first requirement of a successful control effort would appear to be an equality of obligation among the participants.

Similarly, any control scheme must ensure the non-nuclear participants a fair share in future peaceful nuclear developments devised in the industrialized nuclear-weapon states; and it must persuade the non-nuclear countries that they need not search for energy-security at the expense of other objectives. With respect to advanced developments, a special burden of control must be placed on the United States, which is by a large margin the leader in the development of nuclear energy for peaceful purposes. The United States along with other important industrialized countries (notably the United Kingdom, Canada, the large Western European countries, and Japan) could help ensure stringent controls on key future developments, especially breeders, by raising the prospect that other nations would share the fruits of the developments in return for their cooperation in such control. Economic advantages always appear more compelling at a time when the political and security repercussions of a given course of action seem distant. Thus it would be hoped that nations could be found to tight controls on breeders and other prospective developments before these developments progress to a point where the drawbacks of such control become more manifest. The principal way to persuade nations to accept less energy-security than they could otherwise obtain is through the development of institutions, procedures, and expectations that encourage the prospect that the control of commercial nuclear programs will be administered fairly and narrowly. In the long run, nations will forego national isotope separation facilities, reprocessing plants, etc. only if their access to such facilities are assured through international or regional convention, not through the continued good will of a single nation. Since expectations take time to develop, this internationalization of nuclear commerce will have to proceed gradually, in a variety of functional steps. Given the prospective importance of nuclear energy and the widespread desire for energy-security, states will give up energy independence only slowly as they gain assurance that secure access to nuclear power is ensured by the international community.

Equality of obligation and full participation by non-nuclear states in civilian nuclear commerce provide incontrovertible guidelines to the establishment of any control scheme. However, most other conceivable overall objective characteristics of a control strategy raise serious dilemmas; two in particular may be mentioned. Should states be given economic incentive to participate in international control measures? Should the nuclear fuel cycle be centralized? In the first instance, it is reasonably clear that reductions in cost, through for example the provision of free fuel reprocessing, minimal interest charged to fuel inventories, toll-enrichment services, etc., provide a powerful lever to persuade nations to accept concommitant control arrangements. For nations determined to pursue a nuclear weapons program, such savings would of course be ineffective; their value lies in encouraging appropriate response in countries at the moment not committed to nuclear proliferation. At the same time one would wish to effect these economic incentives, there exists the contrary pressure not thereby to subsidize nuclear power and consequently cause a wasteful and rapid expansion of nuclear activities where conventional fuels would do as well or better. Thus a central problem inherent in most conceivable schemes to internationalize nuclear energy will be to devise arrangements which will on the one hand appear economically attractive compared to national approaches to nuclear power development, but no unduly attractive compared to conventional power alternatives!

A similar dilemma is raised by the issue of centralization. Centralized and closed fuel cycles, where the fabrication, reactor, reprocessing, and metal finishing facilities are coterminus at a single location minimize drastically the transportation of fissile material with its consequent vulnerability to illicit diversion. Such centralization would also (probably) ease the safeguard task, and especially that of prociding physical security. There exist potential disadvantages to centralization, however. Above all, centralization would tend to give states complete physical control over the full cycle. It discourages the idea of internationally owned regional fabrication and reprocessing facilities which could service reactors in several countries; it in a sense encourages nuclear antarchy.

Potential Controls

In this section are sketched a few technical elements of a potential control strategy to restrain latent proliferation. "Technical" refers here simply to effects on the actual operation of the nuclear fuel cycle, in distinction to "political" measures effecting national security perceptions. The purpose of the sketch is to provide some picture of the kind of institutional changes that can, and in the long run, must be effected. It does not provide any detailed definition or analysis of the potential measures.

It is natural in beginning a search for international arrangements to control nuclear power to concentrate on critical points of the nuclear fuel cycle, that is, those places where the diversion of fissile material might most easily be accomplished or where an international authority would be able to exert the most leverage if a nation chose to initiate a nuclear weapons program. The first such point that suggests itself is at the source, the uranium mine and mill. Uranium though not rare by any means is nonetheless so far found in relatively few areas, and found in accessible quantity only in the United States, Canada, South Africa, and Sweden (among the non-Communist nations). As indicated in section 2 above, uranium and reactor suppliers are now in competition to provide recipient states as secure a supply of uranium as possible.[99] From a safeguards

[99]The case of the Australian tenders as described in section 2 is particularly illuminating.

perspective, this competition is undesirable. That is, nations wishing to establish energy security will inevitably increase their independence over the nuclear fuel cycle by forcing bidding among the uranium suppliers. What is wanted are agreements among uranium suppliers not to undercut one another in the safeguard terms under which they will sell uranium, and among both suppliers and receivers which will assure the recipient state of a continuing supply of uranium (as long as it accepts safeguards) without permitting the state independent access to uranium regardless of its adherence to safeguards. The goal of agreement among both buyers and sellers, with perhaps the establishment of an international clearing-house for uranium sales, would be simultaneously to reassure buyers that uranium flows will not be arbitrarily cut-off and to permit cut-off if the buyer flaunted safeguard obligation. To prevent uranium transfers outside of such agreement, the agreement might need to require the extension of safeguards to the uranium mine and mill.[100]

A second critical point in the nuclear power cycle occurs at the isotope separation plant. It clearly would be desirable that no such plant be constructed unilaterally by a non-nuclear country, partly because it could be used directly to produce fissile material, and partly because a country without an isotope separation facility

[100] There are at present no international safeguards applied at the uranium mine or mill; safeguards do attach to transfers of uranium of significant amount.

but depending on enriched uranium reactors would be vulnerable to international sanctions if it violated an international safeguard agreement. That is, because enriched uranium reactors could not be made to operate on a complete natural uranium loading, the suppliers of enriched fuel would be in some position to compel compliance with international safeguards. Also, as indicated in Chapter 2, even a relatively small enrichment facility could rather easily enhance the Pu-239 content of dirty plutonium thus providing a cheap way to produce high quality weapons grade material from ordinary reactor-discharged plutonium.

With present technology utilizing the gaseous diffusion concept, isotope separation plants must be relatively large, expensive, power-consuming and technically sophisticated; there is probably no economic rationale for any single non-nuclear country to construct one now. However, centrifuge technology may change this, permitting smaller and less expensive facilities. Moreover, for reasons put forward in detail in Chapter 1, centrifuge plants are inherently much more flexible than gaseous diffusion plants; they allow a relatively easy conversion from the production of low enrichment fuels to production of weapons grade materials. An object therefore of an international control strategy ought to be the discouragement of national centrifuge plants. This will probably require a willingness by the United States to cooperate in the establishment of regional gaseous diffusion plants outside of its borders. Indeed, in July 1971, the American government formally proposed to provide technical information, heretofore classified, on gaseous diffusion to any multinational group of non-Communist states.[101] As alternative to the encouragement and subsidy of multinational gaseous diffusion plants, safeguards benefits would accrue also to subsidy of multinational and large centrifuge plants in preference to smaller dispersed ones. For example, it has been suggested that restrictions could be placed on centrifuge manufacturers through international agreement whereby centrifuges would not be sold to plants smaller than a certain size, thus inhibiting acquisition of small facilities by several countries.[102]

Fuel fabrication facilities provide a third potential focus for control efforts because a relatively small number located a distant point from the power stations themselves could service the entire international nuclear power program.[103] At the same time, there will be little to actually safeguard at fabrication facilities during the next few years since the facility throughput will contain very small amounts of fissile material. Once plutonium recycle becomes prevalent, though, strong safeguards on fabrication facilities will become necessary. Nevertheless, the value of these facilities to a

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[101] Nuclear Engineering International, (November 1971), 933-935. William Hart, "The Proliferation of Uranium Enrichment" Woodrow Wilson School, Princeton University, January 1972 (unpublished), i, 22.

[102] Comments by V. Gilinsky in Civilian Nuclear Power and International Security, 34.

[103] See Chapter 1, section 2.

control effort resides not in their vulnerability to diversion or seizure but in the potential of the international community using them to deny essential services to a country violating an international control agreement. This suggests that fabrication plants be constructed as large regional facilities under international management.

This idea, however, may be better illustrated by reference to perhaps the most critical part of the nuclear fuel cycle, the chemical reprocessing plant. Here is where all discharged reactor material with contained plutonium must be sent, and where the plutonium is separated into a form suitable for weapons purposes. Since, moreover, a relatively small number of reprocessing plants could service the world demand, arrangements to place these plants under some kind of international control and to keep them out of non-nuclear countries, to the extent practical, seem highly attractive. As observed in section 2 of Chapter 1, a 1000 MW_e light water reactor requires a reprocessing capacity of 30 MTU per year. The three commercial plants already built or under construction in the United States have combined capacity of over 2700 MTU per year, sufficient to service 90,000 MW_e capacity. Three other plants of greater total capacity are planned. Combined, these six plants could cover essentially all U.S. reprocessing requirements until at least 1985. Capacity of foreign reprocessing plants already constructed or planned, now totals about 700 MTU per year (enriched uranium) and over 3300 MTU per year (natural uranium).[104] The addition of

[104] See Chapter 1, Table 3.

only three additional plants the size of the American Allied Chemical facility now under construction (1500 MTU per year) could meet all foreign reprocessing requirements up to 1985 and beyond. Not only can a very few plants meet the total world demand, but it should be able to do so at no significant extra cost. The small transportation charge differential entailed by the use of large regional facilities instead of smaller dispersed plants is probably at least compensated by an increased economy of scale.[105] No doubt, economic incentives could be offered reactor operators to have plutonium sent to the regional facilities dispersed throughout the world and managed by international civil servants or by a regional organization. But a more sure way to ensure full cooperation would be through international agreement; all discharged fuel would have to be sent to these plants. By virtue of such an agreement, states would not be deprived substantially of energy security; for they could always construct their own reprocessing plant relatively quickly and cheaply if they ever became convinced that the international group managing the regional facility were acting against their legitimate interests.

Although not a critical point of the fuel cycle in the sense of the preceding, the fissile material itself could be subject to

[105] See Chapter 1, section 2 and 3; especially Tables 6 and 7.

additional controls beyond the mere attachment of safeguards. In particular, attention should be given to the establishment of a "plutonium brokerage" in which the IAEA would play a central role in the disposition of plutonium (and U-235) used and produced in commercial programs. During the next several years, reactor operators will confront a complex economic decision on whether to recycle discharged plutonium or store it in anticipation of initial breeder reactor fueling. In the United States for example, plutonium availability from light water reactors is expected to exceed plutonium demand for breeder development for about a 15 year period after 1973-1974. Annual plutonium quantities thus available for recycling or storage will increase from about 2 tonnes in 1974 to 80 tonnes by 1986 with a cumulative total during this period of roughly 450 tonnes. Outside the United States, roughly similar amounts of plutonium will be available.[106] For reasons outlined in Chapter 3, it is undesirable from a safeguards perspective to have states stockpiling large quantities of plutonium. It would be well to require states not wishing immediately to recycle plutonium to sell or loan the plutonium to a central brokerage. Such a brokerage could then either stockpile the plutonium itself or sell it to states demanding plutonium for recycle and research purposes. The state initially providing the plutonium to the brokerage would maintain

[106] Fred Hittman and Marvin Raber, "The Importance of Plutonium Recycle" in Nuclear News, November 1968, 48-56, 50.

credit for the provision; when it needed the plutonium, the brokerage would return or resell it as appropriate. Such return should probably be strictly required by the state-brokerage agreement if the state can assure the brokerage of the immediate and peaceful destination of the plutonium. In this manner, the brokerage could provide financial inducement for states not to stockpile, and provide additional safeguards over illicit use of plutonium. The financial incentive could it may be hoped help secure the initial willingness of states to enter an agreement which invested the brokerage with suitable powers and resources, and which gave elements within the states some stake in the persistence of the brokerage. However, it is probably not prudent to rely (unless necessary) on the financial incentives afforded by the brokerage to attract the voluntary cooperation of states and reactor operators. Although even this type system would have advantages in reducing national control over stockpiles, it is not likely to secure the universability of an imposed agreement whereby all plutonium not in use must be sent to the brokerage.

As mentioned in section 4, the IAEA Charter permits the Agency to adopt the brokerage function outlined here. Under the Charter, the IAEA could require deposit with the Agency of any excess fissile material over what is needed for stated peaceful uses, provided that such material be returned promptly at the request of the member concerned.[107]

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[107] See fn. 86, this chapter.

How feasible is the economics of such an undertaking by the IAEA? If the reactor operator stored the plutonium himself, he would typically incur a carrying charge of 10 to 12 percent per year on the price of the plutonium plus some storage cost.[108] The price of the plutonium until breeder introduction is imminent would be roughly $10 per gram based on recycling worth; storage costs may be taken as approximately $0.20 per gram.[109] With a 10 to 12 percent carrying charge, this suggests that storage for more than a couple of years would be uneconomic unless a very rapid rise in the plutonium price were expected. Plutonium will in fact rise in value as breeders are introduced and uranium becomes more expensive, but probably by no more than a factor of two during the next decade.[110] Even a two-fold increase would justify storage for only 4-5 years. Thus reactor operators ought to be willing to sell plutonium for roughly the "recycle price" of $10 per gram unless they expect to find both use for the plutonium relatively soon and a very rapid increase in the plutonium market value. Indeed, if the plutonium supply exceeds the recycle demand, operators might be willing to sell plutonium to a brokerage at still a lower figure. In any event, a brokerage willing to buy plutonium at some

[108] Hittman and Raber, 52-53.

[109] *Ibid.*, 53.

[110] *Ibid.*, 53-54.

price roughly equivalent to its recycle value would appear economically attractive to plutonium producers.

Such plutonium could be resold to the producer under many different terms: for example, at the then market price or at the initial purchase price plus some nominal interest charge less than the aforementioned 10-12 percent per year. The cost of such an operation to the brokerage need not be excessive. (Conceivably, of course, it could even operate at a profit). As a very crude approximation the cost (under the second-mentioned term above) might be calculated as the difference in the carrying charge on the reactor operator and the rate of return on its funds that could otherwise be obtained by the brokerage if it invested the money it instead paid out for the plutonium. Assuming this differential at (say) 2½ percent, the cost to the brokerage over the next 12-15 years might be on the order of $200 million, if the brokerage purchased (and eventually resold) all the plutonium produced in the non-nuclear countries.[111] This is not a trivial amount, but neither does it appear impractical; it is equivalent to an extra charge of less than 0.1 mill/kw-hr.

Finally, should the differential be large enough to compensate for a rise in the plutonium price due to an increased recycling value, plutonium recycling itself could be discouraged by the brokerage.

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[111] A crude calculation, assuming an average 2 year storage period before resale and a cumulative plutonium production in the non-nuclear countries of about 350 tonnes.

This would be a safeguards benefit, for recycling permits as part of the normal fuel cycle the finishing and fabrication of plutônium metal such as may be useful for weapons.

The reactor itself does not seem a useful place to concentrate on initially. On the one hand, it is the single most important part of the power cycle -- the place where the power is generated -- and the one part which must indisputably be located in or near the communities whose power needs it is serving.[112] On the other hand, the reactor does not contain (compared to other parts of the cycle) a large amount of easily accessible fissile material. This is not to say of course that reactors should not be subjected to stringent safeguards, but rather that nations will at once probably strongly resist undue international controls on them and not however find them ideal places to effect fissile material diversion. Finally, it seems imperative to develop controls on advanced developments, notably fast breeder reactors, partly because they will involve extremely large and concentrated inventories of fissile material, and partly because the prospect of being able to share in these developments in the future could produce a powerful incentive to non-nuclear countries to join in various cooperative arrangements now, such that they and the nuclear weapon states as well will be found to highly interconnected programs not suited to national co-optation at the time breeders and other advanced developments

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[112]There is one important caveat to this statement. The development of extra high voltage power transmission lines, along the extensive interconnected grids, might permit nuclear power stations to be located at regional centers where they could send electric power to several nations over considerable distances.

become operational.

The critical parts of the fuel cycle, uranium, fuel fabrication plants, reprocessing plants, isotope separation facilities, and the discharged fissile material, each suggest a potential component of an internationalization strategy. Given the scope of present national nuclear programs, the sum of the indicated measures represents a fundamental upheaval in normal international conduct. Nevertheless, the program called for is not utopian. Indeed, one purpose of this last section has been to make the internationalization schemes seem at least within the possible despite their unsettling and radical character. A purpose of the study as a whole has been to impress the necessity of such schemes however unsettling and radical they may be.

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ABSTRACT

The technology, scientists, and technicians required to produce nuclear warheads are widely diffused; and for the most part nations or sub-national groups wishing to acquire nuclear weapons already possess or could obtain the necessary delivery systems appropriate to their purposes. Acquisition of fissionable material thus provides the salient obstacle to the production of nuclear weapons. But fissionable material is also precisely what is used and accumulated in quantity in any civilian nuclear power program; and the intensification and spread of these programs thereby creates management and control problems of colossal proportions.

Confronted with this conversion potential, the international community has instituted systems of national, regional, and international safeguards, the formal and legal procedures that attempt to ensure that nuclear material is not diverted from civil use to weapons or other illicit purposes. But these inspection and control procedures will not be sufficient in the long term to prevent the diversion of nuclear material to weapons purposes. So long as nations have sovereign control, both legally and practically, over their nuclear programs, safeguards, albeit indispensable, will face an impossible task. A system of inspection superimposed on an otherwise uncontrolled exploitation of atomic energy by national governments will not prove an adequate safeguard.

The situation today is therefore characterized by a continuing intensification of civilian nuclear power programs whereby nations

increasingly gain independent and autarkic control over the nuclear fuel cycle and move ever closer to a nuclear weapons capability. This intensification of civil nuclear capabilities unimpeded by new control measures will raise grave threats to international and domestic security, many of them altogether unexampled. A control strategy beyond the present safeguard effort is thus required. Such a strategy would most probably have to include some form of international control of fabrication and reprocessing facilities and the establishment of a plutonium brokerage under the auspices of the International Atomic Energy Agency.