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/ MOVING TOWARD LIFE IN A NUCLEAR ARMED CROWD? /
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This is the final report on Phase I of Contract ACDA/PAB-263. The main purpose of the report is to provide a clear definition of trends in the spread of nuclear technology, and a precise analysis of the problems (political, military and economic) that these trends pose for policy. It explores briefly some policy options in order to bring out more clearly the kinds of action that are necessary and genuinely relevant for coping with the problems. The whole of Phase I work is self-consciously a preface to policy.

We would like to thank the many individuals in the Arms Control and Disarmament Agency and in other government agencies for the information and advice they have provided. The usual disclaimers, however, apply. The views expressed here are those of the authors. They do not necessarily coincide with those of the Arms Control and Disarmament Agency or any other agency of the United States government.



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I. The Trends and the Questions They Pose

"Whatever else hospitals do, they shouldn't spread disease."

Florence Nightingale

What follows is concerned with analyzing trends in the spread of nuclear technology, and with using the analysis to define questions critical for policy. It is intended to raise more questions than it will answer. For good reason. In this complicated and fateful area of policy, very often actions taken for the best of ends, perversely, defeat them. If our policies are to cope with the spread of military-nuclear technology rather than encourage it, it's essential that they be more than symbolic and well intended, more than "allusive and sentimental" (as Robert Oppenheimer called Atoms for Peace). They need to be concrete and aimed precisely at the problems posed by changes in the real world. Otherwise, like the 19th Century hospitals Florence Nightingale referred to, they are as likely to spread the disease as to cure it. But then, it is essential to understand underlying causes and effects. This phase of our work is deliberately a preface to policy.

To Sum Up Some Key Points

1. Many countries, including many agreeing not to make bombs, will come very close to it without violating the agreements.]

o It has been understood from the outset of the nuclear age that designing a bomb and getting the non-nuclear components are much easier than getting fissile material in high enough concentrations for an explosive. Research on bomb design and testing of non-nuclear bomb components are not prevented by agreement, and can proceed in parallel with the accumulation of fissile material. Fissile uranium (in particular U235) or fissile plutonium (especially Pu239) in concentrations high enough to need no isotope separation and only a modest amount of chemical separation are then the key hard-to-get requisites for making a nuclear bomb.

o By 1985, according to their 1975 plans, nearly 40 countries will have enough chemically separable plutonium for a few bombs in the spent fuel produced by their electric power reactors.

o About half these countries have been planning a capacity by then to separate at least that much plutonium from the spent fuel.

o A few years later, if plutonium recycling has become general, many governments will come significantly closer to obtaining chemically separated plutonium metal, even if they do not themselves separate plutonium from spent fuel: Those that manufacture plutonium dioxide fuel rods will have plutonium easily available in their starting and in-process inventories. If they neither separate plutonium nor manufacture their own plutonium fuel rods, nonetheless about 25 or more countries would have very large quantities of plutonium (from 50 to 1400 bombs worth) in fresh un-irradiated fuel.

o Some research (as distinct from electric power) reactors may be fueled by weapons grade uranium and some, like the CIRUS reactor supplied by Canada to India, may produce plutonium for a few explosives. Reactors used for ship propulsion use highly enriched uranium as fuel. Each of these is a potential source of weapons grade material, obtainable without violating agreements. The weapons material these sources might provide will be dwarfed, however, by the plutonium output of electric power reactors owned by an increasing number of countries.

o All of this can happen without violating agreements -- at least any clearly understood, unambiguous agreements: A kind of growing legitimate -- but Damocletian -- "overhang" of countries increasingly near the edge of making bombs.]

o This overhang of countries acquiring material for nuclear weapons as a legitimate byproduct of civilian programs is in addition to those that might get it by an overt military program they have not foresworn; or, by cheating; or simply by shopping, as Libya has tried, for a finished bomb.

2. For this major problem of a growing legitimate "overhang," safeguards will become increasingly irrelevant. The "overhang" requires no diversion, and therefore no violation of safeguards.]

o The U.S. bilateral and trilateral agreements on nuclear cooperation that we have examined (over half of those concluded with 30 countries) leave title to the plutonium in the countries operating the reactors, subject only to safeguards. But the acquisition and storage of this material can grow legitimately under watch by a safeguards inspector.

o The distinction between "safe" or civilian activities and military or "dangerous" activities is becoming increasingly ambiguous

o This ambiguity will confuse and reduce warning that bombs are about to be made, or that they can quickly be made; such ambiguities also weaken sanctions. (Sanctions impose some costs on suppliers as well as on recipients, and the less clear cut the violation, the weaker the resolve of the supplier.)

3. Sophisticated proponents of a safeguard system stress that it is primarily a kind of early warning alarm bell. However, as things stand, the IAEA safeguards system which is designed to detect diversion may actually muffle signs of the critical changes taking place without diversion.

- o The early warning that has always been implicit in the notion of safeguards would permit individual governments to respond appropriately and in time even if no collective sanctions have been defined.

- o But the IAEA rules, designed to protect commercial and industrial secrets, obscure information relevant for the decisions on security by governments.

- o The IAEA treats information reported to it by the individual countries it monitors as to actual quantities of nuclear materials and their physical and chemical states as "Safeguards Confidential." It does not show this critical information to any other governments; much less to the public.

- o As a result, not much is known in or out of governments in any regular way about the distribution by country of stocks of fissile material.

4. The most immediate prospects for acquiring nuclear explosives tend now to be small or less developed countries (LDCs), especially those outside the Soviet orbit, not -- as once expected -- the most advanced industrial powers.

- o The situation may be like that of the Marxist revolution: predicted for the advanced bourgeois countries, it came in the backward ones.

- o This development, among other things, may complicate the problem of slowing the spread of bombs by merging it with problems of the demand by the less developed countries in the third world for equity (or more precisely, equality) with the advanced industrial countries, many of which are also nuclear exporters.

5. The problem of subnational or transnational nuclear terror seems most acute in those countries that are the most immediate prospects for acquiring nuclear weapons.

- o Nuclear terror, while possible in the United States, has recently because of its sensational character, been given an exaggerated amount of attention here: Congress and the press have given it more notice than the worsening problem of proliferation.

- o Some of the countries that may soon acquire nuclear weapons, however, are politically unstable and much more liable to sudden threats of mass destruction from dissident factions.

6. The most likely countries to decide for nuclear weapons appear to be non-aligned by choice or to be outcasts, dropouts or fading members of alliance systems, especially the U.S. alliance system: South Korea, shaken by the collapse in Southeast Asia; Taiwan by that and the U.S. rapprochement with the People's Republic; Pakistan, which left SEATO feeling unhelpt by the U.S. and the U.K. in its conflict with an India that has since shown that it can make and detonate nuclear explosives; Iran, now following a policy of "independent nationalism" in the Middle East and interested in keeping external powers out of the Gulf; Brazil and Argentina asserting independence in the Western Hemisphere; Spain so far excluded from NATO; and South Africa odd-man out of all alliance systems. In the same way the few Communist countries that may move in this direction are outside the Soviet orbit, like Yugoslavia, or moving away from it in foreign policy, like Rumania.

7. For most less developed countries whose civilian programs are moving them closer to a military capability, the civilian economics look particularly poor: Nuclear electric power is capital-intensive and more likely to be economic on a very large scale. But less developed countries are in general short of capital and need electric power generated in smaller units.

- o The oil price increase by OPEC (Organization of Petroleum Exporting Countries) intensified the scarcity of capital and foreign exchange in those less developed countries that are not members of OPEC. Initial predictions immediately after October, 1973, that the price increase would make nuclear electric power generally economic for LDCs, even compared with fossil fuels such as imported or indigenous coal, were misleading and have been revised. The economics of recycling plutonium (recycling is particularly dangerous from the standpoint of proliferation) look especially unattractive in LDCs.

- o The LDCs in OPEC that have suddenly acquired a great deal of capital have small needs for energy and very large supplies of fossil fuel.

- o Investment in nuclear energy is a poor choice among alternatives for the economic development for LDCs. It diverts capital from more productive uses. In short, compared with alternatives, instead of speeding economic development and slowing the spread of military technology, as we had hoped for decades, the subsidized transfer of nuclear technology has slowed development and may speed the spread.

8. Trends in the relative cost of some forms of nuclear electric power most dangerous from a military standpoint make them look much less attractive even from a strictly economic point of view. Programs for such nuclear processes need to be looked at with particular sobriety and skepticism.

- o It would be worth a substantial economic sacrifice to avoid the large political costs in allowing the development of a world of many nuclear armed states. And some sacrifice in the form of extra dollar costs might conceivably be involved in restricting nuclear electric power to less dangerous forms that minimize access to readily fissionable material. However, such extra costs are not at all likely to

be large in relation to total electric power costs; and they may be negative. We may save money as well as potential trouble by foregoing some plainly dangerous activities now contemplated.

o The trends in capital costs of High Temperature Gas Cooled Reactors (HTGRs)--particularly dangerous because they have been designed to be fueled by weapons grade uranium with a 93% concentration in the fissile isotope U235--now make HTGRs look unpromising.

o More important, trends show a drastic worsening in the relative costs of light water reactor (LWR) power with plutonium recycling, compared to such power without recycling.

o The estimated costs to separate plutonium from electric power reactors have increased tenfold in ten years. They remain highly uncertain. Extracting plutonium from LWR spent fuel and making it into plutonium fuel rods to replace some fraction of the uranium fuel and recovering uranium from the spent fuel, it now appears, will be more expensive than using the fresh uranium fuel rods they would replace: 50% more in a large (5 MTU* per day) plant in the United States; 80% more in such a plant in a multinational nuclear center; 400% more in a 1 MTU per day plant which would be quite large for a less developed country. (Costs might double again for plutonium extracted from heavy water reactors (HWRs). Recycling fissile material from HWRs is even less economic than from LWRs since the HWR spent fuel contains plutonium in more dilute form and uranium with much lower U235 content than natural uranium.) Recycling, in short, seems likely to lose rather than save money.

o Nor would it conserve much scarce uranium. A recent OECD (Organization for Economic Cooperation and Development) estimate indicates that for the entire non-Communist world, the cumulative savings from plutonium recycle until the year 2000 might amount to 9 months' supply of uranium at that date. Together with the recovered uranium, the recovered plutonium might reduce requirements for fresh uranium by about 10%.** A recent estimate by the Edison Electric Institute (EEI) suggests a cumulative saving in the non-Communist world of about 13% by the year 2000 or slightly more than OECD's. For the United States, the EEI numbers indicate uranium savings of about 10% by 1990 and 16% by the year 2000.

* 5 MTU means 5 metric tons in uranium content of the spent fuel reprocessed.

**Recovered uranium is contaminated with U236 and is, therefore, equivalent to only about one-half the amount of uncontaminated uranium. We have taken this penalty factor into account in this and following estimates of resource savings from recycling of uranium.

o Based on the EEI projections, savings from uranium and plutonium recycle would amount to about 1% of total energy consumption from 1975 to 1990 and, perhaps, to about 2 percent from 1975 to the year 2000. Such amounts are within the "noise" level of uncertain long-run forecasts of energy resources consumed.

o It follows that even if recycling plutonium and uranium saved money rather than lost it, it could not save much in delivered kilowatt hour costs. If we were to suppose that the costs of separating plutonium and the extra cost of fabricating plutonium dioxide fuel rods were zero, that is, that reprocessing were free, recycling could save only about a tenth of the uranium fuel costs incurred by the non-Communist world up to the year 2000. Since nuclear fuel cycle costs themselves are less than 10% of delivered kilowatt hour costs, that would mean a cost saving of about 1% even if reprocessing itself were to cost nothing. But reprocessing costs will be substantial.

o It cannot be persuasively maintained--though it is often repeated at the expense of some confusion in our anti-proliferation policy--that recycling is an essential to the future of nuclear electric power.

9. The current public debate unfortunately tends to pit extremes against each other: on the one hand advocates of stopping and dismantling all nuclear electric power as equally hostile to the environment and physical security; and on the other, those who appear to defend all forms of nuclear energy as vital to the growth of our own and other advanced industrial societies and as critical to the economic development of the poorer countries.

But the extreme alternatives are not in fact very interesting. It is plain, for example, that we will for a very long time use fossil fuels and nuclear fuels as well. The important choices all lie in between the extremes, such as the choice between reactors that recycle plutonium and those that do not, and in general, choices among various forms of non-nuclear and nuclear energy appropriate at particular times and places.

10. If nuclear weapon or near-weapon capabilities spread among less developed countries, the spread may at some later date alter the decisions of some advanced industrial countries that have so far deliberately foregone the development of an independent force of nuclear weapons.

o Advanced industrial countries like the Federal Republic of Germany and Japan have been both protected and constrained by their alliance relations.

o Alliances themselves may be weakened by the spread. (Nuclear weapons have long been promoted as a substitute for alliance.) If so, as the taboo weakens, some advanced countries may follow the less developed ones.

11. There are several branching processes that may increase the gathering instability we have described.

- o Nuclear exports create not only users of nuclear electric power with the byproduct of fissile material, nuclear exports also create other nuclear exporters. So Westinghouse created Framatome, General Electric created Kraftwerk, and so on. Now it seems India may be in the business of exporting.

- o It is possible to trace serial connections between the Chinese and the Indian explosions on the one hand, and the public and private decisions to edge toward the making of a nuclear explosive in other countries. In fact, though the Indian explosion followed the Chinese by nearly ten years, study of the development of the Indian program plainly shows the linkage. Case studies of other Asian and Middle Eastern countries show analogous links to the Indian explosion.

- o These branching processes are, however, more complex than the exponential physical and biological processes that have suggested the standard metaphors of proliferation. They are not automatic, but depend on a complex set of political, military and economic relations.

- o Nonetheless these cumulating changes point to serious instabilities in the processes of decision both to acquire and to use nuclear weapons. They add up to the prospect of a much more disorderly world.

12. A feeling of fatalism on this subject is growing. A few years ago two of the ablest students of proliferation commented that two views seemed to be emerging: One held that there was no problem (the Non-Proliferation Treaty would take care of it). The other held that there was no solution (nothing could be done about it). Today many seem to hold both of these positions. They base the more comfortable position (that there is no problem) on the hope that the spread might not be so bad in effect anyway. (Many of the countries that may get nuclear weapons, they say, will be quite responsible, especially when equipped with so awesome a capability for destruction.)

13. Our analysis of what it would be like to live in a crowd of nuclear nations leaves very little doubt that the potential spread would introduce new and very threatening dangers in the world. However, while it is very likely that there will be some further spread,

- o How much and how rapidly is not a matter of fate, but a subject for policy.

- o So is the management of the additional spread that does take place.

o That the rate and extent of spread is not immutable is shown by the fact that past and recent plans in various countries to install power reactors and chemical separation plants have altered. In fact they change all the time, responding to pressures of economics as well as domestic and international politics. The 1975 plans that underlie the charts displaying the "yellow overhang" (of countries with enough separable plutonium for a few bombs) and the "red overhang" (of countries planning to separate at least that much plutonium) were deflated somewhat to correct for overoptimism, and the plans have already shifted. Some reactors have been deferred. At least one chemical separation plant (in Korea) has been canceled. We can affect such plans by deliberately changing the economic and the political-military incentives.

14. Affecting the spread and/or managing it will depend on shaping political desires and this, in turn, will depend on the conduct of alliance relationships, as well as on a sober and clearheaded view of the economics and politics of nuclear exports. But there is room for policy choice:

o Among civilian alternatives, including some among distinct forms of nuclear electric power. For example, a choice between nuclear power with and without plutonium recycle.

o Among military alternatives: a) in alliance policy; b) in the development and deployment of non-nuclear technologies that can displace nuclear ones.

o Among arms control alternatives considered in the broadest sense which includes, besides formal agreements, any actions in the joint interest of potential adversaries.

The Shrinking Critical Time to Make Explosives

A few of these key points in the summary deserve a brief expansion and documentation:

First, on past alarms and the present prospects. Past alarms have been mainly false. There have been several: the first immediately after Hiroshima; the next major one at the end of the 1950s. A typical prophecy of 1960, for example, forecast the addition of 12 new countries exploding nuclear devices in the following six years. By comparison with these early alarms the actual increase in the number of countries testing has been very slow. Three additional countries tested at intervals of eight, four, and ten years in the 22 years following the British nuclear explosion.

The error in these early predictions of rapid spread gives some ground for doubting the apocalyptic prophecies that swarm in this field. It is clearly a matter of political will and not merely technical and industrial competence. Nonetheless there is cause for alarm today in the changes that are gathering beneath the surface. Even if the number of countries testing should continue to develop slowly, the civilian nuclear programs now under way assure that many new countries will have travelled a long distance down the path to a nuclear weapons capability. In many cases the remaining distance will be short enough to mean that even a rather small impulse might carry a government the rest of the way, and the movement of one government may provide the impulse for others. This in turn will mean a new and dangerous instability.

Second, the extensive fundamental overlap of the paths to nuclear explosives and to civilian uses of nuclear energy has been recognized since the mid-1940s. We have almost from the start said that the military and civilian atoms were substantially identical yet, paradoxically, that we wanted both to stop one and to promote the other. This paradox was present in the discussions leading up to the Truman-Atlee-King Three Nation Declaration of October 1945, and it saw its most valiant effort to reconcile these opposing purposes in the Acheson-Lilienthal Report of 1946. We discuss this at greater length elsewhere, but it is worth explaining briefly at this point.

The Acheson-Lilienthal Report tried to resolve the dilemma by proposing to "denature" plutonium: that is, to make it ineffective as an explosive. This was to be accomplished by leaving the fuel in the reactors long enough so that the fissile isotope plutonium 239 generated in the uranium fuel rods would in turn generate higher isotopes of plutonium, and in particular, plutonium 240, which was known to have several drawbacks from the standpoint of the state-of-the-art of weapons design of the time. The discussion of this proposal was necessarily muted and limited by the

requirements of secrecy and by the bounds of the current state-of-the-art. The initial report was predicated on the belief that denaturing would impose the formidable barrier of isotope separation for the plutonium and thus, given the elaborate mechanism of international control called for in the Plan, assure some two to three years' warning. This hope was almost immediately modified, but it has generated a long and inconsistent trail of statements that still have their effect in encouraging the belief that plutonium left in the reactor long enough to become contaminated with 20 to 30 percent of the higher isotopes Pu_{240} or Pu_{242} would be unusable, or at any rate, extremely ineffective when used in a nuclear explosive. Since reactors operated "normally" to produce electric power were expected for reasons of economics to achieve maximum "burnup" of the fuel by leaving the fuel rods in the reactor long enough to so contaminate the rods, a kind of denaturing was hoped for as a result of standard reactor operating procedures. However, this hope turned out to be a slender reed.

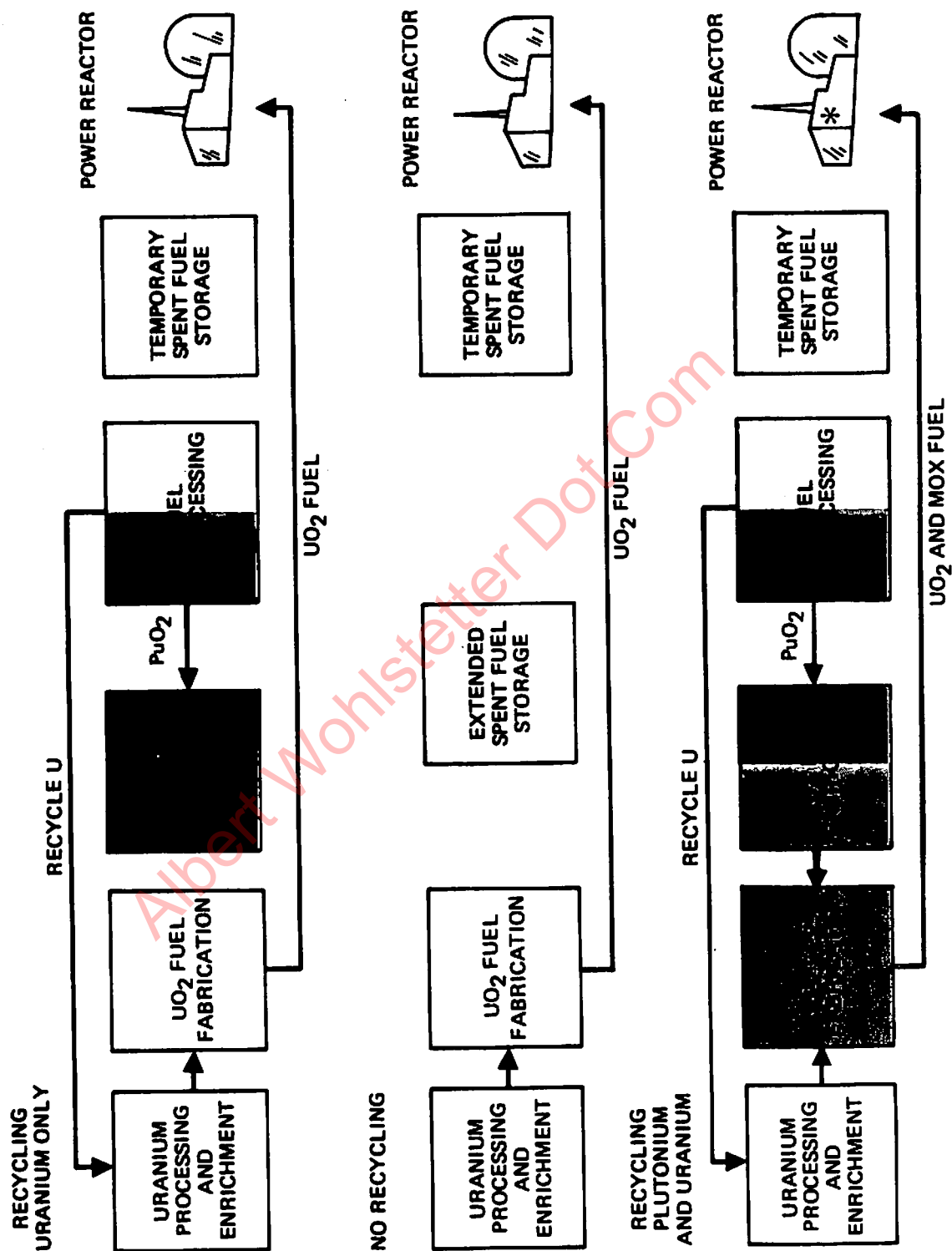
An explosive that is truly nuclear may be made from such power reactor plutonium, that is, it will release 1,000 times the energy per pound of ordinary high explosives. This is now clear from authoritative public sources.* Therefore a need for isotopic separation of plutonium 239 does not form a barrier to making an explosive from reactor-grade plutonium.

For governments accumulating the spent fuel, the barrier to obtaining a high enough concentration of fissile plutonium will be the need to separate the plutonium chemically. This is a less formidable obstacle than isotopic separation, the facility for which costs billions of dollars using present techniques and would take years to construct. The critical time to make an explosive from spent reactor fuel is less than the two or three years originally hoped for. Nonetheless chemical separation is a substantial barrier and perhaps the most important one remaining. It might take a year to construct a chemical reprocessing plant for the purpose, and with the plant, the better part of a year to produce plutonium dioxide from the hot irradiated fuel rods. Depending, however, on what forms of nuclear fuel cycle become general, and where and under whose control the different phases of the cycle occur, governments may start with material considerably closer to the plutonium metal than the irradiated spent fuel. They might in fact, without violating any rules, start with separated plutonium dioxide or plutonium nitrate. That might be perhaps a week or less away from the metal. The rules, in fact do not, in general, preclude stocking the metal itself; and as Dr. Taylor has said, the oxide powder may be used instead.

Figure 1 presents three possible nuclear fuel cycles for the Light Water Reactors (LWRs), involving three alternative dispositions for plutonium.

*See Chapter 3

Figure 1 - PLUTONIUM DISPOSITION ALTERNATIVES 1990



(It is adapted from the six alternatives considered in the General Environmental Statement on Mixed Oxides (GESMO) published by the Atomic Energy Commission in 1974. Among other things, we simplify by not distinguishing permanent and temporary storage.)

The first disposition involves recycling uranium and the temporary or permanent storage of plutonium. The second involves no recycling of either uranium or plutonium and the storage of spent fuel. The third involves the recycling of both uranium and plutonium and involves besides chemical reprocessing the fabrication of "mixed oxide" fuel.

The first is referred to as the basic current alternative by the GESMO, but in fact present practice more accurately corresponds to the second alternative, with no recycling whatsoever. The third alternative has been contemplated since the early 1950s in the United States and has served as a model in plans formed in many other countries before the soaring costs of reprocessing called it into question. Even before this cost increase the more optimistic estimates current at the time GESMO was written showed no substantial savings to be obtained by recycling as far as kilowatt hour costs were concerned. Nor did they show any decisive conservation effects. Plutonium recycling was expected to delay a shortage of uranium by perhaps a year and a half at the 1990s rate of demand. Since then the benefits in conservation have been estimated to be even smaller and the dollar benefits appear negative. However, the alternative fuel cycles have very different implications for shortening the critical time to make a nuclear explosive.

In Figure 1 we have used colors to display closeness to plutonium metal, and for simplicity we have distinguished three states in which plutonium might be found at various points in one or another of these cycles. The first state is in spent fuel. We have colored this yellow to indicate that while obtaining the plutonium in spent fuel is a considerable stride along the road to nuclear weapons, compared to the situation of the present weapons states that started from scratch, there remains substantial further effort. Reprocessing of spent fuel involves remote manipulation of extremely toxic, radioactive substances, facilities with six or seven feet of shielding, lead glass windows, etc., and the handling of substantial quantities of spent fuel in order to produce small quantities of plutonium. Chemical separation of plutonium for weapons, however, can be simpler than the separation of plutonium as an economic substitute for uranium in electric power reactors. The spent fuel can be found of course in all of the three fuel cycles shown.

At the other extreme is the plutonium that can be found at the output or "back" end of reprocessing plants and at the input or front end of plants fabricating plutonium or "mixed oxide" fuel. Such plutonium in the form of plutonium dioxide or plutonium nitrate could be converted to plutonium metal using handbook methods and without remote handling equipment or extensive shielding and the like, but only a glove box.

And as we have said, it should take no more than a week. We have therefore colored red the points in the various alternative nuclear fuel cycles at which plutonium dioxide (PuO_2) or plutonium nitrate ($\text{Pu}(\text{NO}_3)_4$) might be found. Such points do not occur in the light water reactor cycle without recycling of either uranium or plutonium. They do in the other two cases, and especially where the plutonium is recycled.

Plutonium would also be found, if it is recycled, in fresh unirradiated fuel rods at the input end of the reactor. Extracting plutonium from such mixed oxide fuel would be considerably easier than taking it out of the irradiated spent uranium fuel. Plutonium is considerably more concentrated in the mixed oxide fuel rods (4.5% compared to .7%). Unlike the irradiated fuel, it is not highly radioactive and would require no "hot cells" with heavy shielding, remote manipulation, etc., and would require no removal of fission products. We have colored orange the points in this cycle at which fresh mixed oxide fuel might be found.

We can measure the advance towards the ability to manufacture nuclear explosives implicit in the present civilian nuclear electric power programs then by showing first the number of countries, including the present weapons states, that will have enough separable but possibly unseparated plutonium for a few bombs between now and 1985 (the condition yellow). Then the number of countries that have planned to have a capability to separate that much plutonium by 1985 (the condition red). And third, the quantities of plutonium that will be available in fresh reloads of unirradiated fuel (the condition orange) to a large number of countries, if plutonium recycling should become general, and even if these countries do not themselves separate plutonium or manufacture plutonium fuel rods. The results of these three sets of calculations are displayed respectively in Figures 2 and 3, and in Figure 4 and Table 1.

The first thing to be said about the numbers in these figures is that they are very large ones. Chemical separation of plutonium and the enrichment of uranium are civilian activities which have long been regarded as "normal" parts of the nuclear electric power fuel cycle. They may sometimes and in some places be discouraged by various ad hoc national policies, but they have not been subject to a clear cut international or universal national prohibition by supplier countries. The problem of inhibiting or reducing the size of this burgeoning capability is not merely then a matter of an improved watch, to see that a clearly agreed prohibited line is not crossed. Among other things, it would involve defining and moving such a clearly understood and agreed boundary to preclude activities that cannot provide adequate warning. And for whatever dangerous activities remain on the permissible side of the agreed boundary, we need to elaborate consistent unilateral policy to discourage them and encourage other safer alternatives.

Figure 2 – THE OVERHANG OF COUNTRIES WITH ENOUGH SEPARABLE PLUTONIUM FOR PRIMITIVE OR SMALL MILITARY FORCES

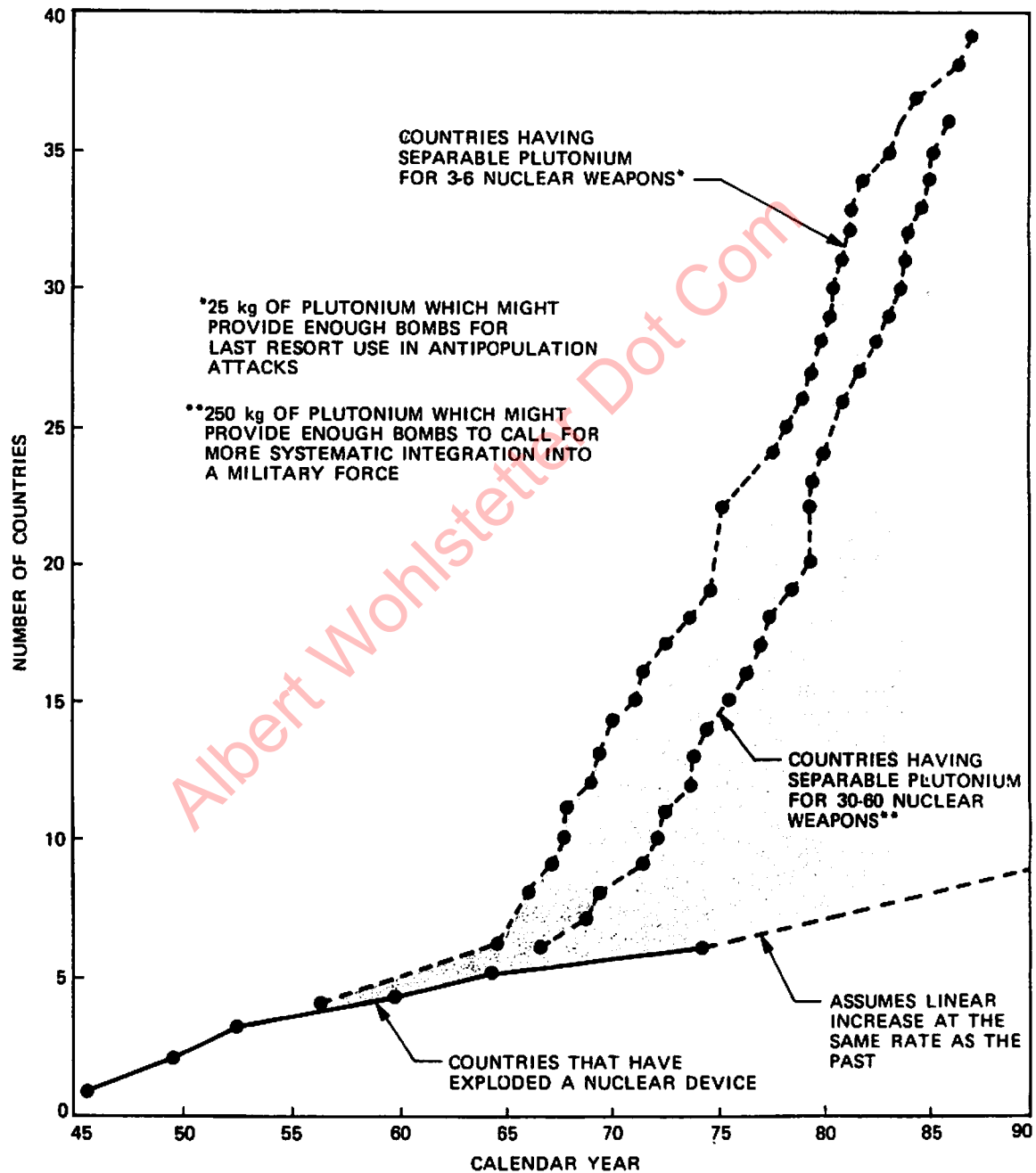


Figure 3 – COUNTRIES PLANNING TO HAVE PLANTS FOR SEPARATING PLUTONIUM OR ENRICHING URANIUM IN QUANTITIES ENOUGH FOR SEVERAL BOMBS

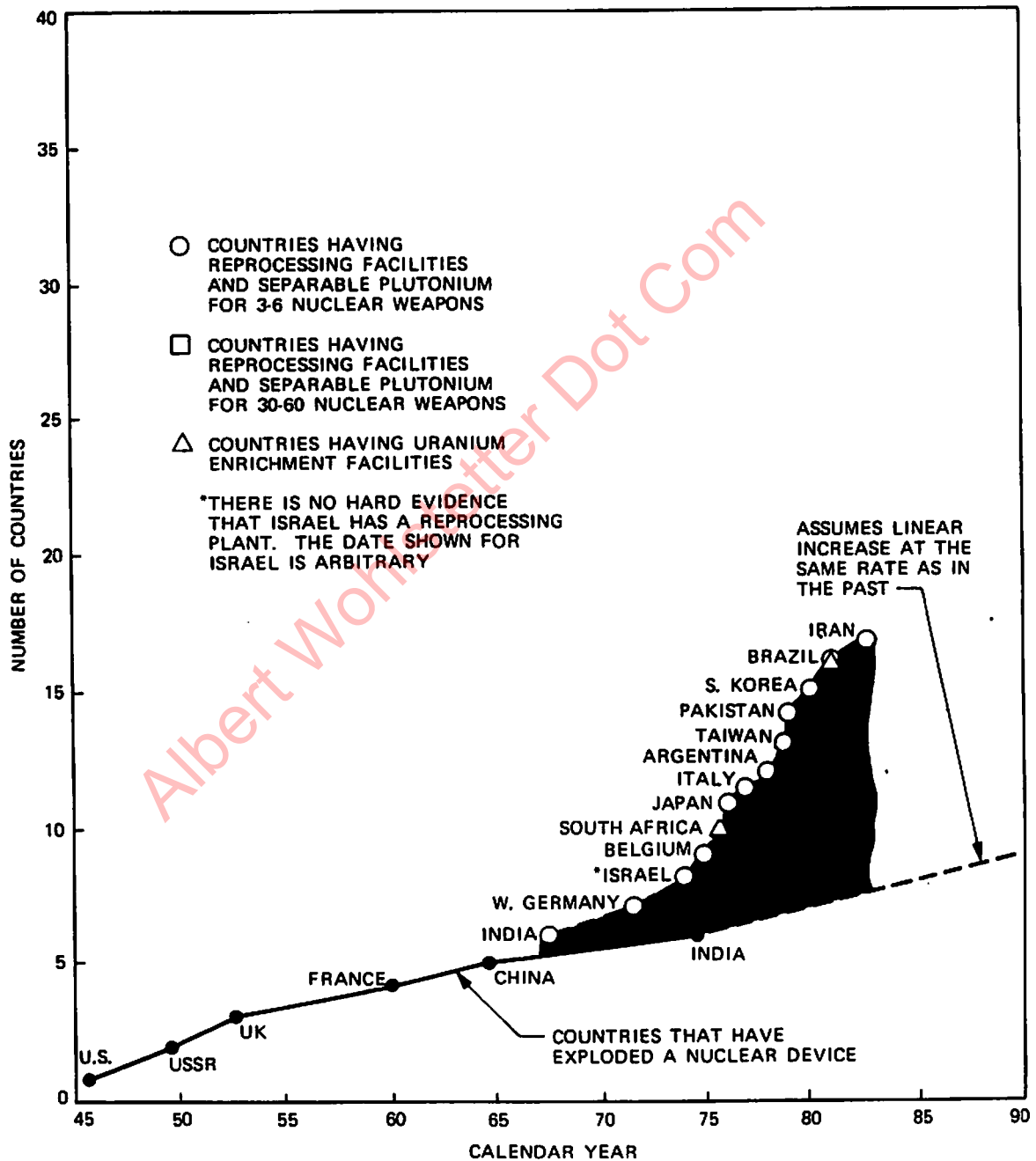


Figure 4 – PLUTONIUM AVAILABLE FROM MOX REACTOR RELOADS IN THE EARLY 1990's
USING ONLY INDIGENOUSLY PRODUCED PLUTONIUM

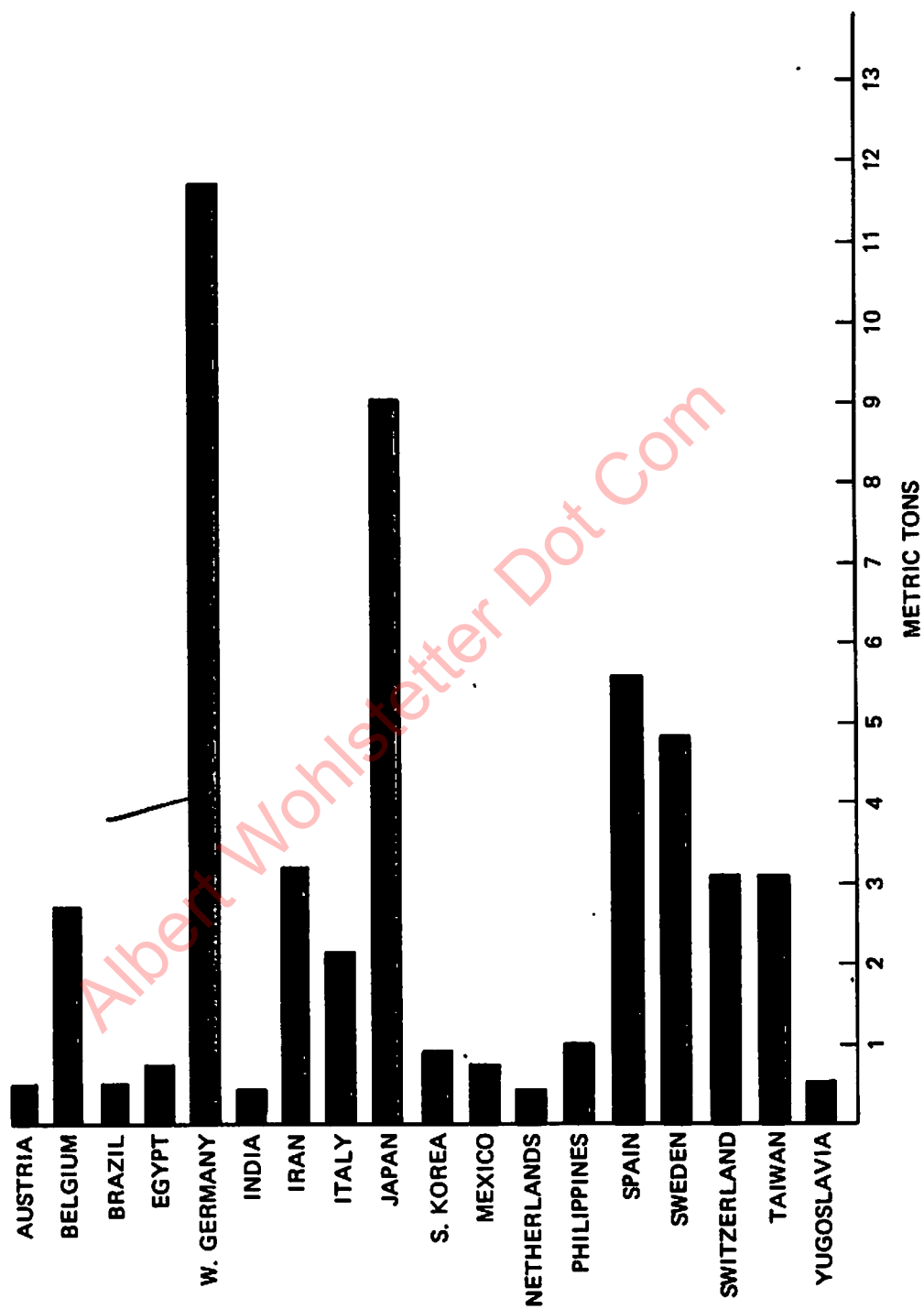


Table 1
PLUTONIUM AVAILABLE FROM MOX REACTOR RELOADS IN THE EARLY 1990s
USING ONLY INDIGENOUSLY PRODUCED PLUTONIUM*

	kg of Pu**	Number of Bombs Worth***
Austria	400	46
Belgium	2,800	325
Brazil	500	58
West Germany	11,700	1,357
India****	360	42
Iran	3,200	371
Italy	2,100	244
Japan	9,000	1,044
South Korea	900	104
Mexico	800	93
Netherlands	400	46
Philippines	1,000	116
Spain	5,600	650
Sweden	4,800	557
Switzerland	3,200	371
Taiwan	3,200	371
Yugoslavia	500	58
Egypt	700	81

*Assuming that one reload is always kept at each reactor. Any country not having MOX fuel fabrication facilities could justify this practice although this may not be standard practice in all countries on this list. Even if this is not the case, a single MOX reload would probably contain 350-900 kg of Pu (40-104 bombs worth). In countries that do have mixed oxide fuel fabrication facilities, there would be still larger amounts of Pu available in process.

**Assuming 580 kg per 1000 MWe BWR reload and 770 kg per 1000 MWe PWR reload, linear scaling for other reactor sizes. See U.S. Atomic Energy Commission, Generic Environmental Statement Mixed Oxide Fuel (GESMO), Vol. III, August 1974, p. IV C-65.

***8.62 kg Pu per bomb assuming 5 kg fissile Pu/bomb and assuming MOX Pu is 58% fissile Pu.

****The figures for India are the result of direct calculation.

The second thing to be said is that this large growth is not inevitable. It presumes the carrying through of plans, negotiations, and constructions not yet committed, and of varying degrees of firmness; some have had setbacks. The growth, moreover, is open to influence, a subject for the elaboration of policy of supplier as well as recipient governments. Some aspects of the policy for the U.S. can be general, but a good deal of it must be developed in packages appropriate to the individual countries. The curves of Figures 2, 3, and 4 are not unconditional forecasts, but indications of what may happen if conditions are not altered. For our present purposes however, the gist of Figures 2, 3, and 4 is that under the present rules of the game, any of a very large number of countries may take these further long strides towards nuclear weapons capability in the next ten years or so without violating the rules--at least no rigorously formulated, agreed on rules.

Governments may be able to appropriate stocks of highly-enriched uranium or plutonium as a means of weapon development. Countries without facilities to produce these may have substantial stocks of them resident in their countries in research facilities or, in the future, in commercial reactors. High Temperature Gas Reactors, for example, would contain 1000-2000 kgs of highly enriched uranium. If plutonium recycle becomes widespread, a single reload for a reactor might contain 350-900 kgs of easily separable plutonium. A national government does not have to steal these stocks or even divert them in order to be very close to being

able to make nuclear explosives. Many Bilateral Agreements assign title to the stocks to the recipient government. Some Bilateral Agreements do not explicitly exclude use for peaceful nuclear explosives. And of course even for those countries that have ratified the Non-Proliferation Treaty, the exclusion of peaceful explosives in Article V would not survive a three-month notice of withdrawal permitted under Article XI.

These paths of approach towards a weapons capability considered here, it should be noted, do not break any precise, generally agreed on rules. They are in addition to paths that exploit the weakness of sanctions against breaking the Non-Proliferation Treaty or bilateral rules, and in addition to paths open to those governments that have not ratified the Non-Proliferation Treaty. Extending the Non-Proliferation Treaty to more countries or increasing the efficiency of "safeguards" or physical security measures would not, therefore, block these paths. The recent wave of interest in measures against "diversion," especially by subnational groups, while useful in itself, distracts attention from the steady spread of capabilities within the rules. Some percentage of the stocks of fissile material might always be diverted within the limits of error of material unaccounted for by any inspection system. In the future when these stocks are very large, even a small percentage of such diversion would yield significant absolute amounts. This tends therefore to be the focus of most attention. Yet it may be much less important than the possibility of accumulating the whole of a significant stockpile of fissile material legitimately, without diversion, and using it later for explosives.

In our study we have distinguished for convenience four kinds of nuclear explosive capability. The first is the sort of capability that has been much in the public eye in the last year or two, due especially to the efforts of Dr. Theodore Taylor to make clear its dangers. It would consist in the manufacture of a crude device derived from stolen fissile material, perhaps not using plutonium metal, but plutonium dioxide powder, yielding as little as ten or a hundred tonnes of energy, and designed for terrorist use by some subnational group, or possibly even a single individual. It might use poorly separated material and be dangerous not merely to explode in anger, but to store and handle. The second capability would rely on a few explosives in the kiloton range. They might be used by governments as a desperate last resort threat against populations. The third capability we have taken arbitrarily as consisting in perhaps 50 such devices, enough to call for plans to incorporate them into a military force. The fourth would be much more sophisticated. It is the kind that a middle industrial power like Japan might contemplate, if it made the decision to become a military nuclear power in the 1980s or 1990s.

In this phase of the study we have focussed especially on the second sort of capability and the conditions for obtaining it. It imposes no stringent requirements for delivery. And we have devoted a chapter to analysis of the complexities involved for a middle power to get a serious and responsible capability in the 1980s. We do not however mean to imply that the primitive last resort capability will actually realize the hopes some governments might place in it. It is likely to be extremely inflexible, vulnerable, and available only for suicidal use. Nonetheless some governments might take this route.

Relating Policy to "Legitimately" Shrinking Critical Time

While it is not our purpose in this first phase of the work to make policy recommendations, our analysis of the trend does define the problems that policy must address. It serves to show the inadequacy of many policies presently proposed.

The most fundamental problem displayed by our analysis is that, for an increasing number of "non-weapons" states, the critical time to make an explosive has been diminishing and will continue to diminish without any necessary violation of the clear agreed on rules--without any "diversion" needed--and therefore without any prospect of being curbed by safeguards that have been elaborated for the purpose of verifying whether the mutually agreed on rules have or have not been broken. This definition of the problem permits us at the very least to observe how much of our efforts (useful though they are for other purposes) are aimed squarely at this basic trouble.

We can illustrate the need for addressing the basic trouble more precisely by commenting on several current proposals for dealing with the problem of the spread of nuclear weapons. Some of the proposals at present most intensely advocated are rather fluid. For example, the form and functions of the Multinational Regional Centers, recently suggested by the U.S. Government, have been changing rapidly. This continuing evolution makes a careful attention to the relation between policy and purpose all the more fruitful. Some variants of these proposals may be useful. Some are plainly irrelevant. Some might have the perverse sort of effect all too familiar in this field.

1. Improvements in safeguards.

Many suggestions are current for improving the IAEA system of safeguards against diversion by national governments: by increasing the inspection budget, e.g., getting more inspectors; by improving the technologies of real-time on-line inspection, etc.; by using more subtle system-analytic methods or game theoretic methods and the like for detecting diversion in significant amounts. But the dangerous activities described shorten the time to make explosives without resorting to "diversion." Hence these improvements in the quantity of inspection or its statistical or technological sophistication are irrelevant for the purpose of preventing the reduction of the critical time. The line drawn between safe activities that are permitted under agreement and dangerous prohibited activities needs to be redrawn and clearly defined to make safeguards relevant. If, for example, the storage of separated plutonium, the manufacture of plutonium dioxide fuel rods, and even the use of recycled plutonium in fresh fuel rods are banned, an increase in the budget or the efficiency of methods for safeguarding of fuel might be feasible and useful.

2. "Collaborative transnational policing" by quasi-public or private groups.

This is not so much a policy put forward by any government as it is a recurring theme advanced by natural scientists and technologists who think of themselves as serving interests that transcend purely national ones. This old theme has recently been revived with the suggestion that the growth in number of countries increasingly near the edge of bomb manufacture will increase the "... opportunities and prospects for 'amateur' transnational sanction. . . by industry, by scientists and other essential technologists."

The suggestion for amateur policing raises doubts first about its virtues compared to the more formal and official varieties of policing and, second, as to its relevance for the problem. Transnational loyalties have a larger scope for operation in some countries than in others. National loyalties and national control of dissidence vary greatly by country. Transnational behavior blocking important government plans seems rather less likely in Taiwan, South Korea, Yugoslavia, and Rumania, for example, than, say, in Japan or Switzerland. And if any amateurs tried, they did not succeed in curbing India's progress toward the manufacture of nuclear explosives even before India's recent restrictions on dissent. Most to the point here, however, is the fact that policing of any sort, amateur or professional, is not enough. It doesn't address the problem posed by a country's legitimate movement along the path toward nuclear explosives. To curb such movements, one needs to redefine what is legitimate. Then sanctions, formal or informal, are conceivable.

3. Physical security against terrorists.

This has been perhaps the principal focus of public interest in recent years. The spectacular possibilities of nuclear terror by dissident groups have been conjured up jointly by the growth in stocks of strategic special nuclear material and by the headlined actions of terrorist groups especially in the Middle East and Latin America (but also by the internal disorder in the United States in the 1960s). It is only natural that the media, the Congress in its Hearings, and inevitably as a result, the regulators of the NRC and others concerned with civilian nuclear industry pay a good deal of attention to this possibility. And the focus on this contingency has been intensified by the efforts of a number of able physicists, in particular Dr. Theodore B. Taylor. However, even if the possibility of theft by subnational groups was completely eliminated, this would not foreclose the possibility that a government might itself divert materials. Still less would it prevent a government from steadily accumulating strategic special nuclear materials within the rules. Though measures of physical security may cause private industry to grumble, they have as one of their attractions that governments themselves are not hostile to them. Rulers have a clear self-interest in depriving subnational groups of nuclear explosives and they can therefore agree on a common policy. A good many problems in the international field are much more recalcitrant: specifically the

problem of reconciling the spread of civilian nuclear power with the restriction of access to fissile material by governments. However, measures of physical security do not address themselves to the problem of the shortening critical time for governments to get nuclear explosives that is taking place without any breaking of the rules. The lopsided media focus on terrorism tends to distract attention from the problem of the spread of nuclear capabilities to more countries.

Some measures taken to ban or discourage the shrinking critical time for governments might, on the other hand, make much more manageable their problem of physical security against theft and subnational terror. So, for example, the choice of a nuclear fuel cycle that does not involve recycling plutonium. (Plutonium separation generates great environmental hazards as well as dangers of theft.)

4. Agreements among nuclear exporters.

According to news accounts, we have been trying to persuade other suppliers to restrict their exports to countries that have ratified the Non-Proliferation Treaty, or that have at least accepted safeguards on all their nuclear activities. But so long as they are under "safeguards," the Treaty does not proscribe capabilities for separating plutonium, or enriching uranium; or stocking separated plutonium or highly enriched uranium, or making plutonium fuel rods or stocking fresh plutonium fuel rods made elsewhere. A safeguard inspector might observe these permitted activities and only confirm that a given country by undertaking them has shortened the time to get nuclear explosives. Similarly, a country that has not ratified the Treaty but agrees to safeguards on all its nuclear activities at most agrees to conduct its dangerous activities under safeguards.

There are important areas for potential agreement among exporters, for example, about the competitive subsidizing of nuclear exports to less developed countries. Export subsidies are a dubious form of international competition at best. However, the current practice of export financing in the case of nuclear exports seems peculiarly irrational from the standpoint of the exporting country, as well as the rest of the world. It involves a transfer or gift of resources from the exporting country, which compared with alternative investments may slow the recipient's economic development and, more importantly, is likely to have the particularly unpleasant external effect of bringing it close to the manufacture of nuclear weapons. It should be possible for suppliers to reach agreement not to subsidize the spread of weapons that might be used to destroy allies or friends, or even themselves.

Other possible agreements might be reached among suppliers of nuclear equipment. Some agreements might be aimed directly at the problem presented by technologies that would so shorten the time to make nuclear explosives as to make timely warning and response infeasible. If importing countries can, without violation, enrich uranium so as to concentrate uranium-235 enough

for explosives, or if they can separate plutonium in forms close to being usable in bombs, exporters should be clear that trilateral arrangements between themselves, the importers, and the IAEA for even the most rigorous inspection will not fulfill the original and essential function of safeguards. They will provide no safety. Nor does it soften the problem to say that the highly enriched uranium has a possible civilian use in research reactors or high temperature gas cooled reactors; and that the separated plutonium might be used, say, in a critical experiment in preparation for the long-awaited coming of breeder reactors; and that the importer has given his word that the materials will be used only for such peaceful ends. Safeguards would be unnecessary if everyone could be taken at his word forever. And genuine safeguards, namely those providing timely warning, will not be possible unless there is enough time left after a violation and before bomb assembly for detecting signals and acting on them. For that purpose, suppliers have grounds for restricting the sale of equipment, materials, and technology to prevent the shortening of the time to acquire nuclear explosives.

Neither the United States nor any other exporting country can claim always to have kept clearly and continuously in mind the essential need to inhibit the spread of nuclear activities such as reprocessing that would defeat the purpose of timely warning. In spite of the statements of various editorial writers, none of these governments can sensibly claim to have been much holier than the others. Nor would it be fruitful to spend much time in keeping score. What is more important, other exporting governments like our own have both an interest in the net gains from trade that might be made from an efficient unsubsidized nuclear export industry and a vital interest in curbing the wide spread of nuclear bombs. For some of the sensitive technologies, the economic benefits that might be foregone are plainly minor. The gains from exporting reprocessing equipment, for example, are likely to be modest at best. Reprocessing appears on the basis of our study to be uneconomic even in very large separation plants and much more so in the small plants required in the Third World. But even if, in defiance of the economics, reprocessing were to become universal, the demand for separation facilities and equipment would be small in relation to the demand for reactors--perhaps 2% of that market. Exporters might of course try to gain some special advantage in competition to sell reactors by tying reactor sales to an offer to supply separation plants to importers eager to get control of readily fissionable material. That, however, is precisely the sort of suicidal competition we should all agree to avoid.

5. Multinational Nuclear Centers

Much of our antiproliferation policy has moved recently in the direction of proposing Multinational Nuclear Centers (MNCs). These were talked of originally for the conduct of chemical reprocessing or for isotope enrichment, both of which are dangerous activities. There is an apparent advantage in a collective management that would mean mutual monitoring. And such arrangements might be useful provided they are clearly and effectively designed to replace and exclude national centers for separation

and enrichment. However, the multinational center proposals which were current in the press until recently would not plainly forbid members of the consortium from also constructing national facilities for undertaking reprocessing or enrichment on their own, perhaps on a smaller but nonetheless militarily significant scale. If they do not forbid national plants from enriching uranium or separating plutonium and if they do not also forbid national stocks of easily used fissile materials, MNCs would not address the basic problem of shrinking critical time. Nor is it clear that they would have the indirect effect of reducing incentives to get national facilities. The economics of plutonium recycling in the multinational centers themselves look poor, and if they are less poor than the economics of national facilities, it is doubtful that economics is what motivates the current interest in national separation facilities.

In fact, insofar as reprocessing is made to appear to be of crucial importance in the nuclear fuel cycle (and insofar as much larger flows of highly enriched uranium come to seem important for the propagation of HTGRs in the future) sovereign nations--especially the less developed ones--are likely to object to the surrender of their sovereign rights to undertake these activities on their own. Some less developed countries now argue that the prospect of MNCs requires them to undertake a national enterprise for separating plutonium as training and preparation for taking an active role in the multilateral enterprise. In this way, the multinational centers may perversely give some apparent legitimacy or reasonableness to national efforts on a smaller scale. MNCs would in any case transfer some of the technology needed for the national efforts.

In some variants, the MNCs would be limited essentially to the storage of spent fuel. That would be compatible with proscribing plutonium recycling and combined with such a proscription would address the basic problem of inhibiting the acquisition by more and more governments of stocks of readily fissionable material.

So would the concentration in MNCs rather than individual governments of facilities for isotopic as distinct from chemical separation, so long as such facilities produced only low enriched uranium suitable for reactor fuel. While the chemical separation of plutonium in MNCs and its shipment to member countries would defeat the purpose of assuring timely warning, the multinational production of low enriched uranium for the reactors of member countries would not have the same problem. Unlike separated plutonium, low enriched uranium is not readily fissionable, and is therefore not usable as an explosive. Centrifuge, or jet nozzle or laser isotope separation might in the future greatly decrease capital costs and so make feasible and economic the operation of enrichment plants in many more countries. The ability to separate isotopes of uranium (and therefore to produce highly enriched uranium for bombs) may then threaten to become widespread. In that case it would help if suppliers of enrichment technology restricted their exports to MNCs or weapon states and if non-weapon states got their low enriched uranium for reactor fuel from MNCs or their traditional sources among the weapons powers.

If not carefully defined in purpose, however, MNCs could as easily as not worsen the problem.

6. Stopping the "arms race" between superpowers.

Resolutions proposing to reduce U.S. and Soviet strategic forces have been advanced recently in the Senate and in the House as anti-proliferation measures. But whatever their other virtues, cuts in superpower nuclear forces or their budgets, a halt by the superpowers to nuclear testing, etc., plainly do not have any direct relevance for proscribing actions by the non-weapons states that without breaking the rules lessen the critical time to get a nuclear explosives capability. It is sometimes suggested that nonetheless they might affect incentives for the non-weapons states to get a nuclear weapon or incentives to lessen the time between the decision to get a nuclear weapon and the actual date when they will have one. In the case of the non-weapons states, a stipulation in the NPT that the superpowers disarm to a vaguely specified extent has offered an ultimate excuse for undertaking nuclear armament on their own. And it appeals to the sense of guilt familiar at least in the United States and the United Kingdom. However, it is doubtful that South Korea, or Taiwan, or India whose potential interest in nuclear weapons is not directly tied to their use against either of the two superpowers, would have their interest reduced at all by even a very extensive reduction in superpower armament (not to say a reduction in British armament). This observation has been substantiated by interviews.

The next phase of our study will focus on the choice of policies that have a functional connection with the problem of the spread of military technology. Here, and in the rest of this present report, it is our purpose to deepen our understanding of that problem.

What follows then offers (1) a primer on the technology, with a more detailed analysis in the appendix, (2) a perspective on the problem of dividing safe or civilian or economic from dangerous military activities, (3) a study of the economic aspects of proliferation, with particular attention to the economics of recycling plutonium and to the economics of nuclear power in less developed countries. (4) Since the prior analysis is devoted especially to the possibility of the spread of primitive last resort capabilities to less developed countries, the next to the last chapter extends and supplements that analysis on the quite different problem of the middle power option, and (5) the final chapter concludes with an analysis of what it might be like to live in a crowd of nuclear armed countries.

II. Primer on Technology

A. What it takes to build a nuclear weapon

After the political decision is made, there are three requirements which must be met in order to build any kind of nuclear device: a design for the device; a reasonable level of skill in working with high explosives, nuclear materials, fuses, and so on; and a quantity of fissile material. We will discuss each of these requirements in turn.

Historically, some people in this country have had a mystical attitude toward "the secret of the atom bomb," as though there was some password or secret grip which would secure instant admission to the Club of Nuclear Powers. On the other hand, the Manhattan project scientists seemed to underestimate the difficulty of bomb design and had as their slogan, "there is no secret to the atom bomb." More recently, nuclear scientists such as Theodore Taylor in "The Curve of Binding Energy" have been emphasizing the ease of construction. The basic principles of bomb design are fairly well known. A few years ago a high school prankster in Florida sent the police a letter claiming that he had fabricated a nuclear device and demanded payment not to detonate it. He enclosed a sketch of his (non-existent) device. The police checked the sketch with Federal authorities, and it was realistic enough that they felt constrained to take the threat seriously. Recently an enterprising television producer hired an MIT student to design a bomb for a special TV report on proliferation. Jan Prawitz, of the Swedish Ministry of Defense, was asked to evaluate the design. His remarks were edited on the TV program to make it appear that the design was a good one. Such incidents have led many to conclude that building nuclear weapons is an extremely simple matter. This conclusion should be treated with caution. For example, in contrast to the edited remarks of Prawitz on the TV special, his full evaluation of the student's design was as follows:

1. The design of the bomb was primitive.
2. Several essential features were forgotten about.
3. The student might not survive the fabrication of the bomb.
4. Should he survive, the probability that the bomb would go off upon "pressing the button" would be less than 50 percent.
5. Should a nuclear reaction start, the explosion yield would be small. The probability that the device would yield as much as .01 - 1 KT would be very small.

6. If a group of qualified scientists or a professional defector were granted more time and better means, including the possibility to undertake experiments, the bomb could be much better.*

There may be no single secret of the atom bomb, but there is a whole collection of ideas, techniques and devices, which are not public knowledge and which contribute to the ability to safely build a reliable bomb with a reasonable yield. These ideas and techniques shade off into the area of technological skill rather than fundamental design.

The second requirement for building a nuclear device is a certain level of technological skill. The non-fissile parts of the bomb (the high explosive lenses, the fuses, and so on) require a reasonably high order of workmanship if the device is to work effectively, but nothing beyond standards which are already available in the civilian market. The fissile materials require very careful handling because of their radioactive character. If plutonium is used, the workers will have to protect themselves against a highly poisonous substance. The methods for coping with plutonium are fairly well-known, however, and a nation with any kind of nuclear power industry should be able to build a cadre of workers able to work safely and effectively with this dangerous substance. The weapon countries, for example, have already found the means to handle large quantities of plutonium in a reliably safe manner.

The final requirement, for fissile material, is probably the most difficult one to meet. The exact amount of fissile material required to make an explosive nuclear device depends on the quality of the design, the desired yield and on the purity of the fissile material employed. Approximately five kilograms of plutonium should be enough for a first nuclear device. More U²³⁵ would be required, perhaps fifteen kilograms for an implosion device.

As everyone knows, fissile material is not easy to get. Only a very small fraction of natural uranium (about .7%) consists of the fissionable isotope U²³⁵. Separating one isotope from another of the same element is a difficult and expensive physical process. Plutonium does not occur in nature, but is produced as a by-product in many nuclear reactors. The separation of plutonium from the other elements found in the used fuel rods of a reactor is a chemical rather than a physical process, and although it is not easy, it is an order of magnitude easier than separating one isotope from another. The methods of acquiring fissile material deserve discussion in somewhat greater detail, since they appear to present the most difficult obstacle to development of a nuclear capability.

*Letter to Roberta Wohlstetter, July 16, 1975.

One way, perhaps the simplest, to acquire fissile material is by means of a gift, theft, or purchase. There are a variety of reasons why a nation possessing fissile material might be willing to give some of it to a non-possessor. It might be given under the supposition that it was to be used for research only, in order to help establish a technological case for the ultimate construction of a nuclear power industry in the recipient country. Or it could be given for political purposes, in order to stabilize a given potential conflict situation or to enhance the prestige of an ally. Or it could be simply purchased, since a nation which really wants nuclear weapons might be willing to pay for fissile material a price sufficiently high to attract a sales offer from a nation which has a nuclear power industry but little interest in acquiring nuclear weapons for themselves. Inhibiting international trade in fissile materials is an interesting challenge for future policy makers.

Theft has ordinarily been considered more of a threat from terrorists of sub-national groups than a threat from sovereign governments. It is not too difficult to protect nuclear fuel when it is actually in the reactor. It is, after all, in a highly radioactive environment and is protected by all the security measures taken to protect the power plant itself. Radioactive waste is also not very attractive as a place to steal fissile material. The reason for this is that great care is taken to insure that radioactive waste will not "go critical" under any conceivable contingencies, and therefore the concentration of fissile material in such waste is always very low. The most vulnerable link in the chain is probably nuclear material while in transit. Whether or not the nuclear reactor fuel (prior to being "burned") is attractive as a target for theft depends on the particular type of reactor for which it is destined: LWR and HWR fuel is not attractive, since it must undergo further enrichment, while HTGR fuel (which may never become particularly common) only requires a chemical separation. After burn but before reprocessing (discussed at greater length below) it is once more vulnerable and valuable. In the United States a considerable effort is being made to upgrade the security of fissile material across the board. Security standards in other countries, however, tend to be much lower. The IAEA, for example, imposes no requirement of any kind on physical security against theft, although they do issue guidelines and strong recommendations.

If a nation is unable to procure fissile materials by gift, purchase, or theft, or if it rejects such means in favor of a more independent source of supply, one alternative which it might consider is isotope separation of uranium. This process requires, of course, a supply of uranium. It is estimated that uranium constitutes about four parts per million of the earth's crust; so it is not particularly rare. Whether a given piece of rock should be considered "uranium ore" depends, of course, on the price you are willing to pay. Table 2 shows how many

Table 2

URANIUM RESERVES^A

Country	\$26/kgU		\$26-39/kgU (Tonnes)	Total (Tonnes)
	Assured (Tonnes)	Estimated (Tonnes)		
1. U.S.A.	300,000	500,000	1,200,000	2,000,000
2. Canada	190,000	190,000	340,000	720,000
3. Sweden	-----	-----	330,000	330,000
4. South Africa	202,000	8,000	88,000	298,000
5. Australia	150,000	75,000	50,000	275,000
6. Greenland (Denmark)	8,500	-----	250,000	258,000
7. France	37,000	23,000	45,000	108,000
8. Niger	40,000	20,000	20,000	80,000
9. Brazil	-----	-----	54,000	54,000
10. Columbia	-----	-----	50,000	50,000
11. Argentina	13,000	8,000	18,000	39,000
12. Israel ^B	-----	33,000	-----	33,000
13. Portugal	7,000	6,000	10,000	23,000
14. Gabon	15,000	-----	5,000	20,000
15. Spain	8,500	-----	10,000	18,000
16. Angola	-----	-----	13,000	13,000
17. Cen. African Rep.	6,000	6,000	-----	12,000
18. Italy ^C	-----	10,000	-----	10,000
19. Japan ^D	-----	8,000	-----	8,000
20. Zaire	1,500	1,500	-----	3,000

A. Unless otherwise noted, from L.G. Poole, "World Uranium Resources," Nuclear Engineering International, February 1975. Expressed in tonnes of U₃O₈ (yellow cake).

B. Nuclear Engineering International, May 1973, p. 391. Contained in Phosphate Rock. Z. Ketzmel, "Uranium Sources Production and Demand in Israel," United Nations Conference on Peaceful Uses of Atomic Energy, Geneva, 1971, A/CONF 49/P/013.

Table 2 (continued)

- C. Pietro Bullio, "Italian Nuclear Power Industry," Nuclear Engineering International, October 1973, p. 784.
- D. Susumu Kiyonari, "Activities of the Power Reactor and Nuclear Development Corporation." Nuclear Engineering International, Vol. 18, No. 206, July 1973.

tonnes of uranium can be extracted from reasonably assured reserves in various free world countries at a price of \$26/kg. The second column shows estimated (but not assured) additional reserves at this price, and the third column shows estimated additional reserves if the price moves up from \$26/kg to \$39/kg. As more intensive exploration is carried out in the less developed countries we can expect that additional reserves will be discovered. So it is perfectly evident that uranium is not particularly rare in and of itself, although high-concentrations are unevenly distributed. The major problem comes in separating out the .7% of natural uranium which is fissionable U^{235} . There are several ways of doing this: such as gaseous diffusion, gas centrifuge, the Becker nozzle, and laser enrichment.

Gaseous diffusion has been, historically, the most used technique. It is based upon the fact that lighter molecules in a gas move faster than the heavier molecules, and thus strike the container walls more often. If one of the walls has holes large enough to let individual molecules through but not large enough to permit bulk passage of the gas, more of the lighter molecules than of the heavier molecules will pass through the barrier. By this device it is possible to slightly increase the concentration of lighter molecules in the gas. The effectiveness of a separation technique is indicated by the "separation factor," which is the ratio of U^{235} to U^{238} atoms after one application divided by the ratio of U^{235} to U^{238} atoms before the application. The theoretical separation factor for gaseous diffusion using uranium hexafluoride gas is 1.00429; in other words, it would require a minimum of 2300 passes to convert uranium hexafluoride from .5% U^{235} to 99% U^{235} . Each stage in gaseous diffusion requires a compressor to keep the gas on the input side of the barrier at a higher pressure than on the output (enriched) side; heating elements are also required at each stage (uranium hexafluoride is solid at room temperature). The net result is that gaseous diffusion plants consume huge amounts of electric power. The three gaseous diffusion plants in the United States (Oak Ridge, Tennessee; Portsmouth, Ohio; Paducah, Kentucky) require 6000 MWe of electricity when operating at full capacity: That is approximately the power consumption of the entire state of Minnesota. The capital cost of a gaseous diffusion plant is also very large. There are only two such plants now operating in the free world outside the United States: at Capenhurst in the U.K. and at Pierrelatte in France. A large internationally financed plant is being built by Eurodif in France which will cost fifteen billion francs, not including the cost of the four 900 MWe nuclear power plants which will be built to supply it with electricity. Gaseous diffusion plants are inherently very large and, therefore, expensive. Because of this, building a gaseous diffusion separation plant will not be an attractive way to acquire fissile materials for smaller countries.

A somewhat less developed technique for isotope separation involves the use of a gas centrifuge. If uranium hexafluoride gas is put in a rapidly rotating cylinder, the heavier molecules will tend to become more highly concentrated near the outer radius. The separation factor which can be achieved in a single stage depends on the geometry of the cylinder, its speed of rotation, and the temperature. However, separation factors of 1.1 to 1.2 have been reported. This means that relatively few stages of centrifuge processing are required to reach high levels of separation. The flow rate per centrifuge is low, however, so that large numbers of centrifuges must be operated in parallel in order to achieve reasonable levels of throughput. The technology of gas centrifuges requires the ability to produce strong, light-weight cylinders able to resist the powerful centrifugal forces generated and also the ability to produce high quality low-friction bearings. There are three major centers of gas centrifuge technology in the free world: the United States; the three nations of the Urenco/Centec agreement (Britain, the Federal Republic of Germany, and the Netherlands); and Japan. The Urenco/Centec group has two pilot plants in operation, each about four times as large as would be required by a modest five weapons-a-year program. A third pilot plant is now under construction. The Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan is not quite so far along. PNC started operating a 180 centrifuge plant in the fall of 1974, and a 250 machine plant is expected to be running soon. They plan to start a 10,000 centrifuge pilot plant sometime in 1978. The electricity consumption of a centrifuge plant is much less than that of a gaseous diffusion plant, but its capital costs (per unit of throughput) are approximately the same as for a gaseous diffusion plant. It is estimated that the centrifuge separation will be comparable in cost to gaseous diffusion by the mid-1980s, but it must be recognized that the high-speed centrifuges represent a high level of industrial technology in themselves.

The Becker nozzle uses the same principle (centrifugal force) as the gas centrifuge. It has sometimes been called a "fixed centrifuge," in fact. The idea is that uranium hexafluoride gas, mixed with hydrogen, is blown at high velocity around a curved track. The heavier molecules tend to go to the outside, and the flow is separated into an inner flow (slightly enriched in U^{235}) and an outer flow (slightly depleted) by a knife-edge at the end of the track. Although a pilot plant which is believed to use this process is now operating in South Africa, and a group in Germany has been promoting the construction of a pilot plant there, it will probably be many years before any substantial quantities of U^{235} are produced by this process. It is hoped that the cost of separation may be cut in half (or more) by this new technique, since it does not require expensive rotating machinery or sophisticated permeable barriers, even though it appears that the electric power consumption of this technique may be at least as great as that of the gaseous diffusion method.

The final technique is laser enrichment. Successful laser enrichment for light elements was announced by both the Soviet Union and the United States in April, 1975. A proposed production technique involves using a finely tuned high power CO₂ laser to differentially excite molecules of different atomic weights; this differential excitation could then be used to separate the U²³⁵ from the U²³⁸. This method may eventually make separation much cheaper, but it is not yet clear how many years and how many dollars will be required before the method comes out of the laboratory and goes into the pilot plant (not to speak of full-scale production).

To summarize, isotope enrichment is still an expensive high-technology capital-intensive process. Although there are a fair number of enrichment plants in operation, and more under construction, outside the United States (see Table 3), we shall see below that chemical reprocessing of reactor fuel to separate fissile material offers a much more promising road for minor countries than the construction of costly enrichment facilities.

The fuel of any reactor has to be periodically removed and replaced by fresh fuel. The "used" fuel is then allowed to "cool" (i.e., a period of about 100 days is allowed to pass so as to allow some of the more radioactive nuclides to decay; this simplifies both handling and subsequent chemical processing). After the fuel rods have "cooled" and been transported to a reprocessing facility they are subjected to head-end treatment, which is required to reduce the many different kinds of fuel elements to a common substance ready for chemical processing. The head-end processes may include the disassembly of a fuel bundle, the removal of fuel-rod cladding by mechanical means or dejacketing by chemical or electrochemical methods, dissolution of fuel but not the cladding, or complete dissolution of the fuel element. Then the chemical separation process itself may be begun. There are several different techniques to perform a chemical separation; all of them have as one of their goals the separation of the plutonium and uranium from all the other materials. Modern methods can separate out over 99% of the uranium and plutonium available. The fissile material may be used either to make more reactor fuel or to make nuclear weapons.

The process of chemical separation of plutonium and uranium is complex, but is simple compared to isotope enrichment. Facilities for the reprocessing of nuclear fuel exist in Argentina, Belgium, France, Germany, India, Italy, Spain, and the United Kingdom. A small pilot plant exists in Taiwan. Such facilities will soon exist in Japan, and they are being talked about for Brazil and South Korea. Two or three of these processing plants reprocess only Materials Test Reactor fuel, and will produce very little plutonium; but several of the plants will have the capacity to produce hundreds or even thousands of kilograms of

Table 3

SOME ANNOUNCED WORLD ENRICHMENT FACILITIES
OUTSIDE THE UNITED STATES

Country	Type	Start Up	90% Enriched U/yr (kg) ⁽⁶⁾
France			
Pierrelatte ⁽⁷⁾	Gaseous Diff.	1958	1,586-1,982
	Gaseous Diff.	1981	37,668
Germany (FRG)			
G/K ⁽³⁾	Nozzle	1967	7.9
Steag ⁽³⁾	Nozzle	1974	----
Urenco ⁽¹⁾	Centrifuge	1974	99
Japan ⁽²⁾			
PNC	Centrifuge	August 1974	≈ 3.5
PNC	Centrifuge	Early 1975	≈ 5.0
PNC	Centrifuge	1978	≈ 200
Netherlands ⁽¹⁾			
	Centrifuge	Early 1974	99
	Centrifuge	1977?	793
South Africa ⁽⁴⁾			
Prototype	Nozzle?	April 5, 1975	
	Nozzle?	1984	19,825
United Kingdom			
Capenhurst ⁽⁵⁾	Gaseous Diff.	1953	1,586
Urenco ⁽¹⁾	Centrifuge	Early 1974	99
	Centrifuge	1977?	793

1. David Smith, "What Price Commercial Enrichment?" Nuclear Engineering International, July 1974, p. 572.
2. "Japan--Centrifuge, Good Progress," Nuclear Engineering International, Vol. 20, No. 225, p. 81,

Table 3 (continued)

3. Robert Gillette, "Nozzle Enrichment for Sale," Science, Vol. 188, No. 4191, May 30, 1975, p. 912.
4. "South Africa--Release More Details on Enrichment Process," Nuclear News, International, Vol. 18, No. 8, June 1975, p. 75.
5. Vincent V. Abagian and Alan M. Fishman, "Supplying Enriched Uranium," Physics Today, August 1973, p. 23.
6. Based on a 0.2% tails assay.
7. H. L. Dreissigacker, "Expected Development for Enriching Uranium in Europe," presented at the DFVLR Colloquium, Porz-Wahn, Germany, May 14, 1970. British translation (Capenhurst Translation 249) issued by the U.S. Atomic Energy Commission as CONF-700557-3.

plutonium annually. Where will they find fuel for these reprocessing plants? The amount of plutonium produced by a power reactor depends on a number of factors. It depends on the type of reactor, on the power (or size) of the reactor, and it depends on the way the reactor is operated. The following production rates appear to be reasonable averages, based on a 75% load factor:

Reactor Type	Annual Fissile Pu Production (Kg per MWe per Year)
Boiling Water Reactor	.23
Pressurized Water Reactor	.237
Pressurized Heavy Water Reactor	.29
Gas Cooled Reactor	.25

These figures are based on WASH-1139, by the Atomic Energy Commission, February 1974. They assume normal operation of the reactor for the production of power. The quality of plutonium produced could be increased by shorter exposure time and more fuel reprocessing per unit time, but there would be significant economic penalties for such procedures. We can use these factors to estimate the amount of plutonium which will exist in the spent fuel elements for each country at any time over the next fifteen years, on the basis of the country's existing and planned power reactors. Experience has shown that there usually is some slippage in the start dates for power reactors: This slippage is greater in the less developed countries. Therefore, we assume that a reactor which is planned to begin operation in the year Y will actually begin operation in the year Y + 2 if it is located in Latin America or Asia, and in the year Y + 1 if it is located in Europe or Canada. Reactors already in operation, of course, were credited with their actual start dates. The estimates given may be too high, however, because of the rather optimistic assumption of a 75% load factor. High load factors are desirable in power reactors, and a 75% factor is often assumed in planning, but in practice power reactors frequently fall short of it either because of breakdowns, faulty maintenance, or lack of demand for electricity. India's nuclear power reactors, for example, have operated at less than 50% of capacity. So one should not place too much confidence in the exact figures listed in Table 4. But even if these figures are high by a factor of two, or more, their basic message remains the same: The growing nuclear power industry is going to be producing a very large amount of plutonium in a very large number of countries. Although this plutonium will require chemical reprocessing to separate it from other materials in the spent reactor fuel elements, this chemical reprocessing is a much simpler operation than isotope separation.

Table 4

PROJECTED ACCUMULATED SEPARABLE FISSILE
PLUTONIUM FROM POWER REACTORS

Country	Separable Fissile Pu Accumulated (kg)				
	1970	1975	1980	1985	1990
Argentina	0	0	350	1,228	2,898
Austria	0	0	0	1,324	3,059
Belgium	0	0	1,272	4,953	9,858
Brazil	0	0	85	866	3,591
Bulgaria	0	0	711	2,291	3,871
Canada	90	1,665	4,938	14,283	27,075
Czechoslovakia	0	75	358	1,984	3,639
Denmark	0	0	0	324	1,134
Egypt	0	0	0	216	756
Finland	0	0	294	1,997	3,877
German Demo. Rep.	51	170	1,188	2,838	4,488
German Fed. Rep.	277	1,657	7,621	21,638	38,927
Hungary	0	0	0	632	1,422
India	18	402	1,032	2,424	4,204
Iran	0	0	0	1,242	5,022
Israel	0	0	0	108	648
Italy	485	935	1,941	6,099	10,774
Japan	74	1,460	10,126	23,671	35,915
Korea (Rep. of)	0	0	281	1,951	6,081
Mexico	0	0	56	1,111	2,221
Netherlands	8	153	628	1,103	1,578
Pakistan	0	61	201	605	1,405
Philippines	0	0	0	226	1,356
Portugal	0	0	0	216	1,296
Rumania	0	0	0	316	711

Table 4 (continued)

Country	Separable Fissile Pu Accumulated (kg)				
	1970	1975	1980	1985	1990
South Africa	0	0	0	513	2,220
Spain	12	588	2,613	4,562	16,836
Sweden	0	212	3,169	9,244	15,629
Switzerland	5	622	1,671	6,366	11,371
Taiwan	0	0	206	1,961	6,241
Yugoslavia	0	0	0	555	1,110

The plutonium from a reactor which has been operated in such a way as to maximize the output of electric power will be less than ideal from the standpoint of weapons manufacture. The reason for this is that only two isotopes of plutonium, ^{239}Pu and ^{241}Pu , are fissionable by thermal neutrons. Presence of substantial quantities of the isotopes ^{240}Pu and ^{242}Pu introduces three problems for the weapon designer:

1. Increase in critical mass. The exact critical mass required for a nuclear explosion when you are dealing with a mixture of isotopes requires some moderately complex calculations. But a single bench mark case may give the reader a feel for the order of magnitude of the problem: You would have to dilute your fissionable plutonium with over 50% non-fissionable isotopes in order to increase the required critical mass by a factor of three. An increase in the required critical mass will induce a roughly proportionate increase in the mass of the total device.
2. Increase in radioactivity. Since ^{240}Pu and ^{242}Pu fission spontaneously, plutonium containing these isotopes will be more radioactive than weapons-grade plutonium. This means that weapon fabrication will be somewhat more difficult, and also that a weapon, once produced, will be more detectible and thus not as suitable for clandestine delivery as a weapon made from purer stuff. These considerations may be important inhibitions to potential nuclear terrorists, but they are not particularly relevant to most national governments.
3. Decrease in yield reproducibility and efficiency. The spontaneous fissioning of ^{240}Pu and ^{242}Pu increases the possibility of pre-initiation, which will have the effect of making the yield achieved by a given device somewhat unpredictable and less efficient. The quantitative analysis of this phenomenon is classified, but one can say that the uncertainty in yield introduced by reasonable quantities of dilutents is small compared to the difference between nuclear and non-nuclear weapons.

There are at least two ways in which a nation could choose to get around these problems. The concentration of militarily undesirable isotopes increases as the burn-up of fuel increases; therefore a nation could get some high-quality plutonium by accepting an uneconomic low-burnup on some fuel loadings. One of the major aims of the various safeguard agreements and inspection procedures is to prevent this sort of fiddling with the fuel cycle. The other alternative is to accept the penalties associated with "normal" spent-fuel plutonium, on the grounds that a less-than-optimal nuclear weapon is better than none. Whether this latter course would be acceptable depends, of course, on the political-military motivations which drive the nation in question

to decide to build a nuclear device in the first place, but it is easy to think of circumstances in which a reactor-grade plutonium bomb would be just about as good as a weapons-grade device.

B. Categories of competence for a first nuclear test

On the basis of the discussion above we can divide the nations of the world into categories, according to the ease with which they could produce a nuclear device.

Category 0 (zero) consists of those states which have built and tested nuclear weapons, and which have military forces dedicated to the delivery of such weapons. There are today just five states in this category: the United States, the Soviet Union, Great Britain, France, and China. From a political, military, and economic standpoint there are obviously tremendous differences between the nations within this category; and in particular there are great differences between the significance of their various nuclear programs. The three "middle" nuclear powers have manifestly less strength than the two "super powers"; it should be made clear to everyone that the mere possession of nuclear weapons does not make a nation equal to the super powers.

Category 0+ (zero plus) consists of those states which have detonated a nuclear device, but which claim they have not produced nuclear weapons. In view of the unverifiable nature of such a claim, we should perhaps lump this category together with the states above. But there is a deplorable tendency to think of "proliferation" in terms of just one weapons test, and forget about all the subsequent developments which are required to achieve something beyond a mere terrorist or desperate last resort capability (see page 19). We intend in later work to explore these requirements in detail, and to investigate policies which might help to encourage nations which have already tested a nuclear device to refrain from moving on up to building a true nuclear weapon delivery capability. We treat 0+ as a separate sub-category (which contains only India at this time) in order to emphasize this distinction, which is so often overlooked.

Category 1 consists of those nations who have full access to the fissile material required to make a weapon and a broad base of manpower trained in nuclear technology. The lower limit on this category may be somewhat fuzzy, but probably most would agree that Japan, West Germany, South Africa, Belgium, Taiwan, Italy, the Netherlands, Canada and Sweden should be included. Some would argue that Canada and Sweden should not be included, because they have neither an enrichment nor a reprocessing facility within their borders. Technically, this is a good point, but both these nations have such a very high level of nuclear expertise that they could construct a small reprocessing facility very rapidly

if they wished to. Taiwan has a "pilot" fuel reprocessing plant, which clearly demonstrates their mastery of the technology required to separate plutonium from used reactor fuel. Some would argue that Israel ought to be included in category 1. There is a widespread suspicion that Israel has some clandestine reprocessing facility and has prepared to assemble nuclear weapons very quickly if the need should ever arise. We do not know if these rumors are true or false; but on the basis of public data Israel belongs in category 2.

Category 2 consists of those states which have at least a reactor within their borders and some base in nuclear technology. The states in category 2 at this time appear to be Israel, Argentina, Switzerland, Egypt, Spain, South Korea, Indonesia, East Germany, Czechoslovakia, Australia, Pakistan, Iran, Norway, Brazil and Mexico. Some of these states do not have power reactors but only research reactors. Research reactors can be used to produce quantities of plutonium which, while not large compared to those produced by power reactors, would still be adequate to support a small nuclear weapons program. For example, the two Norwegian research reactors generate about 3.9 kg of plutonium annually, which is enough to build about four bombs every five years.

Category 3 consists of all the rest of the countries in the world. One must realize that there is a continual tendency, even if they have no desire for nuclear weapons, for nations to move toward the higher categories of competence. This is the natural consequence of the expanding desire for nuclear electric power.

Now let us discuss what these different categories of competence mean if a nation decides that it does want to build a nuclear weapon.

C. How competent is each category?

Suppose a country in category 1 suddenly decides that it is in its national interest to design and test a nuclear weapon. If it had already made extensive preparations for this decision, if it had "kept open the option," then the time required might be very short indeed, and the costs involved might have been essentially already borne. But let us suppose that no such special preparations had been made. Then there are four steps which the power would have to carry out: rework the fissile material required for the bomb; design the bomb; fabricate it; and prepare and conduct the test. Rework means converting the fissile material to be used into metallic form; this step is not strictly necessary, but it would make bomb design easier, could be accomplished within a year, and would only cost about \$200,000. All cost figures here are engineering estimates based on U.S. experience. They should be considered as rough approximations. Design of the weapon could be done, crudely, within a year for a cost of about \$200,000. A category 1 power would probably be more than willing to spend much more than that

in order to improve the quality of the design, but we are interested in this section in estimating minimum possible costs rather than likely expenditures. Ease of fabrication depends on whether uranium or plutonium (which requires a glove box) is to be used. Uranium is easier to work with, but plutonium is easier to acquire. It is easily within the capability of a class 1 power to work with either metal. Setting up for and accomplishing fabrication of a weapon might take a year and cost another \$200,000. The power in question might wish to test their device above ground, but even if they felt constrained to do only underground testing the cost of a modest testing program would not exceed \$250,000 or six months of preparation. All four of these steps could be carried out in parallel rather than in series, so we must conclude that any category 1 power is within a million dollars (or less) and a year of testing a nuclear device if it makes the decision to do so.

A category 2 power which decides to design, build, and test a nuclear device faces a basic decision right at the start: whether to attempt to acquire its fissile material by reprocessing spent reactor fuel or by enriching natural uranium. As our discussion above indicates, the former approach is more practical. If a country would decide to build a reprocessing plant just to support its weapons program it could do so fairly cheaply. By not recovering the uranium, and cutting radiation protection and waste management operations to the minimum required for separating out plutonium, experienced industry personnel have estimated that an adequate plant could be built for around \$50 million and be operating in about four years' time. In the long term, it might be more beneficial to build a more elaborate facility, but we are interested in estimating minimums. It must also be remembered that estimates of capital costs are notoriously subject to error, especially in the absence of a detailed design for the plant in question. The other steps (reworking, design, fabrication, and testing) would be the same as for the category 1 state; they could be done in parallel with the construction of the reprocessing plant and thus the total time consumed would be only about four years, and the total dollar cost only about \$51 million.

If a category 2 country wanted to follow the enrichment route rather than the separation route it would undoubtedly take longer and cost more. The most sensible kind of enrichment plant for them to build at this time would be a gas centrifuge: This would take about five years and cost \$100 million or even more. The level of technological skill required is much higher than for a simple reprocessing plant, and is probably outside the reach of most (but not all) category 2 countries at this time.

A category 3 country which decided to build a nuclear weapon would probably choose to build a reactor and a simple reprocessing plant. Skill in handling nuclear materials would follow as a by-product, but many years and many millions of dollars would be consumed in the process.

A reasonable "minimum estimate" appears to be about six years and about \$200 million. It must be remembered, however, that such estimates are much less reliable than, say, estimates of the time required to go from category 1 to category 0. It should also be remembered that the time and resources required would be drastically reduced if fissile material was given or sold to the country in question. Although such an action may seem unlikely at the present time, it will become less unlikely as the number of countries possessing fissile material grows.

D. Some historical categories: competence and closeness

In 1960 the National Planning Association published a study entitled "The Nth Country Problem and Arms Control" in which they established three groups of nations according to the ease with which they could, if they wished, acquire nuclear weapons. It is interesting to compare their categories with ours above. They defined their three categories as follows:

Group I: those countries able to embark on a successful nuclear weapons program in the near future. Most of these countries are highly industrialized and either have operating reactors, or have already made plans and arrangements for obtaining reactors. A number of these countries have already talked about embarking on a nuclear weapons program.

Group II: those countries economically capable, fairly competent technically, although perhaps somewhat more limited in scientific manpower than the countries in Group I.

Group III: those countries probably economically capable, although more limited in industrial resources and scientific manpower. It is not too likely that any of these countries could presently achieve a successful nuclear weapons program within five years.

Note that the diffusion of nuclear technology which has taken place during the last fifteen years is reflected in the very way the categories are defined. Not all the nations in "Group I" fifteen years ago had nuclear reactors, but all the countries in our "category 1" and "category 2," and even some in "category 3," have reactors. Bearing in mind that our "category 1" and "category 2" are, conceptually, subsets of Group I, let us look at the specific states assigned to the various groups by the 1960 study. The number in parentheses indicates the category to which we placed the country in section 3 above.

Group I

France (0)	Italy (1)
China (0)	Japan (1)
India (0+)	Sweden (1)
Belgium (1)	Czechoslovakia (2)
Canada (1)	East Germany (2)
Fed. Rep. of Germany (1)	Switzerland (2)

Group II

Netherlands (1)	Finland (3)
Australia (2)	Hungary (3)
Austria (3)	Poland (3)
Denmark (3)	Yugoslavia (3)

Group III

Union of South Africa (1)	Norway (2)
Argentina (2)	Spain (2)
Brazil (2)	Mexico (2)

Ungrouped

Egypt (2)	Israel (2)
Indonesia (2)	Pakistan (2)
Iran (2)	Republic of Korea (2)

The grouping worked out in the 1960 report seems to have held up moderately well (so far as gross ordering goes) over time, but it might have surprised the authors that only three out of the dozen countries they placed in Group I actually went ahead and tested one or more nuclear weapons. They had expected up to ten new nuclear powers over the five years 1960-65, and had a feeling that perhaps twenty countries would have tested by 1965. This points up the distinction between having the ability to test a nuclear weapon and actually making the decision to do so. The groups displayed by NPA and the categories we discussed above reflect only the technological competence and the nuclear experience of the countries: They are indicators of the ability of the country to pay the technological and economic price of holding a nuclear test, but they say nothing about the military and political incentives for doing

so. The categories should not be regarded as a ladder towards an ultimately inevitable nuclear weapon which is being climbed by each nation of the world; certainly a nation in category 1 will require less incentive to actually build a nuclear weapon than a nation in category 3, but the likelihood of a particular country building a nuclear weapon can only be determined by a balanced consideration of both costs and incentives. The case of Israel, a category 2 power, illustrates the point very well. There are rumors that Israel is just a "turn of the screwdriver" away from possessing nuclear weapons. We do not know if these rumors are true or false; the fact that they may be true shows that if the incentives are great enough even a small nation with a modest nuclear industry might build atomic weapons.

The real problem of proliferation today is not that there are numerous countries "champing at the bit" to get nuclear weapons, but rather that all the non-nuclear nations without making any conscious decision to build nuclear weapons, are drifting upward to higher categories of competence. This means that any transient incentive, in the ebb and flow of world politics, which inclines a country to build nuclear weapons at some point in the future will be just that much easier to act upon. The general manner in which France went nuclear is apt to be repeated in the future:

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

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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.'*

Source: <http://www.albertwohlstetter.com>

Albert Wohlstetter Dot Com

*Lawrence Scheinman, Atomic Policy in France Under the Fourth Republic, Princeton University Press, Princeton, New Jersey, 1965.

III. Perspective on Inhibiting "Dangerous" Activities

It would be nice if there were a simple dichotomy between safe and dangerous nuclear activities: on the one hand safe, economic, civilian, non-military, peaceful activities that are to be promoted, and on the other dangerous military activities threatening war, a net drain, even in peacetime, on the productive life of humanity and therefore to be not merely discouraged, but banned. Something like that dichotomy has been implicit again and again, from the beginning, in all the broad and in many specific policy statements that call for choosing civilian uses of nuclear energy instead of military uses. If the choice were that simple, there would be little problem in choosing to use nuclear energy for "good" rather than "evil," or in drawing the line between the permitted and the impermissible uses, in watching for any trespass, detecting it in plenty of time, and bringing to bear sanctions or (to use the old phrase) "condign punishment." But unfortunately all these good things do not come in a cluster distinct from the bad ones.

The Inadequacies of the Familiar Dichotomies of Nuclear Activities

Some civilian activities are not economic. They are economically inferior to alternative uses of the same resources; they involve large "opportunity costs," are a net drain on economic development. Worse still, some civilian activities that are economic might nonetheless be so dangerous as to warrant banning. Some have an almost immediate military application.

The reduction to absurdity of the dichotomy came with the proposal to make "peaceful nuclear explosives," called self-consciously "Plowshare." These plowshares, in all essentials, are swords. To make the conceptual point vivid one might push this familiar example just an inessential bit farther than the essential truth. Suppose that a plowshare device were most economic if manufactured in aerodynamic form; suppose moreover that indigenous and transport costs were such that it would be optimal for each country to manufacture it locally; and suppose that plowshare explosives beat all other methods for moving earth for canals or the like that were in great demand at the price at which they could then be supplied. In that case it would be economic (in the precise sense of representing the most productive of the alternative use of the same resources) to make nuclear explosives for the civilian economy that could also be directly used without any change as bombs. They would be, in short, economic, civilian and military. And definitely not "safe."

Plowshare devices are near enough to this hypothetical to have been recognized as such in the Non-Proliferation Treaty. Non-weapons states are asked to swear off making not merely bombs, but "peaceful" nuclear explosives as well. But in principle the difference between Plowshare and some other peaceful nuclear activities is merely a matter of the distance in time for converting the civilian activity to direct military use.

And this distance can be and is increasingly coming to be extremely short. There are not two atoms, one peaceful and one military. They are the same atom. From the start of attempts to get international control, this was recognized to be the "heart of the problem, the close technical parallelism and interrelation of the peaceful and the military applications of atomic energy."* By a curious twist, however, we have from the start talked about promoting the peaceful uses of the atom as if that would automatically displace the military use. That hopeful displacement was presented in its baldest form in the initial speech of President Eisenhower launching the Atoms for Peace program as a solution to the "atomic armaments race." He proposed that the nuclear powers would get the program started by donating some uranium which would thereby be unavailable for weapons, and so form a kind of nuclear disarmament. The displacement was symbolic in both quantity and quality. The transfer, by comparison with the fissile material content of the bomb stockpile, was miniscule. The "disarmament" effects of the donations were quietly forgotten as transfers to civilian technology began to disperse worldwide the foundations for nuclear armament.

But the wishful confusion was present in the earliest declarations of policy by President Truman and Prime Ministers Attlee and King and it persists in the Non-Proliferation Treaty, and in the bilateral agreements of all supplying countries with countries importing nuclear technology. Before and after Eisenhower, clarification has been in order on the criteria of choice and the trade-offs among various civilian uses of nuclear energy. One way or another from the very start those who had advocated promoting the peaceful atom have had to face the problem of how to do it so as not at the same time to spread nuclear weapons. Waffling on the line between safe and dangerous activities has not helped. Nor has the sentimental identification of "civilian" with "economic," nor the rhetorical exaggeration of the immediate promise of the economic uses to foster the rapid development of less developed countries. Still more specific distinctions, for example, between optimal economic alternatives and the next best use of resources need to be made for making sensible trade-offs. Even if it should turn out to be economic to recycle plutonium eventually in the less developed non-weapons states, we have to ask how much difference recycling would make compared with alternative nuclear electric power arrangements that do not call for recycle, and how important indigenous reprocessing facilities in less developed countries are now. Even if some long forgotten suboptimization suggested the present design for High Temperature Gas Cooled Reactors (HTGRs) using uranium enriched to 93% in U²³⁵, how much does one lose by using lower percentages of enrichment, making the reactor fuel much less ideal for weapon purposes?

*J. Robert Oppenheimer, "Atomic Explosives," Lecture May 16, 1946, in The Open Mind, Simon and Schuster, New York, 1955.

The heart of sensible decision making and international bargaining in this field entails making distinctions going far beyond the resounding simple dichotomies. Some of the problems we are running into now in persuading less developed countries to forego national capabilities on such matters as chemical reprocessing have their origin in the early excess of rhetoric about how essential such processes are to the nuclear fuel cycle and how crucial nuclear energy is to their catching up with the advanced countries.

Early Troubles with the Line Between "Safe" and "Dangerous" Activities

The Acheson-Lilienthal Report and other early efforts to achieve international control start with the double political commitment made by the U.S. along with the U.K. and Canada on November 15, 1945 in Washington (the Three Nation Agreed Declaration on Nuclear Energy) to seek . . . "international arrangements to prevent the use of atomic energy for destructive purposes and to promote the use of it for the benefit of society." (Italics added.) The problem was how to reconcile the prevention of one with the promotion of the other, given their extensive identity.

The Acheson-Lilienthal Report (the body of which was written by David Lilienthal, Robert Oppenheimer, Charles Thomas, Chester Barnard, and Harry Winne) took the optimistic and somewhat paradoxical view that the close identity between destructive and beneficial uses would help control.** It reasoned that if control were simply negative; i.e., if it consisted merely in international inspection of nationally owned dangerous atomic facilities, it would never work. You could not get first-class people to serve as policemen, so the inspection would be poor; and national rivalries and considerations of national sovereignty would make the system unenforceable. The Report proposed therefore that an international authority, the Atomic Development Authority, promote civilian nuclear energy and that it own, and in fact have a monopoly of, all dangerous civilian activities, which would have to be distributed in a balanced way throughout the territories of the various nations. The balance would be determined by security rather than economic considerations, as P.M.S. Blackett noted. These dangerous activities monopolized by the Authority would include a very large range from mining through the operation of many power reactors. For example, besides owning the mines it was to own about half the nuclear electric capacity. The other half, in national hands, would get its fissile material only in "denatured" form from the plants owned by the Authority. Because the international authority would have a monopoly of the essentials for the conduct of civilian nuclear energy, it could recruit first-class scientists, not simply as guardians, but to do research at the leading edge of the technology and to help in its transmission; and sovereign nations would have an incentive to cooperate with the international authority.

*U.S. Department of State, A Report on the International Control of Atomic Energy, Publication No. 2498, U.S. Government Printing Office, Washington, D.C., March 16, 1946, p. 1.

**Ibid.

Like the original Acheson-Lilienthal proposal in this one respect, the U.S. Atomic Energy Commission combined in its domestic program regulatory and developmental functions for civilian nuclear energy, but experience made clear that this was not a tenable mix. The purpose of the Energy Reorganization Act was to separate these functions and divide them between the Nuclear Regulatory Commission and the Energy Resource and Development Agency and to make the promotional activity more even handed by requiring attention to non-nuclear fuels. Strong traces of the original proposal, however, survive in the present international institutions: the IAEA "promotes" civilian nuclear energy, while safeguarding materials against diversion. The inspectors offer technical advice and help; and other IAEA staff members spend the largest portion of the IAEA budget to provide information, technical assistance, and encouragement for developing nuclear electric power--especially in the Third World.* The basic statute of the IAEA assigns it the task of seeking "to accelerate and enlarge the contribution of atomic energy to peace, health, and prosperity throughout the world." But the situation today departs a long way from the original ideal. The IAEA does not own, but simply inspects; and "dangerous" as well as "safe" activities are both governed by sovereign nations. Precisely the arrangement that the original report said was unenforceable.

However, the problem of finding a dividing line between "safe" activities and "dangerous" ones that has preoccupied the writers of bilateral and trilateral agreements on cooperation and of the Non-Proliferation Treaty, formed the crux of the difficulties in the Acheson-Lilienthal Report. And in fact, some residual traces of a belief in a solution proposed there persist, namely the possibility of "denaturing" fissile material such as plutonium by adding to it an isotope that has the same chemical properties, but spoil it as an explosive. The Acheson-Lilienthal Report proposed to regard power reactors putting out as much as 1,000 megawatts as safe, provided their power was developed from the fission of "denatured U235 and Plutonium."**

* See "Nuclear Inspector or Salesman?" The Economist, February 28, 1976.

** Though the hope for it was disappointed, what was meant by "denaturing" plutonium-239 is comparatively clear. It is not so clear today what was intended by "denatured U235." Natural uranium is only about .7% U235 and 99.3% U238, and so cannot be exploded. U238 is not readily fissionable by slow neutrons. Natural uranium, then, might conceivably be said to come denatured--to be denatured, so to speak, by nature. But this is rather strained and it is possible that constraints of secrecy at the time contributed to the unclarity. The passage as a whole reads:

"More marginal from the standpoint of safety, but nevertheless important, is another case of an operation which we would regard as safe. This is the development of power from the fission of denatured U 235 and plutonium in high power-level reactors. Such power reactors might operate in the range from 100,000 to 1,000,000 kw. If these fissionable materials are used in installations where there is no additional uranium or thorium they will not produce further fissionable material. The operation of the reactors will use up the material. If the reactors are suitably designed, a minimum of supervision should make it possible to prevent the substitution of uranium and thorium for the inert structure of the materials of the reactors. In order to convert the material invested in such reactors to atomic weapons, it would be necessary to close down the reactor; to decontaminate the fissionable material of its radioactive fission products; to separate it, in what is a fairly major technical undertaking, from its denaturant; and to establish plants for making atomic weapons. In view of the limited amount of material needed for such a power reactor, and of the spectacular character and difficulty of the steps necessary to divert it, we would regard such power reactors as safe provided there were a minimum of reasonable supervision of their design, construction, and operation. If the material from one such reactor (of a size of practical interest for power production) were diverted, it might be a matter of some two or three years before it could be used to make a small number of atomic weapons." Loc. cit., Publication No. 2498, U. S. Department of State, p. 28.

If the Report had been correct, the operation of such a reactor would indeed have been safe, in the sense that it would take two or three years to build a plant capable of removing the unwanted isotopes. But there were hints in the Report itself of some unease about what denaturing accomplished, and a committee of distinguished physicists, including Oppenheimer himself, on April 9, twelve days after the publication of the Acheson-Lilienthal Report, made clear some important qualifications about the effectiveness of denaturing: First, while it was true that constructing a plant capable of separating the isotopes would take between one and three years, . . . "unless there is a reasonable assurance that such plants do not exist, it would be unwise to rely on denaturing to insure an interval of as much as a year."* And it went on immediately to an

*U.S. Congress, Committee on Government Operations, Peaceful Nuclear Export and Weapons Proliferation, A compendium, U. S. Government Printing Office, Washington, D.C., April 1975, p. 200.

even more important qualification about which we know a good deal more today. "In some cases denaturing will not completely preclude making atomic weapons, but will reduce their effectiveness by a large factor."*

This second qualification went somewhat further than the Report, which on page 26 had stated that the reactor material would be "...unusable by any methods we now know for effective atomic explosives," without removing the "denaturants," that is, without separating and removing most of the unwanted isotopes.

Most important, that second qualification about denaturing in itself was not as strong as is warranted by the facts as they are known today. Both the March Report and the April press statement by the committee stressed that the line between "safe" and "dangerous" activities might alter with improved knowledge about the design of nuclear explosives. And there was a good deal that had not been explored even about the properties of the weapons designs of that time. According to Robert Bacher,** former head of the Bomb Physics Division at Los Alamos and member of the committee to discuss denaturing, the discovery of the higher spontaneous fission rate of the plutonium coming out of the Oak Ridge reactor by comparison with the plutonium that had been derived from a cyclotron caused a kind of crisis at Los Alamos during the summer of 1944. It led to the abandonment of gun type weapons for plutonium and a great intensification of the effort on implosion. (Over half the Physics Division was turned over to the study of implosion.) It led also to the use of plutonium that had a very small percentage of the spontaneously fissioning higher isotopes and to a concentration on a workable implosion design for such nearly pure material.

*Ibid.

**Interview, August 1975, See also R. G. Hewlett, and O. E. Anderson, Jr., A History of the United States Atomic Energy Commission, Vol. I, The New World, 1939/1946, The Pennsylvania State University Press, University Park, Pennsylvania, 1962, p. 251, and Trudlow, Edith C., and Smith, Ralph Carlisle, Manhattan District History Project Y: The Los Alamos Project, Vol. II, August 1945 through December 1946, Los Alamos, New Mexico, 1961, and Hawkins, David (ed.), Manhattan District History Project Y: The Los Alamos Project, Vol. I, Inception until August 1945, Los Alamos Scientific Laboratory of the University of California, Los Alamos New Mexico, 1961.

The work in 1946 on what was safe and what was dangerous material from the standpoint of usability in bombs was based pretty much on the state of the art in 1945, and on the state of knowledge about that state of the art. In fact, even for the early designs it seems the more cautious statement by the committee on April 9 that denaturing will not preclude, but would reduce the effectiveness of an atomic explosion "by a large factor," was, as it developed, not nearly cautious enough. It suggested that the expected yield and destructive effect of an explosive made with reactor-grade plutonium would be negligibly small. Oppenheimer in a lecture on "Atomic Explosives," delivered a few weeks later on May 16, 1946, expressed the same view in more explicit form. "Even plutonium can be doctored -- not without prohibitive cost if it is to be completely nonexplosive -- but to be made a relatively very ineffective explosive."* But in actuality, according to the public authority of the former long-term Director of the Los Alamos Theoretical Physics Division, Dr. Carson Mark, the explosion from "essentially any grade of reactor-produced plutonium" would be truly "nuclear," that is "an explosion of at least three orders of magnitude more energy per pound than would be available from high explosives."**

Now the yield of any explosion is not exactly determined. There is a probability distribution of yields, a distribution with a sharp peak and a narrow dispersion in the case of a standard design using materials with few impurities. For a similar bomb using reactor-grade plutonium, the dispersion might be larger, low yields more probable, the probability of a failure larger, and the expected or average yield might be lower. That the probability distribution of yields would make it nonetheless a quite formidable nuclear weapon is evident from the statement we have quoted of Dr. Mark, and from many public statements, for example by Dr. Theodore Taylor, the former Deputy Director of the Defense Atomic

*Loc. cit., Oppenheimer, "Atomic Explosives."

**B.T. Feld, T. Greenwood, G.W. Rathjens, and S. Weinberg, eds., Impact of New Technologies in the Arms Race, Pugwash Monograph, M.I.T. Press, Cambridge, Mass., 1971, pp. 137-138.

Support Agency, and an outstanding nuclear weapons designer at Los Alamos from 1946-56.*

Moreover, the reduction in destructive effect would be smaller than any reduction in the energy yield. The area destroyed by blast overpressure diminishes as the two-thirds power of the reduction in yield, and the reduction in prompt radiation -- which is the dominant effect of a low yield weapon -- is even smaller. To say therefore that ". . .denaturing . . . will reduce . . .effectiveness by a large factor," while vague, was unfortunately misleading. What is more the above refers to primitive designs, and the authors of the Acheson-Lilienthal Report themselves stress that the state of the art of weapons design would improve and would always require a reconsideration of the line between safe and dangerous activities.**

*John McPhee, The Curve of Binding Energy, Ballantine Books, Westminster, Maryland, No. 24503, June 1975, p. 214; Theodore B. Taylor, "Diversion by Non-Governmental Organizations," in Mason Willrich (Ed.), International Safeguards and Nuclear Industry, Johns Hopkins University Press, Baltimore, Maryland, and London, 1973, Chapter 7, p. 181.

**See the Acheson-Lilienthal Report, page 30;

"Only a constant reexamination of what is sure to be a rapidly changing technical situation will give us added confidence that the line between what is dangerous and what is safe has been correctly drawn; it will not stay fixed."

Compare also the quotation from Oppenheimer's "Atomic Explosives" cited in the text above (" . . .plutonium can be doctored . . .to be made a relatively very ineffective explosive.") It goes on

". . .and a difficult one to use in the present state of the art. I don't need to tell you that the art may change and that no kind of control is worth anything which doesn't make provision for such change. It's not only that it can; it probably will, in one way or another."

On the matter of the likelihood of changes in the state of the art as in other aspects of the safeguards problem, the Acheson-Lilienthal Report shows some ambivalence. Contrast the certainty of change in the passage cited from page 30 with the doubts on pages 26, 27.

". . .the development of more ingenious methods in the field of atomic explosives which might make this material effectively useable is not only dubious, but is certainly not possible without a very major scientific and technical effort."

Needless to say, weapons design has greatly improved in the last 30 years, and much information relevant to such design is in the open literature. "I would like to warn people concerned with such problems," Dr. Mark has concluded, "that the old notion that reactor-grade plutonium is incapable of producing nuclear explosions -- or that plutonium could easily be rendered harmless by the addition of modest amounts of Pu²⁴⁰, or 'denatured,' as the phrase used to go -- that these notions have been dangerously exaggerated."*

What gives this history contemporary relevance is the persistence, in the face of such warnings, of the belief that chemically separated plutonium that has a substantial percentage of the higher isotopes such as Pu²⁴⁰ and Pu²⁴², along with Pu²³⁹, is of rather negligible value as an explosive material and therefore is not very dangerous. This residual of the initial denaturing hope persists in the form of statements that the reactor-grade plutonium is barely conceivable as an explosive material. So, for example, an article in the June/July, 1975 issue of Nuclear Engineering International that deprecates the dangers of the reprocessing plant sold to Brazil by the Germans. After indicating that the small enrichment plant would have "little use for military purposes," it goes on to say that the final stage of the reprocessing plant is the only place "where one would find plutonium of a grade that might conceivably be used in an explosive," but that the existence of such plutonium separated from the spent fuel of a power reactor "is not half the problem" it is cracked up to be. Even American government officials in agencies subsidizing loans to countries like India with reprocessing plants take comfort from the fact that "While the plutonium produced by these reactors could be used in an inefficient and unsophisticated explosive program, it is not optimum material for explosive uses because of the high percentage content of the non-fissionable plutonium isotope Pu²⁴⁰."**

Such plutonium is denatured -- sort of. It is a long way from the original concept of denaturing to the notion of making do with less than optimal material, although today we persist in talking about the less than optimal material as if it were safe. And much of our policy may be influenced by remnants of that conviction.

The Gravity of Danger Signals, Warning Time and Response

The initial efforts at international control in the Acheson-Lilienthal Report are interesting in another respect applicable today, namely to show how the problem of sanctions has turned out to be in some ways unexpectedly harder than was originally foreseen; and how it runs into some of its most serious troubles when the violations or dangerous acts

*Carson Mark in Feld, et al op. cit., pp. 137-138.

**Letter of August 18, 1975 to Congressman Findley from Denis M. Neill, Assistant Administrator for Legal Affairs, Agency for International Development, Department of State.

are less serious -- or at any rate less immediately, even if ultimately, dangerous. What should we do about activities that step by step cumulatively defeat our purpose, when none but the last small individual step presents an unambiguously final danger? That is the characteristic way in which the dangers of spread appear today. It is part of the meaning of what we have called "the shrinking critical time," or the increasing "overhang" of countries with a very short critical time to make a nuclear explosive.

That this trouble with sanctions against crossing the boundary between "safe" and "dangerous" activities continues to be left vague after all these years may be surprising. The Acheson-Lillienthal Report was published by the government and very widely disseminated, and its viewpoint therefore may continue to have an intellectual influence greater than the position presented by Bernard Baruch. But Baruch's few modifications to the Acheson-Lillienthal Report became the official U.S. position, and his key point of difference had to do with just this matter of sanctions. It was also one of the make or break issues with the Soviets.

The Acheson-Lillienthal Report tended to think of the signals we would receive under their plan when a country undertook banned dangerous activities, as being signals at the same time of the beginning of an atomic war. When they talked of safeguards therefore and what we should demand of them, they said:

"It must be a plan that provides unambiguous and reliable danger signals if a nation takes steps that do or may indicate the beginning of atomic warfare."*

"The Security which we see in the realisation of this plan lies in the fact that it averts the danger of the surprise use of atomic weapons. The seizure by one nation of installations necessary for making atomic weapons would be not only a clear signal of warlike intent, but it would leave other nations in a position -- either alone or in concert -- to take counter-actions."**

While danger of an atomic attack is even more fearsome than the danger from the spread of nuclear weapons, it also makes easier determining

*U.S. Department of State, A Report on the International Control of Atomic Energy, Publication No. 2498, U.S. Government Printing Office, Washington, D.C., March 16, 1946, p. 9. On the subject of danger signals, as in the case of "denaturing" plutonium, the Report shows some unease and unclarity. There is considerable tension between the downright "unambiguous and reliable" safeguards and the tentative "do or may indicate."

**Ibid., p. 53.

how to respond to its unambiguous detection. Oppenheimer was able to say that there was a strong sanction in the Acheson-Lilienthal plan against violation, namely war.* The doubts that bothered Eberstadt, Baruch's deputy, and the contrasting viewpoint of Thomas, Oppenheimer, Acheson and Herbert S. Marks (Special Assistant to Acheson) are illustrated in an account of the conference at Blair-Lee House on May 17, 1946, where Baruch and his aides raised the subject of sanctions with the Acheson-Lilienthal group.

"What do we say to those who violate? There must be sanctions, retaliation. . . Eberstadt said it was essential to state the truth about the plan: It did not eliminate the bomb. You do not eliminate the bomb merely by specifying a penalty for violations, Lilienthal replied. The public had the wrong impression, Eberstadt insisted. People thought the State Department plan was a system for controlling the bomb. Thomas asked what Eberstadt considered necessary. Outlawry and a penalty, he replied. The board's plan did have a penalty, said Oppenheimer -- war. Marks pointed out that the United States would fight if Russia attacked Alaska. So under the proposed system: violation of the plan would be equivalent to violation of our boundaries.

"Finally, Acheson declared there were only two ways to go further than the Board of Consultants had. One was a treaty requiring that an offender nation meet with an automatic declaration of war by all the others. He thought this meant little. The other way was world government envisioning all wars as civil wars. This meant not a 'damned thing.'***

So long as one was thinking of extreme and immediate dangers, waging war in response might be plausible with or without some formal declaration in the treaty to that effect. Acheson was right that the declaration would add very little.

But what if the dangerous activity isn't that immediately dangerous? What if it consists simply in piling up a little separated plutonium for use in some future peaceful experiment? And what if (just incidentally) that stock of plutonium might greatly advance the development of the capacity to make nuclear weapons if and when one decides to do so? That need not signify any firm intention of ever making a nuclear attack. Response then is likely to be more uncertain as well as considerably milder than going to war.

*Hewlett and Anderson, op. cit., p. 565.

**Hewlett and Anderson, loc. cit.

Baruch's team, which always had a bad press among the Manhattan Project scientists, was concerned about the possibility of smaller violations and, in spite of some impression to the contrary, they did not propose "nuking" violators for minor infractions. The famous archaic, ominous sounding phrase used by Baruch -- "condign punishment" -- has an aura of summary extreme punishment no matter what the provocation. But it literally means exactly the opposite--only the punishments that are deserved or fitting. Baruch's suggestions were all necessarily vague, though Baruch wanted very much to make them specific. He submitted to the U.N. Atomic Energy Committee some proposals that the treaty include "enforcement provisions as follows:

1. Definition of conduct constituting violation.
2. Consequences of such violations, including the procedures to be followed in detecting, establishing, remedying or punishing such violations.
 - a) Administrative action by the Authority.
 - 1) Special investigation.
 - 2) Revocation or denial of licenses.
 - 3) Other action.
 - b) Resort to judicial processes and procedures.
 - c) Reference of serious violation to the Security Council of the United Nations."*

It is easy to see why Baruch was against having the Security Council operate on these matters under the veto system. Even the administrative actions by an international authority to undertake a "special investigation" might have run into the problem of politically determined split votes, rendering it ineffective -- if we may judge by the experience with the various international control commissions in the last 30 years, from one of which Canada recently withdrew in frustration.

The ambiguities as to what is safe and what is dangerous make for hesitation in applying any sanctions at all. The judicial processes in the international field that might be resorted to, then as now, are notably time-consuming and ineffective. A World Court decision coming

*U.S. Department of State, The International Control of Atomic Energy: Growth of a Policy, U.S. Memorandum, No. 1, of July 2, 1946, Submitted to UNAEC Subcommittee No. 1, Washington, D.C., USGPO, 1946, p. 151.

several years later is likely to be split, reflecting at least the ambiguities, if not also the sovereign political differences implicit. Withholding licenses might have been effective if the international authority had a true monopoly. But that raised the question as to who would control the authority, a sore point for the Soviet Union. It is easy to see why the Soviet Union which felt acutely U.S. dominance in the Security Council, was against having the Council operate on these matters except under a veto system.

In the end the sorts of activities that advance a national government towards the ability to detonate a nuclear explosive may not violate any strict promises, or if they do, may do so ambiguously and in a way that seems threatening only in a possibly distant future. To such dangers no responses more belligerent than withholding or withdrawal of some benefit in the form of nuclear materials and services seem plausible, and even they are likely to be easy to argue against.

Civilian Benefits and National Sovereignty

The promise of economic benefits played a major role both in the spread of nuclear technology and in the hope to avoid the spread of nuclear weapons. (1) We have offered civilian technologies as an inducement for nations to forswear bombs and accept safeguards. (2) We have thought of withholding or withdrawing civilian benefits, (or the materials and services needed for civilian programs) as a potential punishment for violations of promises to forswear nuclear explosives. However, whether as a promise or a threat, civilian benefits have had their problems.

As for the promise, we greatly exaggerated the present value of civilian nuclear energy for the economic development of the poor countries, and this only made non-weapon states less willing to accept restraints on civilian programs imposed to reduce their military potential. In fact, it led paradoxically to an insistence by non-weapons states that, in return for a (revocable) promise not to make or accept nuclear explosives, they be given civilian technologies that would carry them a long distance on the way to such nuclear explosives.

As for the threat, the prospect of having civilian nuclear assistance withdrawn became less likely and the terror of the prospect more dilute, insofar as (a) the benefits were not actually as immediate as had been hoped, (b) the withholding could be made to appear as a violation of the pledge to offer assistance, (c) an increasing number of suppliers appeared who were competing in offers of such assistance, and (d) each supplier government developed factions with a vested interest in continuing the supply.

The Power of Positive Thinking about Atomic Power

It is commonplace to observe that the enormous destruction at Hiroshima and Nagasaki provided a strong impulse towards finding a constructive or positive side to the release of nuclear energy. And this is most often attributed to the guilt feelings of the Manhattan Project scientists. In fact, Robert Oppenheimer was very conscious of this impulse and cited Fermi's wry comment on the subject,

"'It would be nice,' Fermi said, not quite without seriousness, 'if it could cure the common cold.' He was talking of atomic energy. It was not yet three years since he had established the first fission chain reaction. Now we were meeting at Los Alamos, in the tired summer of 1945, in the week in which Hiroshima and Nagasaki were bombed. We were meeting at the request of Secretary Stimson's Interim Committee, not for the first time, and not for the last. We were being asked about the future of research and development in atomic energy, not only on the military side, but also, and even more urgently, with regard to its peaceful applications. Mr. Stimson had just issued a statement, after the bombing of Hiroshima, saying that the release of atomic energy faced us with far more than the development of a new weapon. Of course he was right. Among the peaceful applications, among the 'benefits for mankind,' would be the generation of atomic power: electric power from the energy of large-scale, controlled nuclear fission."*

However, as the reference to Henry Stimson suggests, this impulse was by no means restricted to the scientists and engineers. At a meeting of the Interim Committee that considered the use of atomic explosives in Japan, "the Secretary spoke continuously about ways to use nuclear energy for other things 'than killing people.' He wanted the members to get started immediately 'talking and questioning' about methods 'to take advantage of the changed relation of man to his universe.' He wished them to begin to figure the means by which 'the peace of the world would be helped in becoming secure.'** Moreover Secretary Stimson at that time looked forward to a drastic transformation of world politics that would bring about a supranational order hardly less utopian or more precisely

*Robert Oppenheimer, "The Environs of Atomic Power," in The American Assembly (ED.), Atoms for Power: United States Policy in Atomic Energy Development, Columbia University, New York, December 1957, pp. 15-16.

**Quoted in Elting E. Morison, Turmoil and Tradition, A Study of the Life and Times of Henry L. Stimson, Houghton Mifflin Co., Cambridge, Mass., 1960, pp. 635-636.

conceived than the hopes for international order that were raised by the less worldly scientists. His memorandum for the President of April 25, 1945 had said that the "new energy could not be brought within the now obsolete schemes -- nationalism, secret diplomacy, the balance of power. It required a direct and open approach, an offer for the mutual limitation and control of 'the benefits of future developments . . .'"* He recognized that the Soviet Union was a stumbling block, but hoped that future civilian benefits could be exchanged for a halt in military applications of nuclear energy.

The British Prime Minister, Clement Atlee, drafted a letter to President Truman in the summer of 1945 in much the same vein. He talked of "a new valuation of what are called national interests,"** and invoked "an act of faith" by the United States and the United Kingdom. Even so notoriously tough minded a man as Ernest Bevin, the Foreign Minister, early in October favored giving the Russians the knowledge of the atomic bomb process,** and trusting to their good faith in observing future international controls. This inclination of Bevin's did not last through October, but it is interesting that Dean Acheson, whom revisionist historians regard as a prime originator of the cold war, like Bevin, originally favored making substantial disclosures of information to the Russians as part of a program of mutual exchange to build mutual trust, much like that advanced by the utopian scientists movement at the end of the war.

As for the British, their official historian of atomic energy notes, they decided that, "while waiting for mutual trust to be established and utopia to arrive,"*****they would make their own atomic position as strong as possible. And the British reaction to the panel's work for the Acheson-Lillienthal Report in the following spring is suggested by Gowing's summary:

"In two months the panel produced a report in which they believed passionately; in this they differed from the authors of nearly all the other reports on control that had been drawn up."*****.

* Ibid., p. 637.

** Margaret Gowing, Independence and Deterrence: Britain and Atomic Energy, 1945-1952, Vol. I, Policy Making, St. Martin's Press, New York, 1974, p. 65 and p. 81.

*** Gowing, Ibid., p. 67.

**** Forrestal Diaries, Unpublished manuscript, Office of Naval History, Washington, D.C. Cf. Dean Acheson's "Memorandum to President Truman on U.S. Policy Regarding Secrecy of Scientific Knowledge about the Atomic Bomb and Atomic Energy," Foreign Relations of the United States 1945, Vol. 2, the Department of State, Washington, D.C. USGPO, 1967, pp. 48-50. Also interview, Paul Nitze, August 1974.

***** Margaret Gowing, Loc. cit., Vol. I, p. 72.

***** Ibid., p. 88.

Many of the activities connected with the production of atomic power were in fact "dangerous" and the British government was apprehensive about the Acheson-Lillienthal Report on political grounds.

"To transfer development activities to an international authority would mean in practice that atomic energy plants would be built in all the principal countries with the advice and assistance of other nations. Whether the advantages of such a scheme would justify the inherent risk depended on political judgment, and certainly no such scheme could succeed except in an atmosphere of confidence. There were, however, such wide differences of opinion and outlook and policy between the great powers that there was little prospect of general acceptance of the ideal of a supranational authority whose behests would automatically override sovereignty."*

The British doubts were nothing compared to those of the Russians, and P.M.S. Blackett, the Nobel physicist, a Marxist at the time, advanced the view that civilian nuclear energy was likely to be of particular importance to the development of the Soviet Union and of the underindustrialized countries.** He felt they could not entrust so critical a part of their future economic development to an anonymous unvetoable international agency. And this was a main basis of the Soviet assault on the Baruch Plan. Blackett, who opposed a British atomic weapons program was of course much more extreme than the British government on the subject of international control. He hinted darkly that a Russian acceptance of the Baruch Plan would indicate such weakness that the Americans might wage a preventive war against the Soviet Union,*** and (most amusing today in the light of the current attack on the American public utilities as an unthinking lobby for nuclear energy) suggested that the American utilities were behind the desire to stifle the development of civilian nuclear power,**** which he believed would in effect be the result of the Baruch Plan.

Such official and unofficial foreign reactions to the early American efforts to barter supposed civilian benefits of nuclear energy in exchange

*Ibid, p. 89.

**P.M.S. Blackett, Military and Political Consequences of Atomic Energy, London, Turnstile Press, 1948, p. 99.

***Margaret Gowing, op. cit., Vol. I, p. 89.

****P.M.S. Blackett, op. cit., p. 95.

for the surrender of national sovereignty to an international authority should have called into question some of our basic initial assumptions. The optimistic and paradoxical view of the Acheson-Lillienthal Report that the near identity of destructive and beneficial uses of the atom would help international control rested in part on the belief that if the benefits were very large, sovereign nations would surrender many of their sovereign rights to obtain them. But the more important and immediate these civilian benefits were made to appear, the more reluctant nations were to give up sovereign control over the civilian developments or to accept restraints on them simply to avoid supposed military dangers.

In the early period when we were most intensely focussed on our bipolar troubles with the Soviet Union, we tended to neglect the fact that newly sovereign governments, like that of India, would guard even more jealously their sovereign "inalienable" rights to pursue a civilian nuclear energy program so hopefully conceived. Yet Atoms for Peace was in good part directed at the "power-starved," less developed world. The Non-Proliferation Treaty was a highly ambiguous and uncertain set of compromises, reflecting but not resolving the same dilemmas about national sovereignty and the problem of encouraging civilian nuclear energy while discouraging military nuclear energy.

Present hopes for multinational nuclear centers may founder on the same rocks. Sovereign rights to separate plutonium or enrich uranium are less likely to be surrendered the more they appear to be needed for civilian nuclear energy, and the more civilian nuclear energy seems to be central to future economic growth. The less developed countries in particular will not want a permanently subservient role in any technology that is critical for their development. If reprocessing is critical -- or if we or they act as if it is critical -- they are likely to treat multilateral reprocessing as a step towards national reprocessing, or even to claim that multilateral centers require national centers as a precondition. Thus in a perverse way all too familiar in this field the point of the multilateral form would be defeated.

The irony of course is that the crucial character of the role of nuclear energy for the less developed world was and is exaggerated. In fact, if we could have detached ourselves from the emotions about civilian nuclear energy generated in Hiroshima and Nagasaki, we might have more easily questioned that subsidizing civilian nuclear energy was the way to stop the spread of the military technology. Since civilian and military nuclear energy programs overlap so extensively, a more plausible course might have been to subsidize research and development on the improvement of fossil fuels or of more exotic non-nuclear alternatives such as solar electric or geothermal power. It is only recently, however, that this course has begun to be followed in the United States.

It should be observed that even at the beginning there was a small but impressive minority who argued for something like such a course, at least in the sense of avoiding the forced feeding of nuclear energy. In England Lord Cherwell, Churchill's science advisor,* and his frequent opponent, science advisor Sir Henry Tizard,** as well as the distinguished economist, R. F. Harrod; in the United States several scientists and engineers who had been associated with the Manhattan Project;*** and a succession of excellent American economists beginning with Jacob Marshak have tried to put the economic prospects for civilian nuclear energy in more sober perspective.

Nuclear Disarmament and the Problem of "Equity"

The public drive for the civilian application of nuclear energy to displace military application and to make international control more palatable faded in the late 1940s along with the fading prospects for international control and with the intensification of the antagonism between the United States and the Soviet Union: Alan Nunn May and Klaus Fuchs, the takeover in Czechoslovakia, the Berlin blockade, Joe I (the first Russian nuclear test), the invasion of Korea. Late in 1948, the Atomic Energy Commission had advanced a program for developing a materials testing reactor, an experimental breeder, a liquid metal cooled power reactor by General Electric, and a prototype of a submarine thermal reactor by Westinghouse. The reactor for submarine propulsion was brought to full power in 1953, the year when the Korean armistice was signed and the year of President Eisenhower's Atoms for Peace speech.

This famous speech of Eisenhower revived and inflated hopes for the large worldwide benefits to be obtained from civilian nuclear energy. Though nominally a move towards nuclear disarmament it was actually associated with the acceptance of nuclear weapons as "conventional." The same speech states that "atomic weapons have virtually achieved conventional status within our armed services" and displayed in effect a rather relaxed acceptance of both the permanent importance of the role of atomic weapons and an increase in the American reliance on them. We had decided at about the same time to base NATO defense on nuclear weapons. Secretary Dulles had advanced the same massive retaliation theory. And we looked forward to reducing the defense budget as a result of an increased reliance on nuclear firepower (C.D. Jackson, the Life editor who worked with the President in writing the Atoms for Peace speech, was also the author of the "bigger bang for a buck" slogan).

*Blackett, op. cit.

**Gowing, op. cit.

***Cuthbert Daniel, and Arthur M. Squires, "The International Control of Safe Atomic Energy," Bulletin of Atomic Scientists, Vol. 3, No. 4-5, April-May 1947, pp. 111-116 and 185.

This did not mean of course any diminution in the number of international meetings with invocations on all sides to disarmament and a halt to the nuclear arms race. But the Atoms for Peace proposal that brought about the establishment of the International Atomic Energy Agency differed drastically from the Acheson-Lillienthal and Baruch plans on the crucial matter of nuclear disarmament. In 1946 the United States was the only nuclear-armed nation, though its stock of weapons and weapons components had been kept remarkably small, much lower than was generally realized. By 1953 there were three nations that had made nuclear explosives, and both we and the Soviet Union were shortly to acknowledge that this was a distinction that could not in practice be reversed. Robert Oppenheimer was right in saying that unlike the Acheson-Lillienthal Report, the Atoms for Peace plan had no "firm connection with atomic disarmament"; and that its bearing on the prospect of nuclear war was "allusive and sentimental" rather than "substantive and functional." In July 1955 the President at Geneva admitted,

"We have not as yet been able to discover any scientific or other inspection method which would make certain of the elimination of nuclear weapons. So far as we are aware no other nation has made such a discovery."*

The Soviets admitted the same somewhat more obscurely; they referred to "the existence of atomic and hydrogen weapons, in respect of which the institution of international control is particularly difficult."** While we held out the hope that continuing study might turn up effective methods of inspection, in fact developments since have made it even plainer that there is no genuine prospect for developing a politically feasible inspection method that would have a significant chance of finding nuclear weapons (whose diameters according to Dr. Taylor may be measured in inches, whose lengths might be two or three feet, and whose weights might be less than one hundred pounds)*** in territories that may be measured in many millions of square miles. But then any attempt to stop the spread of nuclear weapons implicitly must recognize that such a halt would involve a permanent distinction between weapon and non-weapon states. Talk of equality and non-discrimination cannot conceal that fact.

*U.S. Department of State, Documents on Disarmament 1945-1959, Vol. I, 1945-1956, Publication No. 7008, U.S. Government Printing Office, Washington, D.C., 1960, p. 512.

**U.S. Department of State, Documents on Disarmament, op. cit., p. 465.

***John McPhee, The Curve of Binding Energy, Ballantine Books, Westminster, Maryland, No. 23503, June 1975, p. 107.

Population Bombing as Equalizer

The formative period for Atoms for Peace in the 1950s was a time when it was expected that the new technology of fusion weapons would mean bombs in the 25 megaton range, with areas of destruction measured in many hundreds of square miles, and when the technologies of ballistic missiles were expected greatly to worsen delivery accuracies with median circles of error of 50-75 square miles in area. In fact, the chief significance of fusion technology was to make small and medium yield weapons cheaper and lighter and the worsening of delivery accuracies was transient. However, contemporary understanding of the strategic implications of fusion and ballistic missile technology in the mid-1950s renewed the initial association of A-bombs in Japan with the destruction of cities. That association had been challenged at the start of the decade. But by the end of the decade, some of the most influential views again took population bombing as inevitable, and possibly even "optimal" as deterrent. In this period also the best known rationalizations for the spread of nuclear weapons, those of General Pierre Gallois, seized on the technical developments, as they looked then, as establishing that on the one hand, no government could depend on any other to deter a nuclear attack on itself, since the only reply was suicide; and that on the other hand, any nation with nuclear weapons could undertake its own suicidal defense. All nations are equal in vulnerability in the face of the new weapons, "One can hardly see the difference in nature between the suicide that the U.S. would commit if her policy of deterrence failed and that of France if her strategy was no more fortunate." Gallois had something. Policies that threaten only a suicidal reply are no less convincing for self-defense than in fulfillment of a guarantee. But no more convincing. This line of argument neglects the possibility of a more costly but more persuasive response that avoids suicidal bluffing. Nonetheless, the currency of the notion that a few A-bombs aimed at an adversary's cities are enough to protect one's "vital interests" is a powerful impulse to proliferation, and it leads naturally to the belief that the surrender of the rights to acquire so apparently useful a force calls, in the name of equity, for compensation.

Much of the discussion of discrimination in connection with the Non-Proliferation Treaty rests on the casual assumption that the nuclear forces that non-weapons states forswear would provide them with unambiguous safety. Hence civilian benefits are demanded in compensation: an economic gain in return for a surrender of supposed security. But in fact the acquisition of a nuclear force will not automatically deter the great nuclear powers and may increase the danger by encouraging the spread to neighbors.

The main return for promising not to manufacture or receive nuclear weapons is a corresponding promise by some other countries, backed by a system designed to provide early warning if promises should be broken, and the prospect of avoiding or reducing an increasingly menacing disorder. Such offsetting promises do not take care of threats from those states that have already acquired nuclear weapons. Alliance guarantees will be essential, since in any case a few weapons may by no means suffice for deterrence. This is true in particular for the problem of deterring superpower attack on or coercion of small powers.

Strategic and Tactical Warning Time, and Bilateral or IAEA Safeguards

A safeguards system -- whether bilateral or multilateral -- can at most ring an alarm. But what events do we want to be warned about? Two possibilities: (1) that a government that has been a long way from being able to manufacture explosives is now within a short distance of that capability. (This is a kind of strategic warning.)

and (2) that a government has "diverted" special nuclear material in violation of an international agreement. (This would be a kind of tactical warning.)

These two events differ. The first is more fundamental. It can occur even if the second does not -- if agreements do not preclude drastically shortening the time to make a nuclear explosive. Strategic indications now abound and their implication is that tactical warning is in some cases nearing zero.

MUF, MAF, and IAEA

The focus of safeguards is on the problem of diversion. Therefore, the inspectorate of IAEA, and possibly the inspectors of an exporting country in a purely bilateral arrangement, fix their gaze on the Material Unaccounted For (MUF) and the Limits of Error in the Material Unaccounted For (LEMUF). The NPT safeguards, for example, essentially consist in verification of accounting records to see whether the Material Unaccounted For is within reasonable limits. Americans contend that the Limits of Error can be reduced to less than half of a percent; other members of the NPT think they cannot be reduced much below one percent. From the standpoint of diversion, it is this very small percentage that is problematic.

However, from the standpoint of the future spread of capabilities to make nuclear explosives with a short time delay, it is trends in the Materials Accounted For (what we might call MAF) that are likely to be decisive. For a variety of reasons, the basic data on the special nuclear materials that are adequately accounted for, owned and controlled by national governments, possibly stocked within their territory and tidily reported at regular intervals in accordance with bilateral or trilateral agreements, are not assembled and reported. They are not what "safeguards" are about (if "safeguards" are taken to mean merely inspection to detect violations). Safeguards have to do with material that conceivably may have been diverted.

Moreover, the IAEA safeguards system* specifically prohibits disclosure by any member of the IAEA staff (except to the Director General

*International Atomic Energy Agency, "The Agency's Safeguards System, 1965, as Provisionally Extended in 1966," INFCIRC/66/rev. 1, 1967, IB, paragraph 13.

and other IAEA members designated by the Director General) of any "confidential information" acquired while implementing agency safeguards.

Paragraph 14 of the basic Safeguard System document of the IAEA reads,

The Agency shall not publish or communicate to any State, organization or person any information obtained by it in connection with the implementation of safeguards, except that:

- (a) Specific information relating to such implementation in a State may be given to the Board and to such Agency staff members as require such knowledge by reason of their official duties in connection with safeguards, but only to the extent necessary for the Agency to fulfill its safeguards responsibilities;
- (b) Summarized lists of items being safeguarded by the Agency may be published upon decision of the Board; and
- (c) Additional information may be published upon decision of the Board and if all States directly concerned agree.

Observe that even exception (b) which the IAEA Board might make is limited to lists of items safeguarded. There is no exception for reporting the quantities of such items.

The IAEA interprets its mandate as foreclosing any report on the size, physical state, and isotopic and chemical composition of any stocks of special nuclear material present and accounted for, not to say those missing and unaccounted for at specific facilities, except to a very narrowly circumscribed set of staff members of IAEA. In practice, it has meant that up to now* the data on such material accounted for have not been assembled and published even in the form of frequency distributions of the number of countries with various amounts of material of varied type. Still less has there been any analysis of trends in such accounted for stocks. Attention, in short, has been on the half of one percent that might be unaccounted for and not on the 99.5 percent or so that may present the most important problem.

*i.e., up until the date of our inquiry.

Indeed, the state of public information on these civilian stocks appears to be much worse than that on the supposedly secret and highly sensitive military stocks of missiles and aircraft, etc. which form the regular subject of annual military balances by the International Institute of Strategic Studies and other such organizations. This seems strange. It has its origins in the concern expressed by various competing nuclear exporters about the revelation of commercial and industrial secrets. The text of paragraph 13 of the basic Safeguards System document reads as follows:

In implementing safeguards, the Agency shall take every precaution to protect commercial and industrial secrets. No member of the Agency's staff shall disclose, except to the Director General and to such other members of the staff as the Director General may authorize to have such information by reason of their official duties in connection with safeguards, any commercial or industrial secret or any other confidential information coming to his knowledge by reason of the implementation of safeguards by the Agency. (Italics added)

In the course of checking material unaccounted for an inspector must necessarily come by and use information as to the material that is accounted for. The rules suggest a presumption that any such information is confidential and not to be disclosed. But it seems quite farfetched to suppose that figures on inventories of separated plutonium and highly enriched uranium would reveal any commercial or industrial secrets of significance to competitors. In fact, scraps of such information can be gained from public sources -- where, for example, the source materials were obtained under license from the U.S. government. It is possible to determine that as of a short while ago Spain had an inventory of between 60 and 70 kilograms of separated plutonium at Windscale, England. This fact is indeed of public interest for anyone concerned with the possibility of future uses of plutonium in explosives, but it reveals no secret of commercial importance about reactor design or the like.

Apparently a sweeping restriction, born of fond hopes for preserving competitive advantage in some ingenious trick of reactor design, has resulted in a kind of overkill, a destruction of information of great public interest and little industrial importance. Whatever the genesis of these constraints on disclosure of information about stocks, the effects are quite perverse. It means that where an exporting country has substituted for a bilateral a trilateral agreement between itself, an importing country and IAEA, it is prevented from receiving information on a possible violation. It can receive only information of confirmed violations and then after a substantial delay--and then, only indirectly. This would tend to reduce the warning time about violation and restrict the possibilities that the exporting

country might, by diplomatic means, influence the potential violator to reverse his course. But the most important effects have to do not with warning of violation, but with warnings of the approach towards a nuclear capability -- without violation. For the formation of timely and precisely adapted actions to inhibit the spread, the regular publication and analysis of trends in the stocks of fissionable material accounted for would be extremely important.

The Effective Application of Safeguards as the Assurance of Timely Warning

The proposals in 1945 and 1946 by the pioneers in the discussion of international control of nuclear energy may have been seriously flawed so far as the technical means for assuring control were concerned. They were a good deal clearer and more explicit about the purpose of such controls, however, than the vast bulk of the technical discussions that ensued in the 1950s and the 1960s. Only in recent years has something like the original clarity about the purpose of safeguards been restored. Much of the 1960s discussion of techniques of inspection continued to be troubled by the initial technical flaws, specifically the hope (now generally implicit) for denaturing.

It is hard to understand how so much effort could have been spent in the 1960s on elaborate schemes for "safeguarding" reprocessing plants and plants for manufacturing mixed plutonium and uranium dioxide fuel, both of which would result in stocks of separated plutonium quickly usable in bombs. It may be explained by 1) the implicit persistence of the belief that plutonium separated chemically from power reactor fuel would be safe because it was contaminated by plutonium 240 and 242 (the chemical separation barrier could be removed, so to speak, because the even higher isotopic separation barrier to an explosive remained). Or 2) a focus on the technical means, namely inspection to detect violation, so intense or exclusive as to lose sight of the purpose of the safeguards agreement and the inspection arrangement. The purpose, of course, is to assure timely warning that would deter the manufacture of nuclear explosives or permit appropriate national or international responses to frustrate it.

A concentration on elaborating means to some proximate end (such as "detection") is characteristic of the behavior of large organizations. It is much less characteristic for such organizations to generate thinking concretely about whether the means elaborated are compatible with more remote objectives such as the assurance that no activity will be undertaken that would preclude timely response. It is still rarer to find much soul searching about whether some of the remote objectives are genuinely compatible with each other (like the assurance of early warning, on the one hand, and, on the other, the supposed essentiality of "closing" the fuel cycle by recycling plutonium as a step toward "accelerating and enlarging" the scope of nuclear energy throughout the world.)

If one believed that it was essential to close the fuel cycle, it would provide a powerful impulse to hold fast to the myth of denaturing plutonium. That so many policymakers have continued to cling to this conviction or at least to the hope that diluting plutonium 239 with plutonium 240 or 242 would make plutonium 239 safe is remarkable. Given the doubts that were expressed about such a proposal even before the Acheson-Lilienthal report, it testifies perhaps to our deep wish that power reactor plutonium were safe rather than our firm conviction that it is. Interposing the high barrier of isotopic separation between the use of plutonium for civil and military ends, if it could be arranged, would provide early warning even at today's state-of-the-art of isotopic separation. And early warning, it was understood at the outset, was part of the essence of the problem of safeguards. But the feasibility of such dilution of plutonium was called into question a year before the Acheson-Lilienthal report by a high, scientific authority on the subject--namely, Glenn Seaborg, the discoverer of plutonium--during the writing of the famous Franck report of which he was co-author. The Franck report which was dated June 11, 1945, was directed most immediately against the decision to drop the bomb on Japan, but it also suggested that a "compulsory denaturation of pure fissionable isotopes may be agreed upon by diluting them, after production, with suitable isotopes to make them useless for military purposes, while retaining their usefulness for power engines." Seaborg, commenting on early drafts of the report,* wrote "can't denature 49 by dilution with stable isotopes" (49 was the wartime code for plutonium whose atomic number is 94). Yet the Franck report was issued without change, presaging our persistent ambivalence on this subject.

*Now available at the University of Chicago Library in the James Franck papers.

**Dr. Seaborg, in a letter of March 10, 1976, to Arthur Steiner states,

"My second written comment that 'can't denature 49 by dilution with stable isotopes' certainly refers to my view that isotope Pu-240 was being greatly over-rated as a safeguard against nuclear proliferation. I remember feeling that way the next year when the Lilienthal Board suggested the possibility of denaturing fissionable Pu-239. (Denaturing fissionable U-235 and U-233 is, on the other hand, feasible due to the availability of more stable nonfissionable U-238.) I don't recall why my written comment didn't lead to an alteration in the final version."

One reason the report was unaltered in this respect was very likely that while it ranged widely over the subject of peaceful uses of nuclear energy and international control, it was focused on an immediate decision about an impending military operation; however, it is an early illustration also of how strongly we have hoped to resolve the dilemmas of propagating nuclear electric power without spreading nuclear weapons. We are indebted to Arthur Steiner for this reference and for the reference to Leo Szilard's early views on the subject of denaturing.

The early proponents of the idea of making plutonium safe by contaminating it with stable higher isotopes were ambivalent and troubled by the substantial technical shortcomings of the notion, but they clearly and unequivocally grasped an essential fact of international safeguards which, though reasserted from time to time, has a way of getting lost in the middle reaches of international and national bureaucracies, namely that a safeguard involves more than simply detecting a violation of an agreement; it implies, if it is to deserve the name safeguard, detecting the approach by a government to getting a bomb in time for other governments to do something about it.

Leo Szilard, who discussed the possibility of denaturing even earlier than the Franck report and rather more cautiously (he said, "The possibility would have to be scrutinized carefully"), was quite clear on the critical need for timely detection.

"A system of controls could be considered successful only if we could count on a period of grace in case the controls were denounced or obstructed by one of the major powers. This means that the system would have to be of such a nature that at least one or two years would elapse between the time the nations begin to convert their installations toward the purpose of manufacturing atomic bombs, and the time such bombs become available in quantity."*

The hopes for a denaturing of plutonium that would compel isotopic separation were disappointed. However, chemical separation has remained as a barrier that takes a substantial, if lesser, amount of time to surmount. Any interpretation of safeguards that removes this last barrier of chemical separation for plutonium and leaves practically no warning time should be recognized as abandoning the essential purpose of safeguards.

If the critical time to make an explosive is allowed to shrink to a few weeks, days, or hours, there will not be enough time for political or military action. For one thing, deciding on appropriate political or military responses would take time, and political responses in themselves might be very time consuming. For another, the warning would not begin with the moment of diversion. The first indication of violation an inspector might have, even if he were on the scene, might be some denial of access, ostensibly perhaps because of a bad radioactive spill. This might be only the beginning of a long sequence of events, restricted at first to the inspected government and the inspector. The IAEA safeguards might assure quick detection for a violation shortly after it takes place, but it cannot assure timely detection well before bomb assembly unless agreed arrangements between importers and exporters keep the critical time between violation and assembly long enough.

*Unpublished version of "Atomic Bombs and the Post-War Position of the United States in the World," March, 1945, available in the office of the ERDA historian, excerpted in the Bulletin of the Atomic Scientists, December, 1947.

Both the IAEA and the U.S. Government have reiterated the essential point, that the purpose of safeguards (and therefore the objective that would have to be achieved for the application of safeguards to be "effective") is to assure timely detection and the deterrence of diversion through the risk of early detection. That point was made in a report recently transmitted to Congress by the President.* He said, "The international safeguard system deters diversion by the threat of early detection of diversions should they occur at the national level and by the political consequences resulting from reporting of diversion to the international community." General Starbird repeated the point a short time afterwards: "IAEA safeguards provide for the timely detection of diversion of significant quantities of nuclear materials from peaceful nuclear activities and the deterrence thereby of such diversion by threat of early detection.** His assertion faithfully reproduces the objective of safeguards as clearly defined by the IAEA Safeguards Committee: "The timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear explosive devices or for purposes unknown, and deterrence of such diversion by risk of early detection.***"

The point of it all may sometimes have been lost. But as the Inspector General of IAEA suggests, "The thirty years history of safeguards is one of continuous development and there is no reason why its techniques and concepts should not undergo many further changes."**** And there is every reason that further evolution should clarify and make more precise the tailoring of safeguards to their essential purpose.

* Laws and Regulations Governing Nuclear Exports and Domestic and International Nuclear Safeguards, Message from the President of the United States, May 6, 1975, USGPO, Washington, D.C., 1975, p. 35.

** Statement before the Senate Committee on Government Operations, January 29, 1976. The Assistant Administrator for National Security of ERDA.

*** See IAEA INFCIRC/153 (1971) and B. Sanders and R. Rometsch, "Safeguards Against Use of Nuclear Materials for Weapons," September, 1975, Nuclear Engineering International, p. 683.

**** Ibid.

IV. Some Economic Aspects of Nuclear Proliferation

Knowledge of the economics of nuclear power has two important applications to proliferation work:

(1) Projection of the growth in capacity for nuclear weapons development: The relationship between civilian nuclear power and nuclear weapon development has been explained in a prior section. Our belief is that over the next ten years, growth of civilian nuclear power programs around the world will create the greatest increase in the potential for nuclear weapon development. The more that economics favor nuclear power relative to fossil-fuel power, the more rapid the expected growth. Although non-economic factors will enter decisions on nuclear power, history suggests that economics will be very important. In spite of major promotional efforts by supplier countries, few nuclear power plants were sold to less developed countries during the nineteen-sixties. The cost disadvantages of nuclear power during this period were obviously very influential, since reasons of prestige, independence, and national security all operated in favor of nuclear power.

Thus, an understanding of the economics of nuclear power is important for assessing the likely future extent of civilian nuclear power facilities, with their potential for aiding nuclear weapon development.

(2) Formulation of U.S. policy on nuclear exports: As we emphasize in another section, there are not two separate types of atoms -- "peaceful" atoms and "military" atoms. All civilian nuclear activities contribute to military-development potential. But, not all civilian activities are equally dangerous from a proliferation viewpoint. Those that are considered "too dangerous" need not receive U.S. support. In historical fact, the U.S. has actively opposed dissemination of certain technologies with civilian applications, most especially enrichment technology. Assessing the proliferation potential of a specific activity, thus, is one aspect of formulating U.S. policy towards spread of the activity.

A second aspect of this policy formulation should involve assessing the economic benefits of the activity. U.S. efforts to assist countries in developing civilian nuclear programs are predicated on the assumption that the benefits of such programs cannot be denied, either morally or practically, to the less developed nations. Thus the promise of substantial economic benefits provides the underlying justification for our nuclear exports. But, not all civilian economic activities have equal economic benefits. Some may even be economically inferior to conventional alternatives.

The essence of policy choice with respect to nuclear exports is striking the proper balance between economic desirability and military danger. Both must be weighed in the decision. To ignore economic benefits

implies that all civilian nuclear activities should be opposed. To ignore military danger implies support for all activities no matter how dangerous. Neither extreme appears desirable.

Thus, intelligent formulation of U.S. policy on the dissemination of specific civilian technologies requires an assessment of their potential economic benefits, as well as their military danger. In this part of the report, we present some information on two aspects of economics that are pertinent to forming policy on proliferation.

(a) The economics of nuclear power in less developed countries:
A subject deserving greatly increased attention is the economics of nuclear power in less developed countries (LDC's). Looking ahead from this point in time, a number of countries in this category appear to have strong incentives for developing nuclear weapons: e.g., Iran, Brazil, Pakistan, Israel, Egypt. These countries are generally characterized by intense regional security threats and lack of secure alliance protection against these threats. Many of these countries appear to believe that nuclear weapons offer a desirable means of improving their security, and the path they appear to be using to acquire a weapon capability relies heavily upon civilian nuclear technology. By installing civilian nuclear reactors, they obtain a potential source of fissionable weapon material (the plutonium in spent fuel). By constructing reprocessing facilities, ostensibly for civilian purposes, they can separate the plutonium from spent fuel, obtaining material directly usable in a nuclear weapon. Although safeguard agreements and terms of the NPT prevent use of civilian facilities and materials in weapon programs, these paper barriers will provide little comfort if a country cites "overwhelming national security concerns," withdraws from the NPT (which is permitted with 90 days notice) and refuses to return any nuclear materials.

The proliferation danger posed by civilian nuclear power programs in a number of countries seems clear. Both to gauge the likely growth in these programs and to assist in formulating U.S. policy on assistance to these programs, a thorough analysis of the economics of nuclear power in less developed countries is highly desirable.

The analyses now available appear of questionable validity. In a following section, we review two of these studies. This review indicates that both studies have serious deficiencies. We have not had the time and resources to remedy these deficiencies in this phase of our study. We intend to pursue this further in the future. We believe, however, that better understanding of nuclear economics in less developed countries is very important for U.S. policy and should receive more resources than we will be able to devote within the terms of our current contracts.

We also report on a brief investigation of U.S. subsidies to nuclear power exports. These appear to have been quite substantial in some instances. We raise the matter of subsidies because we believe the U.S.

should review its policy on these subsidies. As demonstrated herein, nuclear power promises very limited economic benefits to less developed countries. Given the military dangers is it sensible to encourage civilian nuclear power abroad through U.S. subsidies?

(b) The Economics of Nuclear Fuel reprocessing: Because reprocessing of nuclear fuel has very serious military implications, we have carried out a thorough review of its technical status and its economic importance. This work was supported primarily under another contract, and is reported fully in The Present Prospects for Proliferation: The Setting of the Problem, Pan Heuristics, September 1975. Because of its relevance, major findings of this review are reported in a following section. Of particular note, reprocessing represents a clear example of the importance of economics in formulating U.S. policy. The military dangers are clear and substantial. If reprocessing can also be shown to be without significant economic benefits, the U.S. has a justifiable basis for opposing its introduction into countries without nuclear weapons.

A. The economics of nuclear power in less developed countries

1. Projected Growth in Nuclear Capacity.

Rapid expansion of nuclear power in less developed countries (LDC's) has been forecast many times in the past, beginning with the original Atoms for Peace predictions in 1954. These predictions have so far been unfulfilled, but the large rise in fossil fuel prices dating from the Middle East October (1973) War has created a widespread belief that the "takeoff" of nuclear power lies just ahead. The Organization for Economic Cooperation and Development (OECD) and the International Atomic Energy Agency (IAEA), for example, have recently predicted rapid expansion of nuclear power capacities in LDC's in the next decade. These predictions have apparently been accepted without significant question.

Our study of the IAEA and OECD projections suggests that these projections should be approached skeptically. In all likelihood, history will reveal that once again the nuclear optimists have greatly overestimated the future growth of nuclear power. The primary basis for this skepticism is provided by a comparison of these projections with actual intentions as revealed by construction activity and orders. Table 5 is a listing of all nuclear plants outside of Europe, North America, and Japan that are operating, under construction, or on order. The most striking aspect of Table 5 is the extremely small amount of nuclear capacity that is actually operating -- 1044 MW (megawatts). This is equivalent to a single plant of the typical size now being built in the U.S. and Europe. The column listing the "Total Initiated Capacity" (the total of operating, under construction, and on order) provides a useful yardstick for the accuracy of projections of installed nuclear capacity in 1985. This is so because it typically takes about 8 to 10 years from the date of order to the date of initial operation. Although this time period is variable and

TABLE 5

NUCLEAR POWER PLANTS IN LDCs
Megawatts of Electric Capacity
(June 30, 1975)

Country	Commercial Operation	Under Construction	On Order	Total Initiated Capacity
Argentina	319	600		919
Brazil		626	2 x 1300 ¹	3226
India	3 x 200	200 + 2 x 220	2 x 220	1680
Iran			2 x 1200 + 2 x 900	4200
S. Korea		564	605 + 629	1798
Mexico			2 x 660	1320
Pakistan	125			125
Philippines			2 x 626	1252
Taiwan		2 x 604 + 951	951 + 2 x 907	4924
Totals	1044	4589	13811	20070

Source: Nuclear News, August 1975, pp. 63-69.

¹ Brazil order figure reflects the two (out of eight in total) reactors in the recent Brazil-German agreement for which construction start-dates have been set (1967 & 1977). (Nuclear Engineering International June/July, 1975, p. 497)

may be somewhat shorter in some instances, historical experience strongly indicates that most of the plants operating in 1985 will have been initiated by now. But, for the projections of the OECD and the IAEA for LDC's to be fulfilled, installed capacity in 1985 will have to be considerably greater than the amount now initiated. This is especially the case for the IAEA projections.

The OECD projects a 1985 nuclear capacity of 25,000 MW for the LDC's in their organization. These countries are Argentina, Brazil, Formosa (Taiwan), India, Israel, South Korea, Mexico, Pakistan, Philippines, South Africa, and Thailand. (Energy Prospects to 1985, Volumes I and II, OECD, Paris, 1975) The amount of capacity now initiated by these countries (from Table 5) is 15,244 MW, or 60% of the amount projected. The OECD does not provide a country-by-country listing nor any details on the methodology used to arrive at the projections.

The IAEA has provided estimates for individual countries, as well as detailed explanations of the methodology used. Table 6 shows, for the 14 countries in which detailed studies were done by the IAEA, the amounts of nuclear capacity now initiated and the amounts projected for 1985. In many instances where no capacity has yet been initiated, very substantial amounts are projected for 1985. The total projected amount in these 14 countries is 5.5 times the amount now initiated. The possibility of installing, by 1985, 5.5 times the amount now initiated seems extremely

TABLE 6

IAEA PROJECTED NUCLEAR CAPACITIES IN 1985
VERSUS CAPACITY CURRENTLY INITIATED
(Megawatts of Electric Capacity)

Country	Initiated ¹ As Of 6/30/75	IAEA Projections For 1985
Argentina	919	3500
Bangladesh	0	1300
Chile	0	600
Egypt	0	1200
Greece	0	2000
Jamaica	0	600
S. Korea	1798	4200
Mexico	1320	7800
Pakistan	125	1325
Philippines	1252	1200
Singapore	0	1650
Thailand	0	1400
Turkey	0	1200
Yugoslavia	0	2800
Totals	5414	30775

Source: Market Survey for Nuclear Power in Developing Countries, 1974 Edition, International Atomic Energy Agency, Vienna, 1974.

¹"Initiated" is defined as capacity currently operating, under construction, or on order.

remote.*

A look at the methods used to arrive at these projections reveals a number of questionable assumptions:

- (1) Projected Growth Rates: The IAEA uses very high growth rates for electricity demand. For the Period 1981-1985, the average growth rate in the 14 countries was assumed to be 9.3% per year.** Although not specified in the report, the method used implies

*The IAEA in its 1975 annual report recognizes that their 1974 projection for 1980 was much too high. The 1975 annual report estimates worldwide installed nuclear capacity at 220,000 to 250,000 MW, about 30 percent less than their 1974 estimate. "IAEA: Move to Nuclear Power Slower Than Expected", Nuclear News, September 1975, p.66. Similar reductions in estimates for 1985 can be expected as actual construction plans become known to the IAEA.

**See Table V-1, Total High Forecast, of the Market Survey General Report, IAEA, September 1973, p. 21. The High Forecast was used in the Market Survey, 1974 Edition, which updates the original study in light of changes in the prices of oil and nuclear power costs that had occurred by early 1974.

that a very similar growth was assumed for 1973-1980. A growth of 9.3% per year, compounded for 12 years, implies a 200% total growth for the period.

Even without the economic impact of the oil crisis, the assumed growth of 9.3% per year to 1985 seems unrealistically high. In fact, since the oil crisis of 1973, there has been very little growth of electric demand in Europe and the U.S. Although figures were not available to us for LDC's, the same factors were at work in these countries, perhaps intensified: rising oil and electricity prices, a desire to conserve on purchases of oil (particularly in LDC's with foreign exchange problems), and a worldwide industrial recession. Although the recession may be expected to be temporary, growth rates in the industrialized countries in the coming decade will be substantially lower than in the immediately prior decade. Because growth in LDC's is closely linked to growth in exports to the more industrialized countries, the LDC's may also expect lower growth. Electricity prices will also be much higher than in the past, encouraging conservation. Although the extent to which these factors will dampen growth in electric demand cannot be estimated without careful analysis, there must exist a strong presumption that they will be significant.

- (2) GNP to Electricity Relation: The growth in electric demand was derived from an analysis implying a fixed relation between growth in per capita GNP and growth in per capita electric demand. There are many theoretical reasons for questioning the validity of this assumption, but even the statistical basis for this assumption appears defective. The relation was derived from cross-country plots of electricity use per capita versus GNP per capita -- whereas what we are interested in is how the change in GNP is related to the change in electricity use. A glance at Figure F-3 in the General Report (page F-5) shows that the correlation between the changes is not at all consistent.
- (3) Relative Cost of Fossil and Nuclear Power: The IAEA study omits coal as an alternative to nuclear power, but coal is much cheaper than oil as a source of fossil energy. This is true now, and the cost advantage of coal seems likely to grow as supply expands. Omission of coal power as an alternative creates a serious bias.

A more fundamental shortcoming of the IAEA study is the inadequate treatment of the uncertainties of nuclear power economics. The analysis in the IAEA Report (1974 Edition) shows such a

marked cost advantage for nuclear power that all future installed capacity (except one one-hundred MW plant in Jamaica) is nuclear. Recent large orders of U.S. utilities for oil-fired turbine plants for peak loads demonstrates that no such overwhelming cost advantage exists. Further, recent cancellations of electric plants, which have affected nuclear plants more heavily than fossil plants in the U.S. and Europe, raise the possibility that nuclear power may be more expensive than the alternatives. This possibility is explored in greater detail in the following section. If, in fact, nuclear power is more expensive than fossil fuel in some applications and locations, the IAEA projections of nuclear capacity will be seriously in error on this ground alone.

2. Nuclear and Fossil Power Costs in Less Developed Countries

The relative cost of nuclear and fossil power is important both for projecting the growth in nuclear power and for formulating U.S. policy on nuclear exports. As we have emphasized previously, nuclear export policy should attempt to balance economic benefits to the LDC's against our concern for the military potential. The greater are the benefits of nuclear power, the more military risk we should be willing to accept, and conversely.

Available official estimates of nuclear versus fossil power costs in LDC's have a number of deficiencies. First, they are based primarily on construction experience in the U.S. and Europe, which may be inappropriate for LDC's. Second, in calculating costs, they assume operating reliability rates based on engineering goals rather than actual experience. These goals have not been met in the U.S. and the increased difficulty of repairs suggests that they are likely to be lower in the LDC's. Third, they ignore the historical experience of capital cost increases, which have been significantly greater for nuclear than fossil plants. Fourth, they use interest rates that are appropriate to industrialized countries, but that underestimate the rates in LDC's. Fifth, they use high prices for coal and oil but ignore the higher nuclear fuel cycle costs that are already evident. All of these deficiencies in methodology operate in favor of nuclear power, and this reflects a basic problem with official nuclear cost estimates: They are generally prepared by agencies and experts with vested interests in the success of nuclear power. There are numerous points in cost estimation where "reasonable guesses" are required of the estimators. When the estimator has a marked bias, the cumulative effect of the bias can be very large.

In contrast to the confident, single-valued estimates presented for future nuclear and fossil plant costs in the OECD and IAEA studies, experts speaking privately generally emphasize the massive uncertainties that characterize future estimates. A recent extensive review of nuclear and fossil power costs in the U.S. found numerous areas of uncertainty. (D. Holliday and V. Taylor, The Uncertain Future of Nuclear Power, Cali-

fornia Seminar on Arms Control, Santa Monica, California, August 1975.) Table 7 reproduces their summary table showing the possible effects of these uncertainties. Of special note is the much wider range of uncertainty for nuclear power costs than for fossil power costs. The authors note that, "As a consequence, we find that nuclear power may turn out to produce electricity that costs several times more than coal power (if the uncertainties are resolved unfavorably for nuclear power) or slightly less (if the uncertainties are resolved favorably)." (Holliday and Taylor, op. cit., pp. 1-2)

A number of modifications must be made in U.S.-based analyses, such as the one cited, to make them applicable to LDCs:

- (1) Higher interest rates should be used, reflecting the greater scarcity of capital in LDCs. Note, however, that loan subsidies by the U.S. or other suppliers will lower the effective interest rate from the internal LDC rate.
- (2) Lower operating rates should be assumed, especially for nuclear plants. Because of the small size of electric systems in LDC's, average load factors will be less than in the U.S. Further, operating experience with nuclear reactors, although limited, indicates greater reliability problems in LDC's. For example, approximate operating capacity factors for the last 12 months (or closest available time period) were 70% (5 months) for a newly commissioned 319-MW reactor in Argentina, an average of 45% for 3 200-MW reactors in India, 56% for a 125-MW reactor in Pakistan. The weighted average of these is 54%. In Japan, which is of course not an LDC, the average 12-month capacity factor for 3000-MW of nuclear power has been about 50%. These are to be compared to 72% operating rates assumed in the IAEA study, and 60% used by Holliday and Taylor in their high estimates of nuclear power costs.
- (3) The ratio of nuclear to fossil plant capital costs is likely to be higher in LDC's than in the U.S. The primary reason for this is that LDC's are limited to the use of much smaller power plants, and scaling laws are such that nuclear units suffer a greater penalty as one moves from larger to smaller sizes. The basic costs in the Taylor and Holliday review were based on 1300-MW plants. For LDC's 600-MW must be considered large. India installed a 200-MW nuclear unit in a small power grid, with the result that the grid collapsed several times when the reactor suffered a forced outage (which occurred not infrequently). (Nuclear Engineering International, May 1975, p. 271)

Table 8 shows, as a function of plant size, the nuclear and oil-fired costs used in the IAEA study. As one moves from 1300-MW to 600-MW, nuclear capital costs relative to

TABLE 7
COMPARISON OF POWER GENERATING COSTS
(1974 Dollars)

	Low Estimate	High Estimate
<u>Nuclear Costs</u>		
Basic Capital Cost	\$430/kw	\$430/kw
Escalation Rate Per Year	2 Percent	12 Percent
Construction Time	7 Years	9 Years
Capital Cost at Start of Operation	\$494/kw	\$1192/kw
Fixed Charge Rate	12 Percent	19 Percent
Capacity Factor	0.70	0.60
Capital Costs Per kwh	9.6 Mills	43.1 Mills
Interest Cost of Fuel Core Per kwh ^a	0.8 Mills	1.8 Mills
Fuel Costs Per kwh	2.5 Mills	5.3 Mills
Operation and Maintenance Per kwh	1.5 Mills	4.2 Mills
Total Nuclear Generating Cost Per kwh	14.4 Mills	54.4 Mills
Government Subsidies Per kwh	<u>4.3 Mills</u>	<u>9.5 Mills</u>
Total Nuclear Cost Per kwh	18.7 Mills	63.9 Mills
<u>Coal Costs</u>		
Basic Capital Cost ^b	\$366/kw	\$415/kw
Escalation Rate Per Year	2 Percent	4 Percent
Construction Time	5 Years	7 Years
Capital Cost at Start of Operation	\$403/kw	\$545/kw
Fixed Charge Rate	12 Percent	14 Percent
Capacity Factor	0.70	0.70
Capital Costs Per kwh	7.9 Mills	12.5 Mills
Fuel Costs Per Ton	\$13.50	\$27.00
Fuel Costs Per kwh	6.3 Mills	12.6 Mills
Operation and Maintenance Per kwh	<u>2.7 Mills</u>	<u>4.1 Mills</u>
Total Coal Generating Cost Per kwh	16.9 Mills	29.2 Mills
Regional Range of Costs Per kwh	14.6- 19.1 Mills	26.9- 31.5 Mills

^aBased on 0.1 kg of reactor fuel per kw of capacity and 7% interest rate.

^bLow estimate includes \$50/kw for sulfur dioxide removal equipment; high estimate includes \$100/kw for such equipment.

^cBased on \$322 basic cost, 6 years construction, 3% escalation, 13% fixed charge, and 70% capacity factor.

^dFrom Project Independence Report, USGPO, Washington, D.C., November, 1974, Table V-24, p. 286, for 70% capacity, adjusted to 13% fixed charge rate.

TABLE 8

CAPITAL COSTS OF NUCLEAR AND OIL-FIRED PLANTS^a

Plant Size (MW)	Nuclear Plant Costs (\$/kw)	Oil-fired Plant Costs (\$/kw)
100	967	362
150	796	322
200	695	297
250	623	279
300	572	265
400	504	244
500	458	228
600	426	216
800	379	200
1000	353	189
1300	325	178

Source: Table XV, Market Survey for Nuclear Power in Developing Countries, 1974 Edition, IAEA, Vienna, 1974, p. 27.

^aAverage of 14 Market Survey Countries -- in 1 January 1974, U.S. dollars (no escalation included).

those for oil-fired plants increase by 8%. A decrease to 300-MW, gives relative capital costs that are 18% higher than at 1300-MW. Because capital costs are 70% to 80% of nuclear power costs, these differences are significant.

- (4) Fossil-fuel capital costs appear to be overestimated. The capital cost estimates in the IAEA study were generated by computer codes sponsored by the U.S. ERDA. These same codes are widely used in estimating relative costs of nuclear and fossil plants (including those reported in the Holliday and Taylor review). Figures cited in the IAEA report, and reproduced as Table 9, indicate these codes to substantially overestimate fossil-fuel capital costs. The figures used in the report are the ones referred to as ORCOST-3. As can be seen in the last column of Table 9, estimates were consistently and significantly higher than reported costs. For all fossil plants, other than the Yugoslavia unit, which was planned rather than actual, the estimated costs were 46% higher than actual costs. Note that estimated costs were adjusted for inflation to make them consistent with reported costs. In contrast, the history of nuclear plant cost estimates has been one of consistent and substantial underestima-

TABLE 9
COMPARISON OF REPORTED AND COMPUTED POWER PLANTS COSTS

Country	Power plant description				Capital costs (US\$/kW) ^a						Ratio of ORCOST costs to reported costs			
	Name	Size (MW)	Type	Comm. date	Reported ^b		ORCOST-1		ORCOST-3		ORCOST-1		ORCOST-3	
					Direct	Total	Direct	Total	Direct	Total	Direct	Total	Direct	Total
Argentina	Lujan de Cuyo	60	OIL	12/71	169.3	215	186	354	193	332	1.1	1.65	1.4	1.55
Argentina	Planned unit ^{c, d}	600	PWR	78	-	360	-	309	-	368	-	0.86	-	1.02
Bangladesh	Ashuganj	60	Gas	7/70	240	337	168	342	177	319	0.7	1.02	0.74	0.95
Chile	Bocamina	125	Coal	12/67	133	203	132	255	142	249	0.99	1.86	1.07	1.23
Egypt	Cairo West	87	OIL	12/68	156	189	123	232	130	218	0.79	1.24	1.17	1.15
Greece	Megalopolis	125	Lignite	10/70	-	278	168	315	177	300	-	1.14	-	1.08
Greece	St. George's Bay	200	OIL	7/71	-	115	119	220	124	212	-	1.91	-	1.85
Jamaica	Old Harbour	68.5	OIL	6/72	165	187	190	362	199	343	1.16	1.93	1.21	1.84
Korea	Seoul 5	250	OIL	12/69	-	136	102	187	106	181	-	1.37	-	1.33
Korea	Inchon 1	250	OIL	12/70	-	138	107	198	113	192	-	1.43	-	1.39
Korea	Planned unit ^{c, d}	565	PWR	10/76	-	344	-	290	-	345	-	0.84	-	1.0
Mexico	Salamanca	150	OIL	1/71	95	119	124	230	129	219	1.31	1.93	1.36	1.84
Mexico	Valle de México	150	OIL	1/71	90	123	124	230	129	219	1.37	1.87	1.43	1.78
Pakistan	Lyallpur	66	OIL	12/67	-	209	142	273	150	254	-	1.31	-	1.22
Pakistan	Korangi	125	OIL	12/70	-	144	141	259	149	249	-	1.80	-	1.73
Pakistan	Kanupp	137	PWR	12/72	-	609	256	541	320	640	-	0.89	-	1.06
Philippines	Gardner 2	200	OIL	12/70	-	157	108	199	114	192	-	1.27	-	1.22
Philippines	Snyder 1	200	OIL	12/71	-	141	115	212	121	204	-	1.50	-	1.45
Philippines	Bataan 1	75	OIL	12/72	-	202	162	307	169	288	-	1.52	-	1.43
Singapore	Jurong	120	OIL	12/72	-	136	142	263	148	251	-	1.93	-	1.85
Thailand	South Bangkok 1	200	OIL	3/71	104	120	111	202	116	196	1.06	1.68	1.11	1.63
Thailand	South Bangkok 2	200	OIL	3/72	96	108	118	214	123	207	1.23	1.98	1.28	1.92
Turkey	Ambarli	150	OIL	12/71	-	258	132	205	139	253	-	1.02	-	0.98
Yugoslavia	Planned unit ^c	250	OIL	12/72	114	147	115	212	121	205	1.02	1.45	1.06	1.4

^a At indicated commissioning date.^b Excluding taxes and duties.^c Cost estimate.^d Costs in 1972 US dollars.

tion.*

The IAEA test of the ORCOST model casts serious doubts on its validity, and, therefore, on the validity of cost comparisons based on it (including those of the IAEA).

Conclusion: The deficiencies in methodology used by the IAEA to compare the economics of nuclear and fossil power in LDC's are sufficiently numerous and serious to make the comparison of little value. Given the importance of these comparisons for U.S. nuclear policy, improved economic analyses should be undertaken.

3. Economic Benefits in Perspective

Ever since the beginning of the "Atoms for Peace" program in 1953, the U.S. has consistently promoted the development of atomic energy for peaceful purposes in all nations. This policy was adopted in the belief that nuclear power promised overwhelming economic benefits and that nuclear weapon development abilities could be separated from peaceful atomic energy programs. Events have demonstrated the latter belief to be erroneous, and a quantitative look at the potential impact of nuclear power shows the former belief to be in error. also. The direct connection between weapon development and civilian nuclear reactors has been demonstrated by India. If events continue on their present course, this demonstration may well be repeated by numerous other countries in the years ahead. At the same time, the promised benefits of nuclear power have proven to be elusive. Somehow they are always just ahead of us, but never quite in hand. If oil prices remain at current levels, nuclear power may well prove to be the cheapest source of power for some countries, but nuclear power is not going to usher in any economic millenium. At best, it may bring slightly cheaper electricity to some countries. For the most part, the annual savings per capita in third world countries will be measured in pennies. As we have cautioned above, the uncertainties are such that nuclear power may well prove more expensive than fossil power. Even if uncertainties are resolved relatively favorably for nuclear power, the nuclear cost advantage seems unlikely to be more than a few mills per kwh. At typical operating rates, 5 mills per kwh cost advantage translates into annual savings of \$25 million for each 1000-MW of installed nuclear capacity. At currently estimated prices, smaller countries would have to invest \$500 million more for 1000-MW of nuclear power than for equal fossil capacity. In view of the capital scarcity in most third world countries, it seems questionable whether possible annual savings of \$25 million justify a \$500 million investment.

Table 10 shows the possible annual savings (assuming \$25 million per 1000-MW of capacity) for the countries and initiated capacities listed in Table 5. Also in the table, these savings are translated into per capita savings. Annual per capita income figures are provided for comparison. The figures show clearly how small will be the beneficial impact of nuclear power (assuming that benefits do materialize). In most countries the benefits are less than one dollar per person per year.

*See U.S. Atomic Energy Commission, Power Plant Capital Costs, WASH-1345, Oct.'74.

ACDA/PAB-263

TABLE 10

POSSIBLE NUCLEAR POWER SAVINGS

Country	Initiated ¹ Capacity (MW)	Possible ² Annual Savings (\$ Millions)	1973 ³ Population (Millions)	1970 ⁴ Per Capita Income (\$)	Possible Annual Savings Per Capita
Argentina	919	23	24	1000	.95
Brazil	3226	81	102	368	.79
India	1680	42	574	88	.07
Iran	4200	105	32	316	3.28
S. Korea	1798	45	32	245	1.40
Mexico	1320	33	22	54	.61
Pakistan	125	3	66	196	.05
Philippines	1252	31	34	228	.92
Taiwan	4924	123	15	N.A.	8.20
Totals		486	901		.54

85

Notes:

¹Initiated capacity is capacity either operating, under construction, or on order. See Table III-1.

²Based on assumed nuclear cost advantage of 5 mills per kwh and 55 percent operating rate.

³Source: U.N. Demographic Yearbook: 1973; estimated mid-year figures. Taiwan figures 1972 yearend, from The Statesman's Yearbook 1974-1975.

⁴Source U.N. Statistical Yearbook: 1973.

The general export subsidies provided by the U.S. DISC program, also favor nuclear over fossil-fuel exports because of the higher capital cost of nuclear plants.

Reliably projecting nuclear capacity very far into the future is impossible, since incentives and costs can undergo substantial unforeseen changes. The Organization for Economic Co-Operation in Europe has recently attempted such a projection on a worldwide basis.* For the countries of Argentina, Brazil, Formosa, India, Israel, Korea, Mexico, Pakistan, Philippines, South Africa, and Thailand, they estimate a combined nuclear capacity of 25,000-MW by 1985 and 50,000-MW by 1990. (Nuclear Engineering International, February 1975, p. 120) Based on 1970 population figures, these are equivalent to per capita savings (assuming a 5 mills per kwh advantage) of 64 cents in 1985 and \$1.28 in 1990.

This brief analysis shows that there is no basis for the claim that nuclear power is essential to successful economic growth. In fact, whether nuclear energy will provide any savings at all relative to fossil energy is very uncertain. But even if nuclear power proves to be cheaper, the savings will be measured in fractions of a percent of GNP.

4. U.S. Subsidies to Nuclear Power Abroad

This section considers subsidies to nuclear exports. In view of the limited economic benefits to less developed countries and the potential military danger to the U.S. from nuclear power abroad, we believe the U.S. should review its policy on subsidies to nuclear exports.

a. Subsidies to Nuclear Exports.

The U.S. Export-Import Bank in 1974 alone authorized direct loans of \$439 million and guaranteed another \$162 million for nuclear power plants and training centers abroad that purchased U.S. made equipment. From the inception of its program of subsidies of nuclear exports, the Bank has directly loaned \$2.47 billion and guaranteed an additional \$931 million. In addition, the Agency for International Development has transferred at least \$30 million in addition to the loan for Tarapur to underdeveloped countries for research reactors, laboratory support, and nuclear technical assistance.

These subsidies for nuclear power are very significant, especially for the less developed countries. The Export-Import Bank reports that it has financed about 60% of the total U.S. cost, and about 25% of total project costs for the nuclear power projects in which it has participated. Export-Import has also given financial guarantees to an additional 10% of total project costs. Its interest rates have gone from 4.5% (in the late 1950s) to 8.5% (in 1975). The maturity of many of these loans is 15 years with initial repayments deferred for five or more years until construction has been completed. In addition, in order to reduce the risk to private lenders, the Export-Import Bank, at least sometimes, gets repaid from the final set of payments. This, of course, increases the effective risk to the Bank.

*As we have noted, these projections seem likely to prove to be overestimates of actual installed capacity.

What would the borrowers have been required to pay for these plants if the U.S. had not subsidized them? This can be estimated by taking the rate applicable to private and/or governmental transactions of comparable maturities in the borrowing countries and comparing the resulting project costs with that actually incurred.

The Export-Import Bank interest rate of 5-6% in the late 1950s and 1960s and the current rates of 8-8.5% are well below market rates in the U.S. and even further below such rates in less developed countries.* This is, of course, the purpose of the Export-Import Bank subsidies. It is in the business of promoting export sales that otherwise would not be made. The Bank's subsidies appear to have lowered the interest rate on a portion of the capital required for nuclear power projects in other countries by 4%-7%, or in some cases, even more. A 1969 analysis by J. H. Cha of the Korean Atomic Energy Research Institute provides an indication of the difference between internal interest rates and subsidized foreign loan rates. He estimates a 6.5% per year interest rate for a foreign loan on a nuclear plant and 16% for internally raised funds for the same plant.**

Many nuclear projects probably would not have been undertaken without the large subsidies available. For example, if the average cost of a twenty-year loan for the project is 10.5% with the Export-Import Bank subsidy and it would be 15% without it, the total project investment cost is reduced by about 24% (in terms of the present value). A subsidy of this proportion strongly biases the choice between nuclear and fossil or hydro power in favor of the former unless large subsidies are also available for fossil fuel equipment. Further, subsidies are available for the initial fuel load of nuclear plants, but not for fossil-fuel inventories. These subsidies could make the difference between having a nuclear project or not having one at all.

*Interest rates have increased greatly with the increase in inflation in the last five years. Public utilities in the U.S. have an average cost of capital today of about 12-15% (for debt and equity combined). Of this the amount that represents an allowance for expected inflation is probably 5-8%. This implies a real cost of capital for these utilities of about 7%. In less developed countries the real cost of capital for corresponding projects must be well over 10%.

**J. H. Cha, "Estimate of Nuclear Power Costs in Korea," Proceedings of an IAEA Symposium in Istanbul, Turkey, October 20-24, 1969, IAEA-SM-126/40, 1970.

Subsidies for nuclear exports make up a large part of the Export-Import Bank's business. The president of the Bank estimates future demand for nuclear export loans of \$750 million a year out of an authorized annual total of \$3.4 billion. He has stated that "Nuclear power rates a very high priority."*

The argument is, of course, made by the Export-Import Bank and by suppliers of equipment that if the U.S. does not provide this subsidy other governments will and the U.S. will lose the business. This is a familiar mercantilist argument that was effectively dealt with by Adam Smith. If other countries want to tax the general population for the benefit of a few suppliers that is their problem. It is not a persuasive argument for the U.S. committing the same folly, especially in view of the military potential of nuclear exports. Further, with a floating exchange rate, specific exports, such as nuclear power plants, are not required to bring about a satisfactory balance of payments.

The U.S. and the other supplier nations are not merely providing the technical means for creating the option for nuclear military forces in other countries; they are helping to pay for this option with their subsidies.

b. The Example of the Subsidy in the Tarapur Nuclear Reactor Loan to India:

In December 1963, the U.S. authorized a loan of \$71.8 million to India for the Tarapur nuclear power station. Interest on the loan was 3/4 of 1% during both a ten year grace period and a thirty year repayment period. This was a very low interest rate, even for 1963, and the maturity period was exceptionally long. In effect, a large part of this loan amounted to a gift. The magnitude of the gift can be estimated by computing the present value of the stream of payments India would make using a discount rate that reflects the competitive market cost of the capital committed. For example, assume that an Indian utility going into the market for a comparable loan would have had to pay 10% (U.S. government bonds then were yielding 4%). The present value of the stream of loan payments from India discounted at that rate equals \$13 million. This represents the real cost of the Tarapur reactor to India, assuming a ten percent discount rate. The remaining \$58.7 million or 84% of the grant amount represents a "gift" from the U.S.

*Ann Crittenden, "Surge in Nuclear Exports -- Spurs, Drives for Controls," The New York Times, August 17, 1975.

B. The economics of plutonium recycle and U.S. policy on reprocessing

1. Introduction, Summary, and Recommendations

Plutonium production of civilian power reactors provides an excellent example of the dilemma inherent in U.S. efforts simultaneously to promote nuclear power and to halt the spread of nuclear weapons. Every time a new country obtains a nuclear power reactor it is moving significantly closer to a nuclear weapon development capability, since the plutonium produced by all nuclear reactors can be made into nuclear weapons. Yet as part of her efforts to impede the spread of nuclear weapons, the U.S. has pledged in the Non-Proliferation Treaty (NPT) to assist countries to obtain nuclear reactors. Through the Export-Import Bank, the U.S. often subsidizes sales of reactors to the less developed countries. Further, the U.S. was instrumental in organizing the International Atomic Energy Agency (IAEA), which has as one of its major objectives, spreading the benefits of nuclear power around the world. At the same time, the U.S. engages in negotiations and actions aimed at preventing additional countries from acquiring nuclear weapons.

A particularly difficult problem for U.S. policy concerns reprocessing, a chemical-mechanical process whereby plutonium is separated from the waste materials in used, or "spent," reactor fuel. Until reprocessed, spent fuel is useless for weapon purposes. If reprocessing were never contemplated in civilian nuclear programs, the plutonium in spent fuel would be less dangerous from a military standpoint (although it still would exist as a potential source of weapon material). Unfortunately, from the anti-proliferation viewpoint, reprocessing has a number of non-military justifications. Thus, reprocessing is one of those dual-purpose (peaceful-military) activities that abound in the field of nuclear energy.

We have pointed out the importance in the nuclear field of distinguishing between civilian technologies and desirable technologies and also between what is civilian and what is economically beneficial. If our primary objective is to impede nuclear weapon development, all civilian nuclear activities are not equally desirable. The extreme example of undesirability is peaceful nuclear explosions. Thus, not all civilian nuclear activities deserve our support. To the extent that our objective is to increase the wealth and production in less developed countries, nuclear activities that promise the most economic benefit are most deserving of our support. But, not all civilian nuclear activities have equal economic benefits. In fact, some may be economically inferior to non-nuclear alternatives.

Appreciation of these distinctions is required to formulate policy on reprocessing. Reprocessing although having civilian applications, is very undesirable because of its military potential. Thus, we can be clear that although reprocessing can be of civilian use, it is not necessarily desirable. If reprocessing is without significant economic benefits, the U.S. has a justifiable basis for opposing its implementation in countries without nuclear weapons.

In the following section, we review the history and possible roles of reprocessing in civilian nuclear programs. We find that in the short-term (the next ten years), the only potential civilian use for reprocessing on a substantial scale is to obtain plutonium to recycle into power reactors. Other non-military reasons for reprocessing are as a part of a breeder reactor program, or as part of an advanced waste disposal system. Neither of these latter two will be developed to a commercial scale of operation in the next ten years. Reprocessing on a pilot scale could be justified as anticipatory to these developments, but large-scale reprocessing in the short-term can only be justified by plutonium recycle. For this reason, we have analyzed the economics of reprocessing in considerable detail. This analysis is presented in a later section.

To summarize the results of our analysis: Future prices in the nuclear field are very uncertain, and the profitability of plutonium recycle is extremely sensitive to some of these prices. Thus, predictions of profitability ten years hence must necessarily be educated guesses. Still, over most of the range of future prices that seem reasonable to expect within the next ten years, reprocessing for plutonium recycle will remain unprofitable. This prediction appears more certain for national facilities in less developed countries, where the small scale of operations will heavily penalize the economics, and for the reprocessing of fuel from heavy water reactors. Even should prices be such as to make plutonium recycle profitable, the magnitude of benefits will be very small -- almost certainly amounting to a savings of less than one percent in nuclear generating costs.

Our economic analysis indicates that the benefits of reprocessing for less developed countries during the next ten years most likely will be negative, but even if positive, will be small. Thus, we conclude that potential economic benefits from reprocessing are inadequate to compensate for the increase in weapon-development capability. On these grounds, the U.S. appears to have good grounds for opposing commercial-scale national reprocessing facilities.

a. Small-Scale Reprocessing Facilities

Small-scale, research and development reprocessing facilities present a special problem for U.S. policy. There is considerable uncertainty about the prospects for development of a commercial breeder. A country could quite justifiably argue that they need to gain experience in reprocessing to prepare for the eventuality of an economic breeder. How should the U.S. respond to requests for "pilot or small-scale reprocessing facilities?" The same judgment is required whether the facilities are small or large:

The question is whether the economic benefits justify the military risks. The costs, benefits, and risks all diminish with smaller size, but how the balance among these alters is not immediately obvious. We suggest that the most important considerations in assessing small-scale facilities are the production rates and agreed-upon stockpiles of plutonium. Economics, per se, provide little guide to the desirability of small facilities. The military risks are dominant, since they far outweigh any possible economic gains from small-scale facilities. On the other hand, it should be possible to accomplish any desired research and development involving reprocessing without production or accumulation of dangerous amounts of plutonium. A facility that can produce only a few hundred grams of plutonium per year is of relatively little concern, if agreement can also be obtained to limit total plutonium inventories to a few kilograms. A reasonable objective for U.S. policy should be to gain agreement that plutonium production rates and stockpiles should be as small as possible relative to the amount needed for a nuclear weapon.

b. Reprocessing of Fuel from Heavy Water Reactors

Heavy water reactors, such as the Canadian CANDU, use natural, unenriched uranium fuel. Their spent fuel elements contain only about 2.3 grams of plutonium per kilogram and no usable uranium. This compares to 6-7 grams of plutonium per kilogram of spent fuel from light water reactor (LWRs). This latter type of fuel also contains some usable U_{235} . Thus reprocessing fuel from heavy water reactors is much less profitable than reprocessing fuel from LWRs. Our analysis indicates, in fact, that HWR reprocessing costs would need to be 10%-30% of estimates for LWR reprocessing in order to make reprocessing of heavy water reactor fuel commercially worthwhile. The following nations are emphasizing such reactors:

Percent of Presently Planned Power

Reactor Capacity

Based on Heavy Water

Argentina	100%
Canada	100%
Pakistan	100%
India	77%

It is especially hard to see how these four states could justify a reprocessing plant on economic grounds.

c. Multinational Nuclear Centers

Since the explosion by India of a nuclear device utilizing plutonium obtained by reprocessing, the U.S. has recognized the potential danger of independent, national reprocessing facilities. As countries such as South Korea, Taiwan, Brazil, and Argentina expressed interest in such facilities or pursued research and development on reprocessing, the initial U.S. response was to propose the establishment of Multinational Nuclear Centers (MNCs). The Centers were originally conceived as containing all phases of the nuclear fuel cycle. Special importance was attached to locating within the MNCs Multinational Reprocessing Centers (MRCs). As the concept has developed and undergone modification, more emphasis has been placed upon spent fuel storage. Reprocessing is not envisaged as an essential part of the MNCs but rather an activity that might be undertaken in the future if justified by economics. This is a substantial improvement over original conceptions. There still appears, however, to be some confusion over whether or not MRCs should be included as part of MNCs. We believe that it would be a serious mistake to encourage reprocessing in any form, whether in national or multinational facilities. Those who favor MRCs appear to reason as follows: (1) many countries have legitimate, peaceful reasons for desiring reprocessing; (2) the U.S. has pledged to support development of peaceful nuclear energy activities; (3) the technology is sufficiently simple so that the U.S. cannot hope to prevent countries from building their own facilities; (4) current safeguard technology is inadequate to prevent national reprocessing facilities from being used secretly to provide fissile material for a weapons program; therefore the best hope for retarding proliferation is to encourage countries to do reprocessing in multinational facilities, where the participating countries could watch each other to prevent cheating.

We believe that reasons (1) and (2) do not justify support for reprocessing, as we have previously explained at length. Reason (4) argues against national reprocessing facilities, and we agree that they are dangerous and should be opposed by the U.S. This leaves reason (3) as the primary reason for supporting MRCs. Granting that (3) is correct, it by no means follows that U.S. support for MRCs will have the desired result of discouraging construction of national facilities. Consider the following:

- (1) Economic justification is crucial to gaining participation in MRCs. Those countries that agree to participate in MRCs will do so because they are truly concerned about the economics of nuclear power and are persuaded that MRCs will offer

meaningful cost savings over national facilities. The supporters of MRCs believe that there are substantial economies of scale in reprocessing, leading to significant cost advantages for the larger, multinational facilities.* This misses the central economic point:

Economics do not favor MRCs but, rather, favor no reprocessing at all, at least for the near term. As is demonstrated later in this report, reprocessing for the purpose of plutonium recycle will be very unprofitable over much of the range of fuel cycle prices that it appears reasonable to expect. Uranium and thorium breeders are in the research and development stage and do not provide an economic motivation for reprocessing yet.

It seems clear that no reprocessing is better for retarding proliferation than is multinational reprocessing. Thus, in so far as non-nuclear countries will be swayed in their decision by economics, the U.S. will more successfully retard proliferation by publicizing the unfavorable economics of reprocessing than by promoting MRCs.

- (2) To the extent that narrow economic considerations are unimportant to a country, MRCs offer little to make such a country prefer the MRC over its own reprocessing center. If reprocessing is desired to lessen dependence on other countries, the MRC will provide it only to the Center country. Even the Center country will be greatly restricted in her freedom of action by the multinational aspects of the Center. Further, a central facility will likely not be satisfactory for a country interested in developing and processing special fuels, such as thorium fuel (as India and Brazil claim to be).
- (3) Most importantly, the MRC will hold no appeal to the country desiring to develop nuclear weapons -- yet these are just the countries of concern. Unless MRCs can be made mandatory for all non-nuclear weapon states, the MRC will fail in its primary objective. But, even those who support controlled reprocessing agree that preventing countries

*There are some legitimate doubts about the existence of these costs advantages, since large-scale, automated, commercial facilities have not been successfully operated. There also appears to be substantial risk of unrepairable failure of major process equipment. Further, transportation and scheduling of many different types of fuels from many countries will add to costs. As far as we know, these have not been thoroughly analyzed.

from building their own reprocessing facilities is impossible. Even if all supplier nations were to provide reprocessing facilities only in the context of MRCs, nations could construct their own.

- (4) A necessary (but not sufficient) requirement for MRCs to succeed is for all suppliers to agree to make MRCs mandatory. This seems unlikely in view of the number of countries that already have some reprocessing capability.
- (5) Will countries that participate in MRCs be prohibited from building national facilities? If not, there is little to be gained. But if made a condition for joining MRCs, will countries of concern be likely to join?
- (6) Finding partners willing to actually participate in multinational reprocessing may prove quite difficult. Those countries of most concern as potential weapon developers are not on the best of terms with their neighbors. Thus, Pakistan seems unlikely to wish to join with India or Iran, Korea, and Taiwan seem unlikely partners with each other or with Japan, and Brazil and Argentina are traditional rivals.
- (7) A plausible result of a U.S. effort to promote MRCs would be to provide reprocessing technology to a number of countries that would not otherwise have had it -- while those countries interested in independent facilities would construct their own.
- (8) By promoting reprocessing, albeit in multinational form, the U.S. will be legitimizing independent national efforts. There will be little ground to argue that reprocessing is undesirable if we are sanctioning and, perhaps, subsidizing it in the multinational context.
- (9) If reprocessed plutonium from MRCs is shipped back to the country of origin, little will have been gained.

If the U.S. chooses not to favor reprocessing in MRCs, it could present a number of arguments against reprocessing:

- (1) Reprocessing is not economically desirable at present.
- (2) Commercial-scale reprocessing is an unproven technology, with substantial risks of unrepairable failure of the process equipment.

- (3) For natural uranium reactors, the type favored by a number of countries of concern, plutonium recycle is very much less economic than for LWRs.
- (4) Plutonium recycle increases the radiation hazards and terrorists threats in the nuclear fuel cycle.
- (5) Plutonium recycle will not free a country from dependence on other resources of nuclear fuel, since plutonium separated from spent fuel can supply only 5-20 percent of the fissile material required (the exact percent depending upon the rate of growth of nuclear capacity).
- (6) Since nuclear fuel-cycle costs represent only about 20 percent of total nuclear electricity costs, a 25 percent cost advantage for plutonium fuel would lower total system nuclear electricity generating costs by one percent (plutonium recycle fuel is less than 20 percent of the total fuel; fuel-cycle costs are 20 percent of the total, and with a 25 percent cost advantage, this yields $.2 \times .2 \times .25 = .01$). But, of course, the costs are much more likely to cut the other way.

By opposing reprocessing, arguing that it is uneconomic and creates unjustifiable risks, the U.S. will lend support to factions within other countries that oppose reprocessing. By supporting reprocessing, even in a multinational context, the U.S. will lend support to those factions that favor reprocessing (whether or not in multinational context). On these grounds, a policy of arguing against the desirability of reprocessing is to be preferred to supporting MRCs.

A final point concerns the relation of U.S. policy on domestic reprocessing to U.S. policy on reprocessing in other countries. Although the economics in the U.S. are not identical with those elsewhere, they are similar. If we proceed with plutonium recycle in this country, we are likely to find it difficult to argue persuasively that other countries should forego this option. Less developed nations will contend that, once again, the U.S. is attempting to monopolize an important technology to the detriment of the poor nations. They will say "why should we give up something that the U.S. is unwilling to forego? If it is so unprofitable, why is the U.S. intent on pursuing it?" Although, the U.S. may offer explanations and counter-arguments, these obviously will be less convincing than a concrete demonstration of our own belief in the present undesirability of reprocessing. This effect on other countries should be a consideration in formulating U.S. policy on domestic reprocessing.

2. Reprocessing: Its History and Role in the Nuclear Industry

a. The History

Reprocessing of uranium after irradiation in nuclear reactors first occurred in the Manhattan Project. One of the bombs dropped on Japan ("Fat Boy") utilized plutonium obtained by reprocessing uranium irradiated in reactors at Hanford, Washington. Production of plutonium in special reactors and separation by reprocessing has been a continuing component of every nuclear-weapon program in the world.

Given the early experience with reprocessing, it is not surprising that U.S. nuclear scientists have always envisioned the reprocessing of spent fuel and use of the recovered plutonium in new fuel ("plutonium recycle") as an intrinsic part of the civilian nuclear power program. Spent fuel from nuclear power reactors contains significant quantities of fissile plutonium (Pu) and uranium 235 (U_{235}). It was natural to think that throwing these away would be wasteful, and the experience in AEC weapon facilities indicated that reprocessing would be technically and economically feasible.

Also, early AEC projections of nuclear power growth showed that standard reactors (light water reactors, or LWRs) would consume so much uranium that we would soon (50 years) run out. The solution to this predicted shortage favored by U.S. atomic scientists has always been the development of "breeder reactors," which were also first conceived during the Manhattan Project. These reactors "breed" more fissile material than they consume, thus greatly extending the nuclear fuel supply.* Reprocessing and plutonium recycle are indispensable to the breeder concept. Thus, there was really never any question about the necessity for reprocessing in the minds of those planning the U.S. nuclear development program after World War II.

In the 1950s and early 1960s, little attention was paid to reprocessing, as effort was concentrated on building nuclear reactors that could economically compete with fossil-fuel power plants. It was simply assumed the reprocessing and recycling of recovered plutonium would be a part of the mature nuclear industry.

By the early 1970s, a number of developments were throwing into question the early assumptions about reprocessing and plutonium recycle:

- The large amounts of radioactive materials projected to be produced by the nuclear industry, combined with growing public concern over radioactive contamination, resulted in increasingly stringent requirements for safety of nuclear processes and handling of radioactive wastes.

*The Breeder concept is described in more detail later in this section.

- Commercial reprocessing operates on a much larger scale and processes different material (zircalloy clad uranium oxide) than weapon-material facilities (uranium metal). Civilian fuel is irradiated to much higher levels than weapon-material, creating unanticipated reprocessing chemistry problems. Further, costs are far more important in commercial facilities. Thus, the experience of the weapon's facilities was proving to be a poor guide to commercial experience.
- The first commercial plant, located at West Valley, New York experienced numerous operating problems and delays in the availability of spent fuel. In 1972, the plant shut down for modification and expansion. Changing regulatory requirements since that time have resulted in numerous changes in the planned modifications. As of August 1975, the plant had still not reopened.
- Increasing concern with the potential danger of plutonium (which has a very small critical mass, is an extremely toxic radioactive poison, and has a half-life of 25,000 years) has led to great uncertainty about the regulatory requirements that would be imposed upon transport, fabrication, and use of plutonium in nuclear reactor fuel.

Since the early 1970s, the problems and uncertainties surrounding reprocessing and plutonium recycle have continued to grow:

- Costs of reprocessing have increased at an astounding rate. The capital costs of the West Valley, New York, plant of 1 tonne per day capacity were \$35M (1963 dollars). The Barnwell, South Carolina, 5 tonne/day facility of Allied Gulf Nuclear Services (AGNS), according to informal statements from ERDA officials, will probably cost over \$1.0 billion (1975 dollars) before it opens. This last facility was begun in 1970, scheduled initially to operate in 1973, but will probably not operate before 1980.
- A few years ago, reprocessing costs were estimated at about \$30 per kg. Now, including waste treatment, storage, and disposal, they are estimated at \$250 to \$300 per kg -- almost ten times as much. Thus even though uranium and enrichment costs have risen substantially in recent years, which is favorable for reprocessing profitability, reprocessing cost increases have been more than offsetting.

- All commercial plants are now shut down for modifications, and a \$64M General Electric plant apparently has been written off as a total failure due to design deficiencies that could not be economically overcome. Two European plants, originally built for weapon programs, had planned to undertake commercial reprocessing by this time, but one has been forced to close for modification and the other has delayed the start of operation.
- The delays in a reprocessing operation reflect regulatory problems, technical problems, and economics:
 - Regulatory requirements are undergoing continuing change and upgrading. In the U.S., some critical decisions about waste management and plutonium recycle have not been made.
 - Technical problems with the automated processes (necessary because of intense radioactivity) have been much greater than originally expected. Repair is extremely difficult and costly once operation has begun because of the radioactivity of the process line.
 - Reprocessing costs have risen so much that these costs seem likely to exceed the value of recovered products; thus reprocessing may not be profitable for the utilities owning spent fuel*.
- The U.S. Nuclear Regulatory Commission has decided on a full-scale review of the desirability of plutonium recycle. Their decision is not expected until 1977. Significant opposition to recycle has appeared, based on concerns about safety, environment contamination, and increased danger of nuclear terrorism. It is by no means certain that recycle will be authorized.
- The U.S. breeder development program has encountered numerous delays and cost escalations. In the U.S., the breeder will probably not be a significant commercial factor before 2000.

*Although some might reprocess, were facilities available, in order to empty their spent-fuel storage facilities, which are now filled beyond the level originally authorized by the AEC.

Other countries, especially France, appear to be having better luck with their breeder programs. The French are operating a prototype, large-size breeder successfully. They are constructing a 450-MW (megawatt electric) reactor and are beginning design and component testing of a 1200 MW_e breeder unit. Should development continue successfully, reprocessing would become necessary to the breeder-LWR cycle. The planned operational date for the first commercial prototype is 1985, which would imply general commercial availability in the 1990s. The decision on ordering the Super Phenix (1200 MW) originally expected in April 1975 has recently been delayed until 1976. There are thus, inevitably uncertainties. The French reactor may or may not turn out to be superior to current American technology when it is in larger scale production for export. In the past, some foreign developments in the reactor field looked promising, but prospects faded and the U.S. LWR technology was adopted. Even if the development continues successfully, it will not justify commercial reprocessing before the 1990s.

b. The Role of Reprocessing in LWR Economics

There is considerable confusion about the role of reprocessing in civilian nuclear power programs. Perhaps because it was from the start assumed to be part of the U.S. program, some people believe it to be indispensable. Others appear to believe that recovering the plutonium (Pu) from spent fuel will permit a country to satisfy its fuel needs without obtaining other nuclear fuel.

The truth is that reprocessing and plutonium recycle can make, at most, only a minor contribution to nuclear power economics. First of all, the fissile plutonium recovered from spent fuel is only enough to supply about 20 percent of the fissile requirement in a corresponding amount of fresh fuel. Second, with the growth rates generally projected for nuclear power, recovered plutonium will provide only 5-15 percent of total fissile-fuel requirements. Third, there will be substantial costs incurred in obtaining the plutonium. It is by no means a "free" fuel. In fact, as the analysis presented below demonstrates, costs to obtain and use plutonium seem likely to exceed for some time the costs of alternative fuels.

*This analysis is explained in greater detail in Albert Wohlstetter, et al, The Present Prospects for Proliferation: The Setting of the Problem, unpublished paper, 1975.

To determine whether plutonium recycle is economic, one can calculate the value of plutonium used as a substitute for enriched uranium in reactor fuel minus the added costs associated with plutonium recycle. Fuel enriched with plutonium is referred to as mixed-oxide fuel (because it is a mixture of plutonium oxide and uranium oxide). Define the gross value (V) of a kg of mixed-oxide fuel (mof) as the value of kg of equivalent U_{235} enriched reactor fuel minus the excess fabrication costs (F), transportation costs (T), and safeguard costs (S) associated with mof, with all costs in dollars per kg of mof.*

The net value of a kg of Pu recycle fuel (V_N) is the gross mof value minus the excess reprocessing costs (R) and any additional permanent waste storage costs (W) associated with obtaining the Pu necessary for a kg of mixed-oxide fuel, again with costs measured in dollars per kg of mof. For recycling of Pu to be profitable, (V_N) must be greater than zero. Whether or not this is true depends upon all of the factors in the above relationships, most of which are uncertain, some almost completely unknown, and some of which vary greatly with the scale of operation. Drawing upon our review of the data on these factors, contained in Proliferation Prospects, a number of important cases are analyzed mathematically in this section. Understanding of the analytical treatment may be aided by an example in descriptive terms.

Consider an example of the economics of recycling in the U.S. for cost estimates and prices as of mid-1975:

To make one kg of uranium enriched to 3.4% U_{235} requires about 6 kg of uranium and 5 Separative Work Units (SWUs). At a price of \$60 per kg of uranium and \$60 per SWU, the cost of the enriched uranium is about \$660. Adding \$100 for fabrication yields \$770 per kg of fuel.

By way of comparison, a kg of plutonium-enriched fuel is estimated to cost \$1040: to obtain the plutonium to equivalently enrich a kg of uranium with plutonium requires reprocessing about 5 kg of spent fuel. Including transportation of spent fuel, the reprocessing cost is about \$220 per kg, or a total cost of \$1100. Reprocessing also recovers some uranium. Because of isotopic contamination, the value of this uranium is uncertain. Optimistically, reprocessing 5 kg of spent fuel may recover uranium worth as much as 6 kg of natural uranium. Giving credit for this recovered uranium, the net cost of the plutonium is $\$1100 - 6 \cdot \$60 = \$740$. Fabrication of mixed-oxide fuel is expected to cost about \$300 per kg, for a total cost of \$1040.

Thus, with these costs and prices, reprocessing and recycling is a more expensive means of obtaining fuel than U_{235} enrichment. Consideration of waste storage costs and safeguard costs does not affect this conclusion.

*Weights of reactor fuel refer to only the weights of uranium and plutonium metal contained in the fuel. They do not include the oxygen weight or the weight of the cladding or other assembly materials.

In our analysis, we consider the most profitable type of fuel to reprocess: spent fuel from a mature PWR, containing 7 gms Pu/kg fuel. This level will not be attained until five years after start-up. Mature BWR spent fuel will contain 16% less Pu/kg making recycling correspondingly less profitable. HWR spent fuel contains only one-third the concentration of plutonium in PWR fuel. This concentration is so low that reprocessing does not appear likely to be profitable under any probable near future circumstances.

In the following analysis, reprocessing is assumed to occur only if plutonium recycle is undertaken, otherwise the fuel rods are assumed to be disposed of without further processing.

Because the ERDA costs (as opposed to charges) for long-term storage and disposal are unknown at this time, we have treated these costs as an unknown in the analysis. Because of the large volume of wastes generated in reprocessing, there is some presumption that such costs with reprocessing will at least equal such costs without reprocessing. Reprocessing will generate a volume of high- and intermediate-level waste (after solidification) equal to about one-half the original volume occupied by spent fuel in assembled fuel cores. The fuel rod claddings (which are intensely radioactive) will also generate a volume of waste about equal to the original volume of assembled fuel cores. In addition, reprocessing and mixed-oxide fabrication will generate almost 6 times this volume of low-level trash, which because of plutonium contamination, cannot be buried but must be given special handling by ERDA.

Safeguard requirements for nuclear materials will be almost entirely a function of plutonium recycle. Without recycle, no plutonium will be available except in very large, highly radioactive containers. The full costs of safeguards (including social costs) with plutonium recycle are not well specified at this time. We have, therefore, treated them as unknown. This does not mean they are unimportant.

Definitions

- V_G : The gross value of a kg of mixed-oxide fuel (kg-mof).
- V_N : The net value of Pu recycle per kg-mof.
- S_N : The relative net saving per kg-mof.
- U: The cost of uranium per kg U_{235} - enriched (UO_2) fuel.
- E: The cost of enrichment per kg UO_2 fuel.
- F: The excess fabrication costs per kg-mof, including conversion of Pu from nitrate to oxide.
- T: The excess transportation costs per kg-mof.

- S: The excess safeguard costs per kg-mof.
- R: Reprocessing costs per kg-mof, net of the value of recovered uranium. On-site waste treatment costs are included, but not long-term storage and disposal costs.
- W: The excess (or savings in) waste storage and disposal costs per kg-mof.
- C_u : Cost per kg of uranium.
- C_e : Cost per kg separative work unit (SWU).
- C_r : Cost per kg of reprocessing spent reactor fuel, including spent fuel transport.
- V_{ur} : The value of uranium recovered in reprocessing 1 kg of spent reactor fuel.
- ΔC_w : Waste storage and disposal costs per kg of spent reactor fuel reprocessed plus the waste storage and disposal costs from the corresponding mixed oxide fabrication, minus the costs of storage and disposal of spent fuel without reprocessing.
- $X: (4.9\Delta C_w + S) / (U + E + F_u)$
- F_u : Cost per kg of UO_2 fuel fabrication.

Formulas

Drawing upon the previous discussion and definitions, the following formulas can be derived.

$$(1) \quad V_G = U + E - (F + T + S),$$

which states that the gross value of kg of mof equals the cost of obtaining the equivalent in U_{235} enriched fuel, minus the excess costs of fabrication, transport, and safeguards associated with mof.

$$(2) \quad V_N = V_G - C_u - R - W,$$

which states that the net value of a kg of mof equals the gross value minus the cost of the natural uranium in it, the net cost of obtaining the Pu in it, and the extra waste storage and disposal costs associated with reprocessing and mof fabrication, as compared to direct disposal of spent fuel. This last term (W) may be negative.

$$(3) \quad U + E = 6.2 C_u + 5.2 C_e,$$

which is the cost of obtaining 1 kg of 3.4% enriched uranium, assuming .2% tails in the enrichment process.

$$(4) \quad R = 4.9 (C_r - V_{ur}),$$

which states that it takes 4.9 kgs of reprocessed fuel to obtain the Pu for one kg of mof, and that the net cost of reprocessing is the cost per kg reprocessed minus the value of the uranium recovered. For justification of this equation, see Appendix 1.

$$(5) \quad V_{ur} = (6.2 C_u + .1 C_e)/5.3,$$

which is explained in Appendix 2.

$$(6) \quad W = 4.9 \cdot \Delta C_w,$$

The difference in waste storage and disposal costs per kg of mof reflects the 4.9 kgs of spent fuel that must be reprocessed to obtain the Pu for 1 kg of mof.

$$(7) \quad V_N = \overbrace{6.2 C_u + 5.2 C_e}^V - (F + T + S) - \underbrace{C_u - 4.9(C_r - (6.2 C_u + .1 C_e)/5.3))}_R - \underbrace{4.9 \Delta C_w}_W,$$

or:

$$V_N = 10.9 C_u + 5.4 C_e - 4.9 C_r - 4.9 \Delta C_w - (F + T + S)$$

V_N is the net value of 1 kg of mof, after allowing for all costs associated with obtaining it. If this value is negative, plutonium recycle is not economic. The costs of obtaining and using mof will exceed the costs of the alternative of U_{235} enriched fuel.

Several features of equation (7) are worth noting. Most important, several of the component cost figures in (7) are multiplied by factors ranging from 4.9 to 10.9. These cost "multipliers" magnify any uncertainties in these component costs. Future costs of most of these are quite uncertain; thus there is a very wide range of possible future values for V_N . As will be seen V_N is negative in much of their range. Since the costs of fabrication and transport enter only with a factor of one multiplier, V_N is much less sensitive to these costs.

A second feature of (7) is the much higher sensitivity to uranium costs than to enrichment costs. This is because the uranium cost enters positively in V_N both for the uranium recovered in reprocessing and the cost of uranium feedstock for U_{235} enrichment, whereas enrichment costs enter significantly only in the U_{235} enrichment.

Although V_n tells whether Pu recycle is profitable or not, it does not indicate the n percent savings relative to the alternative of U_{235} enrichment. This is approximately equal to $V_n / (U + E + F_u)$, where F_u is the fabrication cost of uranium oxide fuel (UO_2) and storage and disposal costs for the UO_2 fuel are ignored. Let

- (8) $S_n = V_n / (U + E + F_u)$ be called the relative net savings per kg-mof.

c. The Uncertain Value of Pu Recycle

The profitability of plutonium recycle is extremely sensitive to the price of uranium and the cost of reprocessing, and somewhat less sensitive to the cost of enrichment. The future values of all of these are highly uncertain. As noted previously, reprocessing cost estimates have escalated by nearly a factor of ten in the last few years. Uranium prices have also increased by nearly a factor of six in the same period. Reprocessing of significant quantities of spent fuel will not occur until the 1980's and the lifetime of the plant spans 15 to 20 years. Estimating costs and prices for this future time frame is more guesswork than science. We have attempted to deal with this uncertainty by analyzing two cases: 1) A low estimate for reprocessing costs and future uranium prices and 2) a high estimate for reprocessing costs and future uranium prices.

(1) Reprocessing costs

Our low estimate of reprocessing costs is based on an analysis supplied to us by ERDA. This analysis yields a figure of \$204 per kg of spent fuel, including on-site treatment and storage of waste and conversion of uranium and plutonium.

Our review of the ERDA analysis indicated that costs of waste treatment, and storage and product conversion were seriously underestimated. Further, operation near rated capacity seems unlikely in view of the complexity of the task and the difficulty of making repairs. Past history bears this out, with all previously operating plants being shut down for long periods.*

* The NSF facility in West Valley, New York, with a rated capacity of 300 MTU's per year, processed only 600 MTU's in its seven year period of operation prior to shutdown in 1972.

On the other hand, the capital charge in the ERDA estimate was based on a very high capital charge of 37% per year. Although this may be appropriate given the riskiness of the initial venture, we consider a 25% fixed charge rate (15% rate of return plus 10% for depreciation, taxes, etc.) to be more appropriate for evaluating the longer-term prospects for reprocessing. Combining these considerations, our estimate of reprocessing costs in the early 1980's is \$300 per kg of spent fuel (in 1975 dollars) for a 5 tonne per day plant. Although we use this as the "high estimate" in the following analysis, this is by no means the highest conceivable cost, given all of the uncertainties about reprocessing technology and regulatory requirements. We, in fact, believe it represents a balanced view of what costs are likely to be.

(2) Uranium prices

Estimated uranium resources in the U.S. are large compared to expected demands in this Century. Total estimated resources available at under \$15/lb U_3O_8 forward costs are 2 million tons U_3O_8 cumulative demand seems likely to be under 1 million tons through the end of this Century. Given this supply-demand picture, uranium prices in the \$20-\$25 per lb U_3O_8 would appear to be a reasonable medium-term expectation.* For our low-cost estimate we have used a uranium price of \$65 per kg U (equal to \$23 per lb U_3O_8). The past boom and bust history of uranium prices makes clear that this is not the lowest possible future price.

In spite of the relatively favorable supply picture, uranium prices have been climbing steadily for the past several years. After Westinghouse cancelled all uranium supply contracts in late 1975, reported prices for delivery in the 1980's shot up to the \$40-\$45 per lb range (from \$25 per lb). This has been taken by many to confirm the likelihood of uranium prices well above \$50 per lb. U_3O_8 in the 1980's. A number of comments are in order:

1) The reported prices include estimates of inflation and escalation and, thus, are not in 1975 dollars.

2) Until the Westinghouse cancellation few utilities worried about deliveries more than a few years in the future. Their sudden desire to obtain long-term assurance of uranium supplies extended demand (in time) beyond the normal contracting period for most uranium mining firms. Thus, there has been a large sudden demand for a previously unwanted commodity (far-future uranium). It will take some time for the market to adjust to the changed situation. As the adjustment occurs, future prices should move down toward the supply-curve price.

* These are higher than the \$15 per lb U_3O_8 "forward cost" estimates because forward costs do not allow for return on investment or recovery of past exploration costs.

3) Very few contracts have actually been negotiated at the very high prices. According to ERDA's 1/1/76 survey of uranium prices, average prices for uranium delivery commitments in all years 1980-1985 are under \$15 per lb. U_3O_8 . Excluding market price contracts (for which no meaningful price is available), the highest reported prices were under \$40 per lb. U_3O_8 in all years except 1982.

4) There appears to have been a large speculative element in the recent price behavior of uranium. The buyers are, for the most part, relatively unsophisticated utilities and they have had to deal with professionals in a very tight market. Uranium prices rose sharply in the 1950's, only to plummet when supply expanded in response to the higher prices. A similar pattern seems quite likely to be repeated.

For all of these reasons, we do not believe recent prices are likely to be sustained for long. However for purposes of analysis we consider as a high estimate a uranium price of \$100 per kg U (\$38.5 per lb. U_3O_8). This might be realized, for example, if mining costs expanded faster than expected or if nuclear power growth is higher than present expectations.

(3) Enrichment costs

Enrichment costs in gaseous diffusion plants are sensitive to the costs of electricity as well as construction costs. Although ERDA plants have low-cost power and were built when construction costs were much lower than today, new private investments will not have these advantages. With electricity at 20-35 mills per kwh and a 25% capital charge on a \$3 billion investment (1975 estimate for a 10 million SWU per year plant), a builder of a new gaseous diffusion plant might charge \$150 per SWU. We take this figure as our high estimate of enrichment charges.

On the other hand, there are a number of possibilities that could lead to lower enrichment charges, at least over the medium term. Perhaps the most likely possibility would be a change in government policy from encouraging private investment to retaining enrichment as a government operation. This could well lead to prices even lower than today, since the government has been raising their prices in order to encourage private investment. A second possibility for lower prices would be the practical development of laser separation. Thirdly, centrifuge separation is still early on the learning curve and costs of this method may decline.

The possible range of prices is obviously very wide. For our low estimate, we have used the ERDA charge in 1975 of \$57 per SWU. We do not defend this as an especially likely value, but rather consider it illustrative of the possible low values.

(4) Other costs

For other elements of cost we have used single-value industry estimates for the 1980's (in 1975 \$). Although these costs are also uncertain, the profitability of Pu recycle is relatively insensitive to them.

(5) The profitability of plutonium recycle: low estimates

In this section we use the low estimates for reprocessing cost, uranium price, and enrichment cost to calculate the potential profitability of reprocessing and plutonium recycle in a number of situations.

(a) Plutonium recycle in less developed countries' national facilities:

First consider national facilities, which will necessarily be small in scale. To make the case relatively favorable, we consider a reprocessing plant with 1 tonne/day design capacity, operating 260 days per year. This would require the output of 8,500-MW of LWRs, more than most LDCs will have by 1985. We use our low estimate for a U.S. 5 tonne/day plant, scaled to a 1 tonne/day plant using traditional chemical industry scaling factors. This would produce enough plutonium to fabricate about 50 tonnes of MOF per year. We use the fabrication costs for a 40 tonne plant with a 10 tonne campaign. For uranium and enrichment costs, we use low estimates:

$$C_u = \$57$$

$$C_e = \$60$$

$$F = \$260$$

$$T = \$30$$

$$C_r = \$639$$

$$F_u = \$100$$

Substituting in equation (7):

$$V_n = 621 + 312 - 3131 - 4.9\Delta C_w - (260 + 30 + S)$$

$$V_n = -2488 - 4.9\Delta C_w - S$$

Comparing this to the cost of UO_2 fuel:

$$S_n = (-2448 - 4.9\Delta C_w - S) / 765 = -3.3 - X,$$

that is, mof will cost about 3 times more than UO_2 fuel without considering waste disposal and safeguard costs.*

(b) Pu recycle in an MRC: Next consider a large-scale Multi-National Reprocessing Center (MRC) with associated large-scale mof fabrication. Because of the larger scale, F and C_r are lower. A transportation charge of \$40 per kg of spent fuel has been added to the reprocessing cost. This reflects a \$10 per kg local transport cost plus \$30 per kg for a 10,000 mile round trip by water, as estimated by ERDA.

$$C_u = \$ 57$$

$$C_e = \$ 60$$

$$F = \$210$$

$$T = \$ 30$$

$$C_r = \$244 \text{ (5 tonnes per day, plus \$40/kg transport)}$$

$$V_n = 621 + 312 - 1196 - 4.9\Delta C_w - (210 + 30 + S)$$

$$V_n = \$-503 - 4.9\Delta C_w - S$$

$$S_n = -.66 - X$$

Thus, ignoring waste disposal cost differences and safeguard costs, mof will cost 66 percent more than the UO_2 fuel cost (of \$765/kg). With these uranium and enrichment costs, C_r would have to fall to about \$130 per kg before V_n would become positive, even assuming $4.9\Delta C_w + S$ were zero. This is about 60 percent of the low estimate for C_r .

(c) Pu recycle in the U.S.: As compared to the previous case, the only cost difference in the U.S. would be lower transport costs associated with reprocessing, \$20 per kg instead of \$40 per kg. This raises the value of V_n by \$98; thus

$$V_n = -405 - 4.9\Delta C_w - S$$

$$S_n = -.5 - S.$$

Thus, at these costs and prices recycling would be very unprofitable in the U.S.

(d) Pu recovery from heavy water spent fuel: Heavy Water Reactor (HWR) spent fuel contains only about 2.3 grams of Pu per kg and no usable uranium. Assuming the value of Pu is determined by its use in PWRs, the net value of mof from Pu taken from HWR spent fuel can be written:

*X stands for the contribution to relative costs from waste storage and safeguard costs.

$$V_N = V_G - C_u - 15C_r - 15\Delta C_w$$

$$(9) V_N = 5.2C_u + 5.2C_e - (F + T + S) - 15C_r - 15\Delta C_w,$$

since it requires 15 kg of spent HWR to obtain the Pu for 1 kg of mof. Using the U.S. value of \$224 per kg for C_r , and other U.S. values for the other variables:

$$V_N = 296 + 312 - (290 + S) - 3360 - 15\Delta C_w$$

$$V_N = \$-3042 - 15\Delta C_w - S,$$

thus demonstrating the much lower profitability of reprocessing spent fuel from HWRs. For reprocessing of HWR fuel to be profitable, C_r (including transport of spent fuel) would need to be less than \$21 per kg. Although reprocessing of HWR fuel might be somewhat cheaper than for LWR fuel, no reasonable difference will affect this conclusion.

(6) The profitability of plutonium recycle: high estimates.

This section repeats the calculations of the previous section using the high estimates for the sensitive variable.

The reprocessing costs required to make $V_N = 0$, assuming $4.9\Delta C_w + S = 0$, are calculated in the following cases. These are identified as C_r .

(a) Future Recycle in the LDC National Facilities:

$$C_u = \$100^*$$

$$C_e = \$150$$

$$F = \$260$$

$$T = \$30$$

* These figures are explained and justified in The Present Prospects for Proliferation: The Setting of the Problem.

$$C_r = \$1032 \text{ (1 tonne/day reprocessing, plus \$20/kg transportation)}$$

$$F_u = \$100$$

$$V_N = 1090 + 810 - 5057 - 4.9\Delta C_w - (260 + 30 + S)$$

$$V_N = \$3447 - 4.9\Delta C_w - S$$

$$S_N = (-3447 - 4.9\Delta C_w - S)/1500 = -2.3 - X$$

$$C_r^* = \$329$$

(b) Future Recycle in an MRC:

$$C_u = \$100$$

$$C_e = \$150$$

$$F = \$210$$

$$T = \$30$$

$$C_r = \$340 \text{ (5 tonne/day reprocessing, plus \$40 kg transportation)}$$

$$F_u = \$100$$

$$V_N = 1090 + 810 - 1666 - 4.9\Delta C_w - (210 + 30 + S)$$

$$V_N = \$-6 - 4.9\Delta C_w - S$$

$$S_N = -.00 - X$$

$$C_r^* = \$339$$

(c) Future Recycle in the U.S.: Costs are the same as above, except that $C_r = \$320$ because of lower transport costs.

$$V_N = \$92 - 4.9\Delta C_w - S$$

$$S_N = .06 - X$$

$$C_r^* = \$339$$

(d) Future Recycle of HWR fuel: Using equation (9) and the U.S. values,

$$V_N = -3740 - 15\Delta C_w - S$$

$$S_N = -2.5 - X$$

$$C_r^* = \$71$$

Thus, even with these high uranium and enrichment prices, HWR reprocessing will be very unprofitable unless reprocessing costs are far below even the low estimate.

(7) Implications of the analysis.

In the cases analyzed, plutonium recycle ranges from very unprofitable to marginally profitable. For most of the range between the high and low estimates, recycle would be unprofitable. Although with such great uncertainties, there are certainly conceivable circumstances that will make recycle profitable, the implication of the analysis is that the odds are strongly against their occurrence.

Further, it should be clearly understood that plutonium recycle will have, at best, a minor impact on the overall economics of nuclear power. Mixed-oxide fuel seems unlikely to become as much as 25% cheaper than uranium-oxide fuel. At a 25% cost advantage, and supplying the theoretical maximum of 20% fuel requirements, mixed-oxide fuel would lower total system fuel cycle costs by only 5%. But, fuel cycle costs are only about 20% of total nuclear generating costs; thus the total effect of plutonium recycle, even assuming a 25% cost advantage for mixed-oxide fuel, would be a one-percent reduction in system generating costs. Further generating costs are only 50% of the delivered cost of electricity; so the reduction in total electricity system costs would be only one-half of one percent.

To obtain this minor savings will require not only reprocessing facilities but special fuel-fabrication facilities and additional fuel-rod design and testing.* As compared to uranium-oxide fabrication, mixed-oxide fabrication is made more difficult by the radioactivity and toxicity of plutonium (requiring that all steps in the process be done automatically or within shielded glove boxes), the relatively small critical mass of plutonium, and the need to safeguard the plutonium against theft. Performing this on the scale necessary for commercial use is still in the development stage, with numerous reliability problems apparent. In particular, any repairs of equipment are difficult and time consuming because of the plutonium contamination.**

*And, perhaps special enrichment and fuel fabrication facilities to process recovered uranium, which will be contaminated with non-fissile U_{236} . See Appendix II.

**A discussion of some of the difficulties in MO_2 fabrication as well as estimates of cost penalties is contained in H. Bairot, P. Haubert, and E. Vanden Bemden, "The Plutonium Fuel Penalty, Design and Production," presented at the American Nuclear Society Meeting on Commercial Nuclear Fuel Technology Today, Toronto, Canada, April 1975.

Experience available on the use of mixed-oxide fuel in LWRs, consists essentially of four small experimental tests. These were conducted by the AEC, Westinghouse, the Edison Electric Institute, and General Electric. Two of these were in small, special thermal reactors. Two were in a commercial power reactor. In one core test, reasonably high burnups were obtained, but in all others, burnups were substantially below commercial levels. A small incidence of rod anomalies and failures were found in most of these tests, but apparently no serious design defects.* Still, before commercial use will be licensed, further design and testing undoubtedly will be required. Mixed-oxide fuel is still in the development stage.

c. The Breeder Reactor

Only .7% of the atoms (U_{235} atoms) in natural uranium can be used directly to produce nuclear energy. The remaining 99.3% consists of U_{238} atoms which do not fission easily and, thus, will not sustain the necessary chain reaction. However, when bombarded by neutrons, some of the non-fissile U_{238} atoms are converted to fissile plutonium atoms. This occurs in LWRs, and the plutonium produced within the reactors actually contributes about one-third of the energy in the reaction. Breeder reactors are designed to enhance this "breeding effect, so that they actually convert more U_{238} to fissile plutonium than the amount of fissile material they consume. This fissile plutonium produced in the breeder can then be separated from the uranium by reprocessing, with some of it being used to refuel the breeder and the remainder used as fuel in LWRs.

By converting U_{238} to fissile plutonium, the breeder concept would greatly increase the energy derived from a given amount of natural uranium (perhaps by as much as a factor of 50). Since natural uranium in high grade ore appears in relatively short supply compared to fifty year projections of demand, assuming only LWR's, there is a strong presumption that breeder reactors will eventually be required to extend the effective supply of fissile material.

Without disputing the eventual need for breeders, it is legitimate to ask, when are breeders likely to be economically attractive? If the answer is not for twenty-five years, then the breeder concept provides no immediate justification for undertaking reprocessing and plutonium recycle (as distinct from small scale R & D on optimal ways of reprocessing). On the other hand, if they are to come into widespread use by 1985-1990, then an immediate start to gain experience with plutonium makes a good deal of sense.

*U.S. Atomic Energy Commission, Generic Environmental Statement Mixed Oxide Fuel (GESMO), Vol. II, WASH-1327, August 1974.

Whether or not breeders are likely to be commercially significant in the near term (before 1990) depends upon: (1) The success of current research and development programs for the Liquid Metal Fast Breeder Reactor (LMFBR), and (2) the future relative prices of LWRs, LMFBRs, uranium, and enrichment. Consider each of these in turn.

There are currently operating LMFBRs in the Soviet Union, France, and Great Britain. The U.S. demonstration of LMFBR is not scheduled to operate until 1982. The early introduction of LMFBRs depends primarily on the success of the development programs with currently operating reactors. Of these programs, the French appears to be most successful. Since July 1974, their Phenix 250 MWe plant has been supplying electricity to the commercial grid with an availability factor of 75 percent. According to those in charge of the program, no major design problems have been encountered, and no unexpected fuel-rod problems have occurred. On the basis of this success, the French are contemplating construction of a 1200 MWe commercial prototype station. The decision on ordering this reactor has been delayed a year from the previously planned decision date of April 1975. The first commercial prototype was planned for operation in 1985, but this seems likely to be delayed also. Even if delays are not experienced, general commercial availability will not occur before the 1990s.

If technically feasible, the question of significant introduction of LMFBRs revolves around economics. Although early proponents argued that the breeder was essential to prevent us from exhausting our uranium supplies, this is an oversimplified view of the resource problem. There is not a single "supply" of uranium, but rather different supplies at different prices. In fact, at some price it would pay to remove uranium from the oceans, where there exists amounts that are very large relative to possible needs for the next fifty years.

The breeder represents one alternative to mining as a means of obtaining fissile material. Thus, the breeder's introduction is economically desirable when (and not before) it will produce fissile material more cheaply than mining. Further, it should be understood that even if economically desirable, breeders are not going to be critically important to overall nuclear economics for a long time. Even if uranium and enrichment costs double from recent values of \$44 per kg U_3O_8 and \$60 per kg of separative work, nuclear generating costs in LWRs will rise by only 2 mills per kwh. In the 1980s we can expect delivered electricity to cost around 50 mills per kwh (in 1975 dollars); thus, even if the breeder were to prevent a doubling of fissile material costs (a doubling that is by no means certain to occur), the savings would be only a small percent of the electric bill. Given the total amount of electricity produced, the dollar magnitude of a few percent savings would be large, and if they could be obtained, they obviously would be desirable. On the other hand, electricity cost changes of a few percent are very small compared to the changes already experienced and that will continue to be experienced due to rising construction costs. Claims that early introduction of the breeder is essential to the viability of the nuclear industry do not stand up to analysis.

Will early breeders be economical? Generally, LMFBRs are expected to be more expensive than LWRs although the margin is quite uncertain. French cost experience has been quite favorable, with the 250 MWe Phenix (built between 1969 and 1973) reported as costing about \$175 million current dollars, or \$750/kw. If no serious problems arise, and the usual scaling laws apply, the 1200 MWe Phenix could well be quite competitive with LWRs. On the other hand, Hans Bethe in recent testimony to Congress presented estimates by Westinghouse Corporation that a LMFBR would cost 50% more than a LWR. Current estimates for LWRs beginning operation in the early 1980s are about \$1000 per kw. On this basis, using a 15% fixed charge rate and a 70% operating rate, the capital cost penalty for an LMFBR versus a LWR would be about 12 mills per kwh. Thus, for the LMFBR to be competitive, LWR fuel cycle costs would need to exceed LMFBR fuel costs by 12 mills per kwh. This appears outside the possible range of fuel cycle costs in this century, since even with \$100 per kg uranium and \$150 per SWU of enrichment, nuclear fuel costs for LWRs would be only about 6 mills per kwh. Most experts expect uranium prices to be much lower than \$100 per kg during this century.*

Thus, if the LMFBR does cost substantially more than the LWR, it will not be economic in this century. On the other hand, all of the costs involved in making the comparisons between LWRs and LMFBRs are very uncertain. These uncertainties appear to be such as to make unwise any major commitments to the LMFBR at this time, such as anticipatory reprocessing of LWR fuel and recycling of plutonium.

2. Reprocessing as a Part of a Long-Term Waste Storage Program

One non-military motive for reprocessing is independent of reprocessing economics: The desire to separate out all very long-lived transuranic elements (actinides) from spent fuel. As removed from a reactor, spent fuel contains radioactive isotopes that will persist for hundreds of thousands of years, making environmentally safe storage of these wastes a matter of great controversy. The possibility exists, however, of removing essentially all of the long-lived actinides (which are only a few percent of the total) by reprocessing, leaving a residual waste product which decays to safe levels in less than 1000 years. Geologic storage for this length of time appears feasible and safe. The actinides can then apparently be recycled into reactors and transformed into shorter-lived isotopes.

*In the wake of the Westinghouse unilateral cancellation of its uranium supply prices in late 1975 (after this report was prepared), uranium prices on a few contracts rose as high as \$40 per lb U_3O_8 (\$114 per kg U). This short-run price response does not contradict the expert opinion that supplies of uranium adequate for needs in this century will be available at costs far below \$100 per kg U. As supply expands over the next several years, prices may be expected to drop toward the supply curve. See the discussion on pp. 105-106.

Although this scheme would involve, in effect, plutonium recycle with all of its problems and risks, it would provide a solution to the very troublesome problem of waste disposal. As a solution to the waste problem, even very high reprocessing costs might be tolerated: At \$500 per kg, reprocessing would add only 2 mills per kwh to the cost of electricity.

Such a waste handling system is in the very preliminary stages of conceptual design in the United States. Considerable improvements in reprocessing technology would be required. Development to a practical stage of application, if it occurs at all, is many years in the future. No other countries, to our knowledge, are seriously contemplating such a waste handling system. Over the near term, large-scale reprocessing for waste disposal purposes is not a realistic possibility.

V. Thinking Through the Middle Power Nuclear Option--Paradoxes and Problems of Proportional Deterrence in the Case of Japan

Overview

"When two nations are armed with nuclear weapons, even if they are unequally armed, the status quo is inevitable."*

. . .

"Under certain conditions, a new form of equality can be established among nations. In questions of security and defense, there can no longer be strong nations and weak nations--at least in facing certain dangers."**

This chapter examines an essential assumption in the argument that middle-sized nations should acquire nuclear weapons to equalize their relations with super-powers--the assumption that an adequate nuclear deterrent against a super-power would be relatively easy to achieve. We use Japan as a specific example.

Of the few analyses of the force requirements for a secure retaliatory capability for middle-sized powers that have appeared, many are marred by methodological deficiencies. One of the purposes of this chapter is to point out some of these deficiencies and to indicate how they may be removed.

The analysis is only preliminary and illustrative, a pilot for more complete analyses that we believe are needed. It would take us well beyond the scope of this project to do a definitive design, costing, and evaluation of alternative middle-sized forces for the 1980s and beyond.

We do not attempt to prove that such forces cannot be built--indeed it is possible that a country with the resources of Japan could develop a secure second-strike retaliatory capability, and manage to maintain this capability as technology on both sides advances. We do believe, however, that the design and development of such forces is not as simple a matter as many proponents of minimum and proportional deterrence would have us believe.

* Pierre Gallois, The Balance of Terror, Strategy for the Nuclear Age, Houghton Mifflin Co., Boston, 1961, p. 7.

**Ibid., pp. 8, 9.

In what follows, we discuss:

- 1) Some of the limitations in the theory of proportional deterrence.
- 2) The need for good and survivable command, control and communications as an essential element in a second-strike retaliatory capability, and the difficulty of securing it.
- 3) The geographical situation Japan faces vis-a-vis the Soviet Union, which appears to impose on Japan the requirement for systems with ranges on the order of 4000 n mi, whether sea or land-based, unless she is to depend on overseas basing and communications at extended distances. At the same time, paradoxically, she is very close to the Soviet Union from the point of view of Soviet offensive operations, either against land or sea-based systems.
- 4) The vulnerability of a Japanese force of land-based ICBMs to Soviet attack using nuclear or non-nuclear weapons. Precision guidance technology of the 1980s could make it possible for the Soviet Union to achieve a high level of effectiveness against a Japanese land-based force even without resort to nuclear attack, and with nuclear weapons she most certainly would be able to do so.
- 5) The possibility that Soviet ASW technology in the 1980s and beyond would be a match against a modest-sized Japanese submarine-based force.

Part of the problem faced by a middle-sized power in going to a submarine-based force is that the average number of submarines at sea at any one time would be a small number and hence fluctuations about the mean value could be exploited by the attacker--a point ignored in some prominent calculations. Similarly the adversary could use search and count strategies in which he waited until some combination of good luck and good ASW conditions gave him a substantially better than average capability to attack the force at sea.

As noted, none of the above establishes that the Japanese could not develop a first quality second-strike retaliatory capability. However, developing such a force is by no means an easy task. And if they were to embark on, say, a program to develop a 4000 n mi SLBM with a quiet SSBN with other good anti-ASW capabilities, they could not guarantee to themselves at the outset that the development would be successful, of reasonable cost, and able to deal with what the Soviets had developed in the meantime.

In short, if dependence on the U.S. has its risks and costs, so does going it alone.

Proportional Deterrence

Proponents of "proportional deterrence" have argued that a medium-sized nation would be able to deter a super-power by being able to inflict levels of damage much lower than those that can be inflicted by the U.S. or Russia on the other. Thus, the argument goes, a medium-sized power can deter a super-power with a modest nuclear force, well within its means.

There are problems with both parts of this argument. The first part contains the seeds of its own contradiction -- it is a paradox. A super-power would have the ability to inflict overwhelming destruction on the population or wealth of the medium-sized power if it so desires, and to threaten to do so in counter-retaliation. If deterrence is proportional to the stakes, just what is the medium-sized power going to defend by an act of limited destruction which invites unlimited destruction in return?

Modern nations have with honor and rationality gone to the extreme of relinquishing their sovereignty and permitting invasion of their homelands by their enemies rather than undergoing further death and destruction when the odds against them were overwhelming. Both France and Japan are among the World War II examples. Why should we then assume that they would ever credibly threaten to inflict finite destruction on a super-power when that super-power could counter-retaliate so overwhelmingly?

This is not to say that there would not be some incremental deterrence potential in an independent nuclear retaliatory capability if everything else were equal. A limited nuclear retaliatory capability in the hands of a medium-sized power would give a super-power adversary some cause for concern. But the effect would be limited. So limited, it would seem, that it is difficult to imagine what plausible actions of the super-power might be altered by this threat. Even in the extreme case of a surrender demand, it is hard to imagine the super-power phrasing it in a way that made nuclear devastation of one's homeland seem the better way out. There is a difference between political survival of a nation's sovereignty and biological survival of its population. Of course this is the starkest, most extreme case. In lesser "vital" matters, the existence of a small nuclear force is likely to be largely irrelevant in the face of an overwhelmingly larger force.

But debating as if all else would be equal sidesteps some of the major effects that can result from the acquisition of nuclear forces by medium-sized countries.

Consider one of the underlying motives for an independent nuclear capability -- doubt in the reliability of a mutual defense agreement with a super-power leads to the belief that instead an independent nuclear deterrent should be developed.

Japan, it might be so argued, should not depend on the U.S. guarantee, because the U.S. might be deterred by the Soviets, or more to the point, the Soviets might be willing to take action against Japanese "vital" interests on the expectation that the U.S. could be deterred from delivering on its guarantee.

But how reliable would be the nuclear guarantee of Japan to itself? How convincing is this one-sided self-suicide pact?

Another way in which all else may not be equal is in the non-nuclear defense or self-defense forces of a medium-sized nuclear power. If the resources needed for the nuclear forces are sizable relative to the nation's resources then their acquisition may cut into other forces needed.

This brings us to the second problem with the argument for an independent nuclear deterrent for medium-sized powers. Can a middle-sized nation embark on the journey to an independent second-strike capability with assurance of success at a modest level of effort?

Japan is a good case to consider, because she undoubtedly has a very high level of technological capability. The Japanese space program now runs over \$200 million a year. This level is a fourfold increase in five years. In FY74-77, seven satellites, scientific and applied, are scheduled for launch by Japanese vehicles. Two launch vehicles are under development, the M and N launchers. By 1977 the M launcher, a solid propellant vehicle, is expected to be able to put about 60 kg into a 500 km by 30,000 km orbit. The N launcher, which has both liquid and solid propellant motors, is to be able to launch 130 kg into geostationary orbit. R & D is underway on improving rocket engines and on guidance and control systems capable of putting several hundred kg into geostationary orbit. The field of guidance technology, an especially critical one, is being worked on by the National Aerospace Laboratory and Japan Aviation Electronics Industry, Nippon Electric Co., and possibly other organizations. Japan Aviation Electronics has been working on inertial guidance since 1965 and is working on a guidance package for the N rocket. Nippon Electric has also carried out a cooperative effort with Tokyo University on real-time radio guidance. Work is being carried out now on an increasingly broad basis on communications, navigation, earth observation, geodetic and other satellites. Japan is also developing ship nuclear propulsion: The technology in the ship Mutsu (its problems are not fundamental) could lead to a future submarine propulsion system.

Most treatments of the technical problems of joining the nuclear club have stopped with the problems of building bombs. Since the days of the Manhattan Project the diffusion of nuclear technology has progressed to the point where it would now be a relatively simple matter for a nation as advanced as Japan to make this step -- to assemble and detonate an atomic bomb.

But technology has also advanced in the means of destroying forces -- of attacking and destroying fixed targets, of locating concealed mobile targets, and in attacking bombers and missiles after launch. Even if Japan were to attempt to maintain only a modest sized "secure retaliatory capability" against the Soviet Union it is not a foregone conclusion that she can do this with a modest investment in forces, in face of the continually advancing means for destroying these forces that will be available to the Russians. To some extent the problems Japan would face are common to all medium-sized powers that might aspire to a super-power deterrent status, and to some extent they are peculiar to the Japanese geographical situation.

Considering the central role that the development of a survivable and effective second-strike capability has had in U.S. strategic force planning, it is curious that so little attention has been given this problem for the case of smaller nuclear powers. There have been calculations, of course, but many of these have had major methodological deficiencies, or have used weapon delivery accuracies or other parameters inappropriate to the 1980's or have implicitly assumed a notable lack of determination or planning on the part of the attacker.

In the remainder of this chapter we outline some of the problems the Japanese would face in trying to develop even a modest "secure retaliatory capability" and illustrate these with exemplary calculations, intended as much to show the deficiencies of some of the methodologies that have been applied to this problem as to give some feeling for how things might turn out.

Nuclear weapons may be cheap and getting cheaper, but the attainment of all the elements of a force capable of withstanding the attacks of a super-power may remain quite expensive relative to the resources of medium-sized powers. And acquisition is not a one-shot matter. The medium-sized power could face continued problems of force obsolescence and replacement. A wider appreciation of these problems may lead to greater realism in the discussion of Nth power independent nuclear capabilities.

The analysis is preliminary and illustrative only -- a pilot for more complete analyses that we believe should be conducted.

Command, Control and Communications

Numerous problems must be solved in designing a second-strike retaliatory force. By no means the least of these is the development of procedures, command posts, communications systems, and information gathering systems into a network for reliably controlling the forces and launching them if necessary under suitable military and governmental control. And this system must be able to not only evaluate the nature of attacks that have been made on the forces, but must be able to survive attacks on itself. (Such systems may be the weakest links in the British and French nuclear force postures -- a point that deserves further analysis.)

The systems which are considered to be the most survivable -- ballistic missiles on submarines -- present the most difficult communications problems. These would be most severe if, in the case of Japan, it were necessary for the forces to be deployed close to European Russia, i.e., far from Japan.

It can be argued that destruction of the decision-making apparatus or of the ability to communicate without destroying the forces will merely introduce delays in their launch. At least the attacker cannot count on the forces never being launched. This is one reason we have stressed survivability of the forces themselves in the calculations below. However, potential vulnerabilities of the command-and-control structure are one argument (among several) against schemes for insuring the survivability of the forces through rapid launch.

Japanese Geographical Situation

From the point of view of Soviet attacks upon Japan the two nations are close together. But from the point of view of Japanese attacks upon the Soviet Union there are vast distances between them. For a Japanese deterrent force capable of only reaching targets in Asian Russia would appear to have too little dissuasive power. Important as Vladivostok is as a port, it could be rebuilt if destroyed. The persuasive power of a threat to its population (estimated at 426,000 in 1970*) would be greatly weakened by the Soviet ability to threaten to destroy every major city on the Japanese mainland in return (Tokyo proper has a population of almost 9 million and is in a metropolitan area of almost 22 million; Osaka has a population of 3 million in a metropolitan area totaling over 13 million; Nagoya has a population of

*"Nuclear Forces for Medium Powers: Part I, Targets and Weapons Systems," by Geoffrey Kemp. Adelphi Paper No. 106, The International Institute for Strategic Studies, London, Autumn, 1974. Estimated as 472,000 in 1972 in The International Atlas, Rand McNally, 1974, p. I.21.

2 million in a metropolitan area of 3 million).*

By far, the greatest concentration of Soviet population and industrial wealth is east of the Urals over 4,000 n mi away. Thus the Japanese would have to reach to intercontinental ranges with their nuclear deterrence forces.

Range/Transit Requirements for Japanese SLBMs

The first and second generations of U.S., Russian, British and French SLBMs had nowhere near a 4,000 n mi range. Only now, with Trident I and the SS-N-8, are the super-powers putting such missiles on submarines. But a Japanese SLBM force which attempts to get by with anything of lesser range by deploying the submarines closer to Europe and Russia would face very major transit problems. Table 11 shows the transit times required to go to various potential operating areas and the approximate missile ranges needed in these operating areas in order to reach the Moscow area. The first entry shows that it is virtually out of the question to try to get by even initially with a system having the range of the first U.S., British, and French systems. These initial systems had a range requiring they operate in the North Atlantic, or possibly the eastern end of the Mediterranean. But for the Japanese to use the North Atlantic would require a 13,000 n mi transit if they were to avoid the Panama Canal and go around South Africa.** The length of time it would take to transit such distances depends of course inversely on the average forward movement of the submarines, or what is called the Speed-Of-Advance (SOA). Although nuclear submarines have generally been designed for maximum speeds of 20 knots or more, fuel consumption becomes excessive at high speed to the extent that time saved by transiting at high speed could be lost in the end by shortened time between refuelings. Using a reasonable 12 knot speed of advance it would take 90 days round trip to transit via the Panama Canal and 110 around South Africa.

This should be compared to the nominal 60 day cruise time for U.S. submarines. The Japanese would have to cope not only with such problems as crew endurance and fuel cost, but also with numerous problems of maintenance at extended distances.

By going to a 2500 n mi range (the published range of the Poseidon missile) the Japanese could use an operating area in the Arabian Sea,

*Figures are from the 1970 Census, The International Atlas, Op. cit., p. I.17.

**We assume that the alternative of forward basing of submarines in the Atlantic and movement of crews by air is not open to Japan.

Table 11

Range and Transit Time Requirements
for Japanese SSBNs

<u>Operating Area</u>	<u>Approximate Missile Range</u>	<u>Approximate Transit Time (Round trip)</u>
North East North Atlantic	1200 n mi	90 days via Panama Canal 110 days via South Africa
Arabian Sea	2500 n mi	41 days
Bay of Bengal	3400 n mi	29 days

Assumptions:

12 knot average speed of advance in transit.
Ranges provide operating area of approximately
200,000 n mi² -- roughly the operating area avail-
able to the first U.S. Polaris boats. Opera-
ting areas computed to 100 fathom line excluding
enclaves and regions above winter limit of ice.

The home port assumed for these calculations is
Yokohama.

Routes are through Straits of Malacca, except
for Panama Canal transit to Atlantic.

approximately equal in area to that used in the North East North Atlantic by our very first Polaris boats. Out of a 60 day operating cycle, roughly two-thirds, 41 days, however, would still be spent in transit. This could be reduced to 29 days round trip transit time if it were possible to use the Bay of Bengal which would, however, require a missile of approximately 3400 n mi range.

In all these cases, however, the Japanese would be operating at great distances from home port. Moreover the submarines would have to transit the waters in and round Indonesia -- in our calculations we have assumed they use the Straits of Malacca.

The straits of Malacca are territorial waters, although the right of innocent passage is recognized in international law. This route requires traveling about 1,000 n mi each way in water less than 100 fathoms deep (the minimum depth used by U.S. SSBNs for submerging) including about 500 n mi in the narrow straits.*

It would be ironic if Japan developed a nuclear deterrent force dependent upon these sea lanes, since one of the major defense concerns of Japan is her dependence on these sea lanes for crude oil. Eighty-seven percent of Japanese crude oil comes from the Mid-East.** "One school of [...] defense thought in Japan, in line with [...] concern for energy resources, has called for a greater capability to defend Japan's vulnerable sea lanes that stretch from the Persian Gulf through the Straits of Malacca to Japan. In particular the crucial issue of the continued use of the Malacca Straits has been debated widely with the costly detour through the Straits of Lombok becoming almost common knowledge. This issue itself surfaced when Indonesia announced it would require tankers of more than 200,000 tons to '...detour through the Lombok and Macassar Straits...' The government of Japan responded by expediting a Japanese financed survey of the passageway so that greater safety measures might be taken."***

In addition to the operational problems associated with such long transits through uncertain waters, the Japanese would face a severe problem in communication with submarines so far away.

*See Richard A. Miller, "Indonesia's Archipelago Doctrine and Japan's Jugular," U.S. Naval Institute Proceedings, October 1972, pp. 27-33, for discussion of the various passages through Indonesia and the international status of Indonesia's inland waters claims.

**John E. Endicott, Japan's Nuclear Option Political, Technical, and Strategic Factors, Praeger Publishers, New York, 1975, p. 31.

***Ibid.

A Northeast Passage?

Japan appears to be deceptively close to European Russia via the Arctic Ocean. However, in spite of rhetoric about using the "Northwest Passage" from early enthusiasts for the nuclear submarine, Arctic passages remain stunts for adventurers and not the stuff for routine, year-in-year out, all weather, all season operations. The first difficulty the Japanese submarine attempting such passage would face would be transiting the Bering Sea and the Bering Straits. These are shallow waters, providing hazardous challenges for the skipper attempting to maneuver between the ice above and the bottom below. The Nautilus was forced to turn back on its first attempt to penetrate the Bering Sea and it was not until a later trip deep in the summer (August) that it was able to find its way.

In case of an emergency on board, one of the first actions a submarine commander is likely to want to take is to surface. This can prove to be very difficult in the Arctic Ocean where the skipper may have to search for many hours to look for a polynya (clear break in the ice) able to accommodate his vessel, and there is the hazard that the shifting ice will close the polynya, forcing a hasty submergence.

Robert E. Kuenne quotes George P. Steele who commanded the "Seadragon" in a voyage from Atlantic to Pacific under the ice-pack as follows:

It had seemed but a small thing that in the last 8 hours only one polynya had broken the solid flow of thick ice overhead, mantled here and there as deep as 79 feet. The classic North Pole sounding of 2,270 fathoms under ice 8 to 15 feet thick had been a cheering note. But as the minutes and hours rolled by it had become increasingly clear that we were in trouble.*

Kuenne then goes on to state:

The "Seadragon" searched for twelve hours and nine minutes to find one opening in which to surface. Moreover, it also had trouble in finding again a polynya in which it had surfaced previously.**

*Robert E. Kuenne, The Polaris Missile Strike: A General Economic Systems Analysis, Columbus, Ohio, Ohio State University Press, 1966, p. 93, quoting George P. Steele, Seadragon, New York, E. P. Dutton & Co., 1962, p. 225.

**Ibid.

With regard to escape he states:

The experience of "Skate" had some parallels. In her summer passage under the ice she found open water in which to surface every day, but in her winter passage she found only one small puddle, two feet square, in twelve days and she was forced to break holes in the ice to surface. She began searching for such a weak point in the ice to break through at 8:00 a.m. on March 16, 1959, and finally found one at 2:30 p.m., or six and one half hours later. This occurred a full two hundred twenty miles from the Pole. In her attempt to surface the craft bounced off the ice once before breaking through, and in doing so provided moments of some concern to the crew. At the Pole she searched for three hours, attempted to break the ice but reversed her movement at the last moment when she found her instruments had misled her into believing thick ice was thin ice, and later surfaced in a narrow crack. Had the ice shifted while she surfaced there it could have trapped "Skate" in a tight grip--and indeed at another breakthrough the ice did shift and led to momentary concern for the safety of the boat. The conventional submarine "Sennet" some years before had been trapped in such a way and had to be freed by ice-breaker.*

A less dramatic problem of polar operations has to do with the inertial navigation systems of submarines. These depend upon gyroscopes which in turn depend upon the earth's rotation and they become poorer and poorer as the North Pole is approached.

It thus appears that whether Japan were to attempt to build a land-based or sea-based deterrent it would have to do so by using forces of intercontinental range, i.e., in excess of 4,000 n mi. The Soviets on the other hand could attack Japan using land-based systems with ranges on the order of 500 to 1,000 n mi.

Japan could develop missiles and submarines capable of Trident-I range. However, it could take longer than to develop shorter range missile systems, and it could cost a good deal more. It seems unlikely that even as technically advanced a country as Japan could manage to deploy a suitable system before the 1990s.

Damage Levels

It is of course impossible to fix in any mathematical way a damage level that will achieve some particular strategic objective. And we have of course argued about the paradox of a nation such as Japan attempting to work the strategy of proportional deterrence on the Russians

*Ibid.

when the Soviets can exert a deterrence out of all proportion against the Japanese. Professor Geoffrey Kemp in Parts 2 and 3 of his recent Adelphi Paper* looks at four alternative damage requirements labeled D₁ through D₄. Damage level D₁ is "the capacity to threaten in a second-strike mode the top ten Soviet cities excluding those protected by the Moscow ABM system permitted under SALT I (assumed to be Moscow and Gorkiy)." The target list for D₂ is the top ten Soviet cities including Moscow and Gorkiy. D₃ is the capability to attack the top fifty Soviet cities and D₄ calls for the ability to threaten the top 200 cities "to reflect more closely the requirements for 'assured destruction' as formulated by Mr. McNamara in the 1960s."** We will primarily focus on requirements to inflict the lower damage levels D₁ and D₂, even though, as we have noted, these may be inadequate.

We will use Kemp's estimate of the basic warhead requirements for these damage levels, simply as a means of pegging or labeling some different levels of damage inflicting capability that might be aspired to under the strategy of proportional deterrence. In terms of number of warheads that must be delivered to targets, damage levels D₁ and D₂ do not differ very much. The main difference of course between D₁ and D₂ would be the warhead requirements for penetrating ABM or surviving Soviet first-strikes. Using one megaton warheads and the requirement of "distributing 5 lbs. per square inch over-pressure over the whole city" Kemp estimates 26 delivered warheads would be required for damage level D₁ and 31 for damage level D₂. We will take a rounded value of 30 as being close enough in these two cases. With 50 Kt warheads Kemp estimates requirements would be 181 for damage level D₁ and 220 for damage level D₂ and we will use the rounded value of 200 for these cases.*** In addition we will be looking at much smaller numbers of weapons delivered to targets in some of the calculations to follow, since it turns out that in some cases even level D₁ would require unreasonably large Japanese forces.

Japanese ICBM Forces

Proponents of small nuclear forces argued in the early and mid-60's that it would be virtually impossible to destroy a force consisting of a moderate number of hardened ballistic missiles. These calculations generally assumed that the attacking force would be launched in a salvo

*"Nuclear Forces for Medium Powers, Part 2 and 3: Strategic Requirements and Options: by Geoffrey Kemp, Adelphi Paper No. 107, International Institute for Strategic Studies, Autumn 1974.

**Ibid, p. 4.

***Ibid, p. 26.

and that inaccuracy and unreliability would drive the required number of attacking missiles to several times the number of missiles attacked.

Today it is becoming increasingly accepted that there is no "technological plateau" that guarantees that it will take several missiles to kill a missile. But it would still appear from the calculations that have been published of missile duels that some 10-20 percent of the ICBMs in the hardened missile force might nonetheless survive. However, as our calculations will show, while the Russians might find it very difficult to reduce the number of U.S. ICBMs that could survive below such numbers, this need not be the case for a Russian attack against a Japanese ICBM force.

Moreover with advanced precision guidance and advanced munitions especially designed for hard targets, it may become possible to destroy most of such a force without resorting to nuclear weapons.

Consider the nuclear case. The first stages of the Soviet attack could involve a salvo of MRBMs or ICBMs against missile silos, air defense, and military command, control and communications. This could destroy most or all of the Japanese missiles (see calculations below) and leave the country open for reconnaissance coverage followed by either bomber or missile attacks against any silos which did not appear to have been destroyed.

Fratricide

Might the fratricide phenomena save enough of the Japanese force? One incoming nuclear warhead can kill another, or at least degrade its effectiveness. This effect is called fratricide and there are many phenomena associated with nuclear detonations that can cause it. If a second weapon is close to a target at the time a first weapon detonates nearby, the second weapon may be destroyed or rendered ineffective by the first detonation. Or if the second arrives a little bit later relative to the first detonation the shock wave from the first may deflect the second weapon causing it to miss the target. Or rocks thrown out by the first detonation may destroy the incoming warhead. After a while a high altitude dust cloud will form from the first detonation which may cause erosion of incoming high speed reentry vehicles. There are "time-windows" between the various effects, however, that have led U.S. analysts to conclude that it is possible to get at least two ICBM reentry vehicles per target onto hardened missile silos without one killing or degrading the other. Because of the tight time constraints imposed by

these time-windows it is also believed that re-programming for unreliability of the booster or post-boost control vehicles would be infeasible.*

One might be tempted to conclude from this line of reasoning that it is impossible to compensate for unreliability by simply increasing the number of warheads allocated to each target. This conclusion would be particularly important in the situation under discussion in which the potential attacker would have a large inventory of weapons from which to draw for attacking a small or medium sized force.

However, results are not that comforting for the little guy. Assume only two time slots per target. Each of the two "slots" per target can have any number of weapons allocated to it. It's just that only at most one of them will detonate effectively. Thus, the weight of the attack can be increased beyond two RVs to compensate for unreliability, but not inaccuracy. This might seem to be a wastefully unproductive use of weapons in the case of Soviet attacks against U.S. ICBMs, but not necessarily so in the case at hand where the Soviets would be working at short range against a small force. See Appendix 3, "Land-based Silo Survivability Formulas," for a discussion of the method of calculation.

Although we have couched much of our discussion in terms of the Soviet use of IRBMs or MRBMs against Japan, it might actually be more economical for them to use part of their intercontinental force rather than modernize their MRBM-IRBM forces. In any event, current estimates of Soviet MRBM and IRBM capabilities are of little value to us, since these have been deployed against quite a different threat.

Suppose, for instance, that the Japanese are able to house their ICBMs in silos as well protected as our Minuteman silos became after fixes were made to them, i.e., 300 psi.** Let us consider attacks in

*See U.S. Congress, Subcommittee on Arms Control, International Organizations and Security Agreements of Committee on Foreign Relations, Senate, Analyses of Effects of Limited Nuclear Warfare, 94th Congress, 1st Session, U.S. Government Printing Office, Washington, D.C., September 1975, and Joseph J. McGlinchey and Jakob W. Seelig, "Why ICBMs Can Survive a Nuclear Attack," Air Force, September 1974, pp. 82-85.

**Plus all other weapons effects associated with a detonation resulting in 300 psi at the target, including electromagnetic pulse and ground shock. The 300 psi estimate is based on the chart "Threat to Minuteman," presented by Deputy Secretary of Defense Packard to the Senate Armed Services Committee, March 20, 1969. See U.S. Congress, Committee on Armed Services, Authorization for Military Procurement, 91st Congress, 1st Session, Part I, U.S. Government Printing Office, Washington, D.C., 1969, p. 178.

which the Soviets use 5-megaton warheads delivered with an accuracy of $\frac{1}{4}$ nautical mile with an overall reliability of 75 percent.* Then the kill probability of a reliably delivered warhead would be 0.97.** The overall kill probability of a single warhead allocated against a target is thus 0.75×0.97 or about 0.73.*** If two weapons per target were used, then the survival probability per target would be about 7 percent. Thus, if the Japanese ICBM force were equal in size to the original French MRBM force--i.e., 27 silos--then only about two of these would be expected to survive the attack. Of course, each of these would have only a finite reliability--perhaps 0.75--and the expected number that would be delivered would be about one and one-half, provided the Japanese were able to reach the decision to launch before follow-on attacks and assuming the Moscow area with its ABM is avoided. This is a far cry from Kemp's level D1.

But, as mentioned above, the Soviets might find it worthwhile to allocate more weapons than the 54 implied above. If, for instance, four weapons per target were used--i.e., with two per fratricide time slot--then the probability at least one weapon arrived at a time slot would be about 0.94. Of course, if two weapons happened to arrive at a time slot, only one of them would be effective, and so the overall kill probability per time slot would be $0.94 \times 0.97 = 0.91$ and the overall kill probability per silo of the attack would be over 0.99--i.e., the survival probability per target $[(1 - 0.91)^2]$ would be less than one percent, actually only 0.8 percent. Out of a force of 27 ICBMs, the expected number surviving would be much less than one, practically zero. It turns out to be 0.2 of an ICBM.

In this situation it is more meaningful to talk about the probability that no ICBMs survive, and this is 80 percent--i.e., in this case the Soviets would have an 80 percent chance of killing all ICBMs in the Japanese force (over 90% if reliability is 0.8 instead of 0.75). And there is a 98 percent chance that no more than one missile would survive.

*Seventy-five percent is probably on the low side. For simplicity, we use cube root scaling of the weapon radius with yield, but we do not assume a "cookie-cutter" damage function. Instead, we use a "sigma-20" damage function as defined in the DIA report, Mathematical Background and Programming Aids for the Physical Vulnerability System for Nuclear Weapons, DI-550-27-74, 1 November 1974. See pp. 45 and 46 for the choice of 20% for the sigma value.

**With a 1000' CEP, quite achievable at these ranges in the 1980s, the same kill probability would result against 1000 psi silos.

***Unrounded figures were used in our calculations. Rounded values are reported in the text.

Of course, if the Soviets wish to push the probability of success of the mission even higher, they could allocate six weapons per target split among the two time slots, three per time slot, which would raise the probability of destroying all 27 ICBMs to 95 percent.

Even if the Japanese went to a 100-missile force (note we are not addressing the question of whether the Japanese could find suitable land on which to deploy such an extensive force), the Soviets could still destroy most of it without overly straining their own resources. Then 200 reentry vehicles (which with MIRVing could come from much less than that number of boosters) would lead to an expected number of seven Japanese ICBMs, of which about five might prove to be reliable. Kemp's level D₁ is six times as large, if we assume the Japanese ICBMs have single 1 MT warheads. By using 300 reentry vehicles the expected number of survivors could be reduced to two, and by going to 400 reentry vehicles the expected survivors could be reduced to less than one, 0.8.

These 400 warheads would represent only a fraction of the total forces the Soviets have deployed against the U.S., and it is worth noting that they need not come out of SALT quotas, which deal only with intercontinental forces.

So far, we have looked only at the simplest, crudest forms of attack, essentially salvo attacks in which all weapons arrive so close together in time that it would be physically impossible for the Japanese to launch their weapons before or during the attack. The Soviets could substantially reduce the forces required or greatly increase the probability of getting every missile by using a combination of missiles and bombers. It would seem foolhardy for the Japanese to assume that they could launch the one, two or seven ICBMs which survived the first salvo in the short length of time before bombers could carry out recce-strike attacks. But if the Russians do not want to count on such delays, they could coordinate the armed recce missions with pin-down attacks against the remaining ICBMs. It would take us too far afield to attempt to get into the specifics of the calculations of such pin-down attacks here; however, the limited geographic area available to the Japanese for deploying their hypothetical ICBM force and the close proximity of the Soviet territory to Japan would argue that it would be much easier for the Soviets to mount such attacks against Japan than it would be against the United States.

One final note on the political symbolism of the hypothetical Japanese ICBM forces: The Japanese might hope to gain some political leverage by actually deploying an ICBM force in hardened silos. But these benefits could very well vanish or turn against the Japanese if, as this force was being gradually deployed, intelligence indicated that the Soviets were constructing hardened, medium-range missile silos in Eastern Siberia or even were observed preparing launch sites for semi-mobile, intermediate-range missiles. An independent, proportional deterrent of Japan.

A Japanese SLBM Force?

Hardened, land-based ballistic missiles do not seem to be a useful avenue of approach for a small or medium power in the 1980s against great powers like the Soviet Union and the United States. But how about the systems which enjoy the greatest reputation for survivability -- submarine-based ballistic missiles?

Kemp, for instance, states, "The overwhelming consensus of opinions in the published literature is that, while there have indeed been technological breakthroughs in ASW techniques, the advantages still favour the hunted rather than the hunter."* But this assessment is based on advanced technology vs. advanced technology.

The success of submarine detection and holding techniques are very dependent on relative technical advantage. For instance in the case of one submarine hunting another, using passive sonar, success is critically dependent upon which submarine has the greater sonar range. If the seeker has the greater reach then he has a high probability of being able to detect the hunted submarine without the hunted submarine knowing he is there, and a good chance of successfully maneuvering behind the hunted submarine. Once behind, it is easier for him to detect and harder for the submarine under trail to detect. With sufficient range advantage the seeker can then often maintain trail for several days without the hunted submarine knowing he is there.** Even if the hider knows or suspects he is under trail, evasion tactics are much less likely to be successful if the range advantage lies with the seeker.

Range advantage depends not only on the relative qualities of the sonars of the two boats, but also on their relative noise levels. Thus, to deny significant range advantage to Soviet SSNs in, say, the 1980s, the Japanese would have to come close to the Soviet 1980s state of the art in both passive sonars and submarine quieting.

And it is not just a form of super-power chauvinism to say that the Japanese would have difficulty in catching up with Soviet ASW and quieting technology. After all, the Soviet Union has been unable to catch up with the U.S. in these fields, though not for a lack of effort or interest.

*Kemp, Part I, op. cit., p. 20.

**The reader may wonder how trail ever is lost under such circumstances. Equipment malfunction, of course, is one possibility. But intrinsic to the sea as a medium is the great variability of acoustic propagation conditions. If conditions worsen, trail may be lost. If they improve the covert trailer may be detected. And changes may occur at one ship's sonar frequencies but not at the others. Or a local noise source may cause the trailer to lose contact.

And note that it is not enough for the Japanese to achieve the technical capabilities that the U.S. or Soviet Union has in the 70s. Japanese boats in 1985 would have to contend with Soviet 1985 technology. And as the Soviet boats (and other ASW systems) continue to modernize their force.

Variability and Choice

We become so accustomed to estimates of expected results or the use of typical conditions in analyses that we may accept these approaches in situations where they are quite inappropriate. For a small force of SSBNs, variations from average situations can be quite large and one can be deceived by taking average results.

Consider for example the question of the number of SSBNs on station. Here the British experience is instructive. It is discussed in an Adelphi Paper by Ian Smart.* Britain has four "Resolution" class SSBNs. According to Smart "major refits for each submarine should occur after every three years of operation, with the target time for a major refit being six months." Even if a major refit took 12 months this means the boats have an in-commission rate of 75 percent. Also according to Smart the British plan to have their boats carry out four patrols a year with each patrol lasting 8 to 10 weeks. Using an average of nine weeks this figures out to be a patrol rate of slightly over two-thirds for those boats in commission. This means that the average number of boats on patrol would be 2 ($4 \times 0.75 \times 2/3$). Yet Britain "has had to concede that it will have only one on station at some times."**

The point is that the Soviets would not necessarily have to attack when the average number of SSBNs was at sea.

Another highly variable factor is the acoustic conditions for sonar search. These vary greatly with sea-state and temperature gradient in the water, among many factors. Thus it might be very difficult to keep track of a large number of boats all of the time, or under typical conditions, but nonetheless there can be occasional periods when the conditions for location are relatively very good.

*"Future Conditional: The Prospect for Anglo-French Nuclear Cooperation," Ian Smart, Adelphi Paper No. 78, August 1971, p. 15.

**Ibid. Smart notes that theoretically the scheduling of patrols and overhauls could be done so that the minimum on patrol would actually be two with these assumptions, and so puzzles over why those on station will drop to one at some times. He guesses, "the most plausible explanation is that experience has shown the need for major refits at more frequent intervals than the designers of the submarine reactors intended." But in any event the British experience has apparently been that the minimum would be one.

Table 12 shows, by way of illustration, the frequency distribution of one factor that affects higher frequency sonar -- wave height. Rough seas generate much noise; calm seas are quieter.* It is interesting to note the great seasonal variation in the North Indian Ocean as a result of the monsoons. These seas are apparently unusually calm during the winter -- the time of the northeast monsoon season. While many other factors would play a role, this suggests that the Soviets would try to conduct any "exercise" against Japanese SSBNs deployed in the Arabian Sea or the Bay of Bengal in this time of calm weather.

Finally, the Soviets might be able to exploit a search and hold strategy. The Soviets need not destroy each submarine as it is located or send out the order to attack all possible Japanese submarines independently of how many submarines are localized at the time of the attack. Instead, the Soviets could set in motion the process of search, detection, localization, and trail using whatever ASW resources they have available, while keeping track of the number of submarines that have been located sufficiently accurately to permit their attack. They can then wait until good sonar conditions or just random variations from the mean rate of success bring the number adequately localized above some threshold value and then order the attack.

If one is talking about a large force such as the approximately 20 submarines that the U.S. has at sea on the average, then the hunting nation might have to wait an unreasonably long time before all but one or two of them are localized. However, the situation is much different in the case of the three, two, or even one submarine that a medium-sized power might have on station.

Just as the deployment of a "counterforce" capability against the Japanese land-based ICBM force might undermine whatever political benefits the Japanese hope to gain from that force, so also would successful Soviet ASW exercises which succeeded in locating all or most of the Japanese SSBNs.

Delousing Away From Home

It is common practice for hostile ASW forces to loiter off submarine ports and attempt to pick up trail on the submarines as they

*". . . It is clear that the rough sea surface, not too far from the location of the measurement hydrophone, is the dominant noise source at frequencies between 1 and 30 kHz [Kilohertz]." Robert J. Urick, Principles of Underwater Sound for Engineers, McGraw-Hill, New York, 1967, p. 166. At low frequencies, say, below about 300 hertz, surface shipping is the dominant source of noise.

Table 12

Frequency Distribution of Wave Height By
Ocean Region

Ocean Region	Height of Waves in Feet					
	0-3	3-4	4-7	7-12	12-20	>20
North Atlantic (between Newfoundland and England)	20	20	20	15	10	15
Mid-equatorial Atlantic	20	30	25	15	5	5
South Atlantic (latitude of Argentina)	10	20	20	20	15	10
North Pacific (latitude of Oregon and South of Alaskan Peninsula)	25	20	20	15	10	10
East-equatorial Pacific	25	35	25	10	5	5
West Wind Belt of South Pacific (latitude of Southern Chile)	5	20	20	20	15	15
North Indian Ocean (Northeast Monsoon Season) (Winter)	55	25	10	5	0	0
North Indian Ocean (Southwest Monsoon Season) (Summer)	15	15	25	20	15	10
Southern Indian Ocean (Between Madagascar and North Australia)	35	25	20	15	5	5
West Wind Belt of Southern Indian Ocean (On Route Between Cape of Good Hope and Southern Australia)	10	20	20	20	15	15

depart. To counter such "port-watch-and-trail" tactics various "delousing" techniques are used. For high confidence these will usually involve the assistance of friendly forces -- aircraft, surface ships, or submarines. These would both help break trail and verify that trail has been broken. Such assistance may be essential if the ASW forces in question have the technological or numerical edge over the evading submarine. If the Japanese were to attempt to use the Arabian Sea or the Bay of Bengal as operating areas, they might find themselves having to deploy forces for delousing in the Indian Ocean, because of the possibility of Soviet ASW forces picking up the SSBNs as they exited from the Straits of Malacca or whatever passage they used through the Indonesian Archipelago.

Identification

False targets can greatly slow down certain types of ASW operations. A particular kind of "false-target" that might cause the Russians some concern would be a United States SSBN. It is unlikely that this would be a problem if the Japanese used the Arabian Sea or the Bay of Bengal since they are unattractive deployment areas for the U.S. In the case of a Japanese Trident-range missile operating in the Northwest Pacific, however, it would be necessary for the Soviets to take some precautions. Generally, however, different classes of submarines have quite distinct "signatures" to passive sonars and in fact often individual submarines within a class can be distinguished. Of course if the submarines have been held under trail from port the problem of mistaken identity would be nil. In any event the possibility of other submarines operating in the same areas as the Japanese submarines might rule out such techniques as massive bombardment of large open areas in the ocean with high-yield nuclear weapons.

Some Exemplary Attack Scenarios

There are a wide variety of measures that can be used for search identification, localization and attack of submarines.

Our calculations are only illustrative for two reasons: First, modeling of ASW operations is a complicated business and it is our desire to keep these calculations simple and relatively transparent. We will, however, discuss some of the implications of more realistic assumptions on our calculations. Second, unclassified information on ASW capabilities is very sparse.

The Case of One SSBN on Patrol

As noted above the British, even with a force of four SSBNs, two full crews per SSBN, and a favorable geographical location must apparently operate at least some of the time with only one SSBN on patrol. And of course it is possible that accidents or unscheduled maintenance

or delays in port may lead to situations where even a larger force would have only one boat on patrol at some times. Thus the case of one boat on patrol is of strategic significance for medium-sized SSBN forces. It deserves attention even though many ASW operational problems and many ASW analytical models become trivial for the one-boat case. We should not neglect this case simply because it lacks intellectual challenge.

If we assume the one SSBN or patrol has evaded watch and trail tactics, the most important parameter of the ASW forces would be their effective sweep rate. This can be thought of as the total ocean area searched per unit of time. In calculating effective sweep rate, however, one has to take account of the fact that detection, whether by sonar or other means, is probabilistic and not certain. Even if detected, an SSBN can take evasive maneuvers with some probability of success. For our calculations, which assume the SSNs have substantial technological advantage in sonars and quieting, we use an effective sweep rate of 90 square nautical miles per hour per SSN. This can be visualized as an SSN traveling at 15 knots with a perfect detection capability out to 3 nautical miles, and with zero detection capability beyond that. Or the searching sub could be traveling at $7\frac{1}{2}$ knots, with a "step function" detection capability that extends out to 6 nautical miles.

We wish to emphasize that the actual range of a sonar will vary quite substantially from time to time due to such factors as changes in propagation conditions and fluctuations in noise.

It seems reasonable to expect that individual search units will be sufficiently coordinated that they will not have overlapping search areas; i.e., their search rates can be assumed to be additive. However, it is incorrect to assume that if the total area searched over time is additive that then the probability of locating a submarine is just the ratio of area searched to area of operation. This is because the probability of detection is not a step function which goes from one to zero at some specific range from search vehicle and because of the difficulty of coordinating an extended search in such a way that the hunted SSBN cannot move from the unsearched to the already swept area. Instead, it seems more reasonable to assume that the conditional probability that a submarine will be detected in a time interval dt is independent of time. This leads to an exponential distribution for the cumulative probability of detection in time t given by

$$P(t) = 1 - e^{-nst/A}$$

in which n is the number of search units, s is the sweep rate per search unit, A is the area to be searched (assumed to contain the submarine), and t is the time since beginning the search.

The expected length of time before the search is successful can be readily found; it turns out to be simply the reciprocal of the coefficient of t ,

$$\text{Mean Search Time} = \frac{A}{ns}.$$

Consider the case of a $200,000 \text{ n mi}^2$ operating area. This would require a missile with a range of somewhat more than 2,500 n mi in the Indian Ocean, if targets as far north as Moscow are to be targeted from anywhere in the area. In this case, using 15 SSNs for the search,

$$\begin{aligned} \text{Mean Search Time} &= \frac{200,000}{15 \cdot 90} \text{ hours} \\ &= 148 \text{ hours} \\ &= 6.2 \text{ days} \end{aligned}$$

The probability of success would be 90% after slightly over 14 days.

Note that there is no major penalty for failure or for taking an extended period to find the sub. (Although the time available will depend on the nature of the confrontation between the two countries, it can also be said that the nature of the confrontation may well be determined in part by estimates of the time required to find the sub or subs.)

Even if the operating area were $800,000 \text{ n mi}^2$ in size, and the Soviets had no a priori information on location within this area, the expected length of time for 30 SSNs* to locate the submarine would still be only 12 days.

SSNs vs Two SSBNs on Patrol

In the case of two SSBNs on patrol, as in the previous section, we take no advantage in our calculations of locational information when the subs begin patrol. We focus our attention on the problems of destroying both of the SSBNs. The Soviets could conceivably search for

*Capt. John E. Moore, Editor of Jane's Fighting Ships, writing in the Foreword to the 1974-75 edition, estimates that by the early 1980s the USSR would have some 120-150 SSNs at current building rates (Jane's Fighting Ships 1974-75, Franklin Watts, Inc., New York, 1974, p. 75).

the submarines and simply attack the first one when it is found, hoping that its destruction goes undetected or that the Japanese are uncertain of the cause of its loss (this assumes, of course, that non-nuclear weapons be used to attack the submarine) at least for the length of time required to find the other submarine or that the Japanese could be deterred from hasty use of the one remaining sub. For our calculations, however, we assume that the Soviets do not attack until both submarines have been located. Thus it is necessary to hold trail on the first submarine while the search goes on for the second. The capability to hold trail is, therefore, important in these calculations, and is represented by the mean holding time H , which we assume to be 8 days. We use an exponential distribution for the length of time trail is held, a result that can be derived from the assumption that the conditional probability of holding trail in a time interval dt is independent of the time since trail was initiated.

The situation as described can be represented by a Markov process with the three states 0, 1 and 2 subs under trail.

The transition probabilities for this process are given by

$$p(j \rightarrow j+1, dt) = (M-j)(2-j) \frac{s}{A} dt, j = 0, 1$$

$$p(j \rightarrow j-1, dt) = j \left(\frac{1}{H} \right) dt, j = 1, 2$$

in which j represents number of submarines under trail at any time, $p(j \rightarrow j+1, dt)$ and $p(j \rightarrow j-1, dt)$ are the conditional probabilities the number of subs under trail will increase or decrease by one in a time interval dt , and M is the number of hunter submarines. It is assumed that each submarine under trail occupies the resources of one hunter submarine which is therefore unavailable for searching.* Thus, if j submarines are under trail, $M-j$ submarines are available for search and the number of submarines that are being looked for will be $2-j$. This explains these two factors in the expression for the conditional probability of going from j to $j+1$ submarines under trail (of course, if N submarines were being hunted the second factor in this expression would be $N-j$, not $2-j$). The conditional probability of going from j submarines to $j-1$ submarines under trail is just the number of submarines under trail j , times the loss rate per submarine under trail, $1/H$, times the time increment dt .

*Better trail-holding might result if two or more submarines, or if submarine and surface or air unit worked together, to hold trail. However, to coordinate it would seem necessary that such a trail be conducted overtly rather than covertly.

We are interested in the situation in which the subs are attacked once both are under trail. This can be modeled by making the state $j = 2$ a capture state of the process, i.e., by modifying the above transition probabilities so that the probability of going from two to one submarine under trail is zero. Then the probability that the modified process is in the state $j = 2$ at time t is just the cumulative probability that the seeking force will have located both submarines and attacked them at or before time t .

It is worth noting that the expected length of time under which two subs will be trailed, given they have both been located, is just $\frac{H}{2}$, i.e., one-half the mean holding time. Thus, for a mean holding time of ²eight days the expected length of time that the two subs would be under trail once both were located would be four days -- more than ample time to attack.

We have developed a computer program to solve the capture state Markov process numerically. Illustrative results are presented in Table 13 for various assumptions on effective operating area, the number of search SSNs, and elapsed time. We have used a maximum of 50 SSNs in the search mode, a number that should be within Soviet capabilities in, say, 1985.*

To achieve an operating area of 800,000 square n mi in the Arabian Sea, the Japanese would need a missile of about 3,100 n mi range if they are to reach the Moscow area from all points in the patrol area. Even then, there would be a fair chance (0.61) that a force of 50 SSNs would be able to locate both submarines on station within 16 days; and there is a 91% probability of success that they would have located both boats simultaneously within 32 days. These calculations assume that at the outset there is no a priori information on the location of the hunted subs than that they are in the operating area. In practice, this would probably be hard for the Japanese to achieve. For one, the Soviets could begin search when a sub has just gone on patrol, so its location would be better known than assumed.

Out-of-Range Patrol Areas

If the ocean area from which targets were in range were too constricted, the Japanese might put their subs on patrol out of range of targets. They could then be ordered to move forward in a crisis. They would have to move slowly, however, certainly with no greater than a 10 knot or so speed of advance, if they are to try to avoid detection. And the slower they moved the more time the Soviets would have to hunt and attack

*We are not assuming that this large a force would be deployed at all times in the operating area -- particularly if it is as remote as the Indian Ocean, but only that it is deployed at the time needed, say as an exercise.

Table 13

Probability of Simultaneously Trailing Two out of Two SSBNs
at Least Once in a Given Elapsed Time

Effective sweep-rate per SSN: 90 nmi²/hr

Mean holding time: 8 days

Initial conditions: No SSBNs Under Trail

<u>Operating Area (nmi²)</u>	<u>Number of Search SSNs</u>	<u>Elapsed Time (days)</u>	<u>Probability Both Located At Least Once</u>
200,000	15	8	0.44
		16	0.74
		32	0.95
	30	8	0.80
		16	0.97
		32	> 0.99
400,000	15	16	0.38
		32	0.66
	30	8	0.45
		16	0.75
		32	0.95
800,000	30	16	0.31
		32	0.57
	50	16	0.66
		32	0.91
1,600,000	50	32	0.58

them, evacuate cities. and work pressures on the Japanese government and populace to back off. Such extended games of nerve do not favor the substantially smaller power.

Operations in the North Pacific

With a missile that had a range of 4,000 n mi or more, such as the Trident I, the fifth generation of U.S. SLBMs, the Japanese would have available large operating areas close to home. Unfortunately, they are also close to the Soviet Union. Numerous systems for wide-area open ocean search or for extended trailing should be examined for this case. Possibilities that suggest themselves, but are by no means certain, are a Soviet SOSUS system for reducing the search area or setting up picket lines; the use of air ASW; and trailing techniques using multiple ASW types such as SSNs assisted by aircraft and surface vessels. A major determinant, again, would be how successful the Japanese were at cutting down noise and any other observables that Soviet sensors of the 1980s might be able to detect.

Other Systems

The above discussion has dealt with the two classes of systems that have figured in most discussions of middle-sized power independent nuclear deterrence forces. There are other potential systems, such as long-range cruise missiles, probably either submarine or surface-ship based. For a given range and payload, these would be of smaller size than ballistic missiles and so would have some deployment advantages over ballistic missiles. The biggest question for the Japanese would be whether they could assure themselves that such a system would give them adequate air defense penetration capabilities far into the future. (There is some controversy in this country over whether stand-off cruise missiles would be effective against Soviet defenses of the 1980s.)

Analysis of this and other options must await follow-on studies.

A Final Note

Perhaps we should re-emphasize that we are not claiming it would be impossible for the Japanese to develop and maintain a modest second-strike retaliatory capability. What we are suggesting is that this is not an obviously cheap way to buy defense -- that reaching Trinity may be only the beginning of a long, expensive, and irreversible journey.

VI. Life in a Nuclear Crowd

Much of the literature on the subject of nuclear spread, especially that written by Americans, views a world with many nuclear powers as vastly more dangerous than today's world. Foreign commentators have not always viewed the prospect so gloomily. To Pierre Gallois, an early expositor of the view that allies could not be counted on to commit suicide, it was natural and stabilizing for each state to possess these most powerful weapons for its own defense. From the perspective of the Third World, the wider distribution of nuclear weapons is sometimes seen as a requirement of distributional justice. On this view, military nuclear power, along with the world flow of income and stock of capital, needs to be shared more equitably. Understandably, not all nuclear advocates in the Third World hold that every nation should have nuclear weapons; they concentrate on the needs of their particular country. Security needs (or perhaps opportunities) are perceived with respect to adversaries armed only with non-nuclear weapons; more urgent concerns are generated by adversaries who have nuclear weapons or who appear to be getting them. Hedges against the breakdown of alliances are sought. And nuclear weapons have symbolic utility. In the words of an Argentinian Parliamentarian (echoing the words of several British Prime Ministers), "it is imperative for Argentina to have this weapon to sit at negotiation tables on equal terms with the world concert of nations."

Despite the existence of a good deal of rhetoric justifying national nuclear weapons programs, few of the countries with the capacity to make them have done so by 1975. They have not acquired nuclear weapons because of high costs, internal political opposition, concern about reactions from neighboring countries, an absence of military threats and a belief in the adequacy of alliance guarantees. As a result, the entry rate into the nuclear weapons club has been low, far lower than has often been predicted.

Two developments now promise fundamental changes: one is the growth in civilian nuclear programs and therefore an increased capacity to acquire nuclear weapons cheaply and rapidly; the other is a weakening of confidence in American guarantees of protection of allies.

As shown earlier in this report, by 1985 about 40 countries will have enough fissile material to make 3 bombs or more; almost as many are likely to have enough fissile material for 30-60 weapons or more. And the prospect in 1985, looking ahead, will be for many more countries to be in a position to acquire weapons cheaply and rapidly.

The second factor, concern about confidence in protection by the U.S., has been widely expressed abroad in the past year by both officials and non-officials in many countries. So far this factor apparently has not influenced governments in countries most firmly a part of the U.S. alliance system, i.e., in Western Europe and Japan, to acquire weapons. In contrast, most of the countries that now appear to be moving toward a weapons

capability are either outside of any alliance system, are on the fringes of the U.S. system of alliances, or are drifting out of the U.S. system. They read ominous signs in the collapse of the U.S. position in Southeast Asia, Congressional opposition to support for South Vietnam and Turkey, attempts to block facilities in the Indian Ocean and support for withdrawals in the Republic of Korea and Europe. Moreover, growing Soviet military power, together with an evident American preoccupation with reducing the likelihood of a U.S.-U.S.S.R. nuclear exchange, is not altogether reassuring to countries that have been dependent on the U.S. One response is to take out nuclear insurance.

The existence of this overhang of weapons-capable countries means that the great powers will have to allow for the possibility that small ones will respond to their actions by acquiring nuclear weapons. Events outside of their control could have this effect anyway. Although this concern has not been absent in the past, notably regarding Japan and Germany, it is now moving to the forefront.

In contemplating the world in 1985-90 one of the most important questions to ask is this: How likely is it that the countries able to acquire nuclear weapons rapidly and at low incremental cost will do so? Analogies with "chain reactions," "branching processes," "super-saturated solutions" suggest an exponential rate of growth in the future in contrast with the low, linear rate of spread since 1945. The Indian nuclear explosion of 1974 may have been the crucial "triggering" event between a linear past and an exponential future.

Although the prospect that many countries will take the additional step and acquire weapons now must be taken seriously, it is not certain. There exist countervailing forces that may substantially moderate the pace of nuclear weapons acquisition in the next decade or longer. The nature of these forces will be discussed later on.

But let us suppose that the "chain reaction" proceeds and that many additional countries acquire at least a few nuclear weapons by 1985. This possibility suggests several additional questions:

- What are the stability properties of relations among nations in a world with a few large, some middle-sized and many small nuclear powers--as well as many more non-nuclear ones? What shocks to the international system seem possible, and what equilibrating mechanisms might exist or be developed?
- What effect would these developments have on the likelihood of war, non-nuclear or nuclear? What are the likely consequences of the use of nuclear weapons?
- How will alliance relations affect decisions on acquisition, and, conversely, how is the wider possession of nuclear weapons

likely to affect alliances?

- What new nuclear threats does this mean to U.S. forces or territory? What might we have to do to survive in a world with many possessors of nuclear weapons?

A. Stability Properties of a Proliferated World

The concept of stability has many different and often ambiguous or conflicting meanings in the field of international relations. In general, instability refers to a change in the status quo, an abrupt change in smooth trends in a function caused either by factors inherent in the international system itself or produced by outside shocks to the system. For example, under the international gold standard system of the 19th century, a financial panic in one country could readily radiate across national boundaries and produce similar panics in other financial centers. This system had, however, a mechanism for restoring equilibrium in the role played by gold together with flexible prices. In the political-military realm the instabilities and the methods of restoring some kind of equilibrium are often more costly. Europe in the middle and late 1930s was in a latently unstable state. The system received shocks by a revanchist Germany under Hitler. The system degenerated into war, and equilibrium -- of a sort -- was only established through the collective efforts of many countries.

Worries about stability in a world in which nuclear weapons are spreading rapidly stem, first, from the observation that a great many rivalries and hostilities exist among -- and within -- nations; second, that the acquisition of nuclear weapons may drastically alter some power relations and have wider repercussions short of war; and third, that it might sharply increase the likelihood of wars, nuclear or non-nuclear and their destructiveness.

Some of the consequences are the following:

1. Changes in status or relationships short of war
 - a. Coercion of some countries by new possessors of nuclear weapons.
 - b. Internal political adaptations in response to new external threats.
 - c. Withdrawal of alliance guarantees by great powers.
 - d. New nuclear possessors becoming sources of weapons for other states and non-states.
 - e. Increase in defensive measures (civil defense, active defense, anti-terrorists) in many nations.

f. Nuclear threats or use by non-governmental groups, but possibly supported by outside powers.

2. Changes resulting in war

a. Nuclear war

- i. Nuclear war between the two great powers
- ii. Nuclear war between a great power and a middle or small power
- iii. Nuclear war between two small powers or between a middle and a small power
- iv. A general nuclear conflagration involving many powers of different strength.

b. Non-nuclear war

- i. Non-nuclear conflict involving the great powers which takes place under the "umbrella" of nuclear threats.
- ii. Non-nuclear war limited to small powers, some of which may possess nuclear weapons and some of which may not.

In general, not all of the probabilities of unwanted consequences can be reduced simultaneously because some may conflict with other important objectives. For example, if the great powers offer protection to allies so as to reduce the likelihood that the allies will be coerced or attacked, then the great powers will have to accept some risk of conflict among themselves. (Or perhaps the choice is between some risk now and a greater risk later.) Or a nation might opt for an unaligned and low armament status in order to reduce the risk of conflict but incur an increased probability of having to make changes in its external and internal policies.

With these two basic types of consequences in mind, those that might produce major changes in the international environment short of war and those that eventuate in war, we can examine a number of simple relationships.

1. The standard two-country model. Most analyses of nuclear stability have used a model of the U.S.-U.S.S.R. relationship in which it is usually assumed, implicitly or explicitly, that

- a. The two countries have no allies or, more generally, no important conflicting interests in third areas. Reducing the probability of nuclear war to zero is taken to be the overriding objective of each government.

- b. The government of each country would commit the country in effect to national suicide in response to a limited nuclear attack. If an attack occurred on, say, a missile field or an air base, the government would retaliate massively against the adversary's population fully expecting comparable devastation to its own population. Implicit in this response is an assumption that there are no divergent interests within each country. It is all or none for everyone. For example, if one region of a country were to be attacked, e.g., Alaska or the Kola region of the Soviet Union, the country attacked would retaliate massively with the assumed consequence of enormous, widespread destruction.
- c. Only the prospect of civil devastation prevents nuclear war. An ability to attrite the opposing military forces is worse than useless because i) it stimulates an unlimited increase in the level of nuclear forces and budgets by the two countries via a feedback mechanism and ii) it creates incentives for pre-emptive attack.
- d. Any use of nuclear weapons will inevitably escalate to an all-out nuclear exchange.

The standard function of this model has been to provide analytic support in favor of mutual reductions in the nuclear forces of the U.S. and the U.S.S.R.--or just the U.S. unilaterally.

Even in the abstract binary world which it assumes, this model has crippling defects:

- a. It typically ignores resource constraints that are sufficient, by themselves, to limit the arms competition feedback process.
- b. The assumptions of inevitable escalation and only massive response to limited attacks requires governments committed only to homicide and suicide. This is not impossible but it is hardly a plausible assumption for most governments. Alternatively, the postulated responses are not to be taken seriously; deterrence alone is the objective and the "go" button need not be connected to anything.
- c. The assumption that there are no external interests worth any risk of nuclear war, yet that any damage within one's homeland warrants an all-out suicidal response attributes to the state a narrowness of interests that would be rejected by most supporters of democratic society if these assumptions were baldly expressed outside of the mind-boggling context of nuclear deterrence.

- d. Finally, this model is inconsistent with the behavior revealed by the governments repeatedly since the advent of nuclear weapons. Most U.S. and U.S.S.R. security policies, including those on nuclear weapons, have been directed toward the support of allies and the deterrence of adversaries in third areas. That is where the great powers come into conflict and where the gains and losses in the competition between them occur.

Therefore, even when building a model which concentrates on the relation between the two great powers, it is essential to include interests in third areas in some way. When this is done, more complex and realistic types of behavior become apparent. Limited uses of force can occur among small countries with the support of the great powers including combat involvement. There might even be conflict directly between the great powers at the non-nuclear level or at the nuclear level which is focussed on and limited to a third area. The possibility of the selective and limited use of non-nuclear or even nuclear weapons against targets in their respective great power homelands cannot be excluded as an outgrowth of a conflict in a third area.

In sum, in a world in which there are important interests in third countries, i.e., in the real world, there cannot be exclusive concentration by the two great powers on deterring attack on each other's homelands without eliminating security guarantees to third countries.

Moreover, there is an important spur to proliferation implicit in this model: absolute avoidance of conflict between the two powers requires the withdrawal of guarantees from countries where great power rivalry exists. This, in turn, increases perceived vulnerabilities and instabilities in these areas, which in turn increases the incentive of third countries to acquire nuclear weapons.

2. A large versus a small country. A model of increasing importance is a two-country case in which the adversaries differ greatly in size. A number of countries that could have nuclear weapons in 1985 might spend only 1% as much on them as the U.S. or U.S.S.R. Would this make the small power effectively equal to the large one? On the view that nuclear weapons would -- and should -- be used against populations, a small power would seem to be able to be about as strong as a large one at only, say, 1% of the cost. However, the larger country would have many more resources for information gathering, offensive capabilities, command and control, civil defenses, and anti-missile and air defenses. With the delivery precision that at least the great powers will possess by the late 1980s, fixed bases, including hardened facilities, will be extremely vulnerable. Land mobile missiles, either operating within small countries (e.g., Israel or Japan) or roughly localizable within large countries (e.g., India or Egypt), can be attacked with missiles able to cover large areas with high blast overpressure. Even submarine forces of middle-sized powers may have serious problems of survival.

As a result, large countries, in general, will have the capacity to destroy smaller ones but not vice versa. This difference in destructiveness implies a difference in bargaining leverage. To be sure, the smaller may be able to damage the larger; it may be able, as DeGaulle put it, to "tear off an arm." In the Gaullist formulation, the stakes at issue for the larger country are not supposed to be comparable to the damage, less than total, the smaller country might inflict. But what about the expected damage to the smaller one in relation to its stakes? Few alternatives are so grim that the prospect of nuclear annihilation would be preferred. Perhaps Israel, faced with an Arab-inflicted "final solution," comes closer to providing such an example than any other in prospect. (But Israel faces most immediately not a great power but several small ones, and it has support from a great power.)

At this stage, the principal inferences that can be made about this case are:

- a. The possession of nuclear weapons by the smaller power is likely to induce caution in the larger in challenging what might be construed by the smaller as its vital interests.
- b. The smaller country would be playing a riskier hand than the larger, for the latter would have an incentive and perhaps the capacity to eliminate the smaller's nuclear force. And even if the smaller country could damage -- perhaps greatly -- the larger, the larger could destroy the smaller.
- c. Therefore there would remain large disparities in power and in bargaining advantage.

Just as the standard two great power model leaves out essentials, there is a similar hazard in employing a large vs. small country model. This pair would not exist alone either. Small countries usually have ties to large ones; they may also be members of regional alliances. Introducing this possibility gives the small power options it would not possess by itself. Moreover, it opens the way for more indirect, although possibly violent and even nuclear modes of conflict. For example, a great power might give nuclear guarantees to a small country threatened by a large one. This, in fact, is common. Even middle sized powers armed with nuclear weapons find additional support useful. The U.S. provides such support to the two middle nuclear powers, Britain and France, as a counter to the Soviet Union. There is, however, an increasing question as to whether great powers will be as prepared in the future as in the past to provide alliance guarantees to nations in a nuclear crowd.

3. The case of two small countries. There could be many pairs of adversaries in which a) both would have nuclear weapons; b) one, as of a

given date, would and the other would not; and c) neither would possess them, but both would have a potential to get them: e.g., today China and India, India and Pakistan, and Iran and Iraq. These binary situations would differ greatly from the U.S.-U.S.S.R. relationship in at least two important respects: a) their conflicts would most likely be direct and not expressed largely through support of third parties; and b) larger powers will be in the background and sometimes would be allied to the small ones.

The eyeball-to-eyeball nature of many of the small country relationships curiously fits the standard great power two-country model less badly than does the U.S. and U.S.S.R. relationship. Even so, its limitations remain substantial. Consider the widely held assumption that any nuclear use should be directed only against populations. Pranger and Tahtinen, in their analysis of the nuclear threat in the Middle East, think that the use of nuclear weapons is much more likely between Israel and the Arabs than it is between the U.S. and the Soviet Union.* We and the Russians, they hold, have evolved a code of behavior for avoiding nuclear war whereas these adversaries in the Middle East have not. Through lack of experience in living with the bomb and as a consequence of deep hostilities, these governments would be much readier to use nuclear weapons, and probably use them indiscriminately against populations. This is a possibility which must be taken seriously, but there are also strong incentives working in such countries for restraint and discrimination in the use of such weapons.

The second difference between small and large country pairs is less speculative. Because a great or middle power ally of a small one can provide it technology and arms and guarantees, the power balance between two small countries could be rapidly altered by either the transfer of weapons or outside combat forces. Analytically, this can be treated as giving the small country limited "drawing rights" on additional resources. Alternatively, it can be treated as converting these into more than two-country games. Pursuing the latter approach, the larger allies of small countries might have several objectives: One is to try to preserve a balance between the two small powers, for example, by sharing technologies for reducing the vulnerability of forces; by offering to replace nuclear forces destroyed by its adversary if and only if the adversary used nuclear weapons first; or using nuclear weapons directly against an ally's adversary that launched an attack with or without the use of nuclear weapons. On the other hand, the large supporting power might support its small ally with the aim of upsetting a local balance. The great powers have exhibited both types of objectives in their relations with small powers.

*R. J. Pranger and D. R. Tahtinen, Nuclear Threat in the Middle East, American Enterprise Institute for Public Policy Research, Washington, D.C., 1975.

An important parameter is the vulnerability of small country nuclear forces to attack by its immediate adversary. The vulnerability of nuclear forces has been a central concern in the U.S.-U.S.S.R. nuclear relationship for many years and this will be no less a concern among small pairs of countries. Indeed, the problem is more worrisome given the capacity of advanced states rapidly to transfer technologies or information which could rapidly make opposing forces vulnerable.

For some pairs of countries, one of the members will have nuclear weapons and the other will not -- for a time. This is the situation today between India vs. Pakistan and China vs. Taiwan (and perhaps Israel vs. Egypt or Syria). This relationship could exist, before 1985, between South and North Korea, or South Africa and neighboring countries, among other pairs. Nuclear acquisition might be seen as deterring a non-nuclear attack by an adversary without nuclear weapons; this might motivate a South Korean or Israeli nuclear program. The nuclear member might also try to coerce the non-nuclear one either through nuclear threats or actual use. The U.S. nuclear attack on Japan in 1945 is the single historical example of such use.

The non-nuclear party in such a pair might accept the asymmetric relation or respond by seeking protection from a nuclear equipped ally or by acquiring nuclear weapons, or both. An effort to redress the balance by undertaking a weapons program could produce a period of high instability. For example, the Soviets apparently considered attacking the Chinese nuclear force during the late 1960s during the period in which the Chinese were starting to deploy their nuclear forces. Perhaps they did not because by then it seemed too late to prevent damage to the Soviet Union. Or perhaps there seemed to be no reliable way to keep China from rebuilding a nuclear capacity short of permanently occupying the country, a formidable undertaking.

Among some small country pairs, neither, at the outset, will have nuclear weapons. One or both might decide to get them out of fear of non-nuclear attack or because one country is also a member of another binary relationship in which it is subject to nuclear threats. Fear that one might be second in the race can be a powerful motivator. The Manhattan Project was stimulated in large part by a concern, unwarranted as it turned out, that Germany was vigorously working toward the bomb. One of the problems with the stability of the nuclear "overhang" situation is that the lead time to acquire weapons from a decision will be greatly shortened. "Races" to get nuclear weapons could be short enough that it could be hard to stop them.

4. Risks of unauthorized acts, accidents, and mistakes. The nuclear forces of the small powers will be small, probably without reliable systems to warn of enemy attack, and perhaps weak in safeguards against unauthorized actions by those in the chain of command.

The forces of small countries are also likely to be especially prone to accidents and mistakes. The great powers possess technologies capable of reducing these hazards in the form of devices for locking, fusing, remotely controlling and releasing warheads. Making them available to small forces would reduce the dangers of unauthorized use. (However, the safer nuclear forces are, the greater the incentive to acquire them in the first place.)

5. Consequences of nuclear exchanges in a nuclear crowd. Much would depend on the context of use, the actions of the great powers and, most importantly, on the outcome of such use. For example, if the use stemmed from the failure, or withdrawal, of a great power guarantee and had less than disastrous consequences, it might legitimate decisions to possess these weapons and induce many other countries to go ahead. On the other hand, if it produced large scale damage to users, especially to the side that used them first, or if it evoked a strongly hostile reaction from one or more of the great powers, the example would be sobering.

Use by a small power might pose a situation so dangerous to other countries that action against it by a larger power, or joint action by several, might be undertaken. Concern about small country nuclear forces could cause the major powers to create nuclear strike capabilities, non-nuclear and nuclear, especially designed for use against small nuclear powers. Such a capacity should be capable of being used with precision and with minimum collateral damage to population and productivity capacity. The purpose would be to reduce or eliminate the small countries' capacity to do mischief, to discredit irresponsible leadership and to strengthen factions favoring more moderate policies.

6. Effects on the general stability of the international system. The discussion so far raises serious questions about the proposition advanced by Gallois and others that the wider dispersion of control over nuclear weapons would have a calming effect on international relations. It suggests that not only the period during which weapons are spreading to additional countries is likely to be a period of exceptional danger, but also the "end position" is likely to be highly unstable. Beyond the 30 or so countries that will have a nuclear weapons option by the mid 1980s, there are another hundred members of the U.N. that are in the queue so to speak. Moreover, there is the heightened possibility of sub-national groups gaining access to these weapons.

On the other hand, there seems little reason for arriving at the opposite conclusion, that a world with say 20 or 30 nuclear powers

would inevitably produce a global holocaust or that small nuclear wars would be a common occurrence. Nevertheless, nuclear threats will be more common and nuclear war more likely, possibly including conflict between the great powers. Although we can assume that these powers will continue to work on the protection of their main nuclear forces in order to keep the risk of surprise attack low, one hazard is that uncertainty about commitments could produce a sequence of actions and reactions leading ultimately to a large scale nuclear exchange.* In 1985, as in 1914, a series of moves in a complex interlinked environment could produce a global catastrophe. Keeping the probability of such a disaster low will be an important objective of the great powers. It will provide an incentive not only to see to the protection of their own nuclear forces but also to help assure the protection of those of allies. This will strengthen incentives to make their commitments to allies both more explicit and more limited than in the past. For example, great power guarantees to small countries may increasingly be limited to deterring nuclear attack by an opposing great power.

Short of nuclear exchanges, the dispersion of nuclear weapons will affect the world distribution of power. It will do so because something real will have changed. On the other hand, world power relationships will probably not be wholly transformed. For instance, it is difficult to find evidence that the British, French and Chinese nuclear programs have radically added to the effective power of these countries and, as we have seen, even greater constraints will be faced by smaller nuclear forces than these. (There is, of course, the real danger that these weapons will come under the control of erratic or mad leaders. There are some on the world scene today whose possession of nuclear weapons would be cause for fright. Such an event would very likely evoke a collective countering response by other threatened states.)

Thirty years ago Jacob Viner assumed that the targets of nuclear weapons would have to be cities because these weapons would remain expensive or scarce.** He also held the view, inconsistently, that many countries would make bombs in only a few years. Small countries with atomic bombs would become relatively more important because large ones would not have a prospect of nearly costless victories over them. He rejected as infeasible a world government as a response to the menace of widely distributed atomic bombs. However, the dispersion of power might produce, he thought, conditions favorable to the creation of a "balance of power" system in which overwhelming concentrations of power could be avoided by "timely negotiation of new alliances." This

*For an analysis of this and other possible sources of instability in a nuclear world, see Stanley Hoffman's chapter in A World of Nuclear Powers? Alastair Buchan, ed., Prentice-Hall, Englewood Cliffs, N.J., 1966.

**Jacob Viner, "Implications of the Atomic Bomb for International Relations," paper presented to the American Philosophical Society, 1945, printed in Jacob Viner, Essays in International Economics, The Free Press, Glencoe, Illinois, 1951.

would restore balance temporarily destroyed. But, on the other hand, great damage would be done by the use of these weapons in such a system. Moreover, power would probably not, in fact, be widely enough distributed for an effective balance of power system (or world government) to be feasible. He saw as the best, although slender, hope of a Concert of Great Powers, based on the U.N. organization together with the conscientious practice of mutually conciliatory diplomacy.

Thirty years later some of Viner's predictions have been proven false and others, in consequence, are untested. The prospect of world government seems at least as remote as it did to Viner in 1945 and the U.N. has hardly been a successful mechanism for maintenance of the peace by the Great Powers. It is doubtful that the fundamental differences that separate the great powers will be overcome enough by the shared sense of danger from the small ones to enforce a structured system upon them. At least, this does not seem likely soon. As for the alternative of a highly decentralized system, it now seems unlikely to emerge despite the "leveling" tendency of nuclear weapons, a tendency which is modest. One can only conjecture as to whether the existence of a highly dispersed power system would provide a stable international system. Equilibrating alliances might be formed. But alliances among small nations possessing nuclear weapons might also seem dangerous and be avoided by countries geographically or in other ways able to do so. Although there could be a long term collective interest in contributing to collective security arrangements, there could easily be a short term perceived advantage in "shirking." In short, for several reasons there does not seem to be a good basis for hope in the dispersion of nuclear powers.

B. The Future of Guarantees in a Nuclear Crowd

Imagine two very different worlds. In one, all countries are members of tightly linked collective security systems, perhaps some of them highly hegemonical in character. Although not all interests are shared among the members of each alliance, confidence in the collective arrangements is high on essential issues of security. So is the expectation that each alliance will persist. The likelihood of independent military action by countries is low. In the other world, there are no fixed alliances. Each country perceives itself as being isolated from others on essential matters of security except for temporary coalitions. Countries are likely to act independently.

The former is a world in which one would expect to see a low demand for nuclear weapons and a high willingness to supply guarantees to counter threats; wars among small nations are likely to be quickly stopped by large ones (e.g., several Arab-Israeli wars); the latter would exhibit the opposite tendencies. Although in the former world, conflict among the blocs is possible, wars seem more likely to occur in the more nearly atomistic situation. To the extent they are limited to small powers, they would not be large on a world scale, but they might be large relative to the size of the combatants.

Neither model corresponds to the world as it has existed in the past or is likely to in the future. But the real world has moved during the past 20 years from one which was largely bipolar to one which is more multipolar in nature. To be sure, even in the high period of bipolarity some countries were outside of the main alliance systems or on its fringes: South Africa, the countries of Black Africa (after decolonization), and the countries of South and Southeast Asia. But almost all developed countries were, more or less firmly, members of alliances. This is the main reason that many developed countries are in the "overhang" rather than the weapon-owning category today. This is most obviously true of Western Europe. As for Eastern Europe, the Soviets provide a combination of protection to their allies along with coercion. The question does not even arise about the possibility of a GDR or a Polish nuclear weapons program. The U.S. has no such power over its allies, and many of them could rapidly acquire weapons today.

The non-communist alliance systems centered on the U.S. are eroding. This weakening is a product of several factors including defeat of the U.S. in Southeast Asia, isolationist tendencies within the U.S., a reduced sense of danger from the Soviet Union (but also a sense of greater Soviet military power). It is significant that none of the additional countries that today seem most likely to acquire nuclear weapons by 1985 are members of NATO, despite the fact that they, together with Japan, are the most technologically advanced nations. NATO, together with other European institutions, provides bonds that still provide a very substantial degree of security to these countries. This is also true for countries such as Sweden and Switzerland that are outside of the alliance but benefit from its existence. The security relationship between the U.S. and Japan performs the same function for Japan.

These alliances not only offer protection from adversaries, they dampen competition among their members. The integration of the FRG into the EEC and its participation in the NATO alliance has played a crucial role in averting German and other European pressures for nuclear weapons. The alliance has also contributed to moderating competition between the U.K. and French nuclear weapons programs (in part perhaps because the British program has been linked to the U.S.; this is one aspect of wider alliance relationship).

The countries most likely to acquire weapons are the non-aligned and marginally aligned countries and those that feel threatened and fear abandonment. Consider the set which includes India, Pakistan, Iran, the Republic of Korea, Taiwan, Israel, South Africa, Argentina, and Brazil. Korean confidence in the U.S. has been affected by the collapse in Southeast Asia. Israel, which recognizes its great dependence on the U.S., nevertheless fears that it might be coerced by us into making fatal concessions or being left in the lurch in a crisis. Taiwan fears the cutting of ties

with the U.S. Argentina and Brazil are rivals and are members of a decreasingly viable Western Hemispheric collective security system. The U.S. is providing arms and has been supportive to Pakistan and Iran, but their ties with the U.S. are hardly close. South Africa has been isolated, and India is openly unaligned.

Proliferation will affect both the demand and the supply of alliance guarantees. The demand, or at least felt need, for alliance support will increase among those countries threatened by rivals acquiring nuclear weapons. Pakistan is a clear case in point today. Support will be sought from other countries in the region (e.g., from China, Iran and the Arab countries in the case of Pakistan); this support may be forthcoming on the theory that if they don't hang together they may hang separately. Most importantly, countries that feel threatened are likely to seek protection from larger powers. (For Pakistan this is sought from China and the U.S.)

It is not clear that the supply of alliance relations and guarantees will be as elastic. Within the great powers, say the U.S., the argument will be advanced that countries with nuclear weapons no longer need guarantees or that guarantees to countries in a region with nuclear powers are too dangerous.

Inhibitions on the part of the great powers to providing alliance guarantees could create an unstable feedback process. A reduced willingness to make commitments would increase small country incentives to acquire nuclear weapons which in turn could strengthen the large power's incentives to pull back, etc. The geographical isolation of the U.S., and the nature of our ties with the rest of the world make it more likely that we may get caught up in such a feedback process. The geographical situation of the Soviet Union and the hegemonical nature of its empire makes it much less likely to withdraw. It might be more restrained about taking on new commitments, however.

Finally, another option for small and middle powers is neutrality and accommodation. This option would mean having no military nuclear capability so as not to appear threatening. It would not be surprising if a number of countries in the overhang category choose this path.

C. Nuclear Linkages

Nuclear decisions in one country will cause reaction in others near and distant.

1. Regional repercussions. A model of a branching process of nuclear acquisition is as follows: Country B decides to obtain weapons because Country A has them or is getting them. But B also has a rivalry, or active hostility, with C and D which now have an increased incentive to get the bomb, etc. Consider Asia: China gets the bomb for several reasons including its rivalry with the Soviet Union. This act has a decisive effect on India which tests a bomb. Another of its adversaries, Pakistan, now feels threatened and starts a program. Iran, which in any case is worried about dominance by the Soviet Union, regards India as a rival. These factors should influence an Iranian decision to create a nuclear option and later trigger a decision to make weapons. At this stage, a number of neighboring Arab countries, which have in any case been concerned about a possible Israeli nuclear force, fear the consequences of an Iran strong in both non-nuclear and nuclear arms. This causes them also to create a nuclear option. Subsequently, most or all of these countries might take the step of acquiring weapons.

This sequence is oversimplified. For example, it leaves out the influence of alliances. But it also conveys how the existence of multiple sets of hostilities and rivalries can produce a sequential branching process, one that will be much more worrisome with many countries in the overhang category.

Are there likely to be "stopping points" which could halt such a process--at least for a considerable period? Consider Germany and Japan. Many analysts predicted in the 1950s and '60s that it was inevitable that countries at the middle power level would soon acquire nuclear weapons and therefore that German and Japanese tests would follow the British, French, and Chinese--say by 1970 or 1975. Within Europe, Sweden, Switzerland, Italy and others would follow in turn or more or less simultaneously with Germany. This has not happened nor is it imminent. The reasons are clear. Germany earlier had been inhibited by concerns about internal stability and throughout has been concerned about the fears and reactions a nuclear weapons program would generate both in Western and Eastern Europe. It has also placed a good deal of confidence in its alliance with the U.S. Japan, less exposed to attack than Germany, has sought to excel in the economic rather than the military realm. Japan too benefits importantly from U.S. protection. The "stopping points" provided by these countries has reduced the pressure on others to go ahead.

Similar stopping points are not evident elsewhere in the world--except for the Soviet bloc where the Soviet Union effectively acts as the "stopper." Stopping points require a structured set of relationships within a region and with outside powers. Such structures exist only in Western and Eastern Europe. Elsewhere, relationships are more fluid.

2. Weakening of the nuclear taboo. The Indian test seems to have had an effect in remote countries; for example in Argentina and Brazil. Acquisition by additional powers could have an effect worldwide in weakening the inhibition against nuclear weapons, even on such industrial powers as Germany and Japan. It weakens the widely shared sense that nuclear weapons are taboo.

The weakening could have a large effect on the internal debates on nuclear weapons. In such debates not only are utilitarian factors important (e.g., how will the U.S. or the Soviet Union react) but also the perceived legitimacy and morality of nuclear weapons. There also has been recognition of a hierarchy--now increasingly challenged--of powers according to wealth and power. It is one thing for the great powers to have these weapons or even for other powers possessing a high level of technology such as Britain or France. But for countries such as Pakistan, or Korea to get nuclear weapons is a different matter. This is likely to strain policies of abstention in countries, whether or not they are directly threatened. If several poor countries get nuclear bombs the pressure within the richer ones also to so do can be expected to increase greatly. Although the factors that have precluded Germany and Japan from acquiring nuclear weapons remain powerful, their spread to a large number of smaller countries would undermine the abstention of these middle powers greatly.* Germany's acquisition of nuclear weapons would probably have serious repercussions in Europe. As for Japan, the Japanese do not do things by halves. If they get nuclear weapons they will have a sizable program, and a nuclear-armed Japan might appear threatening to many. And it might be accompanied by troublesome changes in Japanese politics.

*Of course there could also be more direct regional repercussions on these two countries. Japan would be profoundly affected by a Republic of Korea nuclear program and Germany by weapons programs in, say, Spain or Yugoslavia or in the Middle East.

These reactions are not the only possibilities. Either Germany or Japan might choose the course of increased neutrality and passivity together with an accommodation to dominant powers.

3. The proliferation of sources of supply. The nuclear technology market has changed greatly in the past 20 years. Until recently, only the U.S., the U.K., Canada, and the U.S.S.R. were significant producers of nuclear electric power stations, and the U.S. dominated the export market with Canada in a secondary role. Now France and Germany play a role in this market and Japan and Sweden could do so. Reactors derived from General Electric technology are sold by Kraftwerk to Brazil. Successful South African development of an indigenous enrichment capacity, helped by German technology, would enable it to market not only enrichment services, but also enrichment plants. Germany has already sold Brazil jet nozzle enrichment technology. Germany, or its partners in Urenco might, in the future, sell the more advanced centrifuge technology now under development to other customers. India might, though there is no evidence, become a supplier of more directly weapons-related technologies, such as technologies for the reprocessing of spent fuel.

This increase in the number of supplier countries will greatly reduce the effectiveness of unilateral decisions by any one country or a small group to deny access to nuclear technology. Virtually any medium-sized or larger advanced industrial country could, in time, become a supplier of nuclear components and more than a few might be able to provide entire plants. On the other hand, the number of countries that will be able to supply certain very important types of equipment related to the manufacture of nuclear weapons such as enrichment technology or reprocessing technology will remain small for the next decade. Cooperation among these suppliers could make a big difference in the diffusion of these key technologies, but this requires a greater degree of cooperation among the supplier nations than has occurred so far. Beyond 1985, the prospects for effective supplier limitation of at least current types of technologies seem dim.

A specific weapon related problem is the transfer of separated plutonium and of highly enriched uranium among countries. Significant quantities have been sent by the U.S. and other supplier nations for nuclear research materials testing or naval reactors. Even with safeguards this is a dangerous precedent. Other suppliers of such material, say among the countries which are expected to have at least 250 kg of fissile material by 1985, might have less concern than we do about what is done with their material; or they may simply be unable to apply sanctions if agreements are violated. Furthermore, the growth in the number of potential suppliers is large enough for a market in weapons-usable fissile material to be created. Finally, the possibility of a market in fabricated weapons cannot be excluded.

4. The continuing competition in weapons technologies. The initial testing and construction of a few nuclear weapons is but one stage in a process. Qualitative changes in technology will continue to take place and this will require continuing changes in nuclear forces just as it does in non-nuclear ones. The competition will include development of thermonuclear devices, more advanced delivery vehicles, basing methods, warning systems, and surveillance and command and control systems. If a nation does not compete in these categories, its forces will become increasingly vulnerable and unreliable in performance. One should not assume, however, that a series of "uncontrolled" nuclear arms races will be set off by these pressures. Limitations in resources and the existence of competing domestic and military needs will limit spending on nuclear forces. But such forces risk becoming increasingly symbolic--and dangerous to their possessors.

The situation that will be faced by small nuclear powers is suggested by examining the resources devoted to nuclear forces today. Consider the following three levels of expenditures for nuclear weapons research and production, specialized nuclear delivery systems, strategic intelligence, and command and control system, and (for the U.S. and U.S.S.R.) homeland air defenses.

Great Power Level:	\$10-20 billion annually (U.S. and U.S.S.R.)
Middle Power Level:	\$1-2 billion annually (U.K. and France)
Small Power Level:	\$.1-.4 billion annually (Israel? India?)

On the minimum deterrence theory of nuclear doctrine, the effective power produced by these widely different levels of expenditure should be similar. However, governments can apparently tell the difference between the military potential of forces that differ by factors of ten to a hundred. Britain and France have not produced nuclear forces which appear to anyone to be comparable to those produced by the Soviet Union's order of magnitude greater level of effort.

How do these three levels of expenditure on nuclear forces compare with the resources likely to be available to military nuclear

programs among the prospective nuclear countries? In making such an estimate one should recognize that only under circumstances of great stress will a country devote a large share of its resources to military programs. Israel is unique in devoting about 30% of its GNP to military purposes; the Soviet Union probably devotes around 15%; most nations allocate around 5% or less to defense.*

Among the countries expected to have enough fissile material for three or more bombs in 1985, only Japan and Germany could easily allocate resources to military nuclear programs at the middle power level. ("Easily" in terms of the availability of resources. It would require a large political change for any nuclear weapons program to be undertaken in either country.) If motivated enough, either country could even mount programs at the current great power level of over \$10 billion annually. Among the other nations in the "overhang" status, probably only Iran, (among those that seem to have an incentive to acquire nuclear weapons), could come close to managing a middle level program. For the rest, it would be difficult to go beyond the small power level, although an acute sense of danger might impel larger efforts.

Even though most new nuclear powers are likely to devote two orders of magnitude fewer resources to nuclear military programs than the great powers and one order of magnitude less than the middle level, their nuclear forces will give them the potential of being able to cause a great deal of trouble. Such potentials, if they are not to be highly dangerous for their possessors, place severe requirements on safety, force protection, command and control, security against internal dissidents, and careful planning of missions. It may be possible for small countries to develop forces which satisfy these requirements and for which non-suicidal missions are feasible, but this will not be easy.

The contribution to stability that the great powers can make in a world with small nuclear ones should at least raise questions about the objective, which is endorsed by some arms control agreements, of the great powers ending their "nuclear arms race" and ridding themselves of nuclear arms. Narrowing the difference between the large and small nuclear powers does not promise to contribute usefully to most of the categories of stability discussed earlier. On the contrary, preserving the difference between the large and the small nuclear countries is important and may increasingly be seen to be important as the nuclear crowd grows.

* It appears that most of the existing nuclear powers devote around 1% of their GNPs to their specialized nuclear forces. This is a rough estimate, one that is especially difficult to make for the CPR. However, the Soviet Union is an exception in apparently devoting 2-4% of its GNP to these forces.

5. Prospects for further increases in the size of the crowd. The potential for nuclear spread will have only been partially realized by 1985. By then about one-fourth of the 130 odd members of the U.N. will be in the three weapons or greater "overhang" category. There will remain many more potential entrants during the following decade. The extent to which the remaining three-fourths of the U.N. members move into the "overhang" category or go on to get weapons will depend on: a) whether or not nuclear electric power becomes economic in small, less developed countries; b) what happens to the countries that have acquired weapons; c) the nature of the market in nuclear technologies--including possible markets in separated plutonium and highly enriched uranium or even nuclear weapons; d) the degree of security provided by alliance relationships; e) the nature of the rivalries in various regions and the extent to which local agreements, formal or informal, might limit spread; and f) the extent to which the nuclear taboo is broken. Prediction is difficult here but the main task before us is to try and influence this process, not only to try to forecast it.

D. What Will Proliferation do to Nuclear Doctrine?

The doctrine that nuclear weapons should be targeted mainly against civil populations has dominated most of the academic literature in the U.S., some of the government rhetoric, but less of the governmental operational planning. On this doctrine, the mission of a nuclear force is simple in concept: It is to be able to survive a well executed attack by an adversary (which in a proliferated world might be a great power), reliably receive the order to launch, penetrate to enemy population centers and destroy them. This task is less simple in execution. The U.S. has not been confident of its ability to manage it without a continuing effort.*

This doctrine is likely to be propounded by some leaders of small nuclear countries and some irresponsible leaders may act accordingly. However, we have suggested that the governments that get nuclear weapons may behave more responsibly than the U.S. and the U.S.S.R. have often sounded. For one thing, irrational policies are most readily supportable if they are not operational and many of the small countries confront each other directly. Especially where nuclear contingencies have to be planned as two-sided, which will mean in most cases in time, the incentive to develop limited nuclear options not directed at populations will be great (at least on the average; catastrophic anti-population threats and actual attacks are not ruled out, but they are

* Ironically, this doctrine has in the past been advocated by some Americans who, following General Gallois, proposed that the U.S. provide small nuclear forces to its European allies who could aim them at Soviet cities as a means of strengthening European security and as an alternative to the U.S. providing nuclear guarantees.

not likely to occur often.) Having small and vulnerable forces, the small powers have an incentive to use nuclear weapons, if they use them at all, in very restrained ways--except perhaps as a last desperate resort.

1. The example of Israel's nuclear options. The problems faced by small countries are illustrated by the case of Israel. One contingency is an explicit Israeli nuclear threat early in an Arab-Israeli conflict. But threat against what targets? If used against the Arab armies there would be an uncertain tactical effect unless more than a few weapons were used. More importantly, such use or even direct threat would license the Soviets to provide nuclear weapons to the Arabs if they did not already have their own. There might be a direct Soviet nuclear response against Israel. As for the U.S., we would no doubt warn the Israelis not to use the bomb, warn the Soviets not to give them to the Arabs and warn the Soviets and the Arabs not to use them against Israel.

Israeli nuclear threats or attack against Cairo or Damascus would produce even stronger reactions from foes and friends.

In short, if the Israelis were to threaten use or to actually use the bomb too early, before their backs were to the wall, they would lose U.S. support and evoke a strong Soviet response; if they use it too late, it would not prevent the destruction of Israel. Early use, or even early threatened use, would license the Arabs or the Soviets to retaliate. Only limited, clearly defensive use would reduce the likelihood of a devastating response to a possibly tolerable probability. But by how much? Even limited defensive use could provide an adequate excuse for a nuclear response against Israel.

Might the Israelis try to deter a Soviet response by trying to acquire an ability to attack Soviet military forces on the Soviet Union homeland? Such a force would probably be vulnerable on the ground and in penetrating air defenses. Israel might try to deal with the ground vulnerability problem by basing nuclear weapons at sea. (Israel has two submarines and three on order. These might be equipped with cruise missiles that could be developed by Israel over the next decade.) A submarine force would have to withstand intensive ASW search. An attack on Soviet forces in the region, for example its ships in the Mediterranean, would be painful for the Soviet Union, but losses to its fleet would sanction the elimination of Israeli military power and provide a powerful demonstration of Soviet power, a trade that it might be willing to make. If Israel were to build a missile force able to reach Soviet cities, even Moscow, such a force might give the Soviets pause. It might deter a direct Soviet attack on Israel. On the other hand, it would give the Soviets an even stronger incentive to eliminate Israeli power. They could see aiding the Arabs to acquire nuclear weapons as the least imprudent way to deal with this threat. The Israelis are not likely to attack Moscow in reaction to Soviet military assistance, even nuclear assistance, to the Arabs.

The essential point is that the use of this Israeli force against Soviet forces or homeland would risk suicide. The Soviets are unlikely to confront the Israelis so directly that an Israeli nuclear deterrent against the Soviet Union could be effective.

In sum, the defense of Israel will continue to depend largely on Israel's own non-nuclear forces and on support from the U.S. At best, it appears that an Israeli nuclear capability could be reserved for deterring Arab--or perhaps Soviet--initial use of nuclear weapons or for selective use if Israeli armies are on the verge of defeat under circumstances in which the survival of Israel is at stake.

2. The example of the Republic of Korea's nuclear option. Korea, in the opinion of many informed military experts, has the capacity to defend itself against a non-nuclear North Korean attack. This opinion is close to being concurred in by President Park who has been recently quoted as saying that Korea will be able to defend itself against the North by the end of a five year program of arms build-up. On the other hand, no informed person believes that it could withstand an attack participated in by China or the Soviet Union. Korea will continue to need nuclear guarantees against a nuclear attack and non-nuclear or nuclear support against a larger non-nuclear attack than could be mounted by North Korea alone.

A Korean nuclear weapon program then would be motivated largely by uncertainty on the future of the American commitment. If the U.S. commitment ends, how might Seoul use nuclear weapons? Retaliation on Pyongyang in response to a non-nuclear attack from the North, would, as in the case of Israel, invite and license the Soviet Union or China to aid North Korea in retaliating against Seoul or against its military forces. Nuclear attack along the DMZ appears to be tactically unnecessary given the defensibility of the narrow invasion routes with non-nuclear weapons. And such use would also provide an excuse for nuclear retaliation by North Korea or its allies.

Concern expressed by ROK officials about the threat of non-nuclear equipped Frog missiles attacking Seoul provides another reason, or rather rationalization, for a nuclear program. A Korean worry is that panic in Seoul could create chaos. However, this concern does not seem to be warranted by a quantitative assessment of the damage that could be done. A Frog missile aimed at the high population density parts of Seoul would kill on the average between 10 and 100 people. The North Korean force requirements to do large scale damage to Seoul with missiles or aircraft carrying high explosives would be very large. In contrast, a 20KT nuclear weapon on Pyongyang might kill about 160,000 people and

a 1 MT weapon on Seoul in response would kill about 2.7 million.* The Korean officials could be more reassuring to their people on the relative unimportance of the danger of non-nuclear attack and would be able to reduce the likelihood of panic if they were clearer on these facts themselves.

The alternative for South Korea of assuring an effective non-nuclear defense along the DMZ and counting on the U.S. to keep the Soviets and Chinese out of active combat involvement is not certain to work, but the nuclear alternative seems a good deal more dangerous.

3. The alternative of adopting a no-attack-on-population doctrine. A rule that we should consider adopting and advocating is the outlawing of non-nuclear or nuclear attacks on cities. This rule has been proposed by the International Commission for the Red Cross for the Middle East and has evoked a positive reaction from Prime Minister Rabin. The adoption of such a rule might help some in calming fears in Israel and Egypt that population attacks are to be expected in the next war. Given the frequency of wars in the Middle East, this is by no means a trivial worry. Moreover, it might make a difference in actual conduct in a conflict. Many wars have begun with nations having restrictions on attacking non-combatants which have then often eroded during the course of the war. There is some basis in history for hoping that future conflicts in the Middle East could be stopped before the erosion process had progressed far.

This proposed doctrine is related to the recent dispute over U.S. supply of Pershing missiles to Israel. The Israelis apparently have wanted Pershings in order to be able to deter the more distant Arab nations from joining in a future war and in order to deter Arab missile attack on Israeli cities. The fact that Pershing has very low effectiveness in destroying targets with an HE warhead means that it is militarily effective essentially as a nuclear weapon carrier. Even more accurate, advanced versions of Pershing would be only marginally effective but not cost-effective in this role.

Apart from the advisability of the U.S. providing primarily nuclear weapon delivery vehicles to Israel, how plausible are the Israeli arguments? First, the argument on reaching more distant Arab nations is weak, given the inadequate range of the Pershing in relation to the distance to such cities as Bagdad, Tripoli and Algiers. Second, and more importantly, as the Israeli government knows only too well, the population of Israel is extraordinarily sensitive to the threat of mass, indiscriminate population destruction. The Jewish people should be the first to seek to avert such tragedies. A policy of obtaining missiles useful principally as carriers of nuclear weapons for the ostensible purpose of aiming them at Arab population centers in order to deter attack on

*Please see following page.

*Some current estimates of the increase in fatalities that would be brought about by substituting nuclear for non-nuclear weapons in Third World conflicts have understated the difference this change would make. Like the very early estimates of P.M.S. Blackett, the nuclear calculations may be based on a gross analogy with Nagasaki rather than on specific terrain and demography in the cities in question. Though the number of fatalities we have shown may seem large compared with Nagasaki experience one must remember that Nagasaki is a poor example of the destructive power of nuclear weapons. At Nagasaki the bomb missed the aiming point by nearly 2 miles and the hilly terrain shielded parts of the city from the destructive effects of the bomb. The higher fatalities for Seoul are only partly due to the use of a higher yield nuclear weapon. A well placed 20KT nuclear weapon on Seoul might kill over 350,000. These figures are conservative since the effects of thermal radiation are ignored. The calculations of the effects of high explosive warheads in Korea were based on a detailed demographic map of Seoul and small population units called Dongs. For the 20KT and the 1MT estimates, average densities were used and checked for the approximate correspondence to the details of the demography.

Israeli cities in a conflict appears to be exceptionally risky and imprudent -- and inconsistent with the goal of calming concerns of the Israeli population and reducing the likelihood of actual population attacks.* The alternative of trying to limit attacks to strictly military targets and to avoid population attacks deserves a good deal more attention than it has received. Such an agreement would not deprive the adversaries in the Middle East of the capacity to deliver bombs--nuclear ones if they have them--by aircraft if the no-population-attack understanding were to break down.

E. New threats to U.S. forces and territory.

Americans who depreciate the importance of proliferation or even think that some proliferation might promote our interests abroad tend to ignore the new threats to U.S. forces abroad and to U.S. territory that could result. These are of several kinds: We could be subjected to direct threats from the small countries, even former friends.** We could come under nuclear attack as the result of circumstances we could not control; for example, through an ally taking actions which result in a nuclear response against our military forces. An example would be an attack by a nuclear equipped South Korea against the North leading to a Soviet response against South Korea. Such retaliation could hardly not involve the U.S. forces in Korea, assuming that they were still deployed there.

One reaction by the U.S. to the possession of nuclear weapons by especially dangerous governments could be an attempt to eliminate such a force. This is an action that the Soviet Union appears to have considered with respect to China. But more likely is decoupling of U.S. commitments from nations acquiring nuclear weapons. However, decoupling, as noted above, would increase incentives to get nuclear weapons and to increase investments in existing nuclear forces. This would, in turn, create an increased capacity to attack U.S. forces and even U.S. territory.

By the late 1980s several nations might be capable of delivering nuclear weapons against the continental U.S. As a result, we may find

*Some Israelis express concern that Soviet Scud and Frog missiles now in Arab hands could be launched randomly against Tel Aviv, Haifa and Jerusalem during a conflict. This could produce, over a week, around 2,000 deaths plus additional casualties. Damage inflicted in this way and at this level could in the view of some Israelis be highly disruptive to Israeli morale and to the war effort. This argument supports the position that the appropriate counter is an Israeli missile capability to carry out a similar campaign against the Arabs. On this view missiles are needed rather than aircraft because of their especially terrifying character.

**French assertion of a "tout azimuth" policy in the 1960s, should have given pause to American enthusiasts for nuclear sharing.

it desirable to allocate offensive forces to targeting third country nuclear forces (e.g., those of India) and to build up air defense and civil defense systems and possibly ABMs to cope with these additional nuclear threats.

The problems that might be created for the U.S. and our military forces vary a good deal among regions:

1. North East Asia. A heightened threat to U.S. forces could occur as a result of nuclear weapons programs in South Korea, Taiwan or Japan, countries with which the U.S. has security agreements. For example, as noted above, the use of ROK nuclear weapons could result in nuclear retaliation against U.S. forces in Korea or elsewhere in the region by the U.S.S.R. or the CPR. Taiwanese nuclear weapons would present a similar risk to U.S. forces in Taiwan if U.S. forces continue to be stationed there (a prospect which is becoming increasingly unlikely). Nuclear weapons in the possession of a hostile Japan would present a serious threat to U.S. forces given the large economic and technological resources available to Japan. For example, Japan is developing a capacity through its space program to build missiles able to reach the continental U.S., although any such missile force might be vulnerable to U.S. counters.* In sum, U.S. forces in East Asia and the Pacific could be exposed to attack with nuclear weapons by five countries in the region by 1985 if all of those in the overhang states acquire weapons (U.S.S.R., China, Japan, ROK, Taiwan). Of these, three could have the capacity to reach the continental U.S. (U.S.S.R., China, Japan).**

2. South and Southeast Asia and Australia. The prospective nuclear countries in this region by 1985 are China, India, Pakistan and Australia (and perhaps, by 1990, the Philippines and Indonesia). Either India or Pakistan could threaten U.S. forces and bases in the Indian Ocean-Persian Gulf area (e.g., the U.S. facility being built up at Diego Garcia). India by the late 1980s might have a capacity to build a few ballistic missiles able to reach the U.S. The Philippines or Indonesia could threaten U.S. forces in the Southeast Asia region.

* Any country with long range civilian jet aircraft has the ability to carry nuclear weapons at intercontinental distances. Nuclear weapons might also be carried on ships, merchant or naval. Having the ability to carry nuclear weapons a long distance does not mean that such a force would be well protected or able to penetrate reliably to target. The long range delivery capacities discussed here refer to ballistic and cruise missiles, and military aircraft.

** The Soviet Union will, of course, be able to deliver nuclear weapons to any region.

3. Middle East and North Africa. The most probable nuclear powers in this region by the late 1980s, Israel, Iran and Egypt, could threaten U.S. forces in the Indian Ocean, Persian Gulf and the Mediterranean with the aircraft and missile systems these countries will possess.* They are unlikely to have a capacity to attack the continental U.S.

4. Sub-Saharan Africa. The only prospective nuclear country in this region by 1985 is South Africa. The U.S. has no forces in the region nor is South Africa likely to expend resources on intercontinental systems.

5. Europe. At least 20 countries in Europe could have nuclear weapons by 1985. In addition to the U.S.S.R., U.K., and France, seventeen nations will have accumulated substantial stocks of fissile material by that time: Austria, Belgium, Bulgaria, Czechoslovakia, Denmark, Finland, the two Germanies, Hungary, Italy, the Netherlands, Portugal, Rumania, Spain, Sweden, Switzerland, and Yugoslavia. (However, the Soviet Union will almost certainly prevent the countries in Eastern Europe, with the possible exception of Rumania, from getting these weapons.) Any of them could pose a threat, directly or indirectly to U.S. forces in Europe, the Mediterranean or the North Atlantic. Among these countries, the only potentially new nuclear power that has the resources to build a force capable of reaching North America is the FRG.

6. Western Hemisphere. The U.S. does not have forces deployed in the neighborhood of the two most probable nuclear weapons acquirers in this region, Argentina and Brazil. Nor are they likely to acquire long range delivery systems, beyond the commercial jet aircraft which they own. Canada has long had the capacity to build nuclear weapons but there is no evidence that it will do so. Mexico is developing nuclear electric power capacity and probably could acquire nuclear weapons by the late 1980s, but there is no evidence that it intends to follow this path.

F. The prospects for non-nuclear defense as a factor affecting proliferation.

Some of the countries that will be in the "overhang" category have defense against non-nuclear attack as a principal concern. The Republic of Korea and Israel are instances. Moreover, some of these countries have geography highly suited for defense (e.g., Korea) and for all of them

*In addition, the possibility that Libya or other countries in the Middle East could acquire some weapons by 1985 through purchase of components or of complete weapons cannot be excluded.

the alternative of employing advanced non-nuclear technologies could greatly increase their defensive capacity.*

Some leaders of governments that feel threatened have made explicit the relation between non-nuclear defense and the acquisition of nuclear weapons. For example, Prime Minister Bhutto of Pakistan has said that if the U.S. does not provide conventional arms to Pakistan and the disparity between India and Pakistan reaches the stage where it threatens the stability of South Asia, Pakistan may be forced into a military nuclear program. Bhutto's position is not devoid of logic. Even, or perhaps especially, against a nuclear power, having an adequate non-nuclear posture is vital.

Most importantly, making available modern non-nuclear weapons to countries concerned with non-nuclear threats might, as part of a larger policy package, contribute significantly in some countries to weakening the push to get nuclear weapons.

G. Nuclear threats by extra-governmental groups.

The current nuclear countries are among the more stable countries. Despite this fact, coup attempts have been reported in China, there was an unsuccessful coup against De Gaulle, and there is the recent shift in power in India. Many of the prospective possessors in the next decade have less stable records. Korea, Pakistan, Egypt, Argentina, Brazil, and Iran are not among the most unstable states, but there is a substantial history of coup efforts, successful and unsuccessful in each.

In countries with nuclear weapons, coup plotters will make gaining control of them a high priority task. Although their use in coups and armed uprisings seems very unlikely, capturing the nuclear weapons will be on the standard coup checklist along with surrounding the presidential palace, taking over the main radio station and occupying the local airfield. For this reason, heads of government are likely to pay particular attention to the reliability of the commanders in charge of nuclear units. Concern about this problem may produce a conflict between a desire to protect these weapons from domestic enemies and a desire to protect them from foreign ones. The former suggests that they should be kept in the local garrison under reliable control; the latter suggests that they should be widely dispersed and concealed. One way in which these two conflicting objectives might be partially

* Both the attacker and the defender may possess advanced non-nuclear munitions. However, the invading country must seize territory. This requires a concentration of men and material which exposes it to vulnerabilities not faced by the defender.

reconciled is for weapons to be provided with permissive action links with the keys held by the head of the government and perhaps a trusted aide or two. (The question then will be whether the holders of the keys will be more vulnerable than the weapons.)

Use in domestic conflicts, although unlikely, is not excluded. Some civil wars have been marked by extraordinary bitterness and brutality. A government might find the temptation to deliver a crushing blow against rebel strong points with nuclear weapons overwhelming; rebels, if they gain control of some weapons, might also find the demonstration of their power irresistible. The types of targets that might be chosen can only be guessed at, but rational combatants in such a conflict would have political criteria uppermost and would probably select targets which would avoid great civil damage but have great political effect.

Some terrorists might not be as selective. However, terrorists with a political program seek wider support and would presumably exercise discrimination. Moreover, those that have identifiable bases of support have an important vulnerability. These bases can be retaliated against in response to the use of weapons of mass destruction. In short, some terrorists have many of the vulnerabilities of governments.

The most difficult type of terrorist for governments to deal with is the truly crazy type, the stereotypical anarchist. All responsible governments (by definition) have an interest in keeping nuclear weapons out of their hands. And all such governments will have a strong incentive to retaliate against irresponsible governments that make weapons available to extra-governmental groups.

In any case, it should not be assumed that terrorists will find it easy to lay their hands on nuclear weapons. Governments have a strong incentive to retain a monopoly over this form of power. Even so, cooperative international efforts to reduce the likelihood that extra-governmental groups will be able to obtain bomb materials or complete weapons are likely to be needed. But probably much more serious and difficult to cope with is the prospect that the legitimacy of governments that control nuclear weapons will be challenged from time to time and the chaos produced by such challenges could result in nuclear weapons being lost from governmental control.

Appendix 1The Plutonium Recycle Enrichment Penalty

Plutonium obtained by reprocessing of spent fuel contains a substantial fraction of non-fissile plutonium--a fraction which increases with each succeeding recycle. This fact is important because additional fissile Pu (Pu_f) is required in mixed-oxide fuel to compensate for neutron absorption by the non-fissile Pu. Table 14 shows the isotopic composition of the Pu in spent fuel as a function of the number of recycles.*

The last column shows the composition for fuel with 1.15 times the Pu that would be contained at equilibrium in a BWR reactor where all Pu produced by it was recycled into it (a "1.15 equilibrium self-generated recycle," or SGR). With the 1.15 SGR fuel, 37% additional fissile Pu enrichment is required to compensate for the neutron capture of the 43% of the Pu that is non-fissile: The mixed-oxide fuel contains 2.6% fissile Pu plus .7% fissile U_{235} (contained in the natural uranium with which the Pu is mixed) for a total of 3.3% fissile material, whereas the equivalent U_{235} enrichment is 2.6%.** The 2.6% Pu_f , thus, is equivalent to 1.9% U_{235} enrichment, giving a ratio of 1.37 Pu_f to 1 of U_{235} when the non-fissile Pu is 43% of the total Pu.

Assuming that the Pu penalty is proportional to the percent non-fissile Pu, mixed-oxide fuel using first-cycle recovered Pu (29% non-fissile) would entail a 25% enrichment penalty ($37 \cdot 29/43 = 25$). For a PWR reactor in a mature fuel cycle, standard enrichment is 3.4% U_{235} , making the equivalent mixed-oxide enrichment $(3.4 - .7) \cdot 1.25 Pu_f + .7 U_{235} = 3.4 Pu_f + .7 U_{235}$, or 4.1%. It will take 4.9 kg of PWR spent fuel containing .7 gms of Pu per kg to obtain the Pu needed for 1 kg of MOX.

* U.S. Atomic Energy Commission, Generic Environmental Statement Mixed Oxide Fuel (GESMO), Vol. III, August 1974, Table IV C-5, p. IV C-62.

**Ibid., p. IV C-65.

Table 14

Plutonium Composition--Percent

	1	2	3	4	5	
	Pu recovered from spent U fuel	Pu after one 4-year recycle	Pu after two 4-year recycles	Pu after three 4-year recycles	Equilibrium 1.15 SGR New	Spent
^{238}Pu	2	3	4	6	4	4
^{239}Pu	61	45	34	29	42	43
^{240}Pu	24	28	29	27	27	26
^{241}Pu	10	16	18	17	15	16
^{242}Pu	3	9	15	21	12	11
Pu_f^*	71	61	52	46	57	59

$$*\text{Pu}_f = {}^{239}\text{Pu} + {}^{241}\text{Pu}$$

Appendix 2The Recycled Uranium Enrichment Penalty

According to Sprague,* U_{235} recovered by reprocessing will require additional enrichment to compensate for contamination with U_{236} . Fuel made with recovered uranium must cost the same as fuel made with virgin uranium. We can, thus, calculate the price of recovered uranium that will make this equality hold.

The penalty effect of the U_{236} depends in part on its concentration in the final fuel. According to Sprague, it had been expected to mix recovered with virgin uranium and to process it together. Since recycle uranium will be only about 10% of the total, this would make the U_{236} concentration very low. This maximizes the penalty effect of the U_{236} , reducing the value of recovered uranium to about 50% of the value of virgin uranium.

Here, we consider the alternative of segregating the recovered uranium and processing it separately. This may require a separate enrichment facility (to avoid contamination of virgin uranium) and will involve special fuel rod designs. These may further penalize the value of recovered uranium, but we have not included these factors. Nor have we considered the buildup of U_{236} as recycling continues for additional cycles. We consider only the first recycle.

Figure 4 of Sprague's revised paper is reproduced on the next page as Figure 5. Making use of this figure:

$$(1) \quad d = .065 + .25 W, \text{ where}$$

d is the additional enrichment required to compensate for

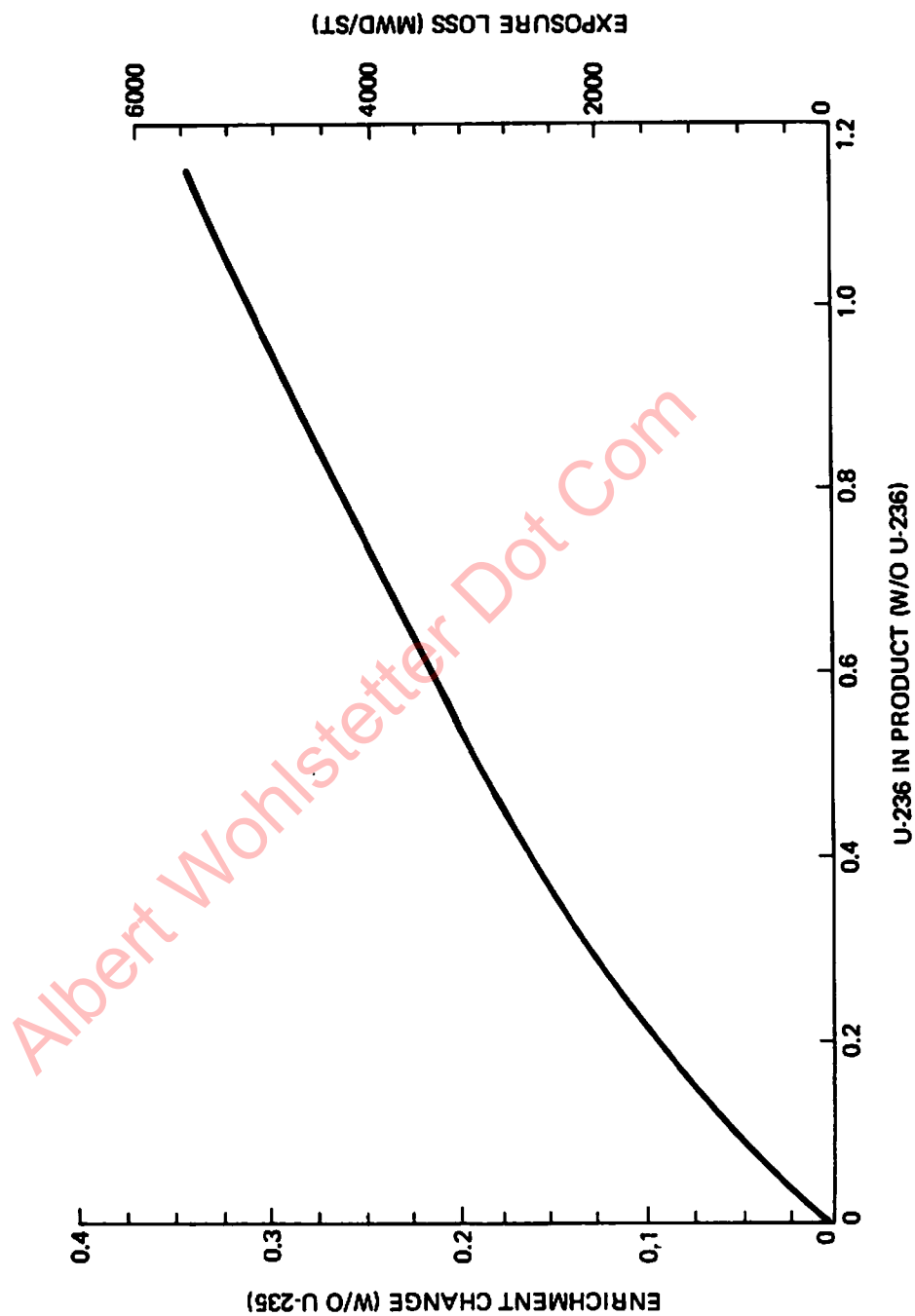
w percent by weight of U_{236} in the fuel.**

The value of w in spent fuel depends upon the initial enrichment and amount of irradiation. For mature cycle PWRs, with an initial enrichment of 3.4% and 30,000 megawatt days/ton of burnup, w is approximately .45%. The U_{235} concentration in this fuel is .9%. Enrichment increases the concentration of U_{236} only about .8 as much as the increase in U_{235} ;

* Herbert O. Sprague, "Fuel Cycle Effect of U-236 in Recycled Uranium," presented at the American Nuclear Society Meeting, June 1974 (available from the author, General Electric, 175 Curtner Avenue, San Jose, California).

** This linear approximation applies in the region of interest here.

Figure 5 — U-236 EFFECT



thus one can define w in terms of the U_{235} concentration in the final fuel, E :

$$(2) \quad w = .45[1 + .8(E - .9)/.9]$$

To make fuel equivalent to 3.4% U_{235} fuel, with recovered uranium, requires an enrichment of E , where

$$(3) \quad E = 3.4 + d, \text{ or using (1)}$$

$$E = 3.4 + .065 + .25 w,$$

and using (2),

$$E = 3.4 + .065 + .25 \times .45[1 + .8(E - .9)/.9]$$

$$E = 3.465/.9 = 3.88$$

To obtain 3.88% U_{235} enriched U from .9% U_{235} requires

$\frac{3.88 - .2}{.9 - .2} = 5.3$ kg of feedstock at .2% tails. The separative work required for 1 kg of 3.88% enriched U , using natural uranium (.7% U_{235}) is 6.3 kg SWU. But since we start with .9% U_{235} , we must allow credit for the equivalent separative work already done: To obtain 5.3 kg of .9% U_{235} requires 1.2 SWUs (.2% tails); thus the separative work required to move from .9% U_{235} to 3.88% U_{235} is $6.3 - 1.2 = 5.1$ kg SWU.

The value of one kg of 3.88% recycled U_{235} must equal the value of one kg of 3.4% virgin U_{235} , since they are equivalent reactors fuels. The value of recycle U_{235} can be calculated by equating the cost of feedstocks and separative work to obtain the two equivalents:

$$(1) \quad \underbrace{\text{Recycled: } .9\% \text{ to } 3.88\% U_{235}}_{5.3 V_{UR} + 5.1 C_e} \quad \text{Virgin: } .71\% \text{ to } 3.4\% \quad \underbrace{\phantom{.71\% \text{ to } 3.4\%}}_{6.2 C_u + 5.2 C_e}$$

where:

V_{UR} = value per kg of reprocessed $U_3 O_8$

C_e = cost per kg - SWU

C_u = cost per kg of virgin $U_3 O_8$

Solving (4) for V_{UR} gives:

$$(4) \quad V_{UR} = \frac{6.2 C_u + .1 C_e}{5.3}$$

for $C_u = \$44$ (per kg) and

$C_e = \$60$ (per kg-SWU),

$V_{UR} = \$67$;

thus the recovered U (with .9% U_{235}) is worth 118% as much as virgin natural U (with .7% U_{235}).

For $C_u = \$100$ and $C_e = \$150$, the result is similar, with $V_{UR} = \$120$.

Appendix 3Land-Based Silo Survivability Formulas

The formulas used are as follows.

For the weapon radius of a 1 MT warhead, $g(H)$, where

$$g(H) = \left[\frac{-1 + \sqrt{1 + 0.36H}}{2.3} \right]^{-2/3}$$

H is the hardness in pounds per square inch and $f(H)$ is in nautical miles. This formula, valid for groundburst weapons and thus somewhat conservative (i.e., giving less than the maximum possible lethal radius), is derived from formula 37, p. 180, H. Brode, "Review of Nuclear Weapons Effects," Annual Review of Nuclear Sciences, Vol. 18, 1968, pp. 153-202. Cube root scaling of the weapon radius to other yields is assumed.

For the survival probability of a point target from a reliably delivered warhead, q , where

$$q = (0.5)^x, \quad x = \frac{(WR)^2}{(CEP)^2 + (WR)^2 \cdot \sigma^2 \cdot \ln(4)},$$

$\sigma = 0.2$. The distance damage parameter, σ , is a dimensionless measure of the variance of the probability of damage as a function of distance between actual ground zero and target. For a "cookie cutter" damage function, $\sigma = 0$.

If n_1 weapons are allocated to one time-slot and n_2 to the other, the probability at least one reliable weapon arrives at the first time-slot is r_1 .

$$r_1 = 1 - (1 - R)^{n_1}$$

where R is the overall reliability per warhead. Similarly,

*See Mathematical Background and Programming Aids for the Physical Vulnerability System for Nuclear Weapons, DI-550-27-4, 1 November 1974, Defense Intelligence Agency for a discussion of WR and σ . The formula for q given above results if the circular coverage function is used to approximate the damage function, as was the case for the DIA system up until 1972. It remains valid as an approximation for $\sigma \leq 0.30$ as discussed on p. 5 of the reference.

$$r_2 = 1 - (1 - R)^{n_2}.$$

Since at most one weapon can be effective per time-slot, the overall survival probability of a target, s , is

$$s = [1 - r_1(1 - q)] \cdot [1 - r_2(1 - q)].$$

If there are T targets, each with the same value of s , the expected (average) number of survivors is Ts . The probability none survive is just the probability all are killed, which is $(1 - s)^T$. Similarly, using the formulas of the binomial distribution, the probability exactly one survives is $T \cdot s \cdot (1 - s)^{T-1}$.

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BIBLIOGRAPHY

Books

- Aron, Raymond, The Great Debate: Theories of Nuclear Strategy, translation by Ernst Pavel, Doubleday, Garden City, New York, 1965.
- Bader, William, The United States and the Spread of Nuclear Weapons, Pegasus, New York, 1968.
- Barnaby, C. G., Preventing the Spread of Nuclear Weapons, Pugwash Monograph I, Humanities Press, New York, 1969.
- Beaton, Leonard, Must the Bomb Spread? Pelican Original, Middlesex, England, 1966.
- Beaufre, General Andre, NATO and Europe, translation by Joseph Green, Alfred A. Knopf, New York, 1966.
- Blackett, P. M. S., Military and Political Consequences of Atomic Energy, Turnstile Press, London, 1948.
- Blizard, E. P., and Abbott, L. S. (eds.), Reactor Handbook, 2nd ed., Vol. III, Part B., Shielding, Interscience Publishers, Inc., New York, 1962.
- Boskey, Bennett, and Willrich, Mason (eds.), Nuclear Proliferation: Prospects for Control, Dunellen, Cambridge, Massachusetts, 1970.
- Brodie, Bernard, Escalation and the Nuclear Option, Princeton University Press, Princeton, New Jersey, 1966.
- Buchan, Alastair (ed.), A World of Nuclear Powers? Prentice-Hall, Englewood Cliffs, New Jersey, 1966.
- Buchan, Alastair, and Windsor, Philip, Arms and Stability in Europe: A British-French-German Inquiry, The International Institute for Strategic Studies, London, 1963.
- Cantril, Hadley, Public Opinion 1935-1946, Princeton University Press, Princeton, New Jersey, 1951.

- Endicott, John E., Japan's Nuclear Option: Political, Technical, and Strategic Factors, Praeger, New York, 1975.
- Feld, B. T., Greenwood, T., Rathjens, G. W., and Weinberg, S. (eds.), Impact of New Technologies on the Arms Race, Pugwash Monograph, M.I.T. Press, Cambridge, Massachusetts, 1971.
- Gallois, Pierre, The Balance of Terror: Strategy for the Nuclear Age, Houghton-Mifflin, Boston, 1961.
- Glassner, Alvin, Introduction to Nuclear Science, Van Nostrand, Princeton, New Jersey, 1961.
- Glasstone, Samuel, Source Book on Atomic Energy, Van Nostrand, Princeton, New Jersey, 1961.
- Glasstone, Samuel, and Sesonske, Alexander, Nuclear Reactor Engineering, Van Nostrand, Princeton, New Jersey, 1967.
- Goldschmidt, Bertrand, The Atomic Adventure, Pergamon Press, Oxford, England, 1964.
- Gowing, Margaret, Britain and Atomic Energy, 1939-1945, St. Martin's Press, London, 1964.
- _____, Independence and Deterrence: Britain and Atomic Energy, 1945-1952, Vol. I, Policy Making, St. Martin's Press, New York, 1974.
- _____, Independence and Deterrence: Britain and Atomic Energy, 1945-1952, Vol. II, Policy Execution, St. Martin's Press, New York, 1974.
- Gueron, J., Lane, J. A., Maxwell, J. R., and Menke, J. R. (eds.), The Economics of Nuclear Power, Progress in Nuclear Energy Series VIII, Vol. I, Pergamon Press, London, 1956.
- Halperin, Morton, China and Nuclear Proliferation, The University of Chicago Center for Policy Study, Chicago, 1966.
- _____, Defense Strategies for the Seventies, Little, Brown, Boston, 1971.
- _____, Limited War in the Nuclear Age, Wiley, New York, 1963.
- Hawkins, David (ed.), Manhattan District History Project Y: The Los Alamos Project, Vol. I, Inception until August 1945, Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico, 1961.

- Heilbrunn, Otto, Conventional Warfare in the Nuclear Age, Praeger, New York, 1965.
- Herz, John, International Politics in the Nuclear Age, Columbia University Press, New York, 1959.
- Hewlett, R. G., and Anderson, O. E., Jr., A History of the United States Atomic Energy Commission, Vol. I, The New World, 1939-1946, Pennsylvania State University Press, University Park, Pennsylvania, 1962.
- Holst, Johan (ed.), Security, Order and the Bomb: Nuclear Weapons in the Politics and Defense Planning of Non-Nuclear Weapon States, Universitetsforlaget, Oslo, Norway, 1972.
- Joshua, Wynfred, Nuclear Weapons and the Atlantic Alliance, National Strategy Information Center, New York, 1973.
- Kaplan, Morton, The Strategy of Limited Retaliation, Center of International Studies, Princeton, New Jersey, 1959.
- Knorr, Klaus, and Read, Thornton (eds.), Limited Strategic War, Praeger, New York, 1962.
- Kramish, Arnold, The Peaceful Atom in Foreign Policy, Harper, New York, 1963.
- Kuenne, Robert E., The Polaris Missile Strike: A General Economics System Analysis, Ohio State University Press, Columbus, Ohio, 1966.
- Lawrence, Robert N., and Larus, Joel (eds.), Nuclear Proliferation: Phase II, University Press of Kansas, Lawrence, Kansas, 1974.
- Loftness, Robert, Nuclear Power Plants, Van Nostrand, New York, 1964.
- MacAvoy, Paul, Economic Strategy for Developing Nuclear Breeder Reactors, M.I.T. Press, Cambridge, Massachusetts, 1969.
- Mason, Edward S., Productive Uses of Nuclear Energy: Report on Energy Requirements and Economic Growth, National Planning Association, Washington, D.C., 1955.
- Maxwell, J. R., Mummery, P. W., and Sporn, Philip (eds.), The Economics of Nuclear Power, Progress in Nuclear Energy Series VIII, Vol. II, Pergamon Press, London, 1959.

- McKnight, Allan, Atomic Safeguards: A Study in International Verification, United Nations Institute for Training and Research, New York, 1971.
- McLain, S., and Martens, J. H., Reactor Handbook, 2nd ed., Vol. IV, Engineering, Interscience Publishers, Inc., New York, 1964.
- McPhee, John, The Curve of Binding Energy, Ballantine Books, Westminster, Maryland, 1975.
- Moore, Capt. John E. ed., Jane's Fighting Ships 1974-75, Franklin Watts, Inc., New York, 1974.
- Morison, Elting E., Turmoil and Tradition: A Study of the Life and Times of Henry L. Stimson, Houghton-Mifflin, Cambridge, Massachusetts, 1960.
- National Planning Association, 1970 Without Arms Control, Planning Pamphlet 104, NPA, Washington, D.C., May 1958.
- _____, The Nth Country Problem and Arms Control, Planning Pamphlet 108, NPA, Washington, D.C., January, 1960.
- The Organization for Economic Cooperation, Energy Prospects to 1985, Vols. I and II, OECD, Paris, 1975.
- Pranger, R. J., and Tahtinen, D. R., Nuclear Threat in the Middle East, American Enterprise Institute for Policy Research, Washington, D.C., 1975.
- Rand McNally, The International Atlas, Rand McNally, Chicago, 1974.
- Rosecrance, Richard N. (ed.), The Dispersion of Nuclear Weapons: Strategy and Politics, Columbia Law Press, New York, 1964.
- Scheinman, Lawrence, Atomic Energy Policy in France Under the Fourth Republic, Princeton University Press, Princeton, New Jersey, 1965.
- Schmidt, Helmut, Defense or Retaliation: A German View, translation by Edward Thomas, Praeger, New York, 1962.
- Shah, A. B., (ed.), India's Defense and Foreign Policies, P. C. Manaktala and Sons, Bombay, 1966.
- SIPRI, Nuclear Proliferation Problems, M.I.T. Press, Cambridge, Massachusetts, and London, 1974.
- Smyth, Henry, Atomic Energy for Military Purposes: The Official Report on the Development of the Atomic Bomb Under the Auspices of the United States Government, 1940-1945, Princeton University Press, Princeton, New Jersey, 1945.

- Soodak, H. (ed.), Reactor Handbook, 2nd ed., Vol. III, Part A, Physics, Interscience Publishers, Inc., New York, 1962.
- The Statesman's Yearbook, 1974-1975, St. Martin's Press, New York, 1974.
- Steele, George P., Seadragon, E. P. Dutton & Company, New York, 1974.
- Stoller, S. M., and Richards, R. B. (eds.), Reactor Handbook, 2nd ed., Vol. II, Fuel Reprocessing, Interscience Publishers, New York, 1961.
- Taylor, Theodore B., and Willrich, Mason, Nuclear Theft: Risks and Safeguards, Ballinger Publishing Company, Cambridge, Massachusetts, 1974.
- Tipton, C. R., Jr. (ed.), Reactor Handbook, 2nd ed., Vol. I, Materials, Interscience Publishers, Inc., New York, 1960.
- Trudlow, Edith C., and Smith, Ralph Carlisle, Manhattan District History Project Y: The Los Alamos Project, Vol. II, August 1945 through December 1946, Los Alamos Scientific Laboratory of the University of California, Los Alamos, New Mexico, 1961.
- Urlick, Robert J., Principles of Underwater Sound for Engineers, McGraw-Hill, New York, 1967.
- Viner, Jacob, Essays in International Economics, The Free Press, Glencoe, Illinois, 1951.
- Wentz, Walter B., Nuclear Proliferation, Public Affairs Press, Washington, D.C., 1968.
- Willrich, Mason (ed.), Civilian Nuclear Power and International Security, Praeger, New York, 1971.
- _____, (ed.), International Safeguards and Nuclear Industry, Johns Hopkins University Press, Baltimore, Maryland, and London, 1973.
- _____, Non-Proliferation Treaty, Michie, Charlottesville, Virginia, 1969.

Articles

- Abagian, Vincent V., and Fishman, Alan M., "Supplying Enriched Uranium," Physics Today, Vol. 26, August 1973.

- Acheson, D., "NATO and Nuclear Weapons," New Republic, Vol. 137, December 30, 1957, pp. 14-16.
- Bairot, H., Haubert, P., and Vanden Bemden, E., "The Plutonium Fuel Penalty, Design and Production," presented at the American Nuclear Society Meeting on Commercial Nuclear Fuel Technology Today, Toronto, Canada, April 1975.
- Beaton, Leonard, "Nuclear Fuel for All," Foreign Affairs, Vol. 45, July 1967, pp. 662-669.
- Beecher, William, "U.S. Believes Israel Has More than 10 Nuclear Weapons," Boston Globe, July 31, 1975.
- Brode, H., "Review of Nuclear Weapons Effects," Annual Review of Nuclear Sciences, Vol. 18, 1968, pp. 153-202.
- Brzezinski, Zbigniew, "Moscow and the M.L.F.: Hostility and Ambivalence," Foreign Affairs, Vol. 43, No. 1, October 1964, pp. 126-134.
- Bull, Hedley, "Rethinking Non-Proliferation," International Affairs, April 1975.
- Bullio, Pietro, "Italian Nuclear Power Industry," Nuclear Engineering International, October 1973, p. 784.
- Bupp, Irwin C., Derian, Jean Claude, Donzimoni, Marie-Paule, and Treitel, Robert, Trends in Light Water Reactor Costs in the United States: Causes and Consequences, Center for Policy Alternatives, M.I.T. Press, Cambridge, Massachusetts, December 1974.
- Carsons, A. B., "U.S. Fuel Reprocessing," presented at the American Nuclear Society Meeting on Commercial Fuel Technology Today, Toronto, Canada, April 27-30, 1975.
- Cha, J. H., "Estimate of Nuclear Power Costs in Korea," Proceedings of an IAEA Symposium in Istanbul, Turkey, October 20-24, 1969, IAEA-SM-126/40, 1970.
- Cohen, Bernard L., "The Hazards in Plutonium Dispersal," Institute for Energy Analysis, Oak Ridge, Tennessee, July 1975. (Revised paper available from author, University of Pittsburgh, Pittsburgh, Pennsylvania.)
- Crittenden, Ann, "Surge in Nuclear Exports--Spurs, Drives for Controls," New York Times, April 17, 1975.

- Dahlberg, R. C., and Brooks, L. H., "Core Design Characteristics and Fuel Cycle," Nuclear Engineering International, Vol. 19, No. 219, August 1974, pp. 640-646.
- Daniel, Cuthbert, and Squires, Arthur M., "The International Control of Safe Atomic Energy," Bulletin of Atomic Scientists, Vol. 3, No. 4-5, April-May, 1947, pp. 111-116, and 185.
- Darmstadter, Joel, "International Flows of Energy Sources," IEEE Spectrum, May 1970, pp. 67-72.
- Dawson, F. G., Deonigi, D. E., and Eschbach, E. A., "Plutonium Buildup and Depletion," Nucleonics, Vol. 23, Part 2, August 1965, pp. 101-105.
- Deutsch, Karl, and Singer, J. David, "Multipolar Power Systems and International Stability," World Politics, Vol. 16, April 1964, pp. 390-406.
- "Energy Prospects to 1985--OECD Assessment of Long-Term Energy Development and Related Policies," Nuclear Engineering International, Vol. 20, No. 225, February 1975, p. 120.
- Epstein, William, "The Proliferation of Nuclear Weapons," Scientific American, Vol. 232, April 1975, pp. 18-33.
- "Forrestal Diaries," unpublished manuscript, Office of Naval History, Washington, D.C.
- Gallois, Pierre, "A French General Analyses Nuclear Age Strategy," Réalités, November 1958, pp. 23-28, 70-71.
- _____, "Nuclear Aggression and National Suicide," The Reporter, September 18, 1958.
- Gilinsky, Victor, Fast Breeder Reactors and the Spread of Plutonium, The RAND Corporation, RM-5148-PR, March 1967.
- _____, Where is Nuclear Reactor Technology Taking Us? The RAND Corporation, P-3589, April 1967.
- Gilinsky, Victor, and Langer, Paul, The Japanese Civilian Nuclear Program, The RAND Corporation, RM-5366-PR, August 1967.

Gillette, Robert, "India and Argentina: Developing a Nuclear Affinity," Science, Vol. 184, June 28, 1974, pp. 1351-1353.

_____, "Nozzle Enrichment for Sale," Science, Vol. 188, No. 4191, May 30, 1975.

_____, "Nuclear Testing Violations: Keeping It All in the Family," Science, Vol. 185, August 9, 1974, pp. 506-510.

Hall, D. B., "The Adaptability of Fissile Materials to Nuclear Explosives," presented at the Symposium on Implementing Nuclear Safeguards," Kansas State University, October 25, 1971.

Halperin, Morton, A Proposal for a Ban on the Use of Nuclear Weapons, Study Memorandum 4, Institute for Defense Analyses, October 6, 1961.

Hittman, Fred, and Raber, Marvin, "The Importance of Plutonium Recycle," Nuclear News, November 1968, pp. 48-56.

Holliday, Dennis, and Plesset, Milton S., An Elementary Introduction to Isotope Separation, The RAND Corporation, RM-4938-PR, June 1966.

Holliday, Dennis, and Taylor, Vincent, "The Uncertain Future of Nuclear Power," presented at the Southern California Arms Control Seminar, Santa Monica, California, August 1975.

"IAEA: Move to Nuclear Power Slower than Expected," Nuclear News, September, 1975, p. 66.

Imai, Ryukichi, "NPT and Future of U.S. Japanese Relations: A Non-European Assessment in 1975," unpublished paper.

_____, "Nuclear Safeguards," Adelphi Papers 86, The International Institute for Strategic Studies, London, March 1972.

_____, "Political Outlook for Nuclear Power in Japan," presented at the Southern California Arms Control Seminar, Palm Springs, California, January 1975, published in The Atlantic Community Quarterly, Vol. 13, No. 2, Summer 1975, pp. 226-243.

_____, "Proliferation and the Indian Test: A View from Japan," Survival, Vol. 16, No. 5, September-October 1974, pp. 213-216.

"Israel, More Power Stations Needed," Nuclear Engineering International, Vol. 18, No. 204, May 1973, p. 391.

"Japan--Centrifuge, Good Progress," Nuclear Engineering International, Vol. 20, No. 225, February 1975, p. 81.

Japan Defense Agency, Japan's Fourth Five Year Plan, Tokyo, October 1972.

"Japan's Military Strength and Defense-Awareness of its People," The Business Community Quarterly of Japan, Summer 1975.

Kahn, Herman, "Nuclear Proliferation and Rules of Retaliation," Yale Law Journal, Vol. 76, No. 1, 1966, pp. 77-91.

Kayonari, Susumu, "Activities of the Power Reactor and Nuclear Development Corporation," Nuclear Engineering International, Vol. 18, No. 206, July 1973, p. 537.

Kemp, Geoffrey, "Nuclear Forces for Medium Powers," Part I, Adelphi Papers 106, The International Institute for Strategic Studies, London, 1974.

_____, "Nuclear Forces for Medium Powers," Parts II and III, Adelphi Papers 107, The International Institute for Strategic Studies, London, 1974.

Ketzmel, Z., "Uranium Sources Production and Demand in Israel," presented at the Fourth United Nations Conference on Peaceful Uses of Atomic Energy, A/CONF 49/P/013, Geneva, Switzerland, September 1971.

Kinderman, E. M. "Plutonium: Home Made Bombs?" presented at the Conference on Nuclear Public Information, organized by the Atomic Industrial Forum, March 5-8, 1972.

Kovon, Dick, "Developing World Needs for Nuclear Power," Nuclear Engineering International, January 1975.

Krone, Robert, "NATO Nuclear Policymaking," Ph.D. Dissertation, UCLA, 1972.

Lambeth, Benjamin S., "Nuclear Proliferation and Soviet Arms Control," Orbis, Vol. 14, Summer 1970, pp. 298-325.

Langer, Paul, Japanese National Security Policy--Domestic Determinants, The RAND Corporation, RM-1030-ISA, June 1972.

Langer, Paul, and Moorsteen, Richard, "Exploring Japanese Approaches to Defense Issues," presented at the Southern California Arms Control Seminar, Palm Springs, California, January 1975.

- Langer, Paul, and Moorsteen, Richard, "The U.S.-Japanese Military Alliance: Japanese Perceptions and the Prospective Impact of Evolving U.S. Military Doctrines and Technologies," unpublished paper, January 1975.
- Maddox, John, "Prospects for Nuclear Proliferation," Adelphi Papers 113, The International Institute for Strategic Studies, London, Spring 1975.
- Marshak, J., "Economic Aspects of Atomic Power," Bulletin of Atomic Scientists, Vol. 2, Nos. 5 and 6, September 1, 1946, pp. 8-9.
- Mazrui, Ali A., "Numerical Strength and Nuclear Status in the Third World," Journal of Politics, Vol. 29, No. 4, November 1967, pp. 791-820.
- McGlinchey, Joseph J. and Seelig, Jakob W., "Why ICBMs Can Survive a Nuclear Attack," Air Force, September 1974, pp. 82-85.
- Miller, Richard A., "Indonesia's Archipelago Doctrine and Japan's Jugular," U.S. Naval Institute Proceedings, October 1972, pp. 27-33.
- Moynihan, Daniel P., "The United State in Opposition," Commentary, March 1975, pp. 21-39.
- Mukerjee, Dilip, "Itching for the Bomb," Far Eastern Economic Review, July 9, 1970.
- "Nuclear News Briefs," Nuclear News, April 11, 1975, p. 111.
- "Nuclear Inspector or Salesman?" The Economist, February 28, 1976.
- "Operating Experience--Reports from World Nuclear Power Station Sites--India--Rajasthan (RAPS)1," Nuclear Engineering International, Vol. 20, No. 230, May 1975, p. 471.
- Oppenheimer, J. Robert, "Atomic Explosives," Lecture, May 16, 1946, published in The Open Mind, a collection of lectures, Simon and Schuster, New York, 1955.
- _____, "The Environs of Atomic Power," in the American Assembly (ed.), Atoms for Power: United States Policy in Atomic Energy Development, Columbia University, New York, 1957.
- Poole, L.G., "World Uranium Resources," Nuclear Engineering International, February 1975, pp. 95-100.
- Power Reactor and Nuclear Fuel Development Corporation of Japan, PNC, Tokyo, 1974.

"A Programme of Nuclear Power," British White Paper presented to Parliament by Lord President of the Council and the Minister of Fuel and Power, Cmd. 9389, Her Majesty's Stationery Office, London, February 1955.

Public Broadcast System, "The Plutonium Connection," Nova Series, No. 214, September 6, 1975.

Puechl, Karl, "Everything Going Up," Nuclear Industry, March 1975.

Quester, George, "What's New on Nuclear Proliferation?" presented at the Aspen Institute for Humanistic Studies, Aspen, Colorado, August 1975.

Read, Thornton, "Nuclear Tactics for Defending a Border," World Politics, April 1963, pp. 390-402.

Redick, John R., "Argentina's Nuclear Connection," Washington Post, September 30, 1974.

Rippon, Simon, "Brazilian Bonanza," Nuclear Engineering International, Vol. 20, No. 231/2, June/July 1975, p. 497.

Rodger, W. A., Pichard, J. K., and Vallance, John M., The Throwaway Fuel Cycle, Nuclear Safety Associates, March 1975.

Rose, David J., "Nuclear Eclectic Power," Science, Vol. 184, April 19, 1974.

Rosecrance, Richard, "Problems of Nuclear Proliferation: Technology and Politics," Security Studies Paper No. 7, UCLA, 1968.

Rosen, S., "Proliferation Treaty Controls and the IAEA," Journal of Conflict Resolution, Vol. 11, June 1967, pp. 168-175.

Rosenbaum, David M., Statement before the Senate Committee on Government Operations, April 24, 1975, p. 3 of typescript.

Rothstein, Robert L., "Nuclear Proliferation and American Policy," Political Science Quarterly, Vol. 82, March 1967, pp. 14-34.

Rowen, Henry S., "Implications of Technologies of Precision for Japanese Security," presented at the Southern California Arms Control Seminar, Tokyo, June 1975.

- Saha, Meghnad, "Science in Social and International Planning with Special Reference to India," Nature, Vol. 155, No. 3930, February 24, 1945, pp. 221-224.
- Sanders, B., and Rometsch, R., "Safeguards Against Use of Nuclear Materials for Weapons," Nuclear Engineering International, September 1975.
- Schlesinger, J. R., Nuclear Spread: The Setting of the Problem, The RAND Corporation, P-3557, March 1967.
- Schuller, Walter, "Fuel Reprocessing in Europe," presented at the American Nuclear Society Meeting on Commercial Fuel Technology Today, Toronto, Canada, April 27-30, 1975.
- Schwab, George, "Switzerland's Tactical Nuclear Weapons Policy," Orbis, Vol. 13, No. 3, Fall 1969, pp. 900-914.
- Seaborg, Glenn T., and Bloom, Justin L., "Fast Breeder Reactors," Scientific American, November 1970, pp. 13-21.
- Shapley, Deborah, "Plutonium Reactor Proliferation Threatens a Nuclear Black Market," Science, Vol. 172, April 9, 1971, pp. 143-146.
- Simons, Howard, "World-Wide Capabilities for Production and Control of Nuclear Weapons," Daedalus, Summer 1959, pp. 385-408.
- Smart, Ian, "Future Conditional: The Prospect for Anglo-French Nuclear Co-operation," Adelphi Papers 78, The International Institute for Strategic Studies, London, August 1971.
- Smith, David, "What Price Commercial Enrichment?" Nuclear Engineering International, July 1974, p. 572.
- Snow, C. P., "The Moral Un-Neutrality of Science," Science, January 1961, p. 259.
- "South Africa--Release More Details on Enrichment Process," Nuclear News, Vol. 18, No. 8, June 1975, p. 75.
- Sprague, Herbert O., "Fuel Cycle Effect of U-236 in Recycled Uranium," presented at the American Nuclear Society Meeting, June 1974. (Available from the author, General Electric, 175 Curtner Avenue, San Jose, California)
- Steele, Richard, Carroll, Raymond, Bishop, James, Jr., and Van Voorst, Bruce, "To Have and Have Not," Newsweek, Vol. 86, No. 11, September 15, 1975, pp. 37-45.
- Stevenson, Adlai E., III, "Nuclear Reactors: America Must Act," Foreign Affairs, Vol. 53, No. 1, October 1974.

"Supplement," Nuclear Engineering International, Vol. 20, No. 229, April 1975.

Szilard, Leo, "Atomic Bombs and the Post-War Position of the United States in the World," March 1945 (unpublished document available in the office of the ERDA historian, Headquarters Building, Washington, D.C. 20545), excerpted in the Bulletin of the Atomic Scientists, December 1947.

Szilard, J., "Nuclear Weapons: A Liability," Bulletin of Atomic Scientists, Vol. 22, September 1966, pp. 15-20.

Taylor, Theodore B., "Diversion by Non-Governmental Organizations," in Mason Willrich (ed.), International Safeguards and Nuclear Industry, Johns Hopkins University Press, Baltimore, Maryland, and London, 1973.

_____, "The Need for National and International Systems to Provide Physical Security for Fissionable Materials," AAAS Symposium, The Energy Crisis: Some Implications and Perspectives, Philadelphia, December 23, 1971.

Turner, S. E., McCullough, C. R., and Lyster, R. L., "Industrial Sabotage in Nuclear Power Plants," Nuclear Safety, Vol. 11, No. 2, March-April, 1970, pp. 107-114.

Viner, Jacob, "Implications of the Atomic Bomb for International Relations," Essays in International Economics, The Free Press, Glencoe, Illinois 1951.

Washburn, A. Michael, "Nuclear Proliferation in a Revolutionary International System," Public International Affairs, Vol. 5, Spring, 1967, pp. 111-133.

Wohlstetter, Albert, "Atoms for Equality?" Consultations 30 and 31, Council on Religion and International Affairs, January 1967.

_____, "Illusions of Distance," Foreign Affairs, Vol. 46, No. 2, January 1968, pp. 242-255.

_____, "Japan's Security: Balancing after the Shocks," Foreign Policy, Winter 1972-1973, pp. 171-190.

_____, "Nuclear Sharing: NATO and the Nth + 1 Country," Foreign Affairs, April 1961, pp. 355-387.

_____, "Perspective on Nuclear Energy," Bulletin of the Atomic Scientists, April 1968, pp. 2-5.

_____, "Strategy and the Natural Scientists," in R. Gilpin and C. Wright (eds.), Scientists and National Policy Making, Columbia University Press, New York, 1964.

Wolfowitz, Paul, "Nuclear Proliferation in the Middle East," Ph.D. Dissertation, Department of Political Science, University of Chicago, 1972.

Woodrow, A., "Nuclear pro and con: The French Debate," Commonweal, Vol. 99, January 18, 1975, pp. 381-382.

"World List of Nuclear Power Plants," Nuclear News, Vol. 18, No. 10, August 1975, pp. 63-69.

Young, Elizabeth, "The Control of Proliferation: The 1968 Treaty in Hindsight and Forecast," Adelphi Papers 56, The International Institute for Strategic Studies, London, April 1969.

Zippe, G., The Development of Short Bowl Ultracentrifuges, Research Laboratories for the Engineering Sciences, University of Virginia, June 15, 1960.

Zoppo, C. E., "Nuclear Technology, Multipolarity, and International Stability," World Politics, Vol. 18, July 1966, pp. 579-606.

Government Documents and Reports

Acheson, D., "Memorandum to President Truman on U.S. Policy Regarding Secrecy of Scientific Knowledge about the Atomic Bomb and Atomic Energy," Foreign Relations of the United States, 1945, Vol. 2, the Department of State, Washington D.C. USGPO, 1967, pp. 48-50

Dreissigacker, H. L., "Expected Development for Enriching Uranium in Europe," presented at the DFVLR Colloquium, Porz-Wahn, Germany, May 14, 1970, British translation (Capenhurst Translation 249) issued by the U.S. Atomic Energy Commission as CONF-700557-3.

International Atomic Energy Agency, "The Agency's Safeguards System, 1965, as Provisionally Extended in 1966," INFCIRC/66/rev. 1, 1967.

_____, "The Agency's Safeguards System, 1965, as Provisionally Extended in 1966 and 1968," INFCIRC/66/rev. 2, September 16, 1968.

_____, Directory of Nuclear Reactors, IAEA, Vienna, 1959-. (Power Reactors: Vol. 1, 1959, Vol. IV, 1962, Vol. VII, 1968, Vol. IX, 1971. Research, Test and Experimental Reactors: Vol. II, 1959, Vol. III, 1960, Vol. V., 1964, Vol. VIII, 1970)

_____, The IAEA Statute (approved October 23, 1956, by the Conference on the Statute of the International Atomic Energy Agency, amended January 31, 1964).

- _____, Market Survey General Report, IAEA, Vienna, 1973.
- _____, Market Survey for Nuclear Power in Developing Countries, IAEA, Vienna, 1974.
- Defense Intelligence Agency, Mathematical Background and Programming Aids for the Physical Vulnerability System for Nuclear Weapons, DI-550-27-74, November 1974.
- International Atomic Energy Agency, Projections of Safeguard Costs 1971-1975, GOV/COM 22/80, October 19, 1970.
- _____, "Safeguards Techniques," Proceedings of Symposium in Karlsruhe, July 6-10, Vols. I and II, IAEA, Vienna, 1970.
- _____, The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons, INFCIRC/153, May 1971.
- Laws and Regulations Governing Nuclear Exports and Domestic and International Nuclear Safeguards, Message from the President of the United States, May 6, 1975, USGPO, Washington D.C., 1975, p. 35
- Project Independence Report, U.S. Government Printing Office, Washington, D.C., November 1974.
- United Nations, Demographic Yearbook: 1973, U.N., New York, 1973.
- _____, Statistical Yearbook, U.N., New York, 1973.
- U.S. Atomic Energy Commission, Generic Environmental Statement Mixed Oxide Fuel (GESMO), Vols. II and III, WASH-1327, August 1974.
- _____, Power Plant Capital Costs, WASH-1345, October 1974.
- U.S. Congress, Committee on the Armed Services, House of Representatives, Review of Arms Control and Disarmament Activities, 93rd Congress, 2nd Session, Hearings of May and July 1974, U.S. Government Printing Office, Washington, D.C., 1974.
- _____, Committee on Armed Services, Senate, Authorization for Military Procurement, 91st Congress, 1st Session, Part I, U.S. Government Printing Office, Washington, D.C., 1969.
- _____, Committee on Foreign Relations, Senate, Hearings on the Non-Proliferation Treaty, Parts 1 and 2, 90th Congress, 2nd Session, and 91st Congress, 1st Session, U.S. Government Printing Office, Washington, D.C., 1968 and 1969.

- _____, Hearings on Continuing Assessment of Actions Underway, Contemplated or Suggested, to Insure Supply of Enriched Uranium Sufficient to Meet Present and Future Needs, 93rd Congress, 2nd Session, U.S. Government Printing Office, Washington D.C., 1975
- _____, Hearings on the Statute of the International Atomic Energy Agency 85th Congress, 1st Session, U.S. Government Printing Office, Washington D.C., 1957.
- _____, Joint Committee on Atomic Energy, Hearings on Actions Necessary to be Taken to Insure Supply of Enriched Uranium Sufficient to Meet Present and Future Needs, 93rd Congress, 2nd Session, U.S. Government Printing Office, Washington D.C., 1975.
- _____, Subcommittee on Arms Control, International Organizations and Security Agreements of Committee on Foreign Relations, Senate, Analyses of Effects of Limited Nuclear Warfare, 94th Congress, 1st Session, U.S. Government Printing Office, Washington, D.C., September 1975.
- U.S. Congress, Subcommittee on Energy and the Environment of Committee on Interior and Insular Affairs, House of Representatives, Oversight Hearings on Nuclear Energy, Part I, Testimony of May 2, 1975, U.S. Government Printing Office, Washington, D.C., 1975.
- U.S. Department of State, Documents on Disarmament, 1945-1959, Vol. I, 1945-1956, publication 7008, U.S. Government Printing Office, Washington, D.C., 1960.
- _____, The International Control of Atomic Energy: Growth of a Policy, U.S. Memorandum No. 1, of July 2, 1946, U.S. Government Printing Office, Washington, D.C., 1946.
- _____, A Report on the International Control of Atomic Energy, publication 2498, U.S. Government Printing Office, Washington, D.C., 1946.
- Wirfs, W. F., A Detailed Analysis of the Safeguards Capabilities of Material Balance Accounting Systems in the Low Enriched UO₂ Conversion and Fabrication Sectors of the Commercial Fuel Cycle, WASH-1140, pp. 115-162.

Appendix 4

INTRODUCTION

Technology for Nuclear Weapons Capability

The United States required several years of immense national effort before the first atomic bomb was exploded at Alamogordo, New Mexico, on July 16, 1945. This time period was required even though the development program was carried out by a war emergency mobilization of the top scientists, engineers, and industrial organizations. Other countries that have joined the nuclear club, have also required a start-up period. France, for example, decided in the 50s to develop a small nuclear force based upon plutonium. France invested in nuclear reactors to produce plutonium (and to develop their nuclear industry) and exploded their first fission weapon in 1960. India, a recent nuclear club joiner, has had a substantial nuclear technology effort for over 20 years. However, the actual decision to demonstrate a nuclear weapon capability may not have been made until after the Chinese nuclear explosion of October 16, 1964.

It is evident that the technical and material barriers are sufficient to require a deliberate national decision to join the nuclear club. Once this decision is made a start-up period is required. The extent of the start-up period, in time and cost, depends on the status of that country's nuclear industry. Some countries, Sweden for example, have an extensive technology base but with no known capability of acquiring, on a continuing basis, the weapons grade material that is necessary to produce an atomic bomb. Other countries such as West Germany and Japan have a sophisticated nuclear technology capability and can acquire weapons grade material in a straightforward manner from their own nuclear industry. This paper is an attempt to assess the necessary start-up period for the various countries in terms of time and money assuming they have made a unilateral decision, i.e., no help from weapon countries, to become nuclear club members.

Possible Paths to Nuclear Weapon Capability

In Fig. 1 all of the possible routes to Nuclear Weapon (NW) capability are schematically represented. The present effort is an attempt to determine the time and expense that is necessary to travel paths 1 through 4. Path 0 represents acquisition of a completed device through purchase, theft, or gift. This path is not considered here.

PATHS TO NW CAPABILITY

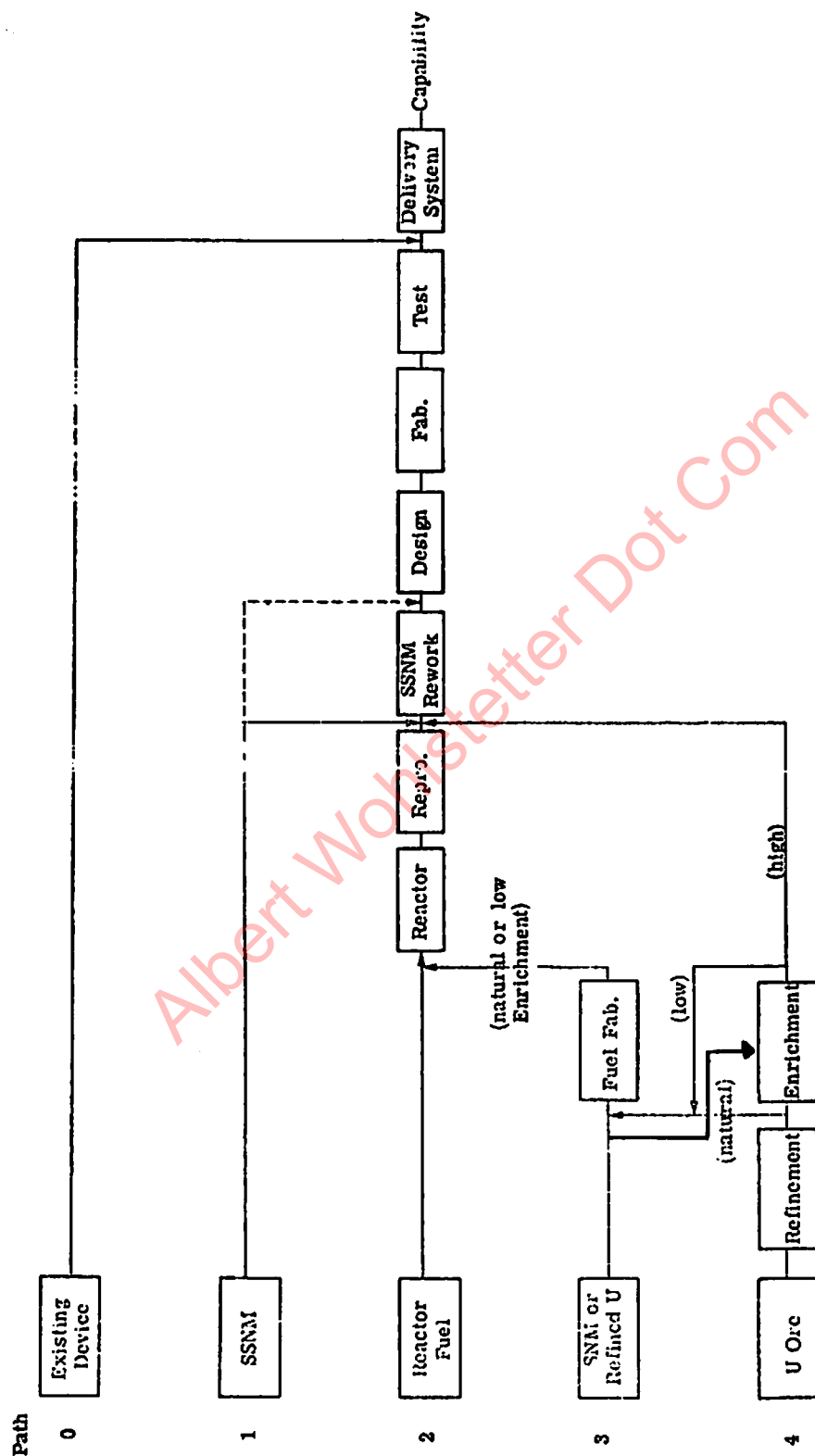


Figure 1. Paths to NW Capability

General Comments

A few general comments are in order to define the magnitude of the effort necessary to follow paths 1 through 4. We shall assume that we are working toward a minimum NW capability of 5 weapons per year. This is an appropriate assumption for most non-NW countries, although Germany or Japan obviously could undertake much larger programs if they were to make the national decision to develop nuclear forces.

Without wishing to delve into classified areas or even into the unclassified areas of critical systems, we shall arbitrarily assert that 5 kg of fissile plutonium (^{239}Pu and ^{241}Pu) or 5 kg of ^{233}U , or 15 kg of ^{235}U is sufficient special nuclear material to make a nuclear weapon. The actual amount of fissile material depends on the desired explosive yield and the details of the design⁽³³⁾. The chemical form of the fissile material, the use of a reflector, and an implosion or gun barrel design all significantly affect the amount of fissile needed. Consequently, the numbers above are only exposition numbers, sufficient to define the magnitude of material needed.

The cost of the delivery system for a minimum NW capability we shall neglect. The basic conclusion is that it need not be a specialized delivery system and might consist of a fighter bomber like an F-4. The weapon itself that could be delivered by these aircraft could be rather primitive. The nuclear weapon might have a maximum dimension of 3 ft. and weigh 2,000 to 3,000 lbs.

Classification of Countries

The design, construction and operation of a large research reactor or nuclear power reactor requires special manpower skills that may not be available unless the country has achieved a certain nuclear maturity. This is also true of specific portions of other elements in the path to NW capability. However, in a general sense, a university or universities with quality physics, chemistry, and metallurgy departments can provide the nucleus of formally trained people with individuals from industry supplementing this group with practical and formal experience. Many of the operations, for example, in generating and fabricating metallic uranium or plutonium are sufficiently documented in the open literature that a well educated individual or group can efficiently adapt the operations to their use even though they may not have had any previous personal experience in working with uranium and plutonium before. In addition to drawing on their intrinsic manpower talent, most countries in the world have participated in the multitude of U.S., IAEA, Russian or other nuclear programs.

The amount of this previous experience and the degree of industrial sophistication can have a significant effect on the time necessary to acquire a specific capability. For this reason we have divided the non-NW countries into three classes to estimate the time necessary to reach NW capability. However, the range within each classification is rather broad and may even overlap the next class. The only reasonably accurate way to evaluate the time and cost involved for a country to join the NW club is to consider that country on an individual basis. Each country can then be evaluated on the basis of its present nuclear facilities, the maturity of its nuclear program, the amount of participation in foreign or international nuclear programs, and the overall sophistication of its industry. Such an effort is beyond the scope of this paper.

Table 1 classifies countries according to their potential to reach a nuclear weapon capability. The primary classification criterion is according to the estimated time that would be necessary to reach a nuclear weapon status. The zeroth category includes those countries that have exploded a fission device. Category 1 includes the countries that have full access to the special nuclear material needed for weapons and have a broad nuclear technology manpower base. We have included in this category Canada and Sweden even though they do not have an enrichment or reprocessing plant located within their country. However, their nuclear technology base is so extensive, they could acquire the necessary facilities in a minimum time period. Partial potential countries, Category 2, have at least a reactor within their borders and some technological base to draw upon. It is not clear if Israel belongs in

Category 1 or 2. The remaining countries are classified as having minimum potential.

Table 1

<u>Category</u>	<u>Country</u>
0	U.S., USSR, U.K., France, China, India
1	Japan, West Germany, South Africa, Belgium, Taiwan, Italy, Netherlands, Canada, Sweden
2	Israel, Argentina, Switzerland, Egypt, Spain, South Korea, Indonesia, East Germany, Czechoslovakia, Australia, Pakistan, Iran, Norway, Brazil, Mexico
3	Remaining Countries

Most of the data utilized in assessing the classification of the various countries is contained in Sub-appendix 4A, Tables A1 through A5. Tables A1 and A2 list the reactors over 1 MW(t) contained within the borders of each country, the start-up dates, and a realistic assessment of the plutonium production (a 75% capacity factor is assumed). These tables provided the data for the graphs in the reprocessing portion of the section on Specific Elements. Table A3 lists the separable plutonium produced based on the actual power generating history. Table A5 is a compilation of free world enrichment plants.

Estimated Time and Costs to Build
and Test a Nuclear Device

Figures 2 through 5 present estimates of the total times and costs that would be necessary for each country category to reach a nuclear weapon status from a civilian nuclear power program base. We have assumed that work on many of the specific elements can be conducted in parallel and consequently the total time period is not just the simple addition of individual periods.

To arrive at a reasonable estimate on the time and costs necessary to develop a specific element in the path to NW status we have had to consider, to various degrees, the present status of critical aspects of the technology in terms of who has it, how was it acquired, and how much did it cost. The section on Specific Elements contains the details on the various elements. Consideration of these details has led to the estimate on the capital cost to acquire the technology on a first time basis, i.e., costs do not include operating or continuing costs. Some cost estimates, design for example, do include manpower costs (and computer time). It must be emphasized that these estimates are order-of-magnitude; specific scenarios, explicitly describing the situation, would be necessary to develop more confident numbers.

A very real portion of the time and economic barrier consists of the necessity to fill the professional and technician manpower requirements that are necessary to design and operate the nuclear facilities. These manpower requirements could be a major uncertainty in the time and costs required to develop the necessary facilities for the production of nuclear weapons via a national program. The reservoir of technological experience is one of the major differences between Category 2 and Category 3 countries.

Figure 2 represents the costs and time necessary for a Category 1 country to achieve NW status. Implicit in the time and cost estimates are that Category 1 countries either presently have access to strategic special nuclear material (SSNM) (plutonium or highly enriched uranium) indigenously and/or they have extensive facilities and nuclear industry experience. Canada and Sweden do not at present have any known reprocessing or enrichment facilities. However, their experience and facilities are so extensive that they could possibly convert a hot cell to a low throughput reprocessing facility or they could construct a new facility in a minimum time period.

Category 2 countries can achieve NW status either by building a reprocessing plant or by constructing an enrichment facility. All of the Category 2 countries contain reactors or soon will contain reactors that would be sufficient producers of plutonium to support a small weapons program. In addition we have implicitly assumed that the necessary technology experience is available within the country (i.e., we have

PATHS TO NW CAPABILITY

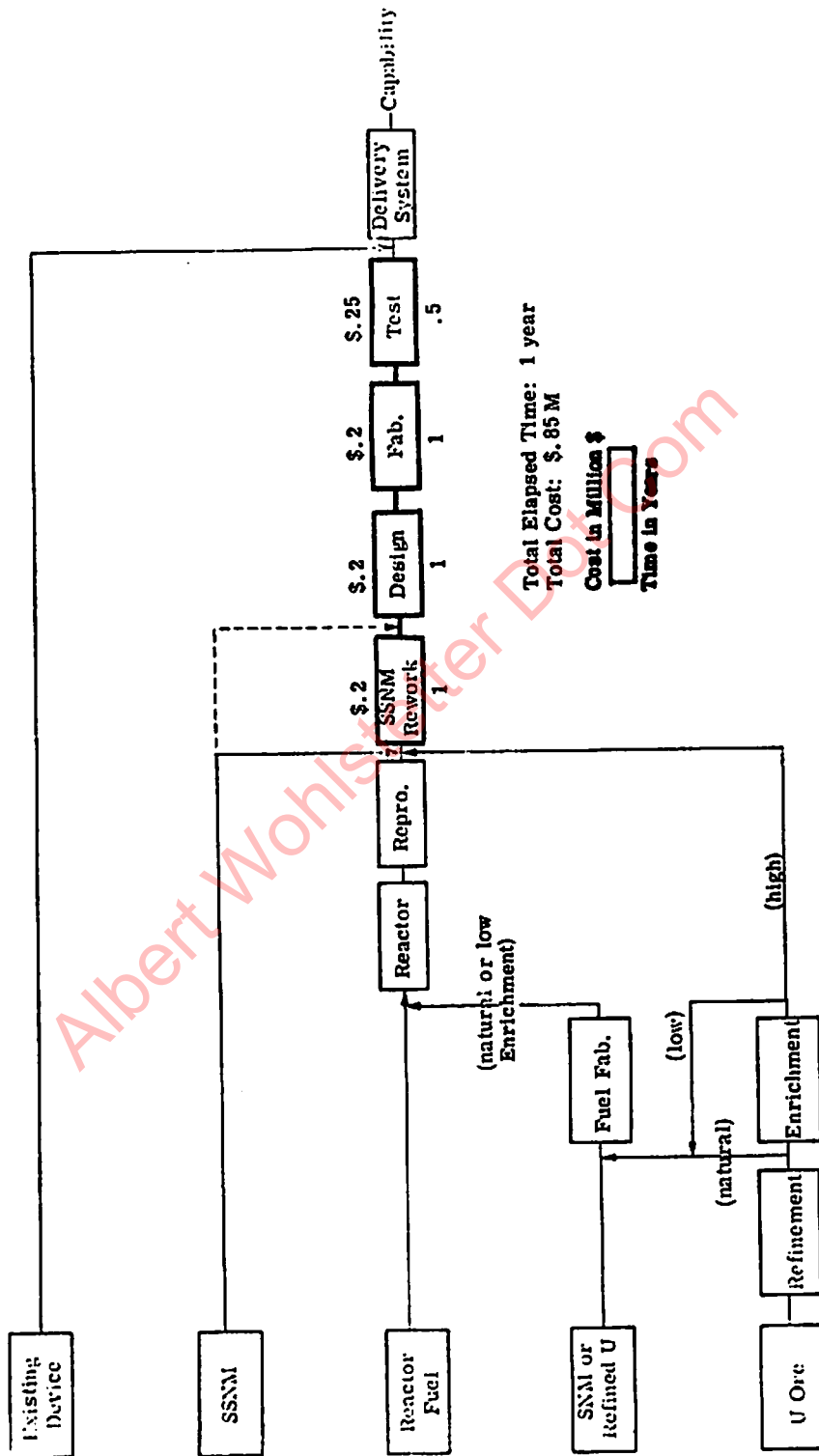


Figure 2. Paths to NW Capability, Category 1

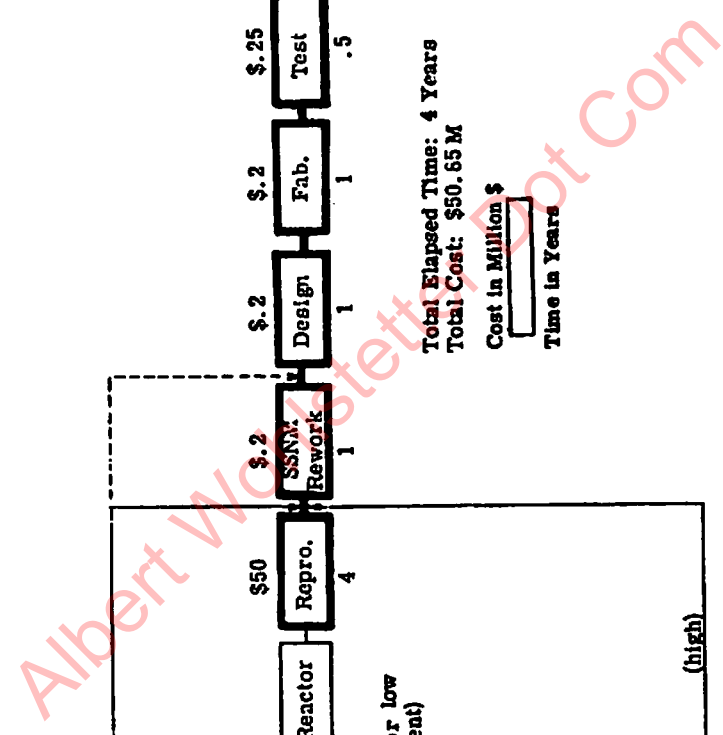


Figure 3. Paths to NW Capability, Category 2 (Reprocessing)

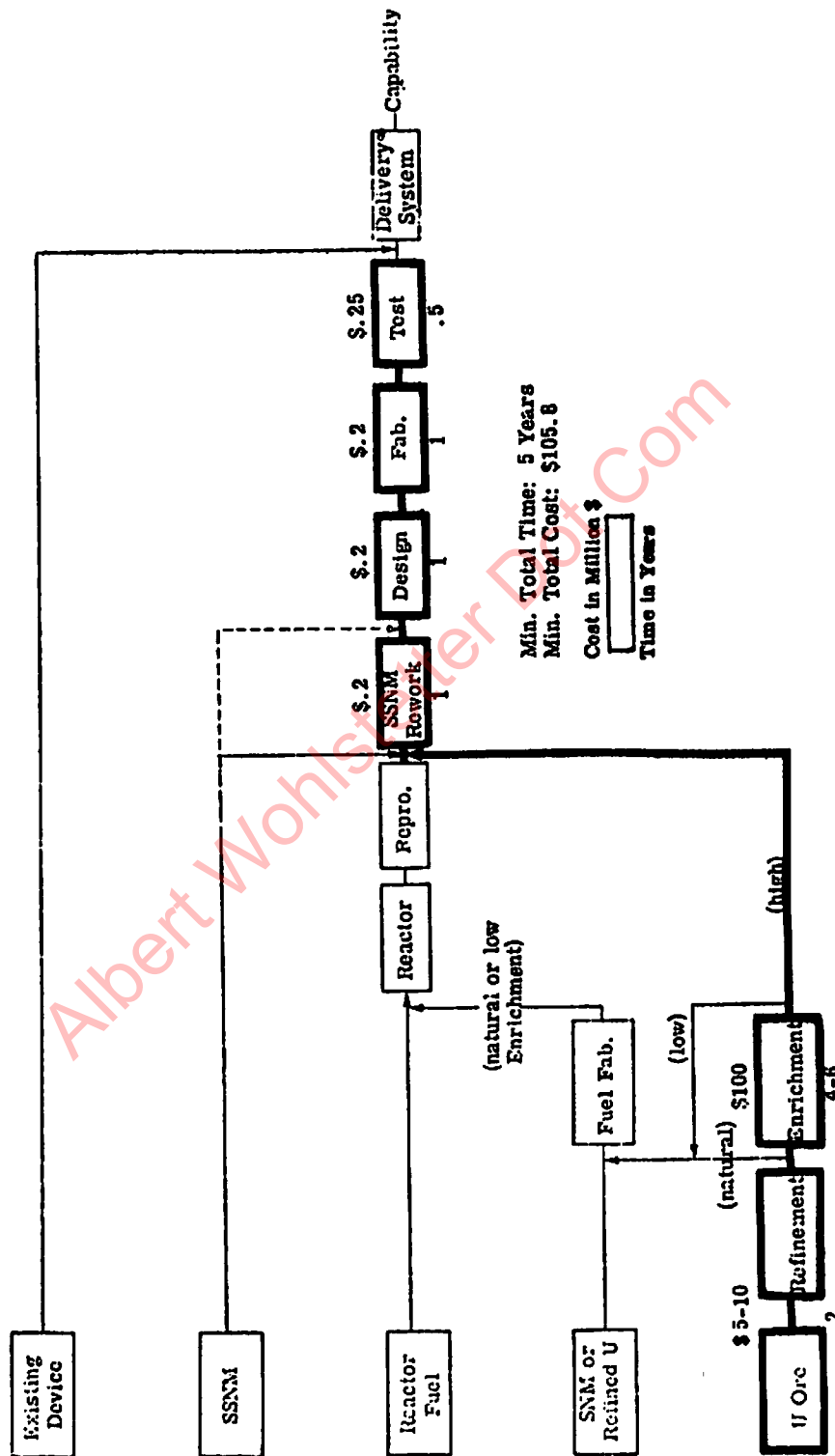


Figure 4. Paths to NW Capability, Category 2 (Enrichment)

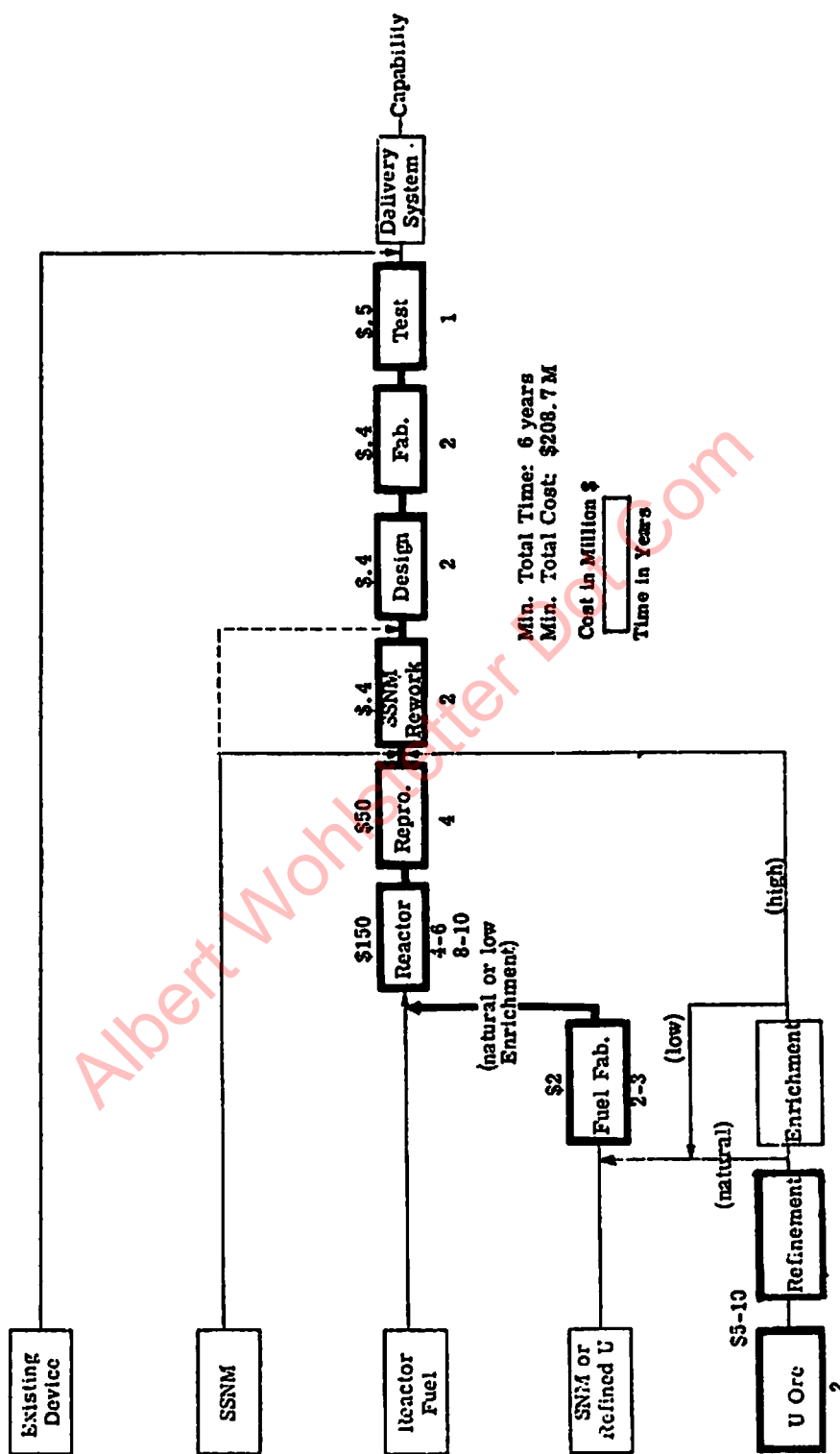


Figure 5. Paths to NW Capability, Category 3

not changed the estimates to take the SSNM and construct a weapon from those given for a Category 1 country). This point is arguable for countries like Egypt, Indonesia, and Iran. Of course, oil rich countries like Indonesia and Iran can afford to buy technology or experienced technicians if that becomes necessary.

The reprocessing plant's estimated cost and construction time are appropriate for a facility that is not much more than a hot cell. The main function of the facility is to recover plutonium from the spent fuel. This may mean that the uranium is not recovered and that the radiation protection and waste management operations are the minimum required to achieve the separation of the plutonium from the spent fuel. The \$50 million cost figure is a consensus of estimates from experienced industry personnel, some with extensive direct experience in reprocessing. However, the estimates, no matter how educated, are indeed just estimates. A detailed cost analysis would be required to accurately pinpoint capital costs, particularly in those areas where little previous capital cost experience has been developed.

The enrichment route to NW capability is assumed to be via centrifuge enrichment plants. At present this is the only logical option for a small scale enrichment operation. The economics for a gaseous diffusion plant only make sense for a large plant on the order of 10,000 tonnes of SWU per year. A gaseous diffusion plant this size costs on the order of \$2-3 billion. Even the United States, which has more gaseous diffusion plant operational experience than any other country in the world, is considering the use of centrifuge technology.⁽¹⁾ The major cost attribute of centrifuge technology over the gaseous diffusion or jet nozzle technology is the amount of electric power needed per kg of SWU (see Section 6 for details). In addition, centrifuge plants are more amenable to a small scale operation.

Category 3 countries do not have the extensive nuclear technology experience and manpower that would enable them to proceed relatively quick to a NW status. Without this basic foundation to build upon, the costs and construction times must be extended. On most elements in the technology path we have doubled the construction times and the cost estimates. Table 2 presents a summary of the estimated time cost estimates for each of the country categories.

Two figures are included in Appendix A to illustrate the number of countries that will have accumulated enough fissile plutonium (in the spent fuel) to make 5 or 50 weapons (Figure A1). Figure A2 presents the countries that have the enrichment or reprocessing capacity to construct 5 or 50 nuclear weapons. Indigenous reprocessing capacity to produce 5 or 50 nuclear weapons is shown in Figure A3.

TABLE 2

<u>Category</u>	<u>Minimum Time (yr)</u>	<u>Minimum Cost</u>
1	1	\$.85 M
2	4	50.85 M (reprocessing)
	5	105.8 M (enrichment)
3	6	208.7 M

Specific Elements

A. Uranium mining, refinement, and conversion

One of the major reasons that nuclear energy is proposed as an alternate to fossil fuel energy is the abundance of uranium ore throughout the world and the relatively low cost (per unit of useful energy) of extracting the uranium from the ore. Table 3 lists the results of a recent survey⁽²⁾ on world uranium reserves. The column listed RAR is the Reasonably Assured Resources and EAR represents the Estimated Additional Resources. RAR represents mineral deposits where measurements of the extent of the deposit are known and samples have been analyzed. In addition, profitable recovery by known processes is assumed. EAR are potential sources that are likely to exist either as extensions of known fields or in regions where uranium is known to occur but has not yet been worked.

Large supplies of uranium are known to exist, particularly in the technologically advanced countries like the U.S., Canada, Australia, and South Africa. It is quite likely that some of the less developed countries which have not been geologically surveyed to the same extent will further extend the known uranium resources in the future. Any new finds, however, will typically require an 8-year lead time before the ore is delivered to a customer.

A recent survey conducted by the United Nuclear Corporation and discussed in Reference 2 has shown that for Light Water Reactor (LWR) power plants the uranium ore costs can be raised some 10 to 18 times the previous nominal costs of \$8/lb U_3O_8 and still be competitive with fossil fuels. Consequently, as the prices rise it will be economical to mine some of the lower grade uranium ores and to search for new discoveries of uranium. This should further extend the uranium resources and possibly lead to more wide-spread use of nuclear energy as less developed countries discover indigenous sources of uranium. Some countries, Brazil for example, have already stepped up their uranium exploration. Brazil spent \$10 million in 1974 on uranium exploration and expects to double its exploration effort in 1975.⁽³⁾ Other developing countries like India and Pakistan do not presently have an economically viable grade of uranium ore resources; however, both countries have initiated programs to supply uranium for their own nuclear power programs. Pakistan has stated that it has enough uranium ore to meet its anticipated needs for the future and expects to be manufacturing fuel for its 125 MW(e) PHWR (Pressurized Heavy Water Reactor) Kanupp power station by the end of 1975.⁽⁴⁾

South African uranium is obtained from gold mining operations where it has a concentration on the order of 0.02%. Israel estimates that its uranium reserves consist of 220 million tons of phosphate rock with a

TABLE 3
TONNES OF URANIUM (From Reference 2)

Country	\$26/kgU		\$26-39/kgU	Total	Output . per Annum
	RAR	EAR			
U. S. A.	300,000	500,000	1,200,000	2,000,000	13,000/1974
Canada	190,000	190,000	340,000	720,000	3,700/1973
Australia	150,000	75,000	50,000	275,000	—
South Africa	202,000	8,000	88,000	298,000	4,000/1973
France	37,000	23,000	45,000	108,000	1,600/1973
Spain	8,500	—	10,000	18,000	112/1973
Portugal	7,000	6,000	10,000	23,000	84/1973
Greenland (Denmark)	8,500	—	250,000	258,000	—
Sweden	—	—	330,000	330,000	—
Gabon	15,000	—	5,000	20,000	600/1973
Niger	40,000	20,000	20,000	80,000	800/1973
Sen. African Rep.	6,000	6,000	—	12,000	—
Zaire	1,500	1,500	—	3,000	—
Angola	—	—	13,000	13,000	—
India	—	—	—	(up to \$78/kgU)	—
Argentina	13,000	8,000	18,000	39,000	43/1972
Brazil	—	—	54,000	54,000	—
Columbia	—	—	50,000	50,000	—
Israel ^A	—	33,000	—	33,000	50
Italy ^B	—	10,000	—	10,000	—

A. "Israel - More Power Stations Needed", World Digest, Nuclear Engineering International, Vol. 18, No. 204, May 1973, p. 391, Z. Ketzmel "Uranium Sources Production and Demand in Israel" Fourth International Peaceful Uses of Atomic Energy, Geneva, 1971, A/CONF 49/P/013.

B. Pietro Bullio, "Italian Nuclear Power Industry," Nuclear Engineering International, Vol. 18, No. 209, October 1973. pp 784-787.

concentration of 0.015%.⁽⁵⁾ Sweden has huge amounts of low grade bituminous shales (0.025% uranium). On the other side of the concentration spectrum, the United States, Canada, and Australia have large reserves in the few tenths of a percent concentration range. Niger is estimated to have some 10,000 metric tons with a 2.8% concentration.⁽²⁾

The technology involved in mining, concentrating, and refining uraniumiferous ores is somewhat involved and requires a large capital expense if conducted on an expanded scale with the intent of being economically competitive with other world suppliers. However, the technology (especially for the higher ore grades) is well documented in the open literatures and most countries including developing countries such as Pakistan have the capability of producing uranium suitable for use in nuclear reactors.

Moreover, the present trend is for international mining companies to participate with local governments in developing uranium resources. For example, Italy is planning to work with Bolivia in studying the commercialization of local uranium deposits.⁽⁶⁾ Companies from Japan, France, and West Germany have formed a Niger uranium exploration company.⁽⁷⁾

Figure 6 shows a simple summary flow diagram for the production of various chemical forms of uranium. Because there is a variety of natural sources of uranium, no single set of steps is uniquely suited to all ores. However, a universal production classification can be considered which consists of concentration, refining, and, if necessary, conversion into uranium metal or hexafluoride.

Concentration consists of separating uranium from the main bulk of nonuraniferous diluents which accompany it in nature; the product is a crude uranium compound still contaminated by substantial (perhaps 1 to 5%) amounts of inert material. Crude uranium concentrates may consist of oxides [U_3O_8], or salts such as sodium diuranate ($Na_2U_2O_7$), or ammonium diuranate [$(NH_4)_2U_2O_7$]. Concentration is usually carried out near where the raw material is found in nature and has as its principal objective the reduction in weight and bulk in subsequent shipment of the uranium.

Refining consists of the removal of the remaining contaminants from crude uranium concentrates. The product is usually one of the oxides of uranium, UO_3 , U_3O_8 , or UO_2 . The purification step removes from the uranium those elements which would interfere with its subsequent use in a reactor or isotope-separation plant.

The most important conversion steps are the production of uranium metal and the production of UF_6 feed for an enrichment plant.

The exact sequence of steps used in a particular process depends primarily on the natural resource and the concentration of uranium in the ore. Uranium has been found and recovered with percentage concentrations of a few percent down to a few hundreds of a percent. Often the

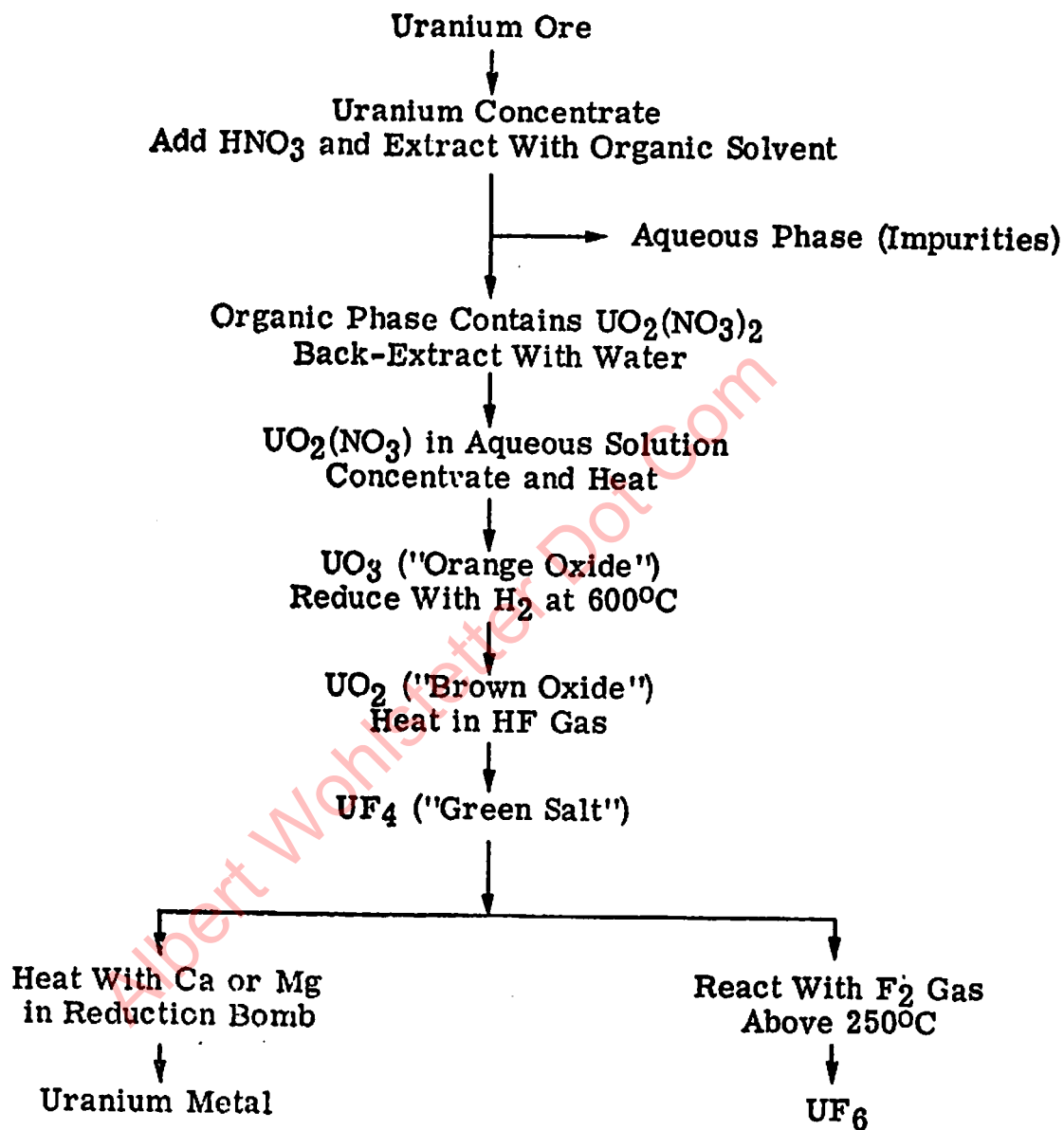


Figure 6. Summary Flow Diagram for Uranium Metal and Uranium Hexafluoride Production

low percentage uranium concentrations are contained in the tailings of other mining processes such as gold, phosphates, or copper.

The uranium ore requirements for producing a single natural uranium reactor [100 MW(e)] would be rather modest, on the order of 12,000 to 20,000 tons of high grade ore for the initial load and anywhere from half that amount to the same annual amount for reload fuel.

A facility of this size could, if circumstances required a compressed schedule, be built on a time scale of approximately two years requiring a capital investment on the order of \$5 to \$10 million. The employees of such a facility, who would not necessarily need special nuclear skills, would number approximately 100.

B. Enrichment

Proliferation of nuclear weapons has primarily been inhibited by the inaccessibility of the fissile isotopes. In fact only one fissile isotope, ^{235}U , occurs in nature and then as a very small percentage of naturally occurring uranium (approx. 0.72%). By far the major fraction in cost and effort of the worlds first nuclear weapons program, the U.S. Manhattan Project, was devoted to the concentration of ^{235}U and to the production of ^{239}Pu from ^{238}U .

Today there are three main technology contenders for the economic enrichment of uranium. Gaseous diffusion, gas centrifuge, and the Becker nozzle or jet nozzle. Gas diffusion plants which at present are the prime producers of enriched uranium can be characterized as a very expensive process that must be done on a large scale, with a correspondingly large capital investment and a huge power consumption. Gas centrifuge technology, which was tested early in the Manhattan Project and later revived in the late 1950s and early 1960s, is presently being tested in pilot production facilities. Although its power consumption is approximately one tenth that of a gaseous diffusion plant, gas centrifuges have an inherently low throughput capability which requires a large number of the technologically sophisticated machines operating in parallel. The Becker nozzle technique has not yet been proven on a production scale. It appears to be competitive in overall cost even though its power consumption per kg of Separative Work Units (SWU) is presently slightly greater than that for a gaseous diffusion plant. Other techniques such as electromagnetic separation and thermal diffusion have been successful in separating heavy isotopes on a very small scale, however they are not competitive on the scale needed for weapons production. Newer technologies such as laser enrichment are in the laboratory research stage of development and are not likely to be available for 5 to 10 years.

All of the known potential practical heavy isotope separation techniques with the exception of laser enrichment achieve only a small

enrichment with a single application of the technique. Therefore, to separate feed materials at a particular concentration into fractions at substantially different concentrations, requires repeated application of the technique. This is most efficiently accomplished in assemblies of the separation devices called "cascades," through which the separated fractions flow countercurrently. The effort involved in separating isotopes is referred to as the separative work and is measured in Separative Work Units (SWU).

C. Gaseous diffusion

Separation by gaseous diffusion takes place because the lighter molecules in a gaseous mixture tend to move faster than the heavier molecules and will consequently strike the container walls more often. If the walls have holes just large enough to allow passage of the individual molecules, without permitting bulk flow of the gas, more of the lighter molecules flow through the wall, relative to their concentration than the heavier molecules. The theoretical separation that can be achieved in one application of this process is $\alpha = (M_2/M_1)^{1/2}$ where M_1 and M_2 are the molecular weights of the isotopic compounds. For UF_6 molecules $\alpha = 1.00429$. Consequently many stages are required to achieve a specified separation.

Each stage in a diffusion plant as shown in Figure 7, requires a compressor to keep the feed material of the stage at a higher pressure than the other enriched side of the barrier. This permits a net flow in a single direction at the barrier. Large amounts of power are required for the compressors and the heating elements.

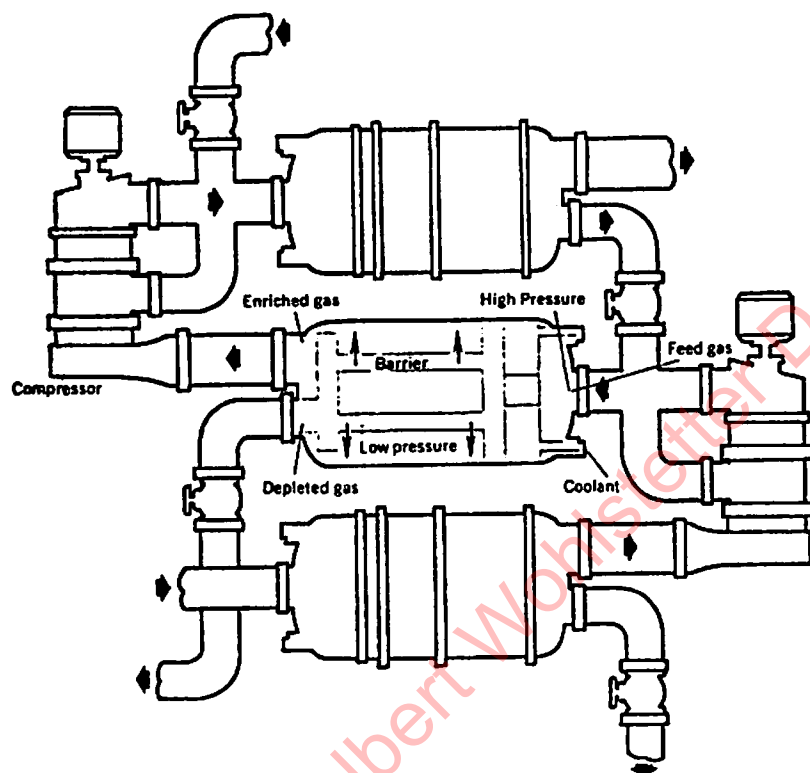
The known free world diffusion plants are listed in Table 4. Besides these plants the USSR and China are known to have diffusion plants.

Table 4
DIFFUSION PLANT CAPACITIES⁽⁷⁾

<u>Plant Location</u>	<u>Country</u>	<u>Capacity (10⁶ kg SWU/yr)</u>
Oak Ridge, Tennessee	US	4.7
Portsmouth, Ohio	US	5.2
Paducah, Kentucky	US	7.3
Capenhurst	UK	0.4
Pierrelotte	France	.4-.5*

*Estimated

Gaseous Diffusion Stage



Gaseous Centrifuge Stage

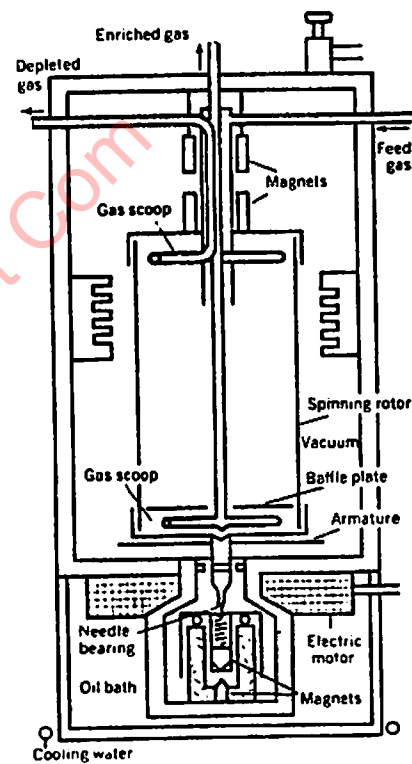


Figure 7. Heavy Isotopic Separation Stages

Construction of gaseous diffusion enrichment plants are very large industrial and financial undertakings. Current U.S. estimates for a 8,750 tonne SWU/yr gaseous diffusion plant is about \$3 billion.⁽¹⁾ The international plant being built by Eurodif (France 42.8%, Italy 25%, Spain 11.1%, Belgium 11.1%, and Iran 10%) in France is expected to cost 15,000 M francs not including the four 900 MW(e) PWR plants that will be utilized to provide the necessary 2400 MW(e) for the diffusion plant.⁽⁹⁾

These cost estimates are for enrichment plants beginning with a natural uranium feed. A plant starting with a feed enriched to 3% ^{235}U (typical light water reactor fuel) would require much less separative work capacity to produce a specified number of kilograms of highly enriched uranium (See Table 5) than a plant starting with natural uranium.

The enormous power consumption of a gaseous diffusion plant also creates a problem, particularly for developing countries with a limited electrical network. The total U.S. gaseous diffusion complex requires 6000 MW(e) of electricity when operated at full capacity, this is approximately the power consumption of the entire state of Minnesota. New plants built with more modern equipment would require slightly less power, approximately 2400 kw hours/kg SWU.⁽¹⁰⁾

Technological barriers for gaseous diffusion plants lie primarily in the construction of the barriers themselves. Both the barrier geometry and material have been highly classified for many years.

A consortium (Brinco) has estimated the schedule necessary for the construction of a large gaseous diffusion plant in Canada.⁽¹⁰⁾

	<u>Time (mo.)</u>
1) Feasibility study phase	24
2) Preparations for construction	12
3) Construction period	66
4) Commissioning and startup - after start of construction	36

D. Centrifuge separation

The gas centrifuge employs a rotating cylinder which imparts a centrifugal force to compress the UF_6 molecules to the outer radius of the cylinder. However, the thermal velocities of the molecules tend to keep the gas molecules evenly distributed throughout the available volume. Since the latter effect is larger for the lighter molecules, there are relatively fewer lighter molecules at the outer radius. The average concentration is achieved at some intermediate radius which gets closer

to the outer radius as the speed of rotation increases. The centrifuge can have a relatively large separation factor but invariably has a smaller flow rate than a diffusion stage. For a centrifuge operating isothermally, the maximum separative capacity of the machine is

$$\text{Max SW} = \pi \rho D (Z/2) [(M_2 - M_1) \mu^2 / 2RT]^2$$

where SW = separative work

ρ = gas density

D = diffusivity

$M_2 - M_1$ = isotopic mass difference

z = bowl length

μ = peripheral velocity

T = absolute temperature

R = gas constant

Note that the separative work is now proportional to the difference in molecular weights and not to the ratio of molecular weights. The above equation also indicates the importance of a rapidly spinning cylinder (4th power of the peripheral velocity) and a low temperature. Figure 8 illustrates the concept of centrifuge building blocks for a centrifuge cascade.

In 1960 results were published⁽¹¹⁾ on centrifuges approximately one foot long, spinning at 350 meters/second at a temperature of 33°C. These parameters yielded separation factors of 1.1-1.2 (compared to the maximum for diffusion of 1.004). Thus only relatively few centrifuges need to be connected in series to achieve substantial changes in concentration. However, because of low flow rates, large numbers of centrifuges in parallel are required for practical level of throughput.

The technological secrets of gaseous centrifuges are in the design and production of light weight machines that have a low friction coefficient (and low power consumption). The light weight bowls must be able to withstand the centrifugal forces derived from the high peripheral speeds. Several countries have produced successful machines with component reliability of 98% to 99%.

The free world involvement in centrifuge technology is primarily in the U.S., the trilateral agreement countries of Urenco/Centec (UK, West Germany, and the Netherlands) and in the Power Reactor and Nuclear

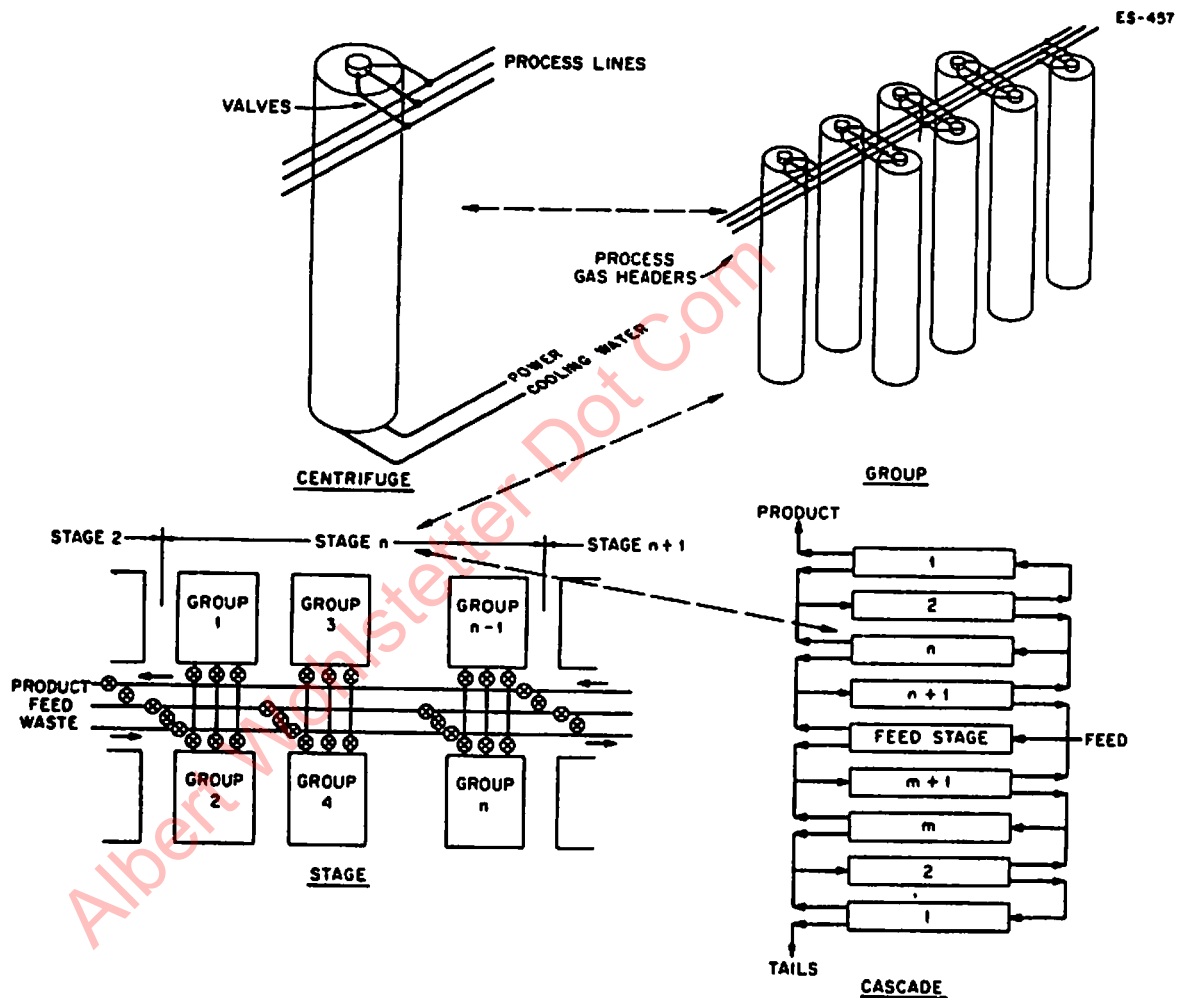


Figure 8. Concept of Centrifuge Building Blocks

Fuel Development Corporation (PNC) of Japan. Typical national development costs in these countries for the last few years have been on the order of \$20 million/yr.

The Urenco/Centec centrifuge effort has two 25,000 SWU/yr. pilot operations in operation and expect a similar capacity German operation to come on line soon. The present projected price from Urenco/Centec for enriched uranium is approximately \$100 per kg SWU. This is expected to be competitive with the diffusion plant price that is likely to prevail in the 1980's.

There are several consortiums of European countries that are producing ultracentrifuge machines or components of ultracentrifuge machines:⁽¹²⁾

Germany	MAN, Dornier, Erno, and Interatom, Uronet
Netherlands	DSM, Shell Kernenergies, VNF, Ryn-Schelde and RCN
UK	BNFL

The Japanese effort is presently much smaller with an 18 stage (10 machines per stage) plant operating since last fall and a 250 machine formation running soon.⁽¹³⁾ A PNC 10,000 machine pilot plant is expected to be started in 1978.⁽¹⁴⁾

The amount of separative work involved for various feed and waste (tails) enrichments and the estimated number of centrifuges necessary to produce 35 kg of ^{235}U is given in Table 5. We have assumed a 5 kg SWU capacity per machine per year.

It is apparent that a 2000 unit centrifuge plant could support a weapons program's material requirements for highly enriched uranium. If the feed were the slightly enriched uranium that is used in the LWRs then the number of centrifuges required is reduced by roughly two-thirds. The numbers in Table 5 are for an approximate 2 weapon per year production rate. If material is required for only one weapon per year then those numbers can be reduced by a corresponding factor of 2.

E. Other separation techniques

The Becker nozzle system which is being developed in Karlsruhe, West Germany (and possibly in South Africa) has progressed to the stage where pilot production plants can be built. Claims have been made that further improvements that are being investigated may produce one kg of SWU for \$35 to \$43.⁽¹²⁾ Employing these economic arguments the industrial group STEAG of Essen (which is participating in the Karlsruhe work) has proposed joint enrichment ventures with the U.S., Canada, South Africa, Australia, and Brazil.

Table 5

<u>Feed Enrichment (%)</u>	<u>Waste Enrichment (%)</u>	<u>Product Enrichment (%)</u>	<u>Feed Weight (kgU)</u>	<u>Separative Work Units (SWU)</u>	<u>Number of Gas Centri- fuge Units Per Year</u>
0.72	0.2	90	6753	8827	1765
		93	6754	8849	1770
		97	6755	8891	1778
	0.3	90	8344	7485	1497
		93	8344	7506	1500
		97	8344	7551	1510
	0.4	90	10928	6607	1321
		93	10928	6632	1326
		97	10928	6672	1334
	0.7	93	1548	2404	481
		93	1688	2188	438
		93	1858	2022	404

Schematic (below) shows flow of gas through a separation element in the Becker nozzle process. Multiple elements are arranged along a cylinder (right) to form one of many stages in the process train.

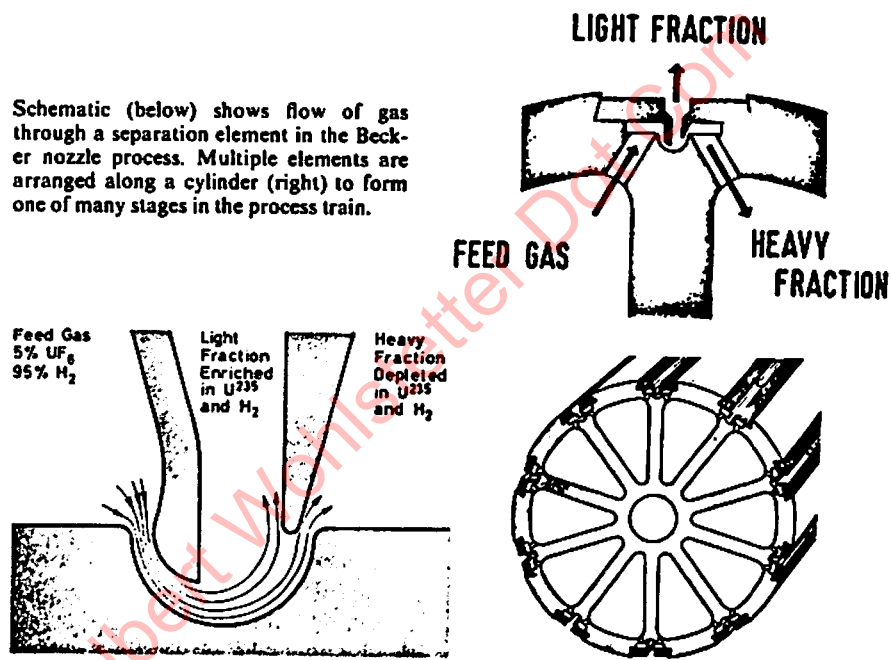


Figure 9. Nozzle Schematic

Several variations of the nozzle process exist, but the one closest to commercial application works like the following:

Uranium hexafluoride gas (mixed with hydrogen) is pumped through a long slit, forming a rapidly moving sheet of gas. The gas strikes a curved wall, bending the sheet through 180 degrees. Centrifugal forces then carry the heavier uranium-238 (which makes up 99.3 percent of the gas) to the outer surface of the sheet, where a knife like-barrier pares it off. The lighter fraction, now slightly enriched in uranium-235, is routed through hundreds of additional stages to reach the desired level of enrichment - about 3 percent uranium-235 for the fuel of light-water reactors or more than 90 percent for gas-cooled reactors or weapons.

Advantages of the nozzle process are that it does not require the hard-to-make porous barriers of a gaseous diffusion plant and that it avoids the highly stressed moving parts of an ultracentrifuge. One disadvantage of the nozzle process is that it consumes more electric power than a gaseous diffusion plant and at least 10 times the power of an equivalent centrifuge plant. This disadvantage wanes, however, where electric power is cheap (even if inconveniently located), as in Brazil.

In South Africa a pilot enrichment plant which is thought to be based on the nozzle technique is operating. Plans have been developed to construct a 5,000 tonne SWU/yr. plant for operation in 1984.

Laser enrichment for light elements has been announced to be successful (April 1975) by the U.S. and USSR. This process requires only a single stage with a power consumption thought to be approximately the same as the ultracentrifuge. A finely tuned, high power CO₂ laser differentially excites the molecules containing the isotope of interest. The removal process for the molecules has not been revealed. This technique could potentially be very effective in cheaply producing enriched uranium. The amount of development effort that will be required and the time schedule to accomplish it can be estimated from the centrifuge development program. Clearly more development (and information dissemination) will be necessary before it is apparent that uranium enrichment is within the reach of every country.

F. Fuel fabrication

A country that intends to achieve a self-contained nuclear program including power reactors and weapons requires a fuel fabrication facility. One way of achieving nuclear fuel cycle independence is to follow the example of Canada, India, Argentina, and Pakistan and build natural uranium power reactors (heavy water reactors) to bypass the enrichment process. The fuel fabrication process for HWRs might consist of pelletizing the uranium oxide, inspecting the pellets, loading preassembled fuel tubes, welding and inspecting end caps, autoclaving fuel rods,

inspection of fuel rods, and final assembly into a fuel bundle with detailed inspection. The technology is available and utilized in fuel fabrication plants in many countries throughout the world. The costs of smaller fabrication plants (approx. 1 tonne/day) has nearly equal costs for operating, fixed, and hardware charges.⁽¹⁴⁾ Larger plants with a 10 tonne/day capacity have a 23% operating charge, 24% fixed charge, and a 53% hardware charge. If the fuel is also to contain PuO_2 (mixed oxide) then the costs are 18% to 25% higher. When considerations of the expected throughput are also taken into account then the cost penalty will probably amount to 70% to 180%.⁽¹⁵⁾ In addition to these cost differences that arise primarily because Pu must be handled in a glove box, there is also a penalty to be paid because of the increased radiation shielding that must be present for the Pu. High exposure plutonium ($^{239}\text{Pu} \leq 80\%$) increases costs by approximately 4% over low exposure plutonium.

Argentina is presently building a fuel fabrication plant for its HWRs. It is expected to be completed in November 1977 (three year construction period).⁽¹⁶⁾ The cost of the 300 tonne/year capacity plant is expected to be \$15 million. Argentina is also developing a mixed oxide capability.⁽¹⁷⁾ Some plutonium has been purchased from West Germany for tests in this facility.

G. Reactors

The most likely reactor type that would be considered by a country determined to develop its own nuclear industry and nuclear weapon capability would be a natural uranium fueled, heavy water moderated reactor (HWR), possibly of the Canadian CANDU type. The CANDU reactor is a particularly attractive plutonium producer since it is designed to be refueled while the reactor is on line. Consequently, it is a relatively trivial matter to control the fuel burnup to maximize the production of ^{239}Pu with a relatively low fraction of ^{240}Pu .^{*} Even when the fuel management is optimized for power production the CANDU pressurized heavy water reactor (PHWR) is said to be 10-50% more effective than LWRs in producing Pu per atom of ^{235}U burned. CANDU's main appeal is the nonreliance on enriched fuel and a more efficient burning of uranium.

Generally, an enriched reactor program is less desirable than a natural uranium fueled reactor as a base for an indigenous NW capability. However, a few comments are in order relative to a LWR or high temperature gas cooled reactor (HTGR) program. A modest diversion of LWR fuel, typically enriched to 3% in ^{235}U , of approximately 2 tonne/year

^{*}Low burnup Pu is not essential for weapon production, it simplifies the handling and most likely results in a better explosive yield per gram of Pu.

would support a nuclear weapons program (See Table 5) if a domestic enrichment facility were available. The separative work needed to improve the ^{235}U enrichment could be handled by a 500 centrifuge enrichment plant.

At the other end of the nuclear fuel cycle, the irradiated fuel is often subject to international or bilateral inspection, i.e., a physical inventory, and is not easy to divert. Typically the reprocessing of the fuel is performed outside the country under safeguards agreements. If these agreements were abrogated, the spent fuel in the country could be reprocessed for the Pu, however obtaining additional fuel would probably be impossible; thus this would seem likely only in cases of last resort, not in deliberate NW development efforts.

General Atomic Company HTGR fuel, which contains fully enriched ^{235}U , is often thought to be highly susceptible to diversion. It is true that no further enrichment is required of the base uranium feed, however, the manufactured fuel for the Fort St. Vrain reactor in Colorado presently consists of uranium thorium carbide microspheres coated with several layers of carbon and silicone carbide. This is not suitable material for a bomb and would require recovery of the ^{235}U from the fuel. The magnitude of the effort, even though the fuel may be cold, is somewhat analogous to that required at a reprocessing plant without the need for handling large quantities of material or have massive radiation shields. See Sub-Appendix 4B for a more complete discussion of future HTGR fuel in relation to nuclear weapon material.

Sub-Appendix 4C contains a discussion on plutonium production reactors and associated reprocessing facilities.

H. Reactor costs

To produce 25 kg of Pu per year, assuming the reactor is of a CANDU type and runs at 75% capacity, would require a reactor of approximately 115 MW(e) installed. This would have a capital cost, which would vary with the country installed, on the order of \$150 million (see discussion below) if purchased from a supplier. If built indigenously, costs could be considerably higher.

The initial core load would require approximately 30 tonnes of uranium and around 150 tonnes of heavy water D_2O for moderation and cooling. (The cooling could be performed by light water if the design were changed slightly). The operation would require approximately 1% to 2% in makeup D_2O per year. Depending on the fuel management program half to a whole core fuel load would be reprocessed per year. The uranium ore requirements, assuming a high grade of 0.2% U_3O_8 , for the initial load would be on the order of 18,000 tonnes.

Some question might be raised as to how likely it would be for developing countries to install a relatively small nuclear power reactor with a 100 to 200 MW(e) capacity. An IAEA economist has recently reported (19) that 100 MW(e) nuclear plants are economic when oil prices go over \$6.12 a barrel. Pakistan reported that a 50 MW(e) plant built in Pakistan is now more economical over its 30 year life span than a fossil fuel plant. Published reports such as these, regardless of their validity, may provide some incentive for developing countries to go nuclear.

Following the Fourth International Atoms for Peace Conference in 1971 the IAEA instituted a Market Survey for Nuclear Power in Developing Countries. A general report was published in September 1973 and an update in 1974. A summary of the report was published in reference 20. The survey covered 14 developing countries with prices estimated as built in those countries. Table 6 lists the break-even oil price for nuclear plants and oil-fired plants. The capital cost prices may be somewhat out of date due to inflation; however, both fossil fuel and nuclear plant costs have increased so that the relative increases may not be significant. The capital cost for a 200 MW(e) pressurized water reactor is also listed in Table 6. Capital costs for a HWR are at least 10% higher than for a PWR. From this data we derived a roughly \$150 million cost for a 100 MW(e) plant. This represents a considerable investment but not out of the financial reach of most countries. This cost for a 100 MW(e) plant should only be considered accurate relative to the other costs listed in the paths to nuclear weapons capability. For the accurate and up to date costs see Chapter IV.

Many developing countries are now upgrading their electrical network to provide better service to industry and to improve the living standard. However, the extent of many electric power networks are limited. Since one usually does not want to have more than 15% of an electrical networks' power generating capacity reside in one station the smaller nuclear power stations are also attractive from this standpoint. A more subjective and very real catalyst for acquiring nuclear power by developing countries is the desire to be in the forefront of a modern technology. South Africa has recently stated that the new prototype enrichment plant they are constructing has provided a positive stimulus to South African industry to upgrade their methods.

I. Heavy water costs

In addition to designing and constructing a heavy water reactor there are other problems in developing an independent nuclear fuel cycle. Reprocessing the fuel is one problem which will be discussed below. Another problem is heavy water. If a country is unable to purchase an initial load of heavy water it will have to produce its own. This is a significant industrial undertaking. Canada has for years purchased heavy water from the U.S. They are now embarked on a program to be self-sufficient.

TABLE 6

IAEA BREAK EVEN OIL PRICES FOR DEVELOPING COUNTRIES

	Plant Size MW(e)	Oil-Fired Plant Cost \$/kw	Nuclear Plant Cost* \$/kw	Break-Even Oil Price \$cost/barrel	Capital Costs for 200 MW(e) plant \$/k3
Argentina	600	226	504	4.92	725
Bangladesh	200	326	821	7.67	752
Chile	300	283	675	6.36	719
Egypt	600	208	469	4.73	671
Greece	500	224	510	5.01	681
Jamaica	150	348	925	8.84	742
Korea	600	210	474	4.77	678
Mexico	600	209	470	4.73	671
Pakistan	250	285	703	6.74	708
Philippines	600	210	474	4.77	678
Singapore	250	274	682	6.62	685
Thailand	200	283	734	7.17	665
Turkey	600	218	489	4.85	703
Yugoslavia	600	202	458	4.68	651

*Includes some fuel cycle costs.

A 400 tonne per year D₂O plant using the Girdler-Sulphide process (a dual thermal exchange technique) would now cost approximately \$150 million. The cost of purchased D₂O presently is \$66/kg and estimated to go to \$100/kg in the late 1970s; 25% of the manufacturing cost goes for steam and electric power, 60% for capital investment, and 15% for operation and maintenance expense. The G.S. process as used in Canada requires huge (28 ft. in diameter, 300 ft. high) pressure vessels to contain the water and hydrogen sulphide gas.

Another potential difficulty in producing a home made reactor is the technology involved in the zircalloy tubing that is utilized in fuel and core components. In 1974 there were 19 suppliers of zirconium tubing in the world.⁽²¹⁾ CANDU reactors use a collapsible zircalloy tubing with a 0.015" thick wall. Close tolerances and rigid quality control practices are required for reliable material.

J. Personnel requirements

The lack of manpower with the special skills needed for the nuclear industry can also present a significant barrier to a rapid nuclear growth. Technically qualified individuals are needed in government, in the power industry, and in educational institutions. The government needs people for the formulation and implementation of national policies on financing, procurement, siting, licensing, waste handling and disposal, surveillance, compliance, and the safety of nuclear power plants.

Industry needs technical people for technical contracting, building, quality control, testing and safe operation of power plants; universities must provide education and training of personnel for design evaluation, maintenance, testing, and operation of nuclear reactors along with research, development, design and manufacturing of reactor systems and components. The base technical support for a new nuclear country should be at least a few hundred people.⁽²²⁾

The U.S. has required, on the average, 55 specially nuclear trained on-site personnel for a single nuclear power station of which 70-75% are technicians and 25-30% professionals. The average cost of training per reactor is \$1.2 million. A typical schedule of training is shown in Figure 10.

It is not likely that any country contemplating becoming a nuclear power would have to start at the beginning in educating and training personnel. The United States has provided a variety of technical assistance to countries throughout the world including:

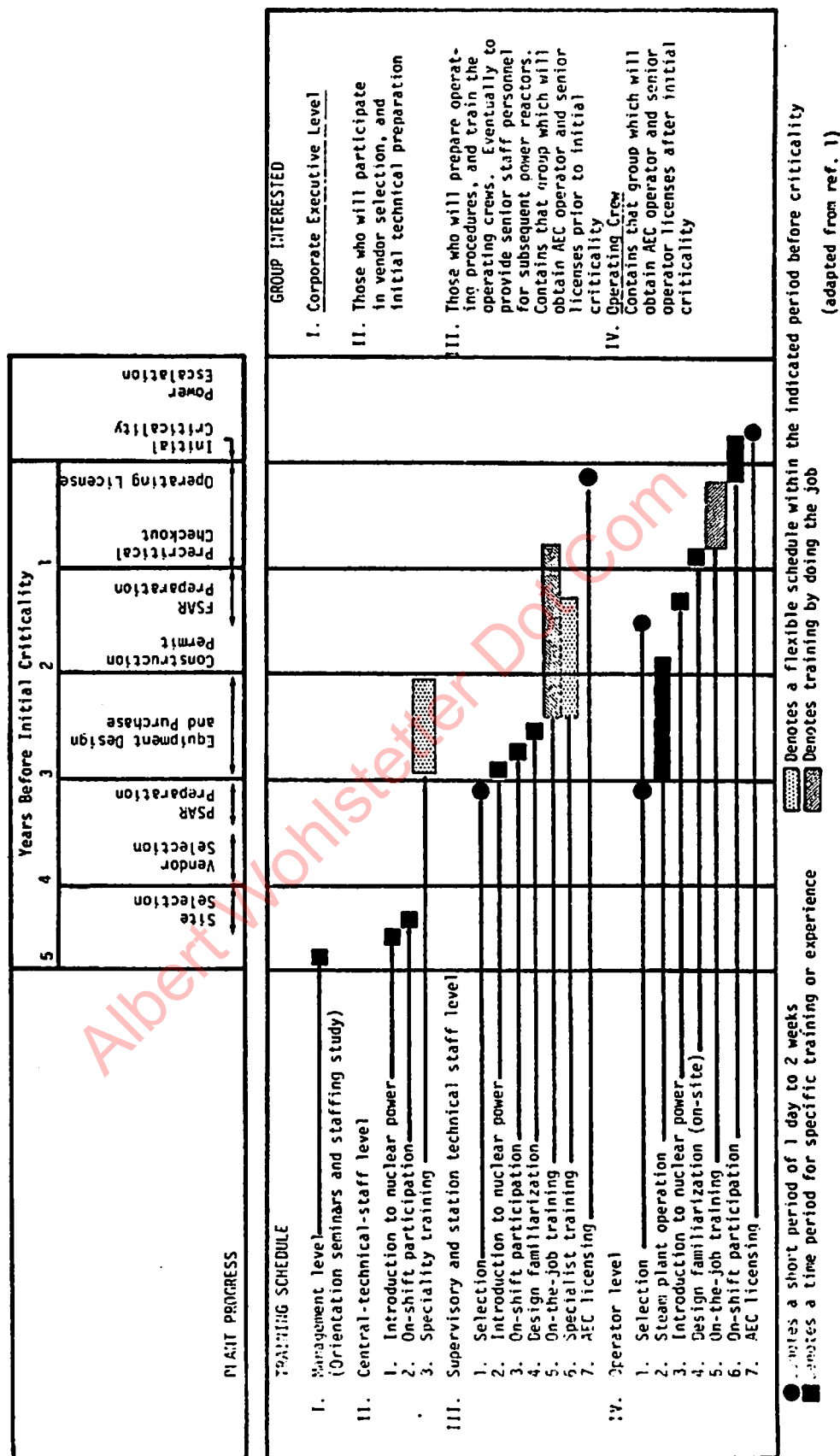


Figure 10. Schedule for Training and Experience

TABLE 7A
FIRST CYCLE

Reactor Type Parameter	BWR	PWR	PHWR (CANDU)	ATR	HTGR	LMFBR			GCFR
						Early Oxide	Advance Oxide	Advanced Carbide	
Thermal Efficiency (%)	34	33	30	31	39	40	40	40	38
Specific Power MW _{th} /MT	28	38	22	13	82	160	195	106	—
Irradiation Level MW _{th} D/ MTU	17000	22600	6900	13700	54500	110000	110000	110000	110000
Fresh Fuel Assay, Wt % U-235	2.03	2.26	0.71	1.2	93.2	—	—	—	—
Spent Fuel Assay, Wt % U-235	0.85	0.74	0.31	0.33	~60	—	—	—	—
Fissile Pu Recovered, Kg MTU	4.8	5.8	1.7	4.3	—	—	—	—	—
Annual Fissile Pu Produc- tion, Kg Pu/MWe.Yr (load factor 75%)	0.23	0.21	0.22	0.28	—	(0.141)	(0.247)	(0.381)	(0.4)

* BWR - Boiling Water Reactor; PWR - pressurized Water Reactor; PHWR - Pressurized Heavy Water Reactor, Canadian Type. ATR - Advanced Thermal Reactor (self sustaining Pu recycle HWR, Japanese design). HTGR - High Temperature Heavy Water Reactor. LMFBR - Liquid Metal Fast Breeder Reactor. GC FR - Gas Cooled Fast Reactor. Other power reactors of interest for Pu production are the Advanced Gas Reactor (British design) with slightly enriched uranium. This reactor generates about roughly 0.13 Kg Pu/per MWe per year.

TABLE 7B
CHARACTERISTICS OF REPLACEMENT LOADINGS (IN EQUILIBRIUM)

Reactor Type Parameter	BWR	PWR	PHWR (CANDU)	ATR	HTGR
Irradiation Level $MW_{th}D/MTU$	27500	32600	9600	13700	95000
Fresh Fuel Assay, Wt % U-235	2.73	3.21	0.71	0.71	93.2
Spent Fuel Assay, Wt % U-235	0.84	0.90	0.15	—	—
Fissile Pu Recovered, Kg/MTU	5.9	7.0	2.3	5.5	—
Annual Fissile Pu Produc- tion, Kg Pu/ MW_e/Yr (load factor 75%)	0.17	0.18	0.22	0.24	—

Bilateral Cooperation Agreements

Research Reactor Grants (terminated 1960)

Equipment Grants

Education and Training

(7100 individual participants up to 1970)

Multilateral Cooperation

Other countries and organizations such as the IAEA have also provided extensive nuclear training programs. Canada, for example, has provided 60 man years of training for Indians and Pakistanis for heavy water reactors. Other countries such as Argentina and India have bilateral agreements to exchange information on nuclear technology, materials, and equipment.

The estimated minimum total time period required to bring a new reactor into operation would be 4-6 years if an established design is bought and 8-10 years if a new design is generated with marginally experienced personnel.

K. Reprocessing

The primary function of a reprocessing plant is to remove the highly radioactive fission products from the irradiated fuel and extract and separate the uranium and plutonium that remains. Chemical processes have been developed that can recover over 99% of the uranium and plutonium. The major difficulty in designing a reprocessing plant is to make the technique simple enough to be operated remotely on a reliable basis. In addition extensive and elaborate radiation shielding must be provided to protect the operators.

The expected accumulation of separable plutonium in nuclear power reactors is shown in Tables 7A and 7B. It is based on a recent report.⁽³⁴⁾ The various pertinent parameters for different reactors in their first cycle is given in Table 7A. Similar parameters for a mature fuel cycle and 75% capacity factor for the reactor, are given in Table 7B.

The plutonium produced in every type of reactor will differ in its isotopic composition depending on the irradiation level (i.e., burn-up) and neutron spectral effects. The numbers given in Tables 7A and 7B are for fissile plutonium, namely ^{239}Pu plus ^{241}Pu . In high burn-up LWR spent fuel, the fissile Pu isotopes will constitute 60-75% of the total Pu produced. In heavy water reactors, with much lower burn-up, the fissile Pu will constitute 80% to 90% of total Pu produced.

The computation of the fissile Pu produced in the various reactors in the world (see Sub-Appendix 4A) is based on the annual fissile production listed in Table 7B. While these values are realistic inasmuch as they are based on actual and updated performance data of reactors, the amount of Pu produced can be increased by shorter exposure time and more fuel reprocessing per year. The maximum amount of generated fissile plutonium under these conditions in the first cycle is approximately:

- 10 Kg/MTU for BWR
- 13 Kg/MTU for PWR
- 5 Kg/MTU for PHWR
- 9 Kg/MTU for ATR
- 8 Kg/MTU for AGR

and for the replacement loadings it is about:

- 15 Kg/MTU for BWR
- 17 Kg/MTU for PWR
- 8 Kg/MTU for AGR
- 6 Kg/MTU for PHWR.

These values are two to three times higher than the values given in Tables 7A and 7B and are consistent with the initial conversion ratio for each reactor. This ratio gives the number of ^{239}Pu nuclei created per ^{235}U nuclei destroyed by fission or capture. The economical and the operational penalty for such a short irradiation time and the load increase on a reprocessing facility would be significant. In order to check how realistic the amounts of separable fissile Pu listed in Table A1 are, which are calculated under the assumption of a uniform reactor operation at 75% of full power, the same quantities are calculated from the actual cumulative electrical energy generated by several reactors in various countries. The results for those reactors, where the information is available, ⁽³⁵⁾ is shown in Table A3. The agreement between Table A3 and A1 is quite reasonable.

The accumulated potential Pu production in reactor spent fuel elements for each country has been calculated and is given in Tables A1, A2, and Figures 11 through 21. For reactors that are already operational, the accumulated fissile Pu is calculated from the actual date of start-up. For reactors which are being built or planned to be built by a certain date, a two-year delay in the start-up time has been assumed for countries in Latin American and Asia and one-year delay in Europe and Canada. For the sake of simplicity, the figures show the linearized accumulated Pu production; namely, the growth rate over each period of 5 years is assumed to be constant, rather than as discrete jumps as new reactors are coming into operation. This may represent a certain over-estimate in the accumulated

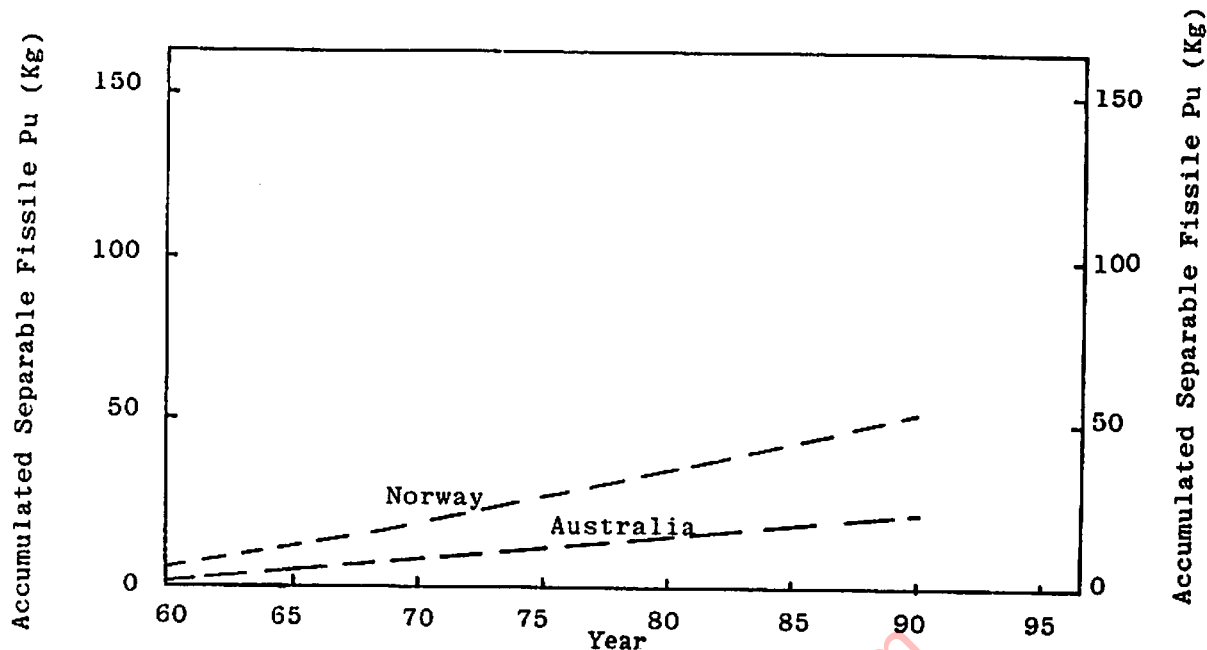


Figure 11. Accumulated Separable Fissile Pu for Research Reactors

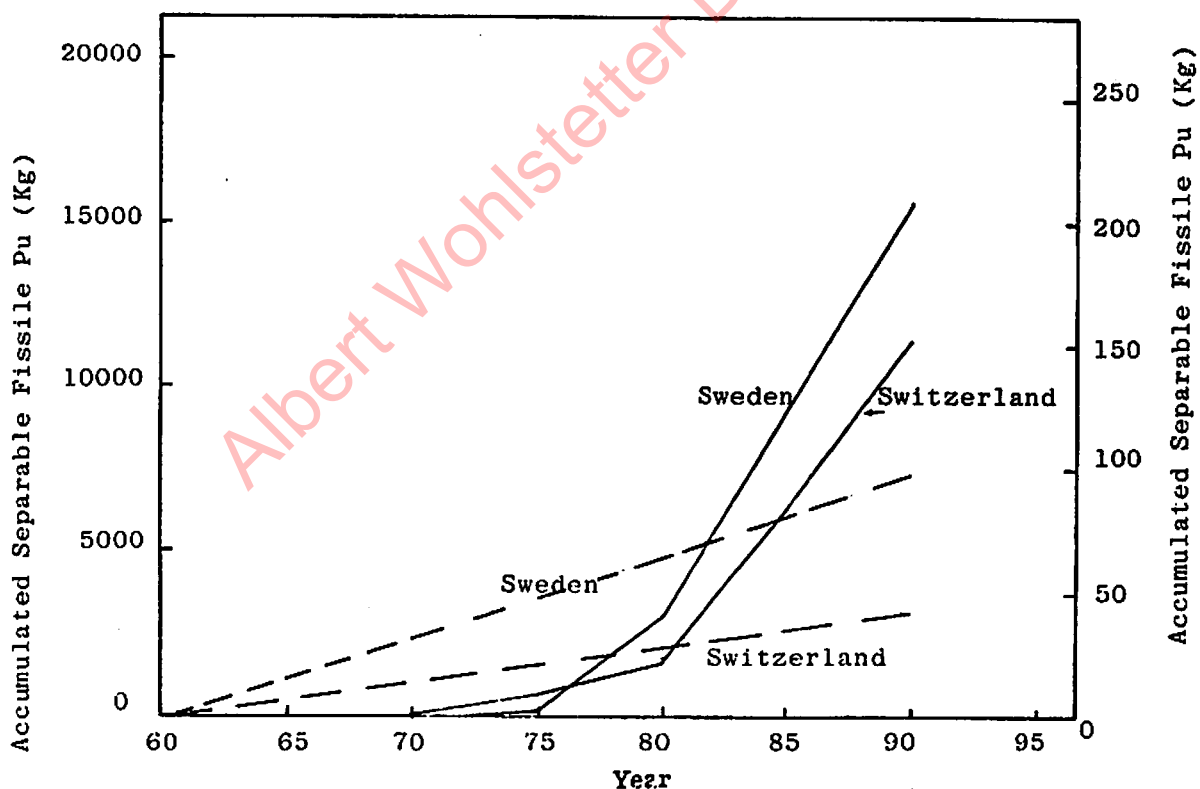
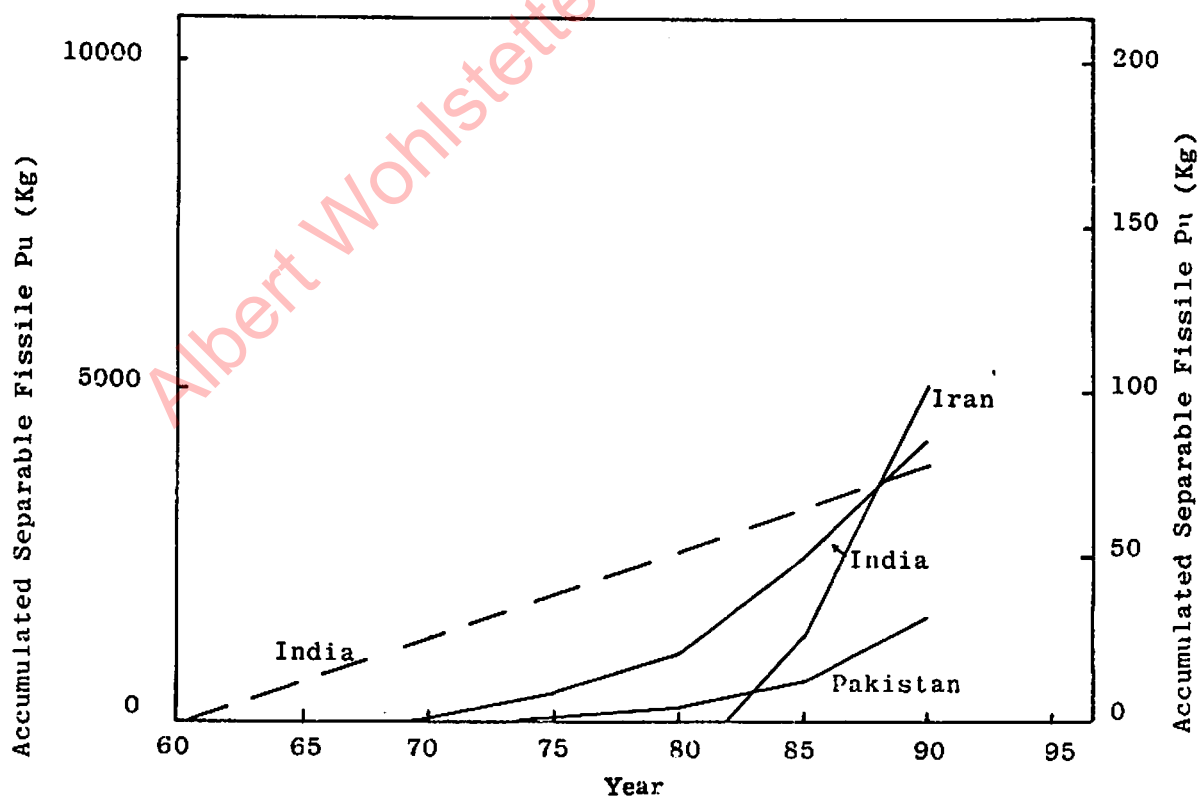
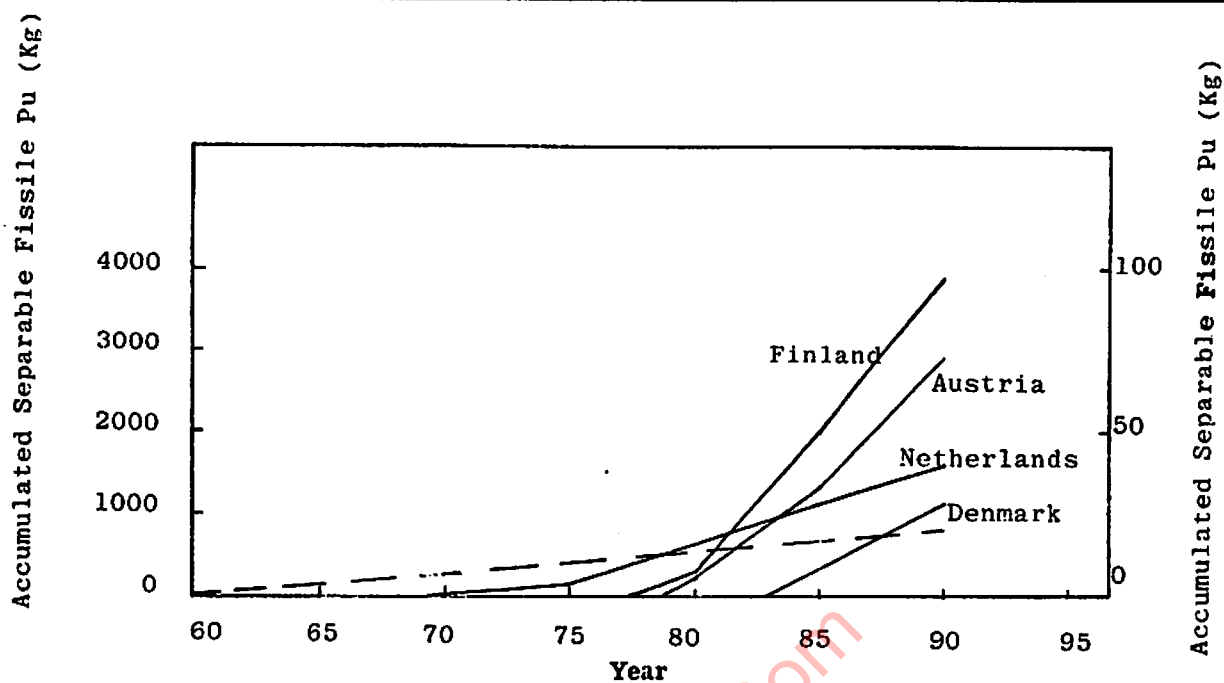


Figure 12. Accumulated Separable Fissile Pu for Power (Solid Line and left hand scale) and Research (dashed line and right hand scale) Reactor.



Figures 12 and 13. Accumulated Separable Fissile Pu for Power (solid line and left hand scale) and Research (dashed line and right hand scale) Reactor.

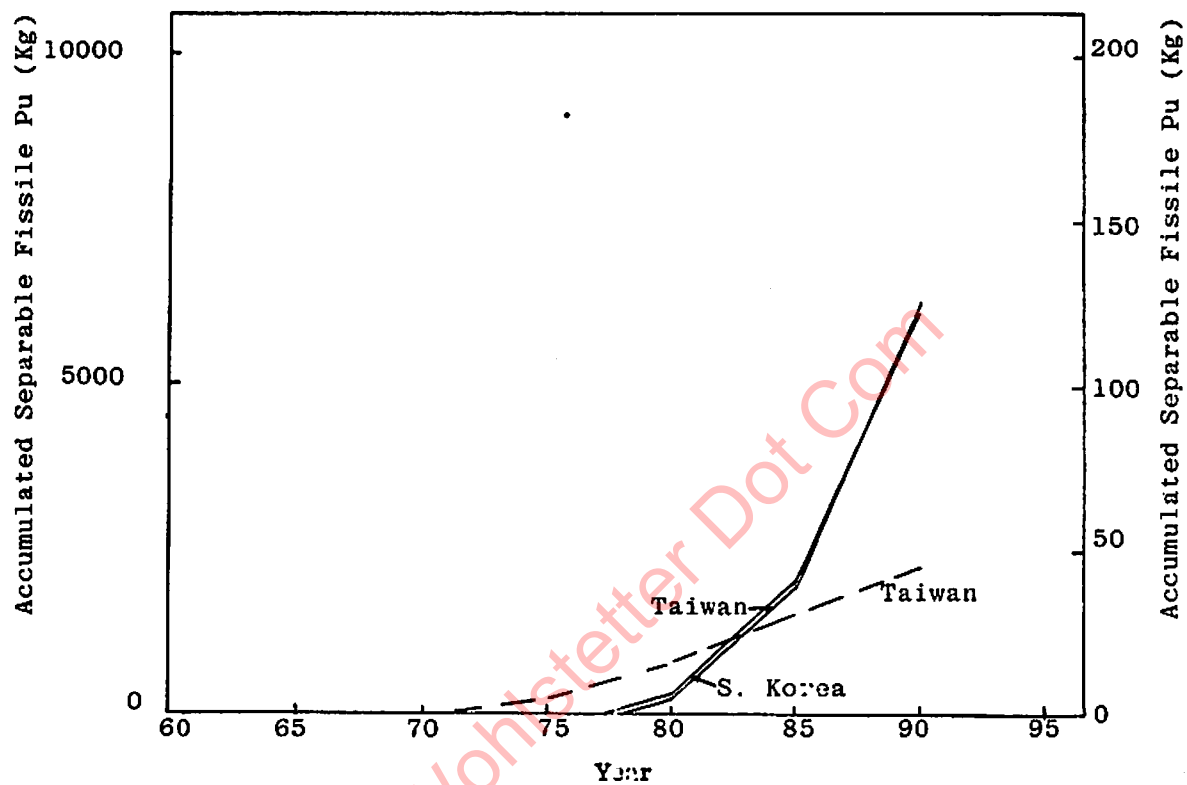


Figure 15. Accumulated Separable Fissile Pu for Power (solid line and left hand scale) and Research (dashed line and right hand scale) Reactor.

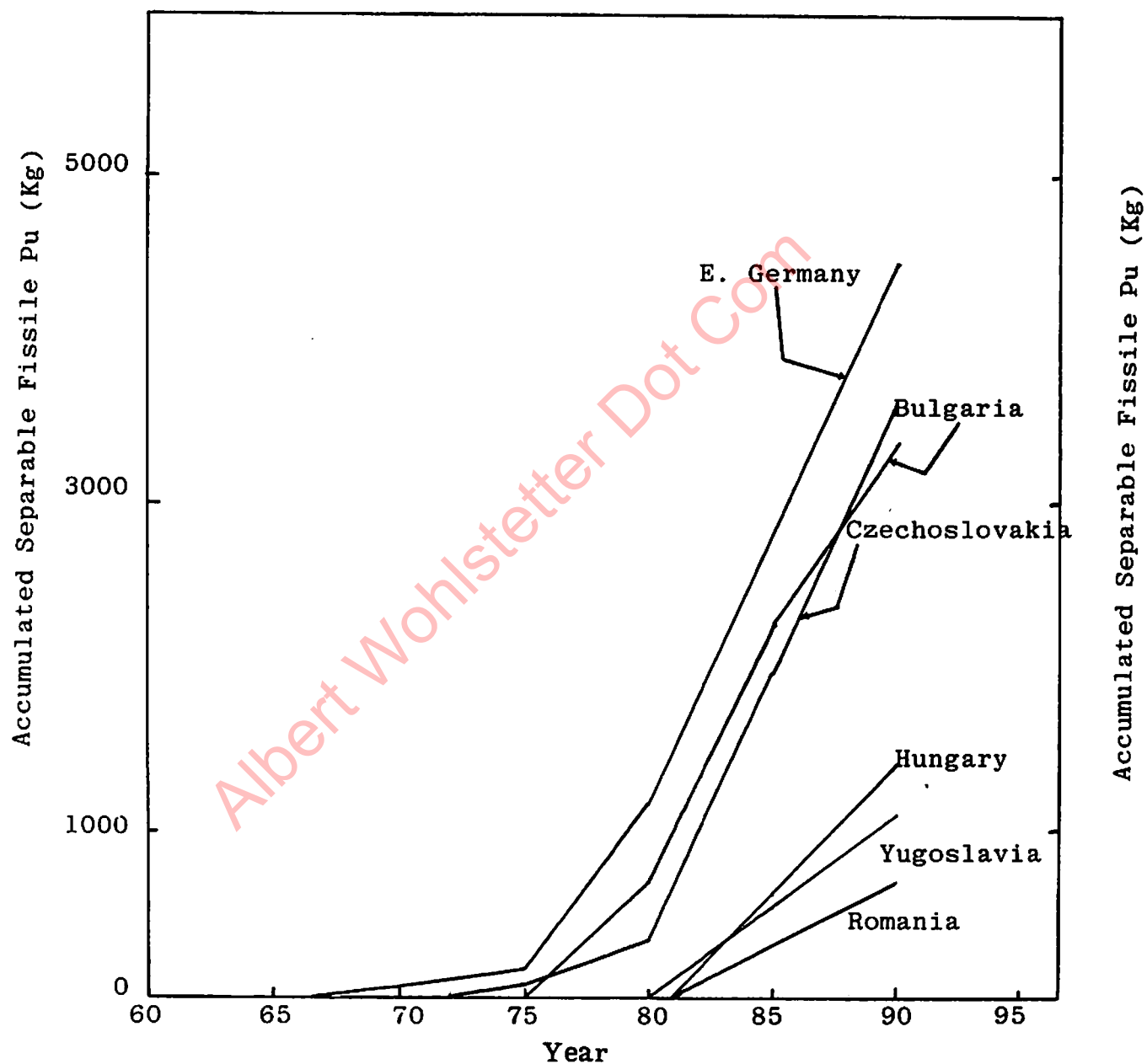


Figure 16. Accumulated Separable Fissile Pu for Power Reactors

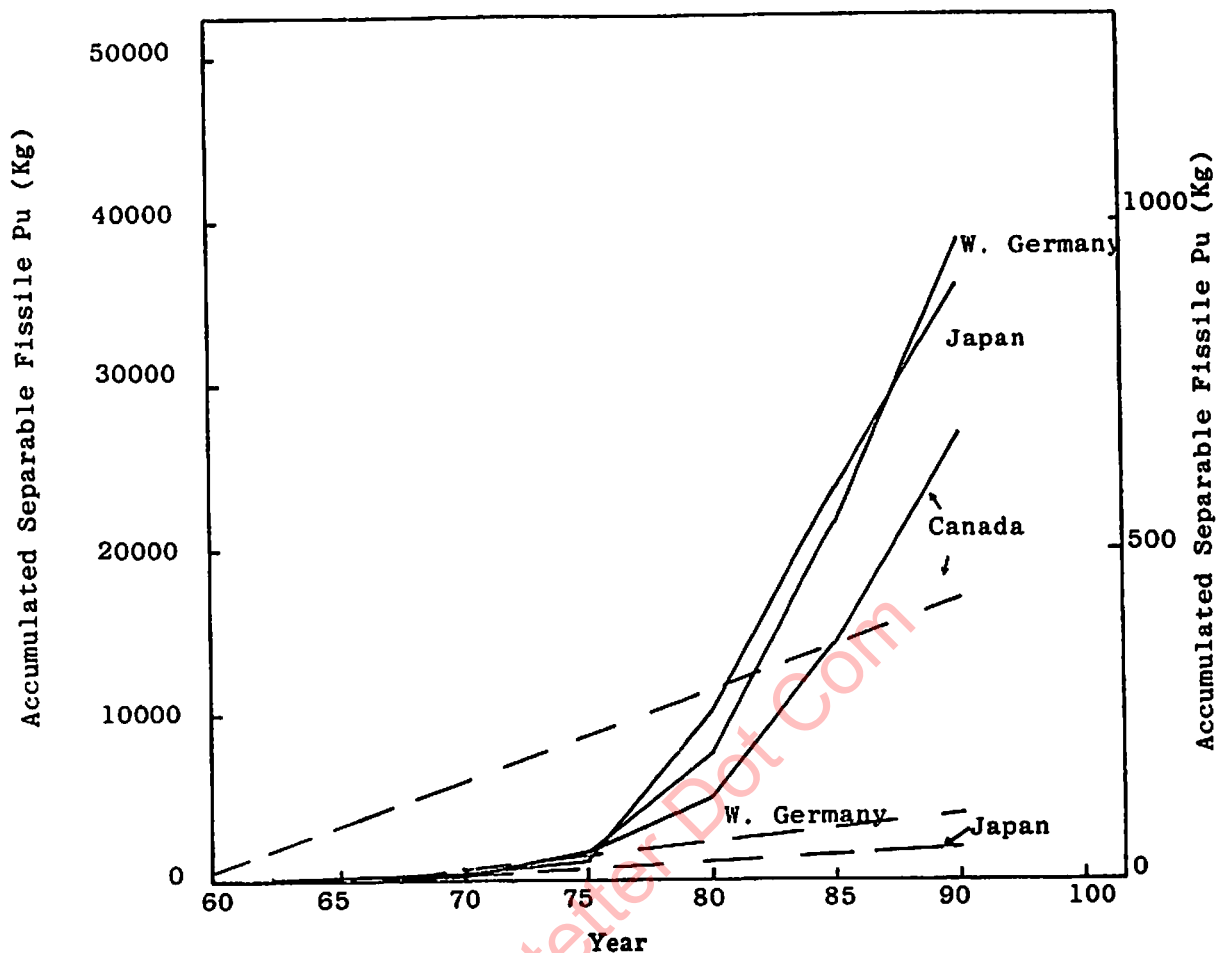


Figure 17. Accumulated Separable Fissile Pu for Power (solid line and left hand scale) and Research (dashed line and right hand scale) Reactor.

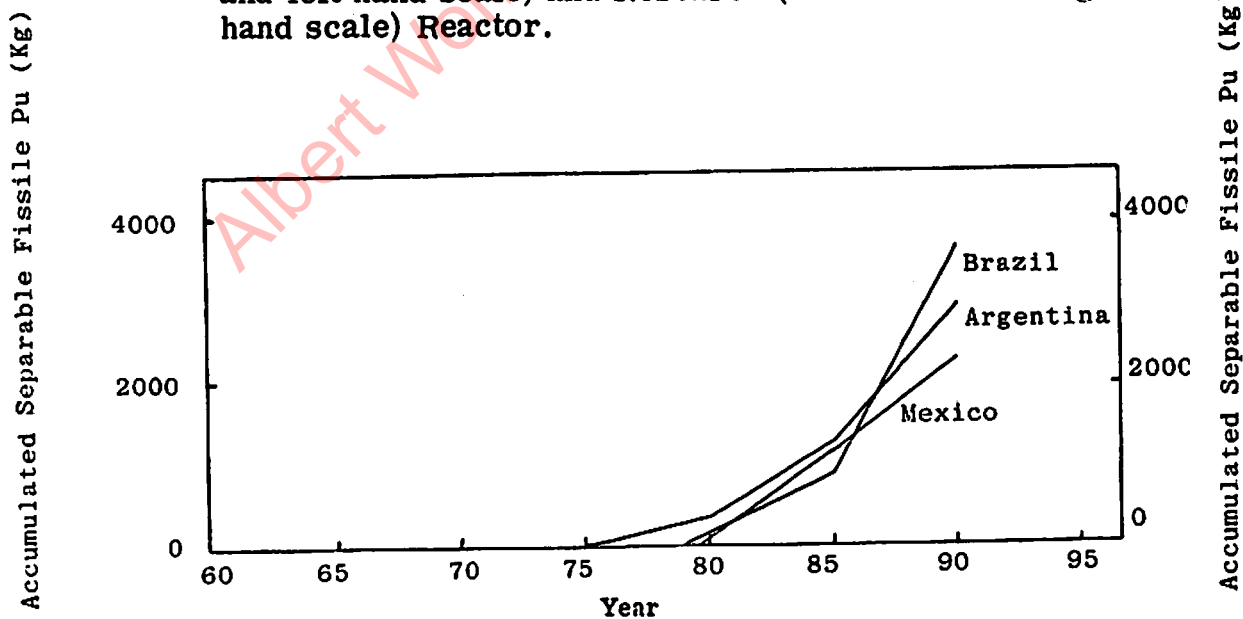


Figure 18. Accumulated Separable Fissile Pu for Power Reactors

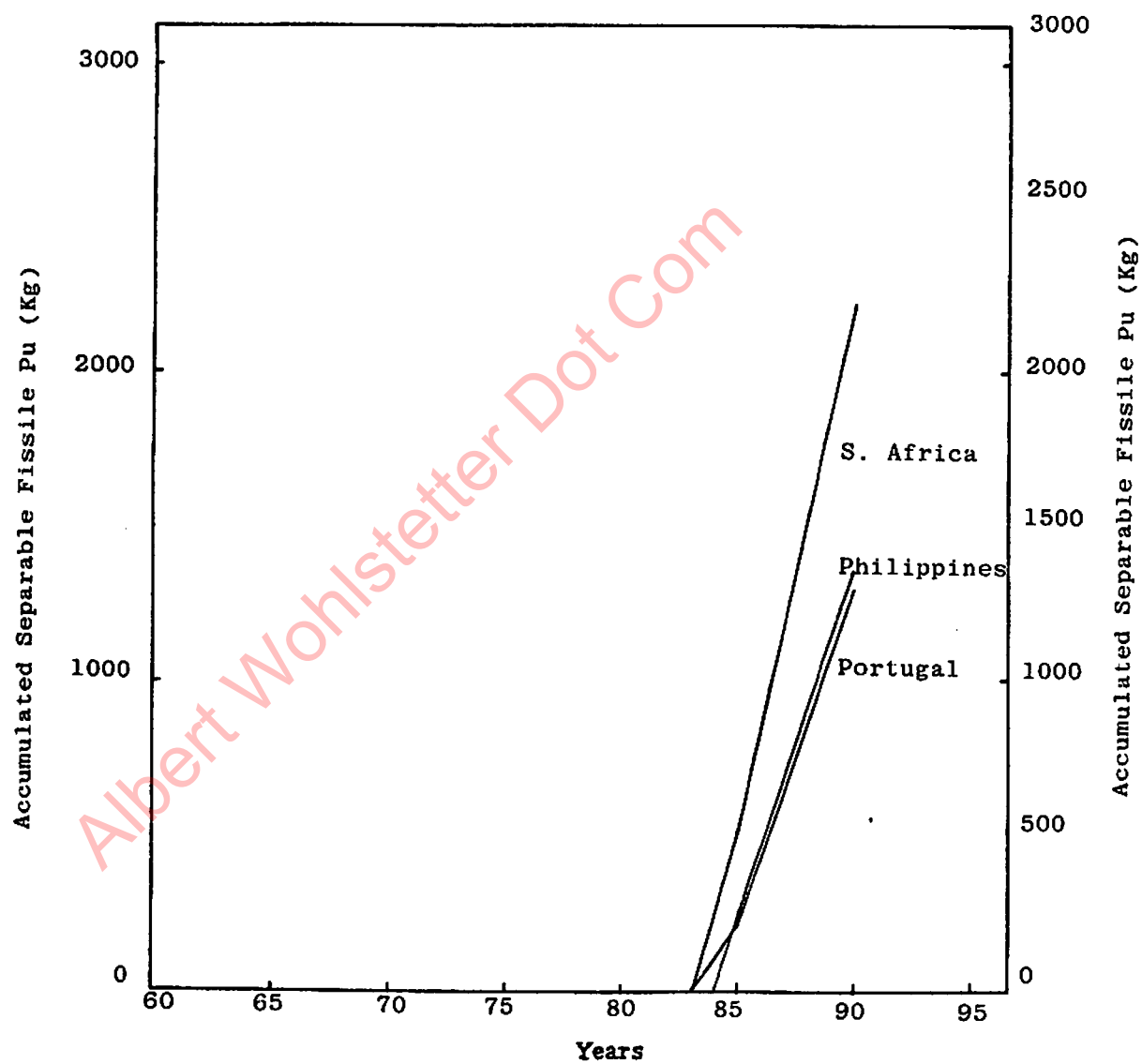


Figure 19. Accumulated Separable Fissile Pu for Power Reactors.

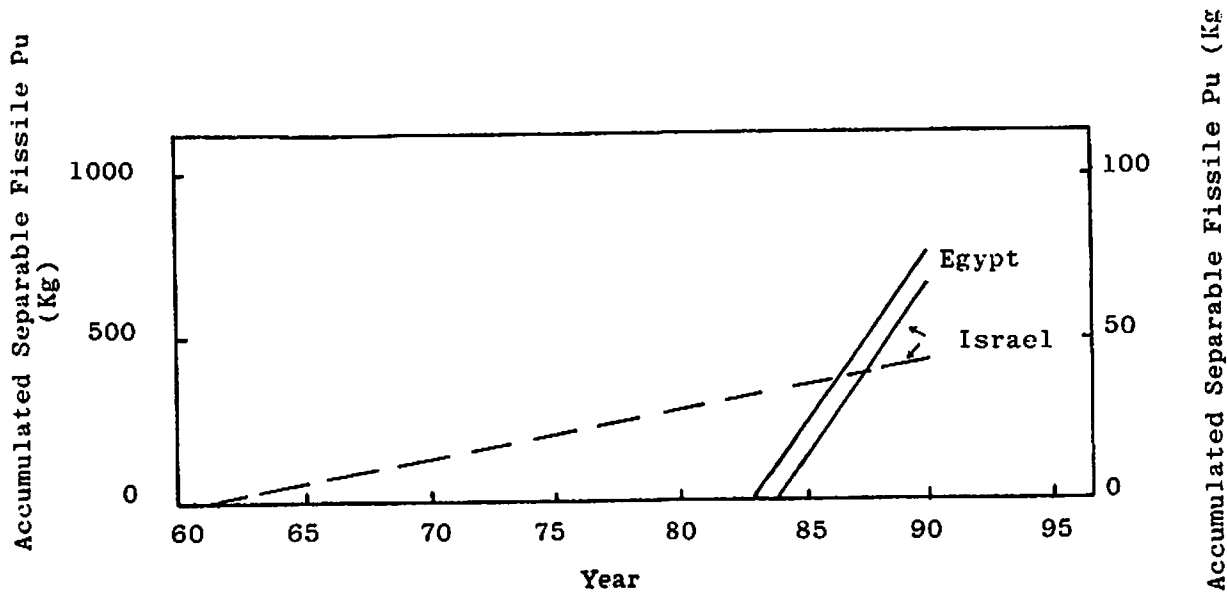


Figure 20. Accumulated Separable Fissile Pu for Power (solid line and left hand scale) and Research (dashed line and right hand scale) Reactor.

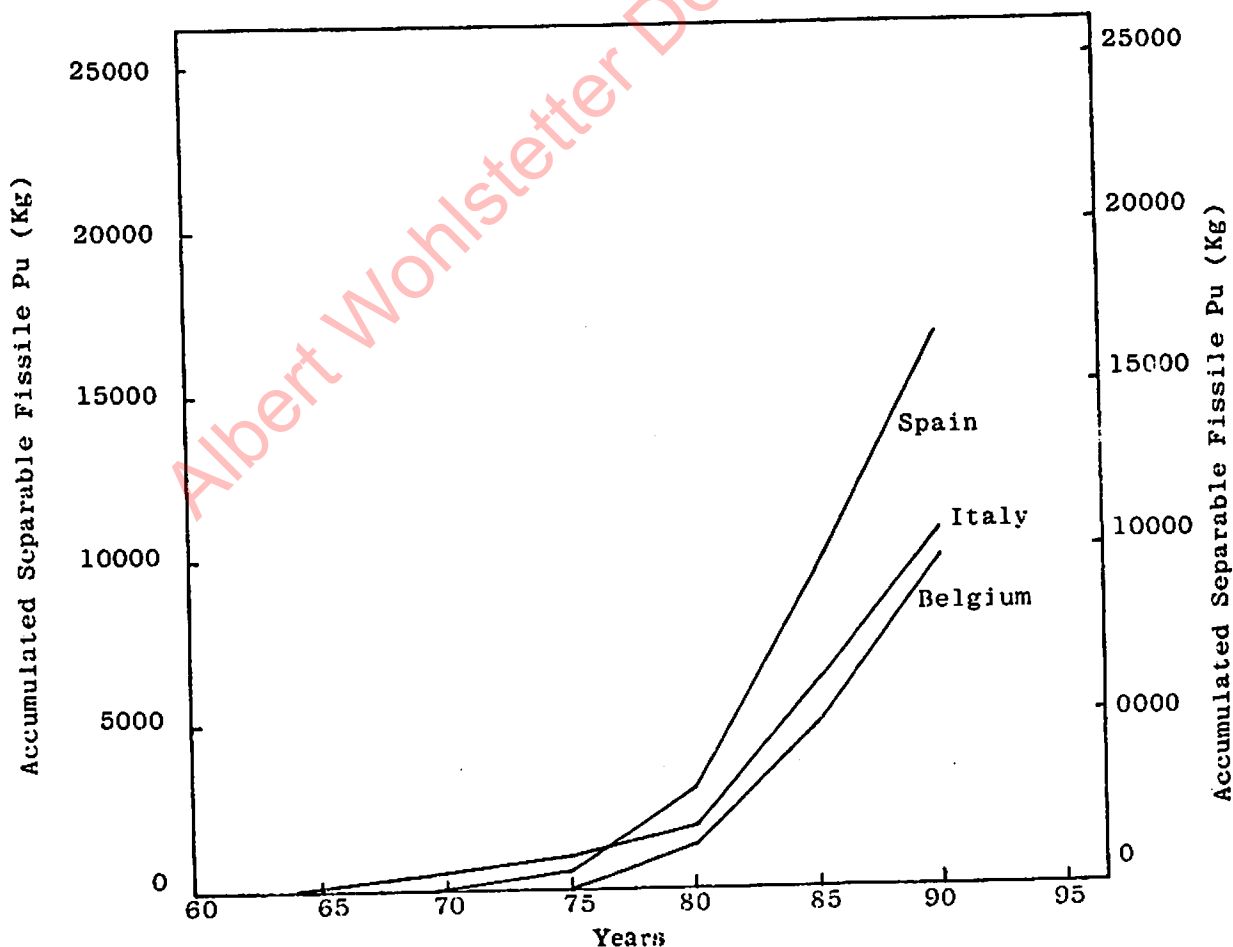


Figure 21. Accumulated Separable Fissile Pu for Power Reactors.

production for periods in between our basic time bins of 5 years. The scale on the left-ordinate represents the accumulated fissile Pu in Kg from power reactors. When applicable, the right-hand scale, which is an expanded one, describes the accumulated fissile Pu in Kg from experimental reactors. The curves for the latter are always in the form of dashed lines. Tables A1 and A2 were used to prepare curves of over-hang countries. Figure A1 contains the number of countries achieving the threshold of 25 and 250 separable Kg of fissile Pu vs. time. Table A3 gives similar curves, but for countries with known reprocessing capabilities. Table A3 modified shows similar curves for countries with known uranium enrichment capabilities. The curve describing the attainment of nuclear-weapon status by the known NW countries is also shown for reference.

Commercial reprocessing operations today attempt to recover 99.5% of the uranium and plutonium.⁽²⁴⁾ Although it would improve the waste management problems considerably if this recovery rate were improved to at least 99.9%, there has been up to now no economic incentive to do so.

Only one commercial reprocessing plant has operated in the United States. This was the Nuclear Fuel Services Plant in West Valley, New York. It was shut down in 1972 after commencing operations in April 1966. In this period 630 tonnes of uranium were processed, with an average uranium recovery rate of 99.0% and an average Pu recovery rate of 97.6%.⁽²⁵⁾ The capacity of the plant was 1 tonne U/day or 300 tonnes U/yr. Cost of construction was \$33 million.⁽²⁶⁾ Approximately 170 regular fulltime employees were utilized by NFS. The estimated cost to build this same plant today is \$220 to \$250 million. However, the plant would not meet NRC regulatory standards.

A new reprocessing plant is being constructed in Barnwell, South Carolina by Allied-General Nuclear Services (AGNS), a partnership of Allied Chemical and General Atomic Company. This plant has a designed capacity of 5 tonnes U/day handling all types of low enriched fuels. The AGNS plant will use the classic Purex solvent extraction technique⁽²⁷⁾ with a shear leach headend system. This technique has a proven record at National Laboratories. The final cost of the AGNS plant is now expected to exceed \$500 million. Additional NRC requirements for safeguards and/or waste management may push this cost even higher. The estimated number of fulltime employees is 300.

Several countries throughout the world have operating reprocessing plants.⁽²⁸⁾ West Germany (35 tonnes/yr), Italy, and Belgium have LWR fuel reprocessing facilities. India reprocesses HWR fuel. Japan and Taiwan have pilot reprocessing plants operating now, and Japan expects to commence operating a 200 tonne U/yr plant in 1976. Even Spain, which has a small nuclear industry at present, has a plant to reprocess highly enriched uranium aluminum alloy fuel at a capacity of 100 kg/year.

Figure 22 illustrates the expected demand and capacity for European reprocessing of LWR fuel by the UK (BNFL), France (CEA), and Germany.(29) Table 8 presents the capabilities of the pilot plants that have operated and the production plants that are expected to be utilized by United Reprocessors. United Reprocessors is a French, German, and UK combine contracting for reprocessing utility fuel.

The estimated cost to construct a 30 tonne U/yr minimum reprocessing plant for Pu recovery is \$50 million. A minimum construction period of two years would be required. At least 100 employees would be required to operate the plant.

L. Strategic special nuclear material rework

Typical forms of uranium and plutonium that are available after reprocessing or at a mixed oxide fuel fabrication plant include nitrates and oxides. It is possible to make a nuclear weapon directly out of plutonium oxide; however, the conversion of the nitrates and oxides to uranium or plutonium metal is not difficult and is fully documented in the open literature (see Reference 27). Figures 23 and 24 illustrate the processes.

The acquisition or construction of the equipment to convert to uranium or plutonium metal would be relatively inexpensive as compared with other processes in the nuclear fuel cycle. An adequate system could be procured within a year's time for less than \$200,000.

M. Weapon design, fabrication and testing

The conceptual design of a nuclear fission weapon is rather simple and has been described in a qualitative manner in the open literature.(30) The necessary condition for a nuclear explosion is to bring a sufficient amount of fissile material together in a favorable geometry for a long enough period to allow the system to self-propagate with prompt fission neutrons that emanate from the fission reaction. Historically two types of design have been detonated: a gun-barrel weapon where a mass of fissile material is shot into a second mass making the system supercritical; and the implosion weapon which consists essentially of a sphere of fissile material surrounded by a heavy metal outer casing and outside this, high-explosive shaped charges. When the high explosive is detonated the sphere collapses inward so that the fissile material is brought together as a compressed, compact, solid supercritical mass, held together momentarily by the heavy metal outer casing.

All of the qualitative concepts discussed above are well known, probably better than some of the technology associated with enrichment or reprocessing. There has been at least one case where an individual

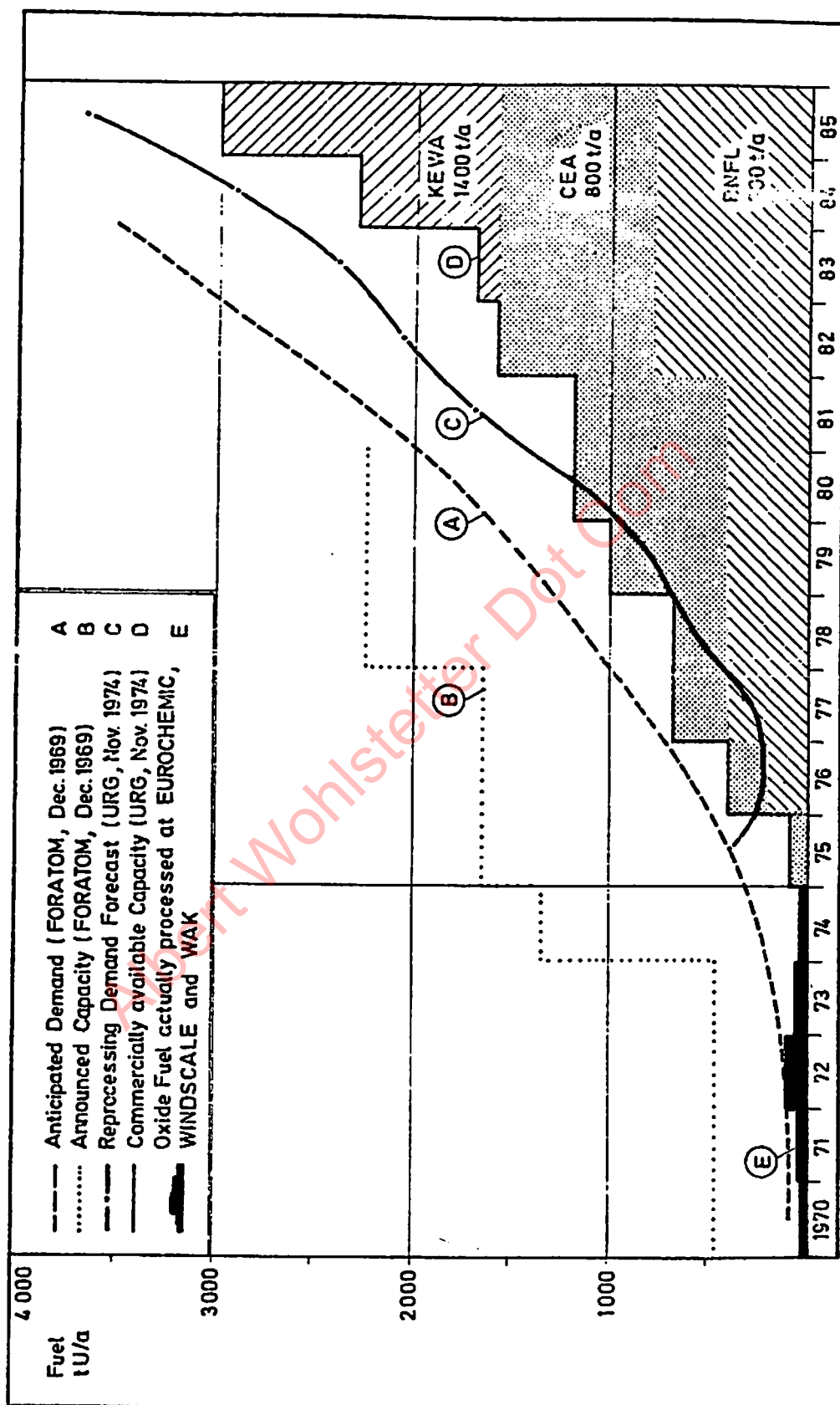


Figure 22. Oxide Fuel Reprocessing Demand and Capacity

TABLE 8
OXIDE FUEL REPROCESSING IN EUROPE (tU)

	Pilot Plants		Production Plants			UKG Capacity (total)
	EUROCHEMIC	WAK	Windscale	La Hague	KEWA	
1967	167 total	32 total	100 total			
68						
69						
70						
71						
72						
73						
74						
75		25		100		100
76		—	200	200		400
77		40	400	300		700
78		40	400	350		750
79		40	400	600		1000
80			400	800		1200
81			400	800		1200
82			800	800		1600
83			800	800	100	1700
84			800	800	800	2400
85			800	800	1400	3000

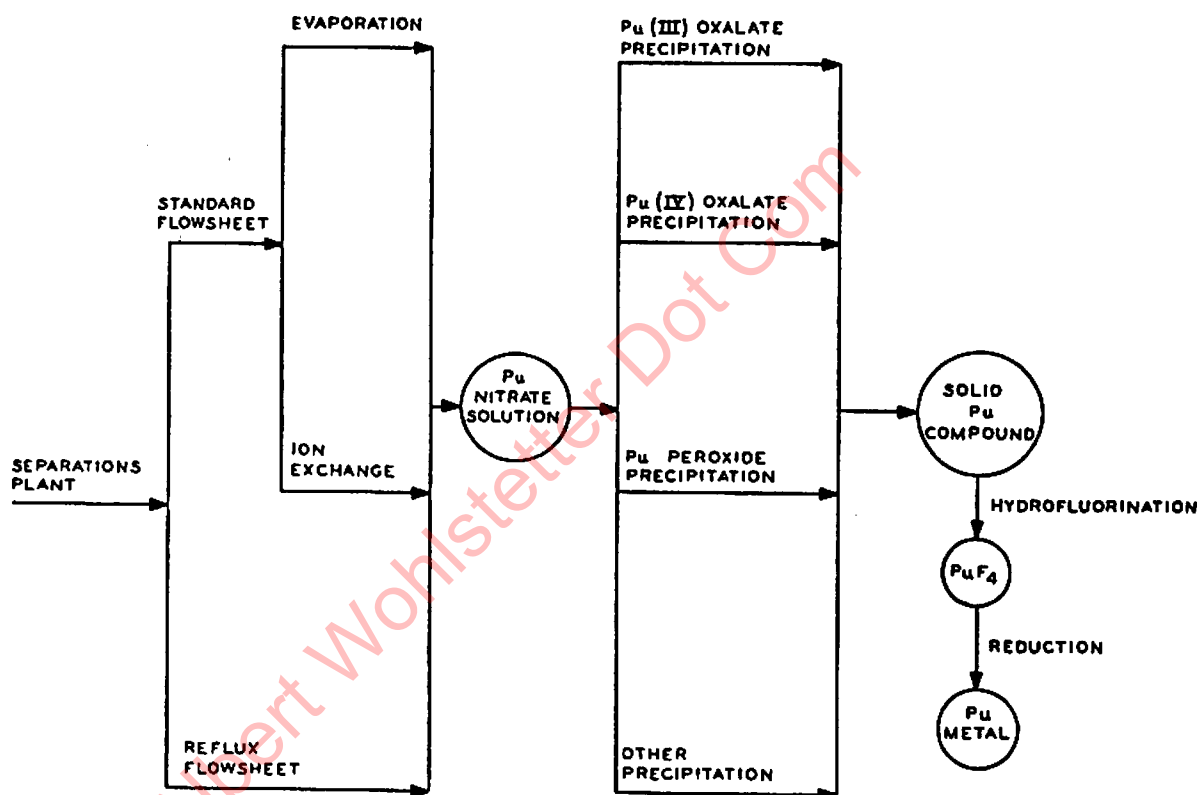


Figure 23. Pu Reconversions

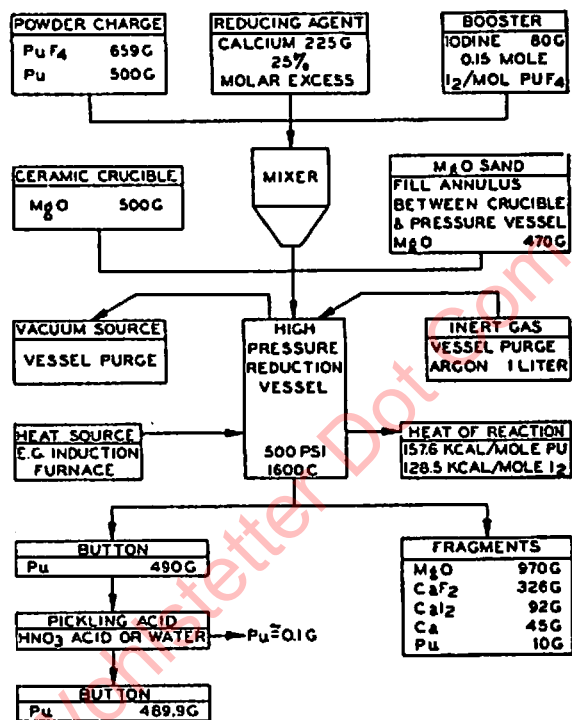


Figure 24. Typical Flowsheet-Reduction of Pu F_4

with no special weapon training has successfully designed a fissile weapon without access to classified literature or computer codes. It appears that the actual design of a crude weapon is the least of the technological problems associated with weapon technology.

The fabrication of uranium metal can be by conventional means, including casting, rolling, extrusion, forging, swaging, drawing, and machining.⁽³¹⁾ Hot-rolling of the alpha phase is a useful method for forming the metal. Because of the ease with which uranium oxides, especially at higher temperatures, it must be protected from air during fabrication either by means of a fused salt or by an inert gas atmosphere. The metal can be machined moderately easily if suitable lubricants and coolants are present to prevent oxidation. Uranium parts can be joined by welding or brazing. Fusion welding is achieved by using a Heliarc torch in an inert atmosphere.

Plutonium metal is also easily oxidized and must be protected during fabrication. In addition, since it is so toxic, machining operations must be conducted in a glove box for operator protection.

A minimum underground testing program for nuclear weapons would consist of drilling shafts (approximately 100 meters in depth depending on the local geology) and sufficient instrumentation to determine the yield of the device. It is also likely that a high explosive test program would be conducted to maximize the effect of the shaped charges.

Overall cost of a minimum test program need not exceed \$250,000 per year.

SUBAPPENDIX 4A: FOREIGN NUCLEAR FACILITIES

This appendix contains a compilation of foreign nuclear facilities excluding the reactors of the nuclear weapon countries (except for India). For these tables we have attempted to list a realistic projection (as of July 1975) for plutonium production and our estimates for the construction of new reactors and other facilities. However, since decisions are being changed daily and new projects are continually proposed it is quite likely that this list will be obsolete within a short time. Nonetheless, the plutonium production is probably reasonably correct for at least the next five years. The large reprocessing facilities (Table A4) are also likely to be correct for at least the next five years. The foreign enrichment facility projections (Table A5) on the other hand have been changing rapidly and any present projection is likely to be subject to a large uncertainty. This uncertainty is compounded by the recent announcements by the U.S. and the U.S.S.R. that laser isotopic separation is possible. These announcements were made relative to the separation of light isotopes. The Lawrence Livermore Laboratory has demonstrated laser uranium enrichment by producing 4 mg of 3% enriched uranium.⁽³²⁾ Although laser enrichment is presently a laboratory experiment that requires significant effort to develop to a production capability it may, since it is expected to be much less capital intensive, change some present projections or at least delay an irrevocable commitment to a possibly more expensive technology.

Tables A1 and A2 list the foreign power and research reactors larger than 1 MW(t). The computation of the fissile Pu produced in these reactors is based on the annual fissile production listed in Table 7B. These values are realistic inasmuch as they are based on actual and updated performance data of reactors; however, the amount of Pu (relative isotopic amount of fissile Pu and absolute amount Pu) could be increased by shorter exposure time and more fuel reprocessing. A significant economic and operational penalty must be paid for this type of fuel management for a civilian nuclear power plant. We have assumed for these tables that the reactors are operated for power production at a 75% capacity factor. In addition to the capacity factor we have assumed a one year delay from the official operating date for future European, Japanese, Canadian, and South African reactors. A two year delay is assumed for all other future nuclear power plants.

Table A3 is a listing of the accumulative separable plutonium content of spent fuel that is based on the actual operating history of power reactors through the end of 1974. The data base for the table was taken from the Nuclear Generation Chart of the March 1975 issue of Nuclear Engineering International. Table 7A was used to convert from MWh to fissile Pu content. Comparison of this table with the data in Table A1 shows that the accumulated Pu based on the actual operating history through 1974 is between 18%

to 133% of the assumed power generation of Table A1. Most yields are above 80% of those given in Table A1. It might be expected that as operating experience is gained the actual values would more closely approximate those of Table A1. From previous experience it is not likely that Table A1 values will be underestimates of the Pu production.

From the data in Tables A1 and A2, curves representing the number of countries accumulating sufficient separable fissile plutonium for n weapons can be drawn as a function of time. Figure A1 shows two curves representing the number of countries accumulating, in the spent fuel, sufficient fissile plutonium for 5 nuclear weapons and for 50 nuclear weapons

Figure A1 represents strategic special nuclear material that has been produced but not SSNM that is actually separated and available for weapon production. In Figure A2 potential nuclear weapon countries with known reprocessing or enrichment capacities located within the countries' borders are shown. The curve represents the time to produce sufficient strategic special nuclear material for roughly 5 and 50 nuclear weapons. In Figure A3 the curve represents the countries with sufficient reprocessing capacity to produce plutonium for 5 or 50 nuclear weapons.

TABLE A1
POWER REACTORS

LOCATION	TYPE	MW _e	REACTOR SUPPLIER	START(1) DATE	PU PROD Kg.Yr	Separable Fissile Pu Accumulated (kg) Through			
						69	74	79	84
ARGENTINA									
Atucha 1	PHWR	319	SIEMENS	1975	70	0	0	350	700
Cordoba	PHWR	600	AECL	1982	132	0	0	0	396
Atucha 2	PHWR	600	AECL	1984	132	0	0	0	132
					Total	0	0	350	1,228
AUSTRIA									
Tullnerfeld 1	BWR	750	KWU/AEB	1978	126	0	0	252	882
Stein-St. Pantaleon 1	PWR (2)	1300	-	1983	221	0	0	0	442
					Total	0	0	0	1,324
BELGIUM									
Doel 1	PWR	390	W-ACEC-COCKERILL	1975	70	0	0	344	694
Doel 2	PWR	390	"	1975	70	0	0	300	650
Doel 3	PWR	900	FRAMATOME-ACEC-COCKERILL	1981	162	0	0	0	648
Tihange	PWR	870	"	1976	157	0	0	628	1,413
CNW 1	PWR	1000	W-ACEC-COCKERILL	1982	180	0	0	0	540
CNW 2	PWR	1000	"	1983	180	0	0	0	360
Tihange 2	PWR	900	FRAMATOME-ACEC-COCKERILL	1981	162	0	0	0	648
					Total	0	0	1,272	4,953
BRAZIL									
Angra 1	PWR	626	W	1979	113	0	0	85	650
Angra 2		1200	-	1984	216	0	0	0	216
Angra 3		1200	-	1985	216	0	0	0	0
					Total	0	0	85	866
BULGARIA									
Kozloduy 1	PWR	440	AEE	1975	79	0	0	395	790
Kozloduy 2	PWR	440	"	1977	79	0	0	237	532
Kozloduy 3	PWR	440	"	1979	79	0	0	79	474
Kozloduy 4	PWR	440	"	1980	79	0	0	0	395
					Total	0	0	711	2,291
						0	0	0	3,871

TABLE A1
POWER REACTORS (Cont)

LOCATION	TYPE	MW _e	REACTOR SUPPLIER	START DATE ⁽¹⁾	PU PROD Kg/Yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
CANADA										
N'DP	PHWR	25	AECL	6/62	6	45	75	105	135	765
Douglas Point	PHWR	206	"	1/69	45	45	270	495	720	945
Pickering 1	PHWR	514	"	8/71	113	0	386	951	1,516	2,081
Pickering 2	PHWR	514	"	1/72	113	0	339	904	1,469	2,034
Pickering 3	PHWR	514	"	7/72	113	0	283	848	1,413	1,978
Pickering 4	PHWR	514	"	7/73	113	0	170	735	1,300	1,865
Gentilly 1	BLVHWR	250	"	6/72	55	0	142	417	692	967
Bruce 1	PHWR	732	"	1/79	161	0	0	161	966	1,771
Bruce 2	PHWR	732	"	1/78	161	0	0	322	1,127	1,932
Bruce 3	PHWR	732	"	1/80	161	0	0	0	805	1,510
Bruce 4	PHWR	732	"	1/81	161	0	0	0	644	1,449
Bruce 5	PHWR	732	"	1/82	161	0	0	0	483	1,288
Bruce 6	PHWR	732	"	1/83	161	0	0	0	322	1,127
Bruce 7	PHWR	732	"	1/84	161	0	0	0	161	966
Bruce 8	PHWR	732	"	1/85	161	0	0	0	0	805
Gentilly 2	PHWR	600	"	1/80	132	0	0	0	660	1,320
New Brunswick	PHWR	600	"	1/81	132	0	0	0	528	1,188
Pickering 5	PHWR	508	"	1/81	112	0	0	0	448	1,308
Pickering 6	PHWR	508	"	1/82	112	0	0	0	336	896
Pickering 7	PHWR	508	"	1/82	112	0	0	0	336	896
Pickering 8	PHWR	508	"	1/83	112	0	0	0	224	784
					Total	90	1,665	4,938	14,283	27,075
CZECHOSLOVAKIA										
Bohunice 1A	GCHWR	112		1/72	25	0	75	200	325	400
Bohunice 2A	PWR	440	AEE	1/78	79	0	0	158	553	948
Bohunice 2B	PWR	440	"	1/80	79	0	0	0	395	790
Czechoslovakian 3	PWR	440	"	1/80	79	0	0	0	395	790
Czechoslovakian 4	PWR	440	"	1/81	79	0	0	0	316	711
					Total	0	75	358	1,984	3,639
DENMARK										
Unnamed	LWR	900	-	1/83	162	0	0	0	324	1,131

TABLE A1
POWER REACTORS (Cont)

LOCATION	TYPE	MWE	REACTOR SUPPLIER	START DATE ⁽¹⁾	PU PROD Kg Yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
EGYPT										
First	PWR ⁽²⁾	600	-	1 '83	108	0	0	0	216	756
FINLAND										
Louisa 1 (C)	PWR	420	AEE	7 '77	76	0	0	190	570	950
Louisa 2 (C)	PWR	420	AEE	4 '79	76	0	0	57	437	817
TVO 1 (C)	BWR	660	AA	8 '78	112	0	0	47	607	1,167
TVO 2 (C)	BWR	660	AA	8 '81	112	0	0	0	383	943
					Total	0	0	294	1,997	3,377
GERMANY (Democratic Republic)										
Rheinsberg 1	PWR	80	AEE	5 '86	14	51	91	161	231	301
Nord 1-1	PWR	440	"	1 '74	79	0	79	476	869	1,264
Nord 1-2 (C)	PWR	440	"	1 '76	79	0	0	316	711	1,106
Nord 2-1 (O)	PWR	440	"	1 '78	79	0	0	158	553	944
Nord 2-2 (O)	PWR	440	"	1 '79	79	0	0	79	474	569
					Total	51	170	1,188	2,838	4,444
GERMANY (Federal Republic)										
Gundremmingen-Block A	BWR	237	GE	4 '67	40	110	310	510	710	910
Lingen	BWR	256	AEG	8 '68	44	70	290	510	730	950
Karlsruhe Mzfr	PHWR	52	SIEMENS	9 '65	11	48	103	158	213	268
Ortshelm	PWR	328	SIEMENS	3 '69	59	49	344	639	934	1,229
Stade	PWR	630	SIEMENS	5 '72	113	0	301	866	1,431	1,996
Würgassen	BWR	640	AEG	3 '72	109	0	309	854	1,400	1,944
Biblis 1	PWR	1150	SIEMENS	1 '75	207	0	0	1,035	2,070	3,105
Biblis 2	PWR	1240	"	8 '77	223	0	0	539	1,854	2,769
Brunsbüttel	BWR	771	AEG	8 '76	131	0	0	448	1,103	1,758
Neckar GKN	PWR	805	KWU	4 '77	145	0	0	359	1,124	1,849
Isar KKI	BWR	870	AEG-KWU	1 '78	148	0	0	296	1,036	1,776
Philippsburg 1	BWR	864	KWU	1 '77	147	0	0	441	1,176	1,911
Philippsburg 2	BWR	864	KWU	1 '79	147	0	0	147	882	1,617
Tier-Untrop	THTR	300	HRB	1 '78	66	0	0	132	462	742
Kalkar SNR-300	LMFBR	282	INTERATOM-NEKA	1 '81	40	0	0	0	160	340

TABLE A1
POWER REACTORS (Cont)

LOCATION	TYPE	MWE	REACTOR SUPPLIER	START DATE(1)	PU PROD Kg./Yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
KKN-Niederrheinback Kruemel Unterweser Gundremmingen-Block B Gundremmingen-Block C Kernkraftwerk Sud. Kaerlich Grohnde	GCHWR	100	SIEMENS	1 '76	22	0	0	88	198	302
	BWR	1260	AEG	1 '80	214	0	0	0	1,070	2,140
	PWR	1230	SIEMENS	1 '78	221	0	0	442	1,547	2,652
	BWR	1249	KWU	7 '80	212	0	0	0	954	2,014
	BWR	1249	"	7 '81	212	0	0	0	742	1,802
	PWR	1300	KWU	7 '80	234	0	0	0	1,053	2,223
	PWR	1300	BBK	7 '79	234	0	0	117	1,287	2,457
	PWR	1294	KWU	1 '81	233	0	0	0	932	2,097
					Total	277	1,657	7,621	21,638	38,927
HUNGARY Paks 1 Paks 2	PWR	440	AEE	1 '81	79	0	0	0	316	711
	PWR	440	AEE	1 '81	79	0	0	0	316	711
					Total	0	0	0	632	1,422
INDIA Tarapur 1 Tarapur 2 Rajasthan 1 Rajasthan 2 Madras 1 Madras 2 Narora 1 Narora 2	BWR	200	GE	10 '69	34	9	179	349	519	689
	BWR	200	GE	10 '69	34	9	179	349	519	689
	PHWR	200	AECL	1 '74	49	0	44	264	484	704
	PHWR	200	AECL	1 '79	44	0	0	44	264	484
	PHWR	235	DAE	6 '79	52	0	0	26	286	546
	PHWR	235	"	1 '81	52	0	0	0	208	468
	PHWR	220	"	1 '83	48	0	0	0	96	336
	PHWR	220	"	1 '84	48	0	0	0	48	288
					Total	18	402	1,032	2,424	4,204
IRAN Iran-1 Iran-2 Iran-3 Iran-4	PWR	1200	KWU	1 '82	216	0	0	0	648	1,728
	PWR	1200	KWU	1 '83	216	0	0	0	432	1,512
	PWR	900	FRAMATOME	1 '84	162	0	0	0	162	572
	PWR	900	"	1 '85	162	0	0	0	0	810
					Total	0	0	0	1,242	5,022

TABLE A1

POWER REACTORS (Cont)

LOCATION	TYPE	MW _E	REACTOR SUPPLIER	START DATE ⁽¹⁾	PU PROD Kg Yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
ISRAEL Unnamed	LWR	600	-	1 '84	108	0	0	0	106	648
ITALY Latina	GCR	150	TNPG	1 '64	20	120	220	320	420	520
Garigliano	BWR	150	GE	6 '64	26	145	275	405	535	665
Trino Vercenese	PWR	247	W	1 '65	44	220	440	660	880	1,100
Cirene	LWCHR	40	AMN	1 '78	10	0	0	20	70	120
Enel 4	BWR	840	AMN-GETSCO	4 '76	143	0	0	536	1,271	2,006
Enel 5	PWR	952	ELECTRONUC-ITAL	1 '80	171	0	0	0	80	1,710
Enel 6	BWR	982	AMN	1 '81	167	0	0	0	668	1,503
Enel 7	PWR	1000	ELECTRONUC-ITAL	1 '81	180	0	0	0	720	1,620
Enel 8	BWR	1000	AMN	1 '81	170	0	0	0	680	1,530
					Total	485	935	1,941	6,099	10,774
JAPAN Fukushima 1	BWR	460	GE/TOSHIBA	3 '71	78	0	299	689	1,079	1,469
Fukushima 2	BWR	784	GE	3 '74	133	0	111	776	1,441	2,106
Shimane	BWR	439	HITACHI	3 '74	75	0	63	438	813	1,188
Mihama 1	PWR	320	W	1 '71	58	0	232	522	812	1,102
Mihama 2	PWR	470	MHI	7 '72	85	0	213	638	1,003	1,488
Tsuruga	BWR	340	GE	3 '70	58	0	280	570	860	1,130
Tokai 1	GCR	159	GEC	7 '66	21	74	179	284	389	494
Tokai 2	BWR	1067	GE	10 '77	181	0	0	407	1,312	2,217
Takahama 1	PWR	781	W	7 '74	141	0	71	746	1,451	2,156
Takahama 2	PWR	781	MHI	12 '75	141	0	12	717	1,422	2,127
Genkai 1	PWR	529	MHI	1 '76	95	0	0	380	855	1,330

TABLE A1
POWER REACTORS (Cont)

LOCATION	TYPE	MW _E	REACTOR SUPPLIER	START DATE ⁽¹⁾	PU PROD Kg/Yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
Ohl 1	PWR	1122	W	4 '78	202	0	0	354	1,364	2,374
Ohl 2	PWR	1122	W	10 '78	202	0	0	289	1,279	2,289
Mihama 3	PWR	781	MHI	7 '77	141	0	0	353	1,058	1,763
Fugen	LWCHR	200	HITACHI	11 '76	48	0	0	196	436	676
Ikata	PWR	566	MHI	4 '78	102	0	0	179	689	1,199
Hamaoka 1	BWR	540	TOSHIBA	6 '75	92	0	0	422	882	1,342
Hamaoka 2	BWR	840	TOSHIBA	3 '79	143	0	0	119	834	1,294
Fukushima 3	BWR	784	TOSHIBA	1 '75	133	0	0	665	1,330	1,995
Fukushima 4	BWR	784	HITACHI	6 '77	133	0	0	344	1,009	1,674
Fukushima 5	BWR	784	TOSHIBA	1 '77	133	0	0	399	1,054	1,729
Fukushima 6	BWR	1100	GE	10 '77	187	0	0	436	1,371	2,306
Monju	LMFBR	300	-	3 '78	42	0	0	74	284	494
Onagawa	BWR	500	TOSHIBA	3 '77	85	0	0	149	571	999
					Total	74	1,460	10,126	23,671	35,915
KOREA (South)										
Ko-Ri 1	PWR	564	W	4 '77 (3)	102	0	0	281	791	1,301
Ko-Ri 2	PWR	600	W	1 '82 (3)	108	0	0	0	324	864
Nae-Po 1	PHWR	600	AECL	1 '82	132	0	0	0	396	1,056
Nae-Po 2	PHWR	600	AECL	1 '83	132	0	0	0	264	924
Chang-Yung 1	-	800	-	1 '84	176	0	0	0	176	1,056
Chang-Yung 2	-	800	-	1 '85	176	0	0	0	0	880
					Total	0	0	281	1,951	6,081
MEXICO										
Laguna Verde 1	BWR	654	GE	7 '79	111	0	0	56	611	1,176
Laguna Verde 2	BWR	654	GE	7 '80	111	0	0	0	500	1,055
					Total	0	0	56	1,111	2,221
NETHERLANDS										
Dordrecht	BWR	55	GE/GKN	3 '69	9	8	53	98	143	188
Borssele	PWR	477	KWU	10 '73	86	0	100	530	960	1,390
					Total	8	153	628	1,103	1,578
PAKISTAN										
Kanupp	PHWR	125	CGE	10 '72	28	0	61	201	341	431
Chasma-Barrage	-	600	-	1 '83	132	0	0	0	264	924
					Total	0	61	201	605	1,403

TABLE A1
POWER REACTORS (Cont)

LOCATION	TYPE	MW _e	REACTOR SUPPLIER	START DATE (1)	PU PROD Kt/Yr	Separable Fissile Pu Accumulated (kg) Through			
						69	74	79	84
PHILIPPINES	PWR	626	W	1/84	113	0	0	0	113
	PWR	626	W	1/84	113	0	0	0	113
					Total	0	0	0	226
PORTUGAL	LWR	600	-	1/83	108	0	0	0	216
	LWR	600	-	1/85	108	0	0	0	0
					Total	0	0	0	216
ROMANIA	PWR	440	AEA	1/81	79	0	0	0	316
						0	0	0	711
SOUTH AFRICA	LWR	960	-	1/83	171	0	0	0	342
	LWR	960	-	1/84	171	0	0	0	171
					Total	0	0	0	513
SPAIN	BWR	440	GE	3/71	75	0	281	656	1,031
	GCR	480	GC	7/72	02	0	155	485	775
	PWR	153	W	8/69	28	12	152	292	432
	PWR	900	W	7/78	162	0	0	243	1,053
	PWR	900	W	1/80	162	0	0	0	810
	PWR	900	W	1/78	102	0	0	321	1,314
	PWR	900	W	1/79	102	0	0	162	972
	BWR	930	GE	8/79	158	0	0	66	856
	PWR	901	W	1/78	162	0	0	324	1,134
	PWR	901	W	7/79	162	0	0	81	891
	BWR	930	GE	1/82	158	0	0	0	474
					Total	12	588	2,813	4,502
YUGOSLAVIA	PWR	615	W	1/80	111	0	0	0	555
						0	0	0	1,110
SWEDEN	BWR	440	ASEA-ATOM	2/72	75	0	212	587	962
	BWR	380	"	1/75	99	0	0	495	930
	BWR	760	"	2/75	129	0	0	634	1,273
	PWR	809	W	2/75	146	0	0	718	1,448
	PWR	900	W	1/79	102	0	0	162	972
	PWR	900	W	7/80	162	0	0	0	729
	BWR	590	ASEA-ATOM	7/76	99	0	0	347	842
						0	0	0	1,337

TABLE A1
POWER REACTORS (Cont)

LOCATION	TYPE	MW _e	REACTOR SUPPLIER	START DATE ⁽¹⁾	PU PROD Kg Yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
Barstbeck 2	BWR	580	"	7/78	99	0	0	149	644	1,139
Forsmark 1	BWR	900	"	7/73	153	0	0	77	842	1,607
Forsmark 2	BWR	900	"	7/81	153	0	0	0	536	1,301
					Total	0	212	3,169	9,244	15,729
SWITZERLAND										
Bernau 1	PWR	350	W	12/69	63	5	320	635	950	1,265
Bernau 2	PWR	350	W	3/72	63	0	178	493	808	1,123
Mühleberg	BWR	306	GETSCO	10/72	55	0	124	349	574	799
Georgen	PWR	920	KWU	11/78	166	0	0	194	1,024	1,854
Graben	PWR	1140	GETSCO	1/81	194	0	0	0	970	1,940
Lellistadt	BWR	940	"	1/80	160	0	0	0	800	1,000
Kaiserstuhl	BWR	924	"	1/81	157	0	0	0	628	1,413
Roth	-	900	-	1/81	153	0	0	0	412	1,377
					Total	5	622	1,671	6,366	11,371
TAIWAN										
Chin-Shan 1	BWR	604	GE	1/78	103	0	0	208	721	1,236
Chin-Shan 2	BWR	604	"	1/79	103	0	0	0	103	518
Kuosheng 1	BWR	951	"	4/82	162	0	0	0	446	1,255
Kuosheng 2	BWR	951	"	4/83	162	0	0	0	264	1,064
Nr. 5	PWR	907	W	4/83	163	0	0	0	285	1,099
Nr. 6	PWR	907	W	4/84	163	0	0	0	122	937
					Total	0	0	206	1,971	5,241
					TOTAL	1,020	8,000	38,993	121,031	229,217

NOTES

1. The separable fissile Pu (²³⁹Pu + ²⁴¹Pu) production per year is based on Ref. 34 (Feb. 1974) for reactors in equilibrium in terms of the uranium fuel cycle. (See Table 7B) Annual fissile Pu production is assumed to be (in Kg Pu MW_e Yr): 0.17 for BWR, 0.18 for PWR, 0.22 for Heavy Water Reactor and 0.13 for GCR. A load factor of 75% is included. Power reactors which will become operational after 1985 are excluded.

2. The accumulated separable fissile Pu is calculated from the actual start-up date for operational reactors. For reactors which are in the initial stage of construction, or are in the planning stage, approximately two year delay from the announced official date of the start of commercial operation is assumed for countries in Latin America and Asia. Similarly, one year delay is assumed for Japan, Canada, Europe and South Africa. The column "start date" reflects these assumptions unless specific information was provided to warrant a change.

3. Type of reactor assumed.

4. Based on private communications from KAERI president to A. Wohlstetter, June 1975.

Reference: "World List of Nuclear Power Plants" Nuclear News Buyers Guide 1975, Vol. 18 Number 3, pp. 45-56, Mid Feb. 1975.

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TABLE A2

RESEARCH REACTORS ≥ 1 MW (t)

Location	Type	MW th	Operating Date	Fuel	Pu Prod kg/yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
Argentina RA-3	Tank	8	5/67							
Australia HIFAR	Tank, D ₂ O	10	1/58	Nat. U	0.7	8.4	11.9	15.4	18.9	22.4
Austria ASTRA	Pool	12	9/60	Enr. U						
Belgium BR-1 BR-2	(CCR) Tank	4 100	5/56 7/61	Nat. U	0.2	2.7	3.7	4.7	5.7	6.7
Brazil ISAR-1	Pool	5	9/57	Enr. U						
Bulgaria IRT	Pool	1	8/61	Enr. U						
Canada NRX NRU MINR WR-1	Tank, D ₂ O Tank, D ₂ O Pool HW, Organic	33 110 2 60	7/47 11/57 2/59 11/65	Nat. U Nat. U Enr. U Nat. U	2.2 7.3 4.0 TOTALS	49.5 87.6 16.0 153.1	60.5 124.1 36.0 220.6	71.5 160.6 56.0 288.1	82.5 197.1 76.0 355.6	93.5 233.6 96.0 423.1
Chile CNEN	Pool	5	/73	Enr. U						
Czechoslovakia VVR-S	Tank	4	9/57	Enr. U						
Denmark DR-2 DR-3	Pool Tank, D ₂ O	5 10	12/58 1/60	Enr. U Nat. U	0.66	6.6	9.9	13.2	16.5	19.8

TABLE A2
RESEARCH REACTORS ≥ 1 MW(t) (Cont)

Location	Type	MW(t)	Operating Date	Fuel	Pu Prod kg/yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
Egypt WWR-C	Tank	2	7/61	Enr. U						
Germany, Fed. Rep. FRM	Pool	4	5/68							
FRG-1	Pool	5	10/58							
FR-2	Tank, D ₂ O	44	7/66	Nat. U	2.9	10.2	24.7	39.2	53.7	68.2
FRJ-1	Pool	10	11/71							
FRJ-2	Tank, D ₂ O	23	12/67	Nat. U	1.5	9.0	10.5	18.0	25.5	33.0
FRG-2	Pool	15	2/68							
FMRB	Pool	1	10/67							
FRN	Pool	1	8/72	U-235						
BER-2	Pool	5	12/73		TOTALS	13.2	35.2	57.2	79.2	101.2
Greece Democritus (GRR)	Pool	5	7/61	Enr. U						
Hungary WWR-C	Tank	2	3/59	Enr. U						
India APSARA	Pool	1	8/56	Enr. U						
CIRUS	Tank, D ₂ O	40	7/60	Nat. U	2.64	23.1	38.3	51.5	64.7	77.9
FBTR (C)	FBR	50	/75 ?	Thor	(7, U233)					
Iran UTRR	Pool	5	11/67	Enr. U						
Iraq WWR-C	Tank	2	1/63	Enr. U						
Israel IRR-1	Pool	5	6/60	Enr. U						
IRR-2	Tank, D ₂ O	26	12/63	Nat. U	1.7	10.2	18.7	27.2	35.7	39.2

TABLE A2
RESEARCH REACTORS ≥ 1 MW (t) (Cont)

Location	Type	MW th	Operating Date	Fuel	Pu Prod kg/yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
Italy ISPRA-1 ANOCARDO RS-1 RC-1	Tank, D ₂ O Pool	5	3/59	Nat. U	0.33	3.8	5.2	6.9	8.5	10.2
	U-ZrH	7	9/59	Enr. U 90%						
	Pool	1	6/60	Enr. U 20%						
	Pool	5	4/63	Enr. U 90%						
	D ₂ O, Organic Fast	40	3/67	Nat. U	2.64	7.5	20.7	33.9	47.1	60.3
Japan JRR-2 JRR-3 KUR JRR-4 JMTR JOYO (C)	Fast	130		33% ¹ /UO ₂						
	Tank, D ₂ O	10	10/60	Nat. U	0.66	6.1	9.4	12.7	16.0	19.3
	Tank, D ₂ O	10	9/62	Nat. U	0.66	4.8	8.1	11.4	14.7	18.0
	Tank, D ₂ O	5	6/64	Nat. U						
	Pool	25	1/65	Enr. U						
Mexico RCN	Tank	50	3/68		2.4					
	Fast	50	75		TOTALS	10.9	17.5	24.1	30.7	37.3
	Pool, U-ZrH	1	11/68	Enr. U						
	Tank	45	11/61							
	Pool	2	4/63							
Netherlands HFR IIOR KSTR	Aqu. Homog.	1	4/74							
	Tank, D ₂ O	25	6/59	Nat. U	1.65	17.5	25.7	34.0	42.2	50.5
	Tank, D ₂ O	2	12/66	Nat. U	0.13	0.4	0.8	1.2	1.7	2.1
					TOTALS	17.9	26.5	35.2	43.9	52.6
Norway HBWR JEEP-2	Pool	5	12/65	Enr. U						
	Pool	1	8/63							
Pakistan PARR										
Philippines PIRR-1										

TABLE A2
RESEARCH REACTORS ≥ 1 MW (t) (Cont)

Location	Type	MW _{th}	Operating Date	Fuel	Pu Prod kg/yr	Separable Fissile Pu Accumulated (kg) Through				
						69	74	79	84	89
Poland										
EWA	Tank	10	1/58	Nat. U	0.66					
MARIA (C)	Pool	30	Unknown	Enr. U					17.8	21.1
Portugal										
RPI	Pool	1	4/61	Enr. U						
Romania										
WWK	Tank	3	7/57	Enr. U						
(Super Triga)	Tank	14	77	Enr. U-90% (60 kg)						
South Africa										
SAFARI-1	Tank	20	3.65	Nat. U						
Spain										
JEN-1	Pool	3	10/58	Enr. U						
Sweden										
R-2	Tank	50	5/60	Nat. U	3.3	31.9	48.4	64.9	81.4	97.9
Switzerland										
SAPHIR	Pool	5	4/57	Enr. U						
DORIT	HW	20	8/60	Nat. U	1.32	12.4	19.0	25.6	32.2	38.8
Thailand										
TTR-1	Pool	1	10/62	Enr. U						
Turkey										
TR-1	Pool	1	1/62	Enr. U						
Uruguay										
RUDI	Pool	1	73	Enr. U						

TABLE A2
RESEARCH REACTORS ≥ 1 MW (t) (Cont)

Location	Type	MW th	Operating Date	Fuel	Pu Prod kg/yr.	Separable Fissile Pu Accumulated (kg) Through			
						69	74	79	84
Venezuela RV-1	Pool	3	10/65	Enr. U					
Yugoslavia R-A	Tank, D ₂ O	10	12/59	Nat. U	0.66	6.6	9.9	13.2	16.5
Zaire TRICO	Tank, U-ZrH	1	72						
Taiwan TRR	LWCHWR	40	1/73	Nat. U	2.64	0	5.3	18.5	31.7
									45.0

Notes: The separable fissile Pu ($^{239}\text{Pu} + ^{241}\text{Pu}$) production per year is based on Ref. 34 for reactors in uranium fuel-cycle equilibrium. Annual fissile Pu production is assumed to be (in Kg Pu/MWth/yr) 0.058 for BWR, 0.059 for PWR, 0.066 for HWR and 0.055 for GCR. These values are valid for 75% load factor. The Pu production in an HWR including the first loading is 0.066 Kg Pu/MWth/yr.

Reference: Power and Research Reactors in Member States 1974 Edition International Atomic Energy Agency, Vienna 1974

TABLE A3

ACCUMULATIVE SEPARABLE PLUTONIUM CONTENT
OF SPENT FUEL BASED ON ACTUAL OPERATING HISTORY
OF REACTORS THROUGH THE END OF 1974

Location	Reactor Type	Cumulative Electric Generation (MWeh)	Reactor Power (MW _E)	Accumulated Separable Fissile Pu through 1974 (Kg)
<u>Canada</u>				
NPD	PHWR	1.5×10^6	25	50
Douglas Point	PHWR	6.0×10^6	206	200
Pickering 1	PHWR	1.2×10^7	514	400
Pickering 2	PHWR	1.1×10^7	514	366
Pickering 3	PHWR	7.4×10^6	514	246
Pickering 4	PHWR	7.0×10^6	514	233
Gentilly 1	BLWHWR		250	25
			Total:	1520
<u>W. Germany</u>				
AVR (Kahl VAK)	BWR	6.1×10^5	15	16
Gundremmingen	BWR	1.3×10^7	273	341
Lingen	BWR	7.8×10^6	256	205
MZFR	PHWR	2.1×10^6	52	70
Obrigheim	PWR	1.4×10^7	328	380
Stade (1)	PWR	1.3×10^7	630	352
Wurgassen	BWR	3.1×10^6	640	82
			Total:	1446

TABLE A3 (Cont'd)

Location	Reactor Type	Cumulative Electric Generation (MWeh)	Reactor Power (MW _E)	Accumulated Separable Fissile Pu through 1974 (Kg)
<u>India</u>				
Tarapur 1	BWR	4.6×10^6	200	121
Tarapur	BWR	4.5×10^6	200	118
			Total	<u>239</u>
<u>Italy</u>				
Latina	GCR	9.8×10^6	150	194
Garigliano	BWR	1.3×10^9	150	342
Trino Vercellese	PWR	1.1×10^7	247	<u>298</u>
			Total	654
<u>Japan</u>				
Fukushima 1	BWR	8.6×10^6	380	226
Mihama 1	PWR	5.3×10^6	320	144
Mihama 2	PWR	7.6×10^6	470	206
Tsuruga	BWR	1.1×10^7	340	289
Tokai 1	GCR	7.6×10^6	159	<u>150</u>
			Total	1015
<u>Netherland</u>				
Dodewaard	BWR	2.1×10^6	55	<u>55</u>
			Total	55

TABLE A3 (Cont'd)

Location	Reactor Type	Cumulative Electric Generation (MWeh)	Reactor Power (MW _E)	Accumulated Separable Fissile Pu through 1974 (Kg)
<u>Pakistan</u>				
Kanupp	PHWR	1.3×10^6	125	<u>43</u>
			Total	43
<u>Spain</u>				
Garona	BWR	9.0×10^6	440	237
Vandellos	GCR	8.1×10^6	480	160
Jose Cabrera	PWR	5.7×10^6	153	<u>154</u>
			Total	551
<u>Sweden</u>				
Oskarshamn 1	BWR	4.9×10^6	440	129
Oskarshamn 2	BWR	4.1×10^5	580	<u>11</u>
			Total	140
<u>Switzerland</u>				
Beznau 1	PWR	9.9×10^6	350	268
Beznau 2	PWR	7.8×10^6	350	211
Muhleberg	BWR	4.9×10^6	306	<u>129</u>
			Total	608

Note: The conversion of the cumulative power generation into accumulated separable fissile Pu is based on Ref. 34. The conversion factors for reactors in equilibrium-uranium-fuel-cycle are:
 2.63×10^{-5} Kg Pu/MWeh for BWR, 2.71×10^{-5} Kg Pu/MWeh for PWR, 3.33×10^{-5} Kg Pu/MWeh for HWR and 1.98×10^{-5} Kg Pu/MWeh for AGR and GCR.

TABLE A4
NUCLEAR FUEL REPROCESSING PLANTS

Country	Type of Fuel	Start of Operation	Feed Capacity (Tonne U/yr)	Pu Product/yr. ^(a) at Capacity (kg)	Comments
Argentina ⁽¹⁾		1968 ⁽⁵⁾	200 kg/yr	---	167 tonnes U have been processed
Belgium (Mol) ⁽⁴⁾	Metal/LWR		80	516 (1077) ^(c)	Eurochemic is not expected to process any more fuel
Eurochemic	MTR ^(b)	1966	40	---	French military and civilian reactors
France ⁽⁴⁾		1958	500	2150	Will increase production gradually until 1978
Marcoule	Metal	1975/78	400	2580	32 tonnes U have been processed
La Hague	LWR				
Germany ⁽⁴⁾		Sept 1971	36	232 (206)	
WAK, Karlsruhe	LWR	1983/84	1400	9030	
KEWA	LWR				
India ⁽¹⁾		1967	100	230	
Trombay	HWR		150	968	Assume all LWR fuel
Tarapur	HWR & LWR				
Italy ⁽⁴⁾		1970	5	---	
Eurex 1	MTR	1975	10	64	
Japan ⁽²⁾	LWR				
Tokai-Mura	LWR & Nat U	1976	200	1290	Assume all LWR fuel
Spain ⁽¹⁾					
Moncla					
Taiwan ⁽³⁾	MTR		100 kg/yr	---	Small pilot plant

TABLE A4
NUCLEAR FUEL REPROCESSING PLANTS (Cont)

Country	Type of Fuel	Start of Operation	Feed Capacity (Tonne U/yr)	Pu Product/yr (a) at Capacity (kg)	Comments
United Kingdom ⁽⁴⁾ Windscale 1 Windscale 2	Metal Nat U	1964	2500	10, 750	Shut down 1973 after processing 100 Te will restart 1976 at 200 Te/yr and 1977 400 Te/yr
	LWR	1970(76)	400	2580 (645)	
Downreay ⁽¹⁾	Highly Enriched U and Pu	1982	400	2580	
			1	---	

(a) For LWR fuel we use an average production rate between PWR and BWR fuel. We assume a mature fuel cycle which produces 6.45 kg of fissile plutonium per tonne of uranium reprocessed. Heavy Water Reactor (HWR) fuel is assumed to have an average recovery of 2.3 kg Pu/TeU. Metal Fueled Reactors (that are used for power production) are assumed to produce 4.3 kg of fissile Pu per tonne of uranium.

(b) MTR - Materials Test Reactor uranium aluminum alloy fuel. Usually enriched to 20% or higher in ²³⁵U, normally produces very little Pu.

(c) Assumes all 167 tonnes of uranium that have been processed were LWR fuel.

Reprocessing References

1. The Nuclear Industry, 1970, p 264.
2. Nuclear Engineering International, February 1955, page 82, World Digest.
3. Epstein, William, "The Proliferation of Nuclear Weapons", Scientific American, Vol. 232, Number 4, April 1975, p 18.
4. Schuller, Walter, "Reprocessing in Europe", ANS/CNA Joint Topical Meeting on Commercial Nuclear Fuel Technology Today, April 28-30, 1975, Toronto, Canada.
5. Science Vol. 184, No. 4144, p. 1315, June 28, 1974.

TABLE A5
ANNOUNCED FOREIGN ENRICHMENT FACILITIES

Country	Type	Capacity kg SWU/yr	Start Up	90% Enriched U/yr (kg)	Comments
France Pierrelatte (7)	Gaseous Diff. Gaseous Diff.	4-500,000 9,500,000	1958 1981	1,586-1,982 37,668	Military Plant Eurodif Plant
Germany (FRG) G/K (3) Steag (3) Urenco (1)	Nozzle Nozzle Centrifuge	2,000 25,000	1967 1974 1974	7.9 99	At Karlsruhe Karlsruhe Production Prototype Centrifuge on Dutch Territory (Prototype)
Japan (2) PNC PNC PNC	Centrifuge Centrifuge Centrifuge	180 Machines 250 Machines 10,000 Machines	August 1974 Early 1975 1978	≈3.5 ≈5.0 ≈200	Experimental Cascade Experimental Cascade
Netherlands (1)	Centrifuge Centrifuge	25,000 200,000	Early 1974 1977?	99 793	Prototype for Urenco/Centec
South Africa (4) Prototype	Nozzle? Nozzle?	5,000,000	April 5, 1975 1984	19,825	
United Kingdom (5) Capenhurst (1) Urenco	Gaseous Diff. Centrifuge Centrifuge	400,000 25,000 200,000	Early 1974 1977?	1,586 99 783	Military Plant Prototype at Capenhurst

1. David Smith "What Price Commercial Enrichment?" Nuclear Engineering International, July 1974, p 572.

2. World Digest Nuclear Engineering International, February 1975, p 81.

3. Robert Gillette "Nozzle Enrichment for Sale" Science Vol. 188, No. 4191, p 912, May 30, 1975

4. Nuclear News, Vol. 18, No. 8, p 75, June 1975.

5. Vincent V. Abagian and Alan M. Fishman, "Supplying Enriched Uranium", Physics Today, p 23, August 1973.

6. Based on a 0.2% tails assay.

7. H. L. Dreissigacker "Expected Development for Enriching Uranium in Europe" presented at the DFVLR Colloquium, Porz-Wahn, Germany, May 14, 1970 and British Translation (Capenhurst Translation 249), issued by the U. S. AEC as CONF-700557-2.

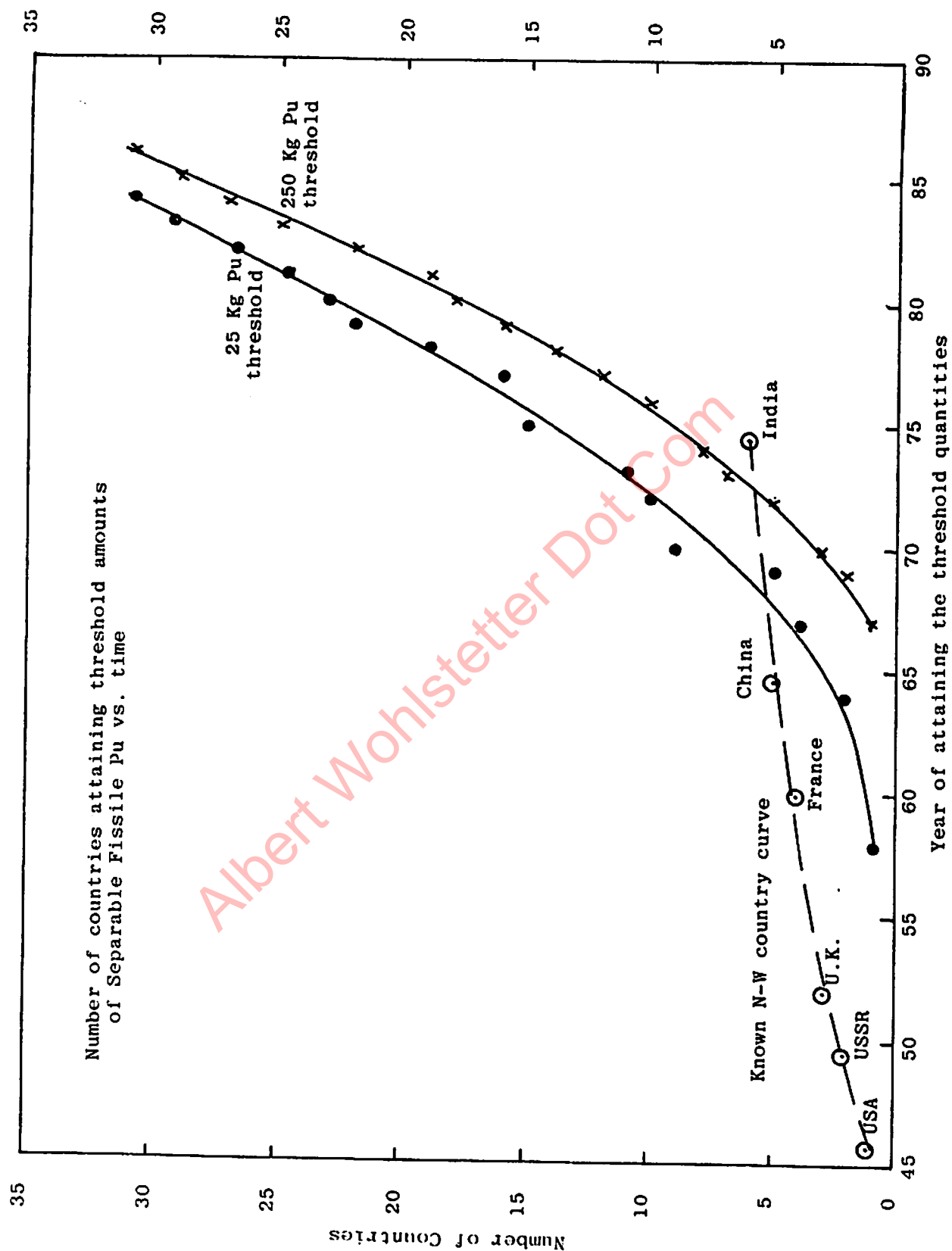


Figure A1. Countries With Accumulated Fissile Plutonium

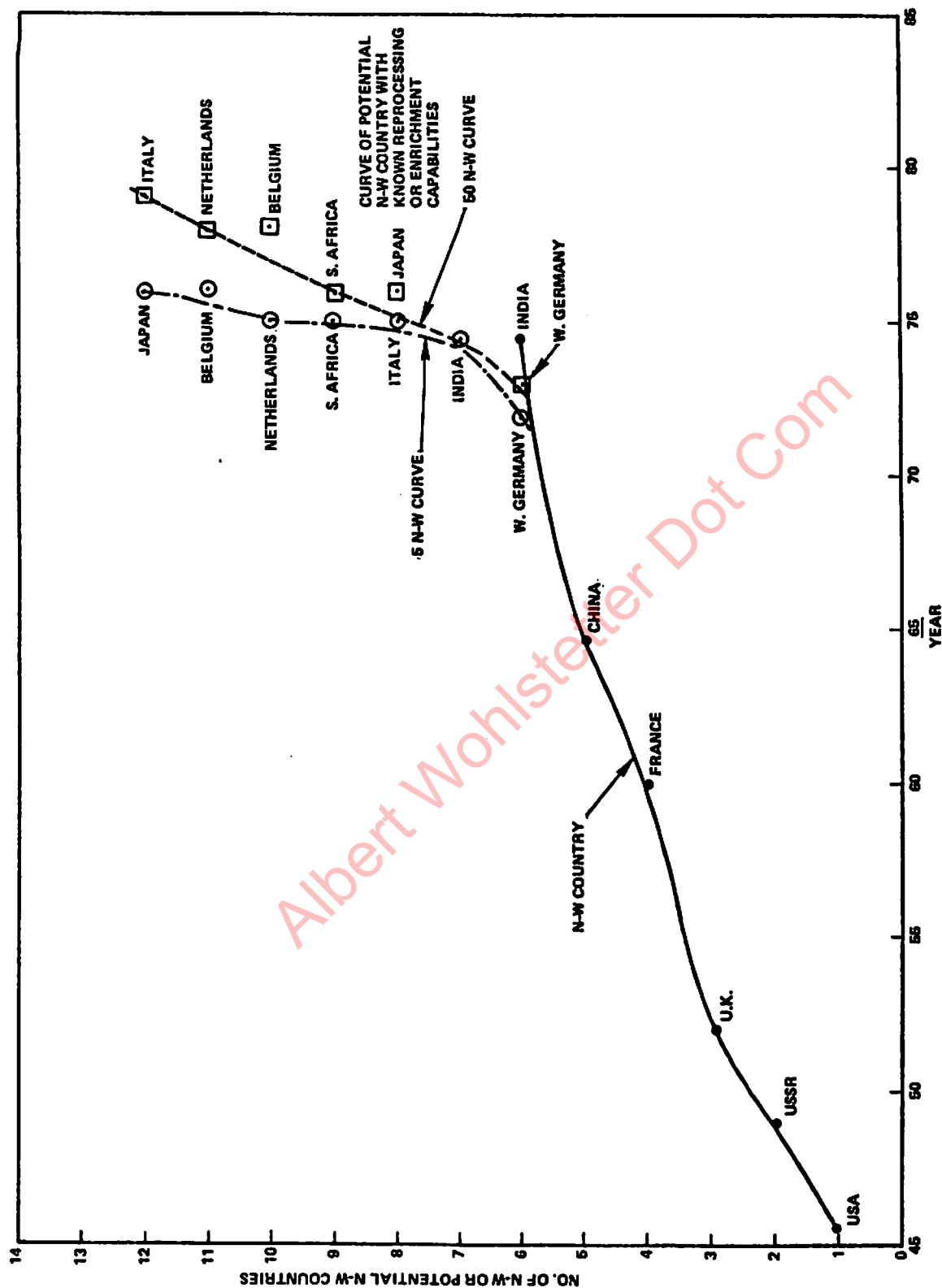


Figure A2. Countries With Enrichment or Reprocessing Capacity to Produce 5 N-W and 50 N-W's.

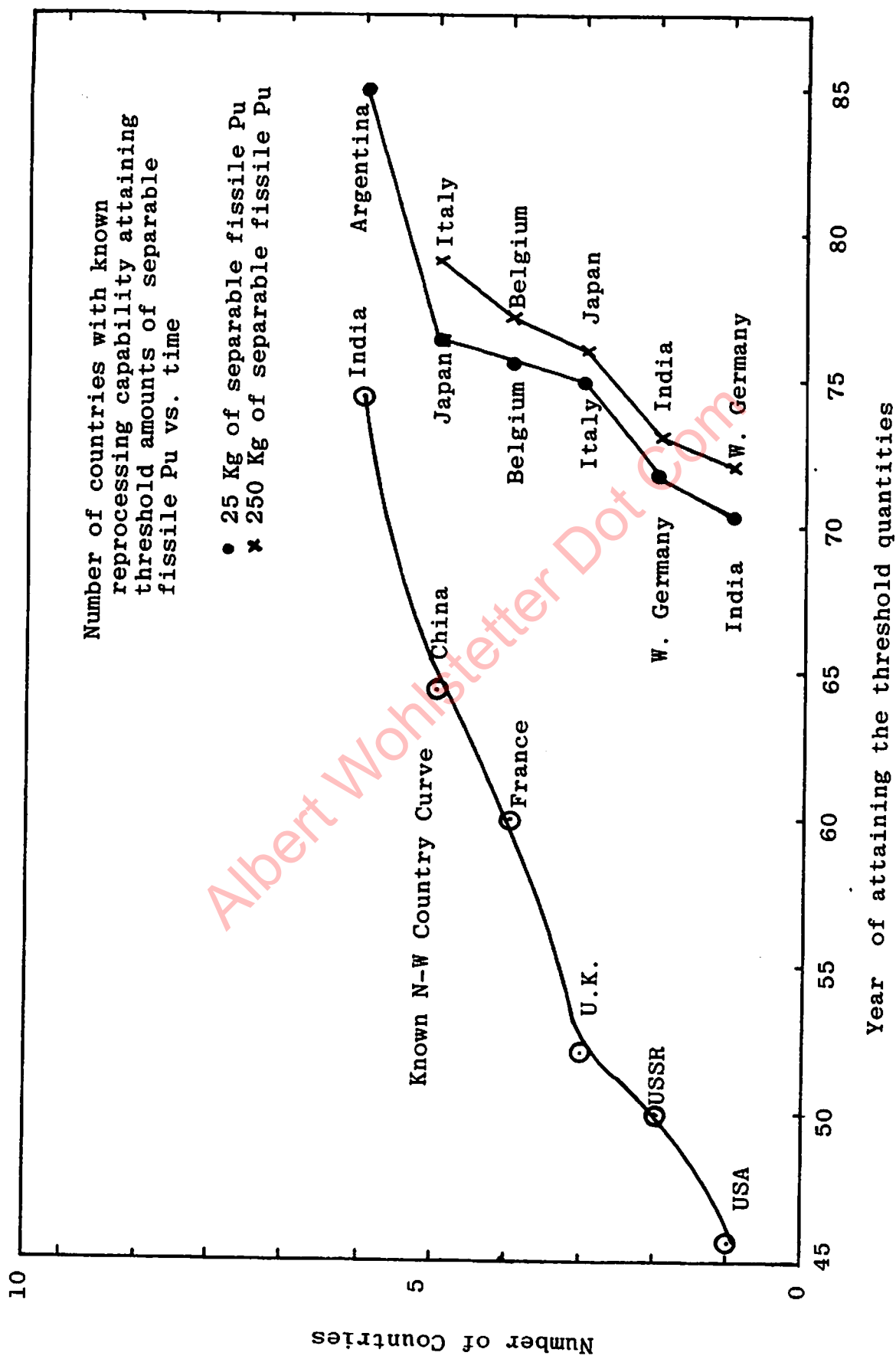


Figure A3. Countries with Reprocessing Capacity to Produce 5 and 50 N-W's.

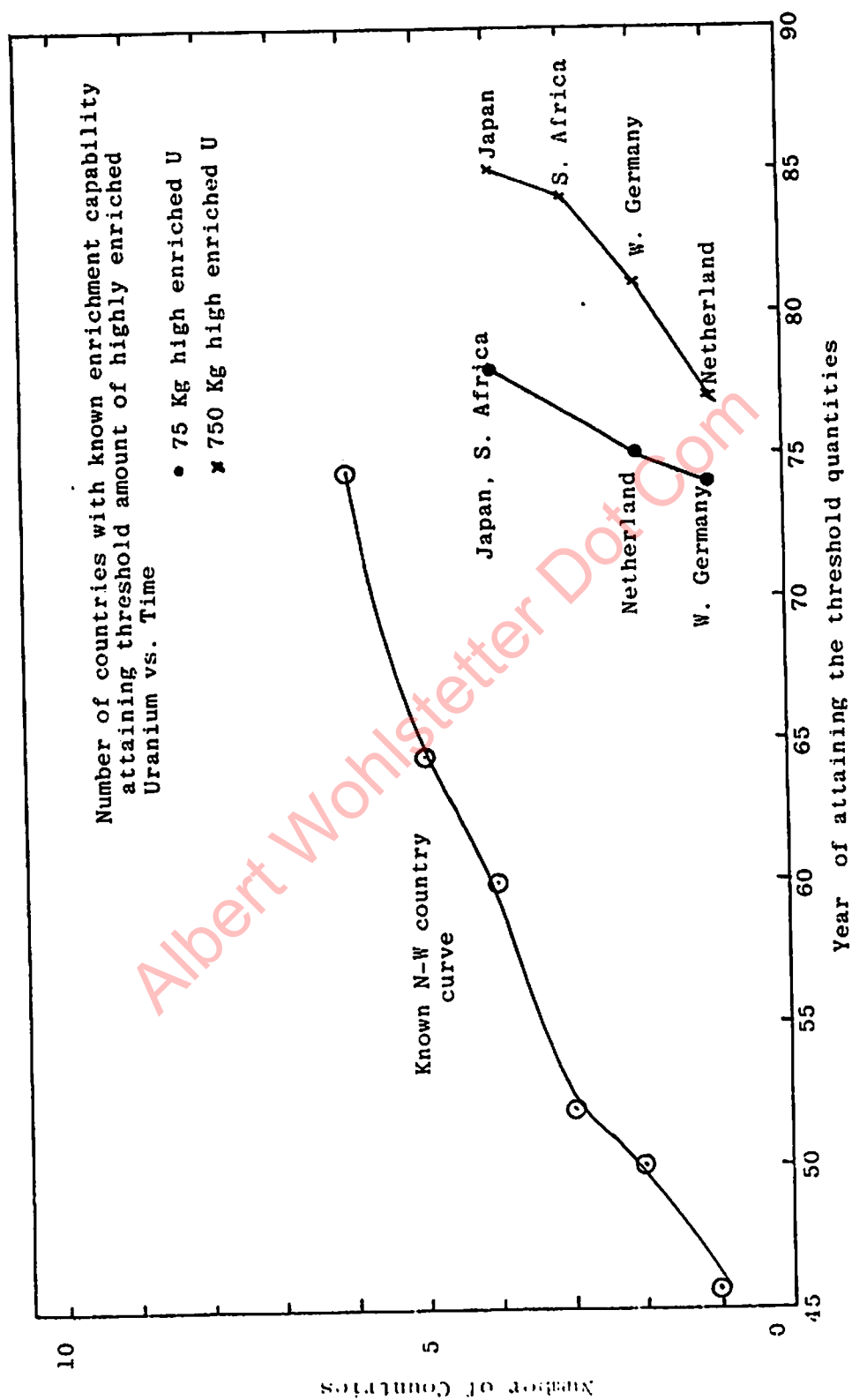


Figure A3. Modified

SUBAPPENDIX 4B: HTGR FUEL

A few descriptive technical details on the General Atomic Company HTGR are pertinent to a discussion on paths to a nuclear weapon capability. The uranium used in the initial core and in subsequent core loads (until HTGR reprocessing and recycling become viable) is enriched to 93% in ^{235}U . This is, of course, ideal weapon material. Any country possessing significant quantities of the highly enriched ^{235}U could proceed relatively quick to nuclear weapon fabrication. The situation is not so simple after the highly enriched uranium goes through the fuel fabrication process.

The main features of the High Temperature Gas-cooled Reactor (HTGR) are high temperature operation; gas coolant; graphite moderator and reflector; highly enriched uranium (^{235}U and/or ^{233}U) thorium fuel cycle; homogeneous fuel with graphite structure, cladding, and fuel diluent; and fission-product control.

There are a number of inherent physics features of the HTGR that might be considered as relative assets when compared with light water reactors. Among these features are the overall plant efficiency (roughly 40% versus 33% for LWRs), the inherent stability of the HTGR, and the thermal integrity of the core. Relative liabilities of the HTGR include the high (and uncertain) capital cost of the reactor, the increased safeguards liability associated with highly enriched uranium, and the paucity of cost, engineering, and operating data for HTGRs. At the present time the HTGR position in the U.S. and World Nuclear power market is highly uncertain.

The largest HTGR constructed in the U.S. is the Fort St. Vrain Reactor. This generating plant (330 MWe) was designed to serve as a prototype for larger, truly commercial facilities of 770 MW(e) or 1160 MW(e). The total initial fissile loading for this reactor includes 1,020 kg of ^{235}U . HTGR fuel is designed to have a four year residency time with an equilibrium annual loading of 219 kg of ^{235}U for Fort St. Vrain. A 770 MW(e) design requires approximately 1.8 times as much fissile material.

The basic fuel elements of an HTGR reactor consist of a graphite block (which serves as the reactor moderator). This is 79.3 cms high with hexagonal cross section that is 35.9 cm across the flats. The graphite block is drilled lengthwise with two sets of holes: one to allow the passage of helium coolant, the second to contain fuel rods. Fuel rods are formed by the molding of selected blends of fuel particles with a graphitic pitch; each fuel rod is 5.1 cm in length and has a diameter of 1.58 cm. Fuel particles which are the basic material for the rods and elements are shown schematically in Figure B1. These fuel particles have a core of either uranium dicarbide (highly enriched in ^{235}U or recycle ^{233}U) or ThO_2 . Particle diameters are 500-800 μm .

All future HTGRs will use two particle types as shown in Figure B1, which are categorized by the coatings which have been applied to them. Particles are classified as BISO or TRISO coated particles. BISO particles are coated with a relatively porous buffer layer of carbon and then with a dense coating of pyrolytic carbon. TRISO coatings, in addition, have a silicon carbide coating placed between two layers of pyrolytic carbon. BISO coatings are used for particles initially loaded with ThO_2 while TRISO coatings are used for particles loaded with uranium.

To make strategic special nuclear material out of HTGR material the fuel elements would most likely have to be reduced to at least the uranium carbide pit of the fuel particle. Even assuming a uranium carbide weapon would work, it would not be as effective as a weapon constructed out of uranium metal.

The initial or head-end steps of the HTGR fuel reprocessing flowsheet include size reduction, or crushing, burning to eliminate the graphitic moderator, classification of particle type with additional crushing or grinding as required, and dissolution in nitric acid solutions. Figure B2 shows schematically all of the reprocessing steps for cold or irradiated fuel elements. If the feed for the recovery operation begins with the fuel rods rather than the elements then possibly one of the crushing and burning operations could be eliminated. Regardless, the recovery of uranium from manufactured HTGR fuel is a significant undertaking; one that probably indicates that the country or group has the technology to reprocess any irradiated fuel.

A recent unpublished position paper(35) produced by General Atomic Company staff includes their assessment of the effort involved in recovering sufficient ^{235}U from fresh HTGR fuel elements to construct a nuclear weapon.

"It would require a technically skilled, scientifically competent and well-equipped group of 12 to 15 people with general process experience on the order of one month to recover enough U-235 from a truckload of HTGR elements. The necessary equipment for such an operation would cost nearly \$200,000, exclusive of the filtration systems, and is sufficiently specialized so that its accumulation and locale would be traceable through suitable federal investigative channels. Any attempt to fabricate recovered uranium into a weapon would, of course, require additional time, equipment and materials. It is reasonable to expect location and recovery of the material during the period required for processing. Recovery by a poorly equipped group would require at least three months, if it could be done at all. In this case, the operation would probably not be traceable as a result of unique equipment used, but the sensitivity of radiometric tech-

COATED PARTICLES

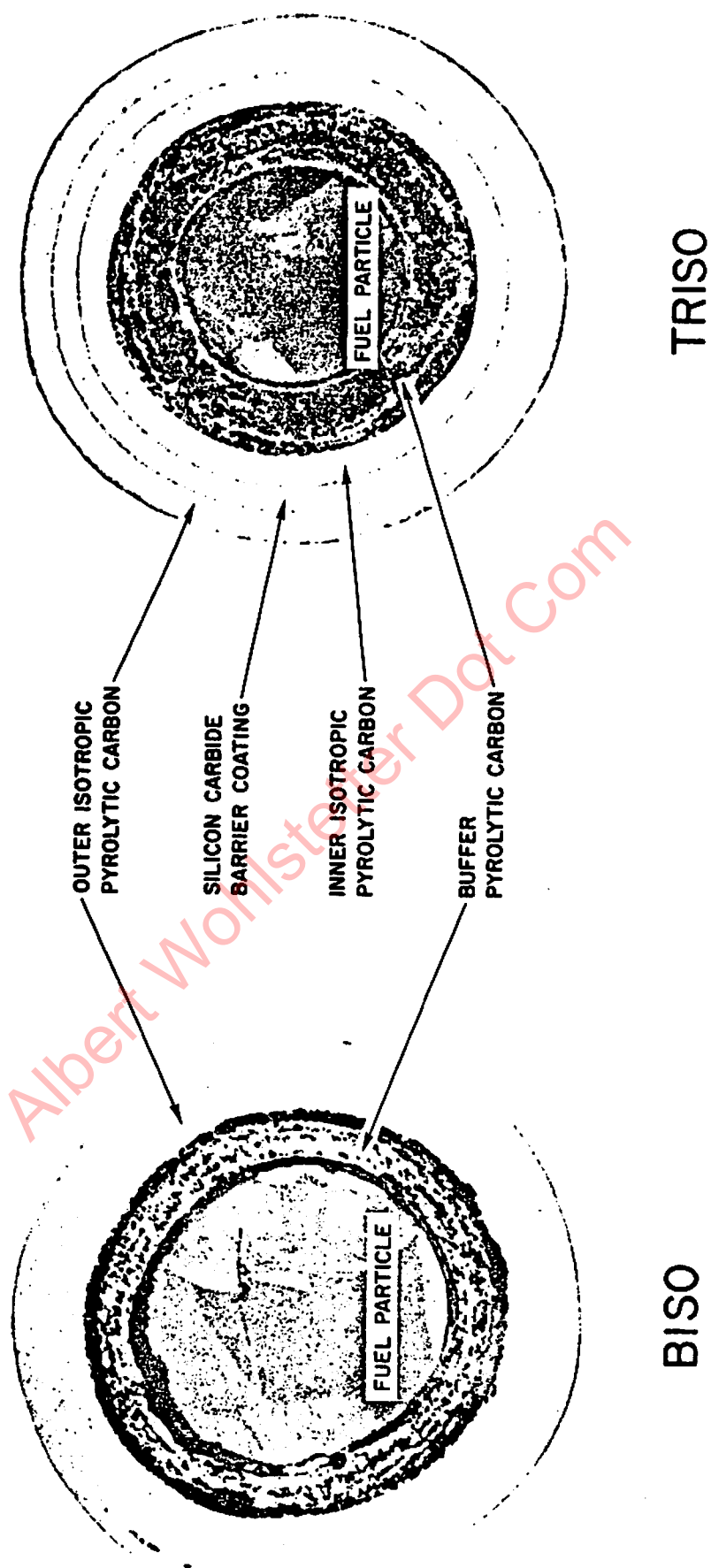


Figure B1

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niques developed for geological and radiological surveys indicates that the thorium in the truckload of fuel would be above the detection threshold for aerial survey. Intelligence work, including aerial survey as an aid, would have a good probability of detection leading to recovery during the period required for processing."

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Clearly reprocessing cold HTGR fuel to recover the fissile material is a significant technical effort. However, because of the radiation problems it is much easier to handle the cold HTGR fuel than irradiated LWR fuel. The scale of effort required to reprocess cold HTGR fuel should be compared with the scale of effort required to reprocess irradiated LWR fuel as shown on p. 231ff of this appendix.

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REPROCESSING FLOW DIAGRAM

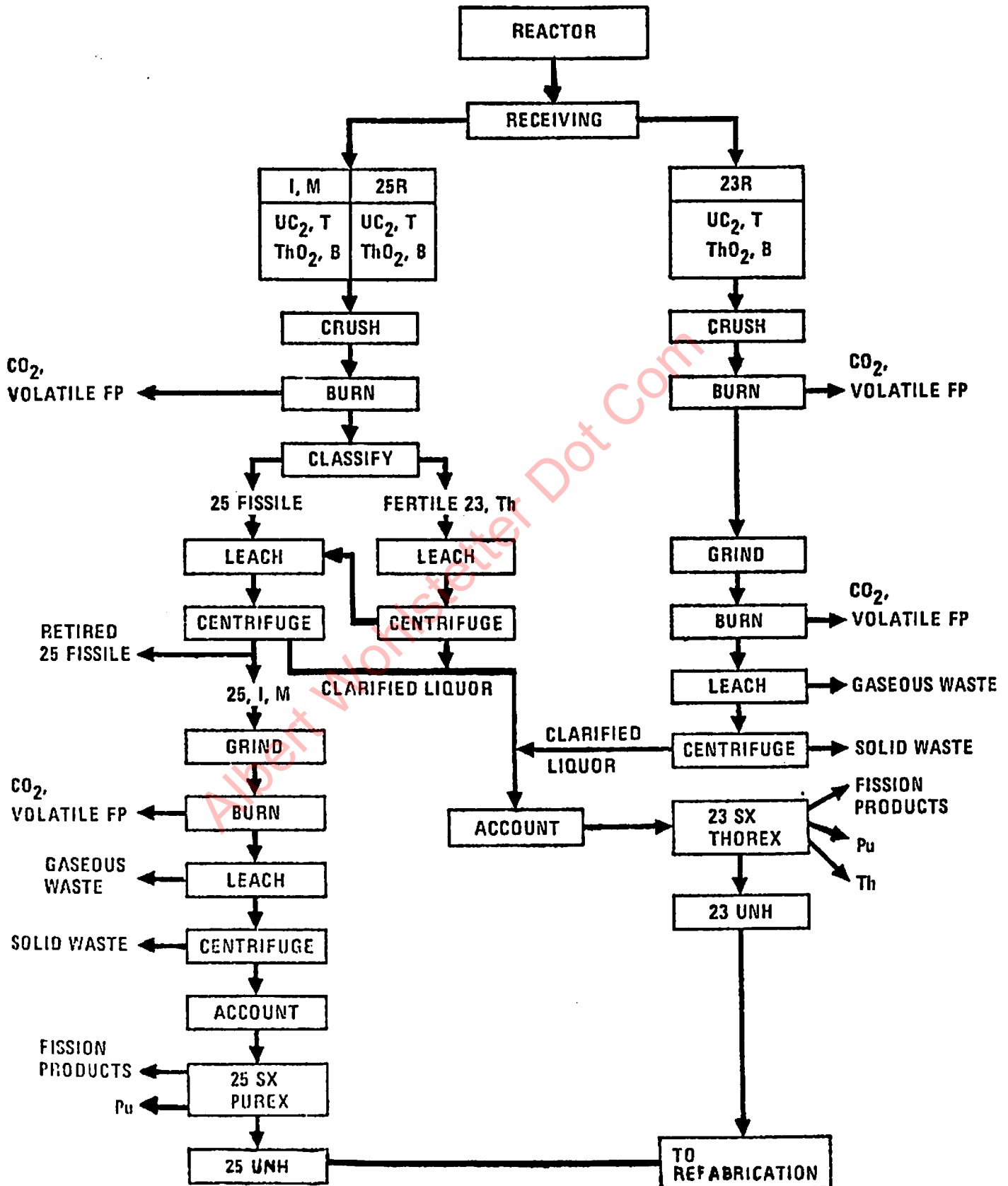


Figure B2

SUBAPPENDIX 4C: PRODUCTION REACTORS

The United States, United Kingdom, and France all followed a direct path to nuclear weapons by constructing and operating plutonium production reactors. In these reactors heat production was of secondary importance; high fissile content plutonium (weapons grade) was the main function of the reactor.

Graphite was used as the moderator in the first nuclear reactor and in the first Pu production reactors. It was a logical choice since graphite has a sufficiently low thermal neutron absorption cross section to allow the use of natural uranium as the fuel and graphite was and is available at a reasonable cost. However, reactor grade graphite must be relatively free of neutron absorbers such as boron and vanadium and should have as high a density as possible. Consequently some care must be exercised in the choice of materials and in the manufacturing process.

The amount of graphite required for the moderator and reflector of a natural uranium reactor depends somewhat on the specific design and power level of the reactor. In all cases, however, the overall dimensions and amount of graphite required are large--on the order of 600 tonnes. A minimum mass to reach criticality would be approximately 27 tonnes of natural uranium metal and 320 tonnes of graphite. The large volume is necessitated by the inferior neutron moderating properties of carbon relative to H_2O or D_2O . A typical geometry for a graphite reactor core and reflector might be a cylinder with a diameter of 37 ft and a height of 27 ft. This would then have to be surrounded by a biological shield which might be concrete 7 ft thick. A cutaway schematic of the experimental (X-10) natural uranium-graphite reactor (built and operated at Oak Ridge) is shown in Figure C1 along with the graphite stack in the X-10 reactor. The graphite stack is the moderator and the core structural material with built-in fuel channels. This simple structure with a corresponding low cost is characteristic of natural uranium-graphite reactors. The uncomplicated structure also results in relatively short construction times. The X-10 reactor was completed in November 1943--less than one year after CP-1, the first nuclear reactor, went critical on December 2, 1942. Construction on the Hanford project, which involved much larger reactors, was begun on March 22, 1943. The first of the initial three production reactors began operation on September 26, 1944 and the first plutonium was delivered on February 2, 1945.

The power level for a graphite reactor is primarily determined by the coolant. Air, pressurized CO_2 , and water have all been used as the coolant for Pu production reactors. The limiting power level for production reactors is usually the surface temperature of the aluminum fuel cladding.

Fuel elements for a production reactor have historically consisted of natural uranium metallic slugs clad in aluminum or magnesium alloys. Typical dimensions of a solid fuel slug are 1.4 inch diameter and 8 inches long. This is a convenient size for loading and reprocessing. A fuel channel contains several fuel slugs that are moved through the core to obtain the desired burnup. Each time a new fuel slug is inserted in the channel another slug falls out the other side into a discharge channel (CANDU Reactors utilize the same principle). Since the discharge channel contains light water no special precautions have to be maintained against inadvertent criticality of the natural uranium fuel elements.

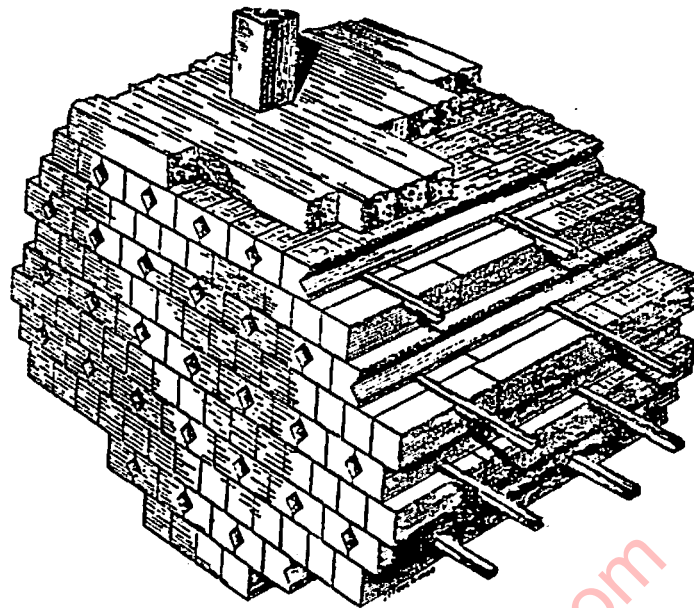
A schematic of a typical fuel slug for a production reactor is shown in Figure C2. This schematic is for a Hanford type reactor which happens to be cooled by a thin annulus of water. More modern fuel designs utilize an annular fuel slug with a central coolant hole.

The simplistic design of the fuel slug is important for the reprocessing and recovery of the plutonium from the irradiated fuel. There are two distinct advantages of production type fuel over the more complicated power reactor fuel:

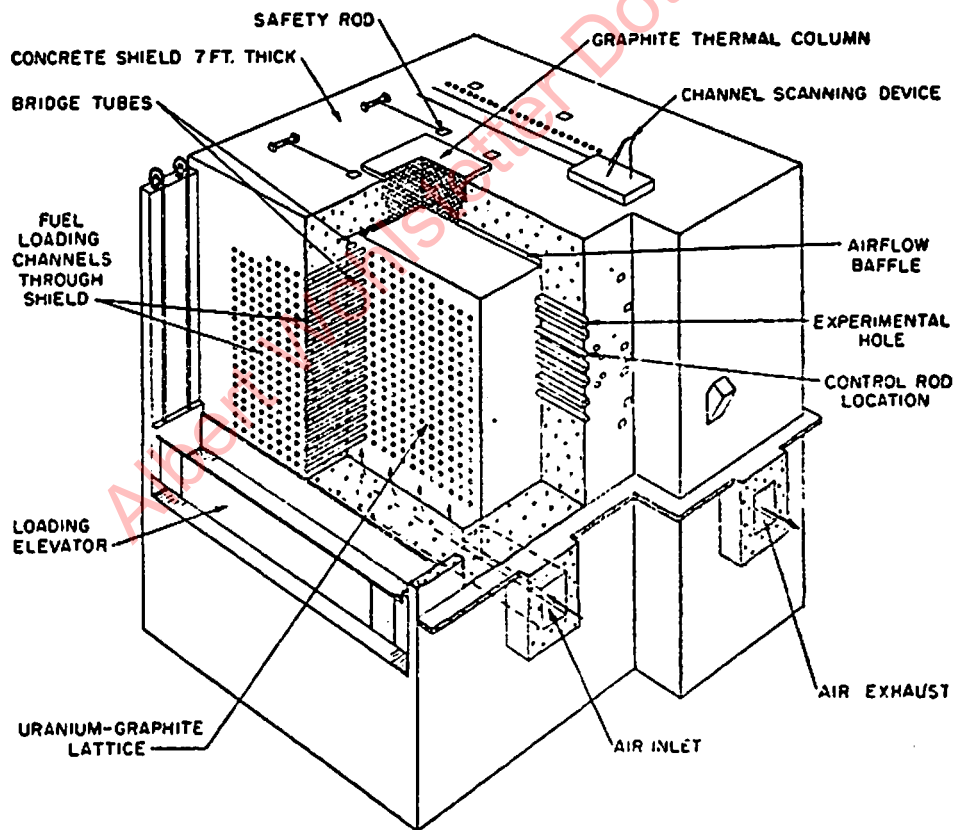
1. The fuel has a relatively low burnup 2500-4500 MWD/TU which is approximately an order of magnitude less than for LWR fuel. The resultant amount of fission products is correspondingly lower with less radioactivity and somewhat easier chemical processing.
2. The head-end portion of a reprocessing plant is much simpler for production reactor fuel. No complicated mechanical shear operation or disassembly of the individual fuel elements from an assembly is required. The aluminum cladding can be removed chemically by a caustic solution (NaOH for example) and the metallic fuel is quickly dissolved (possibly 2 to 3 times faster than oxide fuel) in nitric acid.

It appears that the direct path to plutonium production via a production reactor and associated reprocessing plant has the least total cost. Moreover, the construction time is also a minimum (assuming the wartime construction time periods can be used as a rough guide, i.e., approximately 8 months for the X-10 reactor and a 20-month period for the Hanford reactors). Design and construction time is simplified considerably by not requiring sophisticated heat exchangers and electrical generating equipment.

One large expense that can be estimated with some confidence for a production reactor is the graphite. Reactor grade graphite, machined, is roughly \$1.50 per pound which leads to a two million dollar cost for a reactor. Another large expense associated with the design of produc-



Graphite stacking in Oak Ridge reactor.



Cutaway drawing of (X-10) natural uranium-graphite reactor at Oak Ridge National Laboratory.

Figure C1

SELECTION OF REACTORS

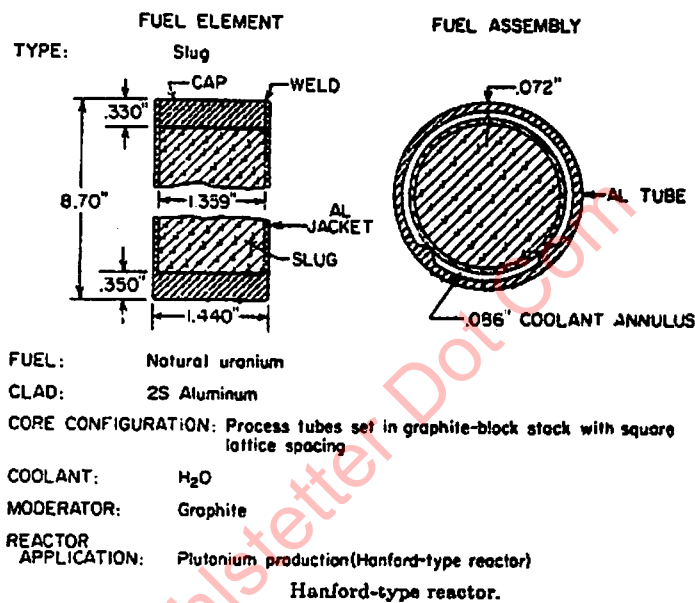


Figure C2

tion type reactors is minimized since pertinent designs are readily available in the open literature. Consequently a dedicated production reactor (a few hundred megawatts thermal power with roughly a Pu production capacity of a few weapons per year) with an associated reprocessing facility could be built in a time period of roughly two years. A generalized estimated total cost for the reactor and reprocessing facility has an inherent uncertainty so large as to be practically useless; however, our estimate is roughly \$100 million. The uncertainty could be considerably reduced if the cost estimate pertains to a specific country with a known industrial and technology base.

Detection of a covert construction and operation of a plutonium production facility is rather difficult since it is not likely that a Category 1 or 2 country would have to be dependent on another country for any critical items. The graphite and uranium could be made available in most countries. The size of the facilities is not so large as to be totally obvious or undisguisable. Some hint of a production facility might be derived from considering the overall size, the existence of tall stacks and the use of a large local water supply for cooling. Any or all of these features could be concealed with some cost penalty.

SUBAPPENDIX D: MIXED OXIDE FUEL

If plutonium is recycled in thermal reactors then mixed oxide fuel will become part of the fuel cycle for commercial nuclear power reactors. Mixed oxide fuel consists of a mixture of PuO_2 and natural UO_2 . The plutonium isotopes ^{239}Pu and ^{241}Pu are fissile materials that can be substituted for ^{235}U . This substitution is not on a one for one basis since the nuclear reaction (fission) characteristics of the Pu isotopes differ considerably from that of ^{235}U . Basically, the fissile Pu isotopes have a consistently higher fission cross section particularly at neutron energies slightly above thermal energies. This yields a propensity for high power peaking in mixed oxide rods, particularly when located adjacent to uranium rods. There are a number of other small changes in various reactor parameters that arise due to the use of plutonium fissile isotopes rather than ^{235}U . These differences are summarized in Table D1.

The consequence of these differences is that it is not likely that only Pu fissile isotopes would be burned in a thermal reactor that was originally designed for ^{235}U . A more likely situation would be that 25% of the fuel would consist of mixed oxides with the remainder the normal slightly enriched UO_2 fuel.

Incorporation of some mixed oxide fuel in an LWR core can be accomplished in several ways.

1. Island type designs are used in which the mixed oxide rods are grouped in the center region of an assembly. This is generally an option in BWRs.
2. A fuel management scheme is used where the mixed oxide fuel assemblies are not used in various control locations (PWR option).
3. The number of control rods in the core is increased (PWR option).

Several feasibility experiments have been successfully conducted to prove out the efficacy of the above schemes. Mixed oxide fuel presents new strains on safeguard procedures for civilian nuclear power plants. The recovery, storage, and transportation of plutonium is particularly vulnerable as a nuclear explosive constituent. Stringent safeguarding procedures are likely to be required for plutonium in any chemical form. The fabricated mixed oxide fuel is also somewhat more vulnerable than the slightly enriched uranium LWR fuel since only a chemical separation is required to obtain weapons grade material from the fuel rods rather than the much more complicated isotopic separation. This chemical separation on cold fuel is significantly easier than separating Pu from irradiated fuel rods. However, the task is still formidable, since at most the fissile Pu content in a mixed oxide rod is 5%. Consequently, at least 100 kg of mixed oxide fuel must be processed to obtain 5 kg of fissile Pu.

TABLE D1. CAPSULE COMPARISON OF URANIUM AND PLUTONIUM
NUCLEAR DESIGN CHARACTERISTICS*

Parameter	Plutonium Core	Reason for Difference	Consequence
Moderator Temperature Coefficient	More Negative	Increased resonance absorption and spectrum shift	Improved stability and transient characteristics except for steam break
Doppler Coefficient	More Negative	Pu-240 resonances	Improved transient characteristics
Cold-to-Hot Reactivity Swing	Increased	Larger moderator temperature coefficient	None-boron used for compensation
Installed Reactivity	Reduced	Reduced depletion rate-Reactivity saturates	None
Control Rod Requirement	Increased	Larger moderator and doppler coefficients	Possible increase in number of rods
Control Rod Worth	Reduced	Thermal flux reduced	Possible increase in number of rods
Boron Worth	Reduced	Thermal flux reduced	None
Xenon Worth	Reduced	Thermal flux reduced	Improved stability
Fission Product Poisons	Increased	Increased yields-Increased resonance absorptions	Reactivity penalty
Local Power Peaking	Increased	Increased water worth	Fuel management action required
Delayed Neutron Fraction	Reduced	$\beta_{pu} < \beta_u$	Rod ejection accident reanalysis

Qualifications:

1. Effects can be modified by changes in design H/F
2. Successive recycles influence the parameters

* Reference Richard F. Denning, "Utility Quality Assurance Provisions for Mixed Oxide Fuel," Proceedings 14th Annual Meeting Institute of Nuclear Materials Management, Inc., June 20-22, 1973, San Diego, CA, pp. 150-179.

REFERENCES

1. Draft Environmental Statement Expansion of U. S. Enrichment Capacity, ERDA 1543, June 1975.
2. L. G. Poole, "World Uranium Resources," Nuclear Engineering International, Vol. 20, No. 225, Feb. 1975, pp. 95-100.
3. "Industry Report 1974-75," Nuclear News Buyers Guide, Vol. 18, No. 3, Mid-February 1975, p. 44.
4. "Pakistan-Nuclear Programmed Stepped-Up," World Digest, Nuclear Engineering International, Vol. 19, No. 222, Nov. 1974, p. 902.
5. "Israel--More Power Stations Needed," World Digest, Nuclear Engineering International, Vol. 18, No. 204, May 1973, p. 391.
6. "Bolivia--Plan Exploration Deal," International, Nuclear News, No. 17, Sept. 1974, p. 74.
7. "International Briefs," Nuclear News, Vol. 17, No. 10, Aug. 1974, p. 63.
8. Vincent V. Abagian and Alan M. Fishman, "Supplying Enriched Uranium," Physics Today, Vol. 26, Aug. 1973, pp. 23-29.
9. "Iran to Participate in Eurodif Project," International, Nuclear News, Vol. 18, No. 2, Feb. 1975, p. 31.
10. M. Y. el Baroudi and P.A.T. Keeping, "A Canadian Initiative in the Uranium Enrichment Field," Nuclear Engineering International, Vol. 19, No. 217, June 1974, pp. 508-510.
11. G. Zippe, "The Development of Short Bowl Ultracentrifuges," Research Laboratories for the Engineering Sciences, University of Virginia, 15 June 1960.
12. David Smith, "What Price Commercial Enrichment?," Nuclear Engineering International, Vol. 19, No. 218, July 1974, p. 582.
13. "Japan--Centrifuge, Good Progress," World Digest, Nuclear Engineering International, Vol. 20, No. 225, Feb. 1975, p. 81.
14. "Japan--Centrifuge Work Started," World Digest, Nuclear Engineering International, Vol. 20, No. 224, Jan. 1975, p. 12.

15. H. Barriot, et al., "The Plutonium Fuel Penalty, Design and Production," ANS/CNA Topical Meeting on Commercial Nuclear Fuel Technology Today, April 1975.
16. "Argentina--Plan Uranium Oxide Plant," International, Nuclear News, Vol. 17, No. 9, July 1974, p. 63.
17. Private communication.
18. Survey of Canada, Nuclear Engineering International, Vol. 19, No. 217, June 1974.
19. "Developing Countries--Oil Costs Give Edge to Smaller Plants," Nuclear News, Vol. 17, No. 8, June 1974, pp. 88-89.
20. Dick Kovon, "Developing Worlds Need for Nuclear," Nuclear Engineering International, Vol. 20, No. 224, Jan. 1975, pp. 38-42.
21. "Technical Survey No. 13--Nuclear Pipework and Special Tubular Components," Nuclear Engineering International, Vol. 19, No. 213, Feb. 1974, pp. 98-101.
22. J. H. Pelladino, et al., "Technicians, Technologists and Engineers for Nuclear Power," Fourth International Atoms for Peace Conference, Paper 6.3-1, Geneva, Switzerland, Sept. 6-16, 1971.
23. The Nuclear Industry--1970, WASH. 1174-70, U. S. Atomic Energy Commission.
24. David J. Rose, "Nuclear Eclectic Power," Science, April 19, 1974, Vol. 184, p. 356.
25. "Final Safety Analysis Report to the U.S. Atomic Energy Commission," Nuclear Fuel Services Corporation, 1973.
26. The Nuclear Industry--1970, WASH. 1174-70, U.S. Atomic Energy Commission.
27. Fuel Reprocessing, Vol. II, Reactor Handbook.
28. William Epstein, "The Proliferation of Nuclear Weapons," Scientific American, Vol. 332, No. 4, pp. 18-33, April 1975.
29. Walter Schuller, "Reprocessing in Europe," Proceedings of Joint Topical Meeting, ANS/CNA on Commercial Fuel, Technology Today, Toronto, Canada, April 27-30, 1975.

30. W. J. Biddle, "Weapons Technology and Arms Control," Praeger Publishers, 1972.
31. S. Glasstone, "The Principles of Nuclear Reactor Engineering," Von Nostrand Co., 1955.
32. Nuclear News, Vol. 18, No. 9, p. 82, July 1975.
33. Mason Willrich and Theodore Taylor, "Nuclear Theft, Risks and Safeguards," Ballinger Publishing Co., 1974.
34. Nuclear Power Growth, WASH. 1139-74, U.S. Atomic Energy Commission.
35. "Nuclear Power Generation Charts, Nuclear Engineering International, March 1975.