ENRICHED URANIUM VERSUS PLUTONIUM: PROLIFERANT PREFERENCES IN THE CHOICE OF FISSILE MATERIAL

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Recent events in Iraq and North Korea have sparked renewed concern over the spread of nuclear weapons. A recurrent question in discussions of nuclear proliferation is which fissile material, enriched uranium or plutonium, states prefer for their weapons programs? An answer would shed light on the development of nuclear weapons programs in the past, and also serve as a predictive mechanism to help understand how future programs may develop. This study is an attempt to evaluate the factors influencing a state's choice of fissile material. The bulk of the article is comprised of a discussion of earlier nuclear programs: those of the United States, Soviet Union, United Kingdom, France, China, Israel, India, South Africa, Pakistan, Brazil, Argentina, and Iraq.[1] A full history of these programs is not intended; rather, the factors that influenced the choice of fissile material in each case are discussed.

The choice of fissile material must be preceded by the more basic decision to produce fissile material at all. An examination of the historical record amply demonstrates that a state's rationale for seeking fissile material has often played an important role in determining the material chosen. Mastery of the nuclear fuel cycle can yield new sources of electricity, commercial revenue, and naval propulsion. Programs that yielded nuclear weapons have been undertaken with a mix of military and non-military applications in mind, and the benefits listed above, among others, have often played a significant role in the choice of fissile material. Foreign assistance and the urgency of production have also been important influences. This article concludes with a rough taxonomy of the aforementioned programs in order to identify forces that have repeatedly influenced states' choices of fissile material. Only a modest fraction of the programs will be identified as having been predominantly influenced by the innate technological accessibility of the two metals.

Both enriched uranium and plutonium were produced for the first time in the early 1940s by researchers in the United States.[2] Uranium, a naturally occurring element, has a number of isotopes. The preferred isotope for weapons—U^{235}—comprises only 0.7 percent of natural ore. Typically, the concentration of U^{235} must be increased to about 90 percent before uranium is suitable for weapons, though lower concentrations can be used. Increasing the concentration of U^{235} relative to the more plentiful isotope U^{238} is a laborious process known as "enrichment." Plutonium is not a naturally occurring element and therefore must be produced, typically by bombarding U^{238} with neutrons in a nuclear reactor. The chemical extraction of plutonium from spent reactor fuel is known as "reprocessing." Considerably less plutonium than uranium is needed to make a simple fission weapon.

It would be difficult to generate dollar/kiloton of yield figures for the two metals, and plots of cost versus production time would be even more

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elusive. The necessary production facilities are complex and technically demanding and so defy easy estimations of cost. Many types of enrichment techniques, reactors, and reprocessing facilities exist, and even a single label, say "centrifugation," in reality describes a wide range of technologies. Production techniques have developed over decades and presumably will continue to evolve. Hence, an a priori assessment of the innate technological accessibility of enriched uranium and plutonium is difficult; hopefully, some insight can be gleaned from the historical record.

THE UNITED STATES

Technological accessibility was not the critical factor in the American program's choice of fissile material. In the early 1940s, the production of fissile material involved technologies that were either entirely novel, in the case of reactors, or unproven at the relevant scale of application, in the case of enrichment techniques. A conscious decision was made to pursue many paths in parallel to guard against failure and speed the production of a weapon that could end the war. The paths competed among themselves for funds and resources; when it became clear that centrifuge technology could not contribute before the end of the war, the program was dropped. By the war's end, four technologies had been industrialized: production reactors and reprocessing facilities, gaseous diffusion, electromagnetic separation, and liquid thermal diffusion. Many other enrichment techniques were explored: centrifuges, countercurrent electromigration, countercurrent molecular distillation, fractional sublimation, the ionic centrifuge, gaseous thermal diffusion, ether-water, chemical and photochemical separation, and the isotron. Both uranium and plutonium programs culminated successfully at about the same time: the devices exploded at Trinity and over Nagasaki used plutonium, the explosion at Hiroshima used uranium.

The relationship between bomb design and the choice of fissile material became apparent for the first time during the American program. Fission weapons can be built in two basic configurations: "gun-type" devices where two subcritical masses of fissile material are rapidly assembled into a critical whole, and implosion devices where a single subcritical mass is compressed into a critical state. In the midst of the American effort, it was discovered that plutonium, because of its higher rate of spontaneous fission, was unsuitable for the far simpler gun-type design. The simultaneous development of implosion and enrichment was then absolutely necessary, each in the event the other proved unworkable.

THE SOVIET UNION

Important similarities can be established between the initial Soviet and American efforts to build nuclear weapons. Just as fear of a German weapons program catalyzed the American effort, the explosion at Hiroshima catalyzed the Soviet program. Stalin is reputed to have told a group including Igor Kurchatov, director of the Soviet nuclear effort:

> A single demand of you comrades. Provide us with atomic weapons in the shortest possible time. You know that Hiroshima has shaken the whole world. The balance has been destroyed. Provide the bomb -- it will remove a great danger from us.[3]

Stalin's urging was not the start of the Soviet program; work had already begun in earnest in 1943 after a two-year lull in nuclear research caused by the German invasion. Rather, the American explosions transformed the Soviet effort into a crash program to build a bomb. Stalin directed that work should proceed "on a broad front, on a Russian scale."[4] Concerned now with time more than expense, the Soviets went on to develop both the uranium and plutonium routes.

The scant evidence available suggests that although serious research on isotope separation (mass spectrography and thermal diffusion for instance) was on-going as early as 1940, the Soviets had concerns about the practicality of enriching uranium.[5] At their strongest in 1940-41, these concerns persisted after the resumption of the program[6]; a 1943 memo from Kurchatov emphasizes the prospects of using plutonium especially since "*this solution will obviate the need to separate the uranium* ..." [emphasis as in original].[7] A falling out between Peter Kapitsa, another prominent weapons scientist, and Lavrenti Beria, the head of Stalin's secret police and overall leader of the weapons program from 1945 to 1953, has been attributed to Kapitsa's reluctance to work on enrichment.[8] Kapitsa is said to have written to Stalin complaining that by imitating the American program (presumably by pursuing enrichment technologies), the Soviets were pursuing a way that "is very long and expensive."[9]

At both the research and production stages, the Soviet uranium program lagged behind the plutonium effort. Whether the dilatory progress of the uranium program is a reflection or a confirmation of the Soviets' concerns about the practicality of the process is unclear. There is, however, solid evidence that serious work had begun on isotope separation before the first Soviet reactor went critical in December 1946.[10] Kapitsa's letter to Stalin was written in November 1945.[11] A group of German physicists taken to the Soviet Union after Germany's surrender began work on enriching uranium immediately after the destruction of Hiroshima.[12] More convincingly, Kurchatov is reported to have made isotope separation one of the nuclear program's top three goals as early as 1943. The other two goals, completion of an experimental reactor and design work on both the uranium and plutonium bombs, also suggest that the two routes were meant to proceed in parallel.[13]

The first Soviet production reactor went critical two years later, in early-to-mid 1948.[14] Though the evidence is less convincing, it can be argued that work on industrial-scale enrichment facilities began before this first production reactor went critical. Kramish argues that work on enrichment facilities was probably underway in 1947.[15] Work on "factories for enrichment" is also reported to have taken place in the fall of 1947.[16] In addition, the Soviet Union's first gaseous diffusion plant came on line in 1949 (the same year the Soviet Union tested a nuclear device made with plutonium).[17] It is unknown when work on this plant was begun, but 20 months elapsed at Oak Ridge between when site work began for the American K-25 gaseous diffusion plant and when the cascade was first charged with UF_6; and an additional eight months elapsed before the plant was truly complete.[18] If the Soviet effort followed a similar time scale, it is likely to have been initiated before criticality in the first production reactor.

Like the American program, the Soviet effort after 1945 was characterized by a driving sense of urgency. A solid argument can be made that the Soviets felt plutonium the more promising route, and indeed their reactor program matured more quickly. However, the need for fissile material was so pressing that enrichment was also pursued. At both the research and production stages, substantial work on enrichment was on-going before the plutonium program had vindicated itself. Therefore, despite the more rapid success of the plutonium route, the two programs can be said to have proceeded in parallel.

GREAT BRITAIN

Britain is one of the few cases in which the decision to produce fissile material was made in the absence of any compelling push towards uranium or plutonium, other than the inherent ease of access. By the end of 1945, it had been decided that Britain would develop a nuclear arsenal; furthermore, it was believed a scarcity of personnel (engineers, draftsmen, and construction workers) would prevent the exploration of both routes.[19] It was subsequently decided that the British arsenal would rely exclusively on plutonium. Production facilities to produce an equivalent number of uranium bombs were estimated to be 10 *times* more expensive. Though less important, industrial applications of the two materials were also considered, and plutonium was rated slightly more desirable on this basis as well. (Production reactors would generate electrical power and plutonium could be used in the future as reactor fuel, whereas an enrichment program would require less natural uranium initially and would make possible reactors moderated by light-water.)[20] The decision to develop reactors came in spite of the extensive experience Britain had had with gaseous diffusion during the Manhattan Project.[21]

A year later, this decision was reviewed, and it was decided to also build a gaseous diffusion plant. This change of heart was not the result of a reevaluation of the costs of such of a plant; rather, new needs had been perceived both for the production reactor program and for Britain's nuclear efforts as a whole. Shortages of natural uranium fuel for the reactors were feared, and enrichment would allow U^{235} in depleted fuel rods to be salvaged and recycled. In addition, supplies of slightly-enriched uranium would insure against any overestimate of the reactivity of the nascent production reactors. Finally, fast reactors, perceived as the future of atomic power, would require more concentrated fuel because of the lower fission cross-sections for fast neutrons.[22] Hence, enrichment was pursued, not as a redundant source of fissile material for weapons, but rather to buttress the plutonium program and advance efforts in reactor research. Plutonium was the first and the more desirable choice for the United Kingdom's weapons program.

FRANCE

Accounts of the development of the French nuclear program generally describe three phases. Prior to 1952, the program was devoted to basic and peaceful scientific research. The year 1952 marked the start of the first French five-year plan for atomic energy, which was directed toward the industrialization of nuclear technology. Simultaneously, the direction of the Commissariat à l'Énergie Atomique (CEA) passed from researchers to technocrats. Between 1954 and 1958, the program gradually transformed from an industrial to a military one, spurred in part by the 1956 Suez crisis. Premier Felix Gaillard's 1958 order to develop a weapon merely formalized the tacit direction of the French program.[23] The various stages of the French program are of interest because the decisions that determined the fissile material used in France's 1960 test at Reggane in the Sahara were made during the second, or industrial, stage.

The rationale for the 1952 five-year plan needs little explanation; at the time, mastery of nuclear technology appeared the latest requisite for national greatness. The specific provisions of the plan are of considerably more interest, however. Crafted by Pierre Guillaumat, minister for reconstruction and Gaillard, then holding ministerial responsibility for the CEA, the five-year plan called for the construction of two large reactors and a reprocessing facility.[24] Bertrand Goldschmidt, head of the CEA's chemistry division at the time, wrote later: "The progress of the CEA's research & mineral prospecting program determined, more or less automatically, the direction to be followed, namely, that of plutonium production in natural uranium reactors."[25] At the time, France's indigenous uranium reserves appeared modest, and no uranium was available internationally. Yet, fissile material would be necessary for any sustained nuclear development program, in particular to fuel power stations and submarine reactors. Plutonium produced in natural uranium-fueled reactors could eventually be used as fuel in more advanced reactor types, which would produce more fissile material than they consumed. Such were the stated reasons for the plan.

The course of earlier research also strengthened the case for plutonium. The French had successfully developed a pair of research reactors, the first of which, ZOE (Zero power uranium Oxide fuel and Eau lourde (heavy water)), went critical in December 1948. Furthermore, the French had significant experience with reprocessing by 1951.[26] In contrast, research on enrichment has been described as "in its infancy" as late as 1955. The simultaneous pursuit of both enrichment and reactors was deemed impractical because of the scarcity of uranium, the high cost, and the technological demands such a dual-track program would make.[27]

While the French saw the reactors of the 1952 plan as the first step in a program that would progress from natural uranium-fueled reactors to designs using fuel enriched with plutonium to full-fledged breeder reactors, it should not be assumed that the decision to acquire plutonium via the G1 and G2 reactors at Marcoule was made solely on the basis of peaceful concerns. Goldschmidt, who was intimately involved with the program, takes pains to emphasize that even during this, the industrial stage of the program, military applications, while unstated, "figured prominently in the minds of most of those who had proposed or who were otherwise responsible for the plan."[28] Hence, it should not be said that the eventual use of plutonium in the French weapons program was an artifact of earlier decisions made during a peaceful program. Both military and non-military applications were considered at the five-year plan's inception, and plutonium emerged as the clear choice.

At this late date, it is easy to overlook the significance the availability of uranium held in the minds of decisionmakers in the years immediately after World War II. Proven deposits of uranium ore were confined to a few areas in the Belgian Congo, Canada, and Czechoslovakia. At the war's end, 97 percent of the world's uranium output was controlled by the state participants in the Manhattan Project—the United States, Canada, and the United Kingdom—and this control continued for a number of years.[29] While intensive prospecting subsequently revealed ore in Portugal, Australia, South Africa, and France, among other places, there was a lag before these reserves could be exploited. Interestingly, the resulting uranium shortage played a role in both the United Kingdom's development of an enrichment capability and France's decision to develop reactors.

The fate of a 1950 Norwegian attempt to secure uranium for a reactor is illustrative. The United States and United Kingdom were unwilling to provide uranium, and the French, believing themselves to be the only remaining supplier, would only sell subject to conditions the

Norwegians found unacceptable. Gunnar Randers, the head of the Norwegian project, circumvented the French by buying 10 tons of uranium that had been purchased by the Netherlands in 1939 and hidden during the war.

CHINA

The Chinese nuclear program owes much to Soviet assistance. At the program's inception, the Chinese decided to pursue both the enriched uranium and plutonium routes with the help of Soviet designs, equipment, and personnel. The 1960 cutoff of Soviet aid and the subsequent Sino-Soviet split found both programs unfinished, however. A scarcity of technical resources and difficult economic times dictated that only one route be brought to completion. By happenstance, progress on the enrichment program was considerably more advanced.[30] Only site preparation and foundation work had been completed on the reactor site at Jiuquan. In contrast, Lewis and Xue argue that at the time of the Soviet withdrawal much key equipment, including diffusion barriers, the most demanding element, had already been delivered to the gaseous diffusion plant at Lanzhou.[31] It was decided that only the uranium work would continue, and the highly-enriched uranium (HEU) used in China's 1964 test was produced at the Lanzhou plant. Work on the reactor at Jiuquan was eventually resumed, but China's first plutonium explosion was not until 1968.

The acquisition of components from abroad has been the rule rather than the exception among recent nuclear programs. Assessing the impact of these purchases is problematic, however, because a state will have an incomplete notion of what components can be purchased when a program is initiated and purchases typically continue long after the decision to pursue a technique has been made. Nonetheless, two cases besides China exist in which critical systems were delivered from one state to another, clearly simplifying the choice of fissile material. Both India and Israel received extensive assistance in developing nuclear facilities. Their choices of fissile material balanced the preferences of the acquiring state with the willingness and ability of the supplier to provide technology.

ISRAEL

Israel is widely believed to have produced and reprocessed plutonium at facilities built with significant assistance from French firms acting with the blessings of their government. A series of French and Israeli contacts in the fall of 1956 yielded French assistance in the construction of a reactor and reprocessing facility at Dimona, Israel. The Suez crisis, which coincided with the later half of the negotiations, reinforced both Israel's commitment to acquire a nuclear deterrent and France's willingness to provide the necessary technology.[32]

Israel's interest in the nuclear fuel cycle dates from the establishment of the state itself. Early work on uranium extraction from indigenous ores and heavy-water production may have been initiated with reactors devoted to power production and desalinization in mind. However, security concerns are generally believed to have motivated Israel's 1956 move to acquire a sizeable reactor, Israel's first significant investment in a nuclear infrastructure.

The Israelis asked the French specifically for a natural uranium-fuelled, heavy-water moderated reactor.[33] This choice reflected not only Israel's preferences but also the capabilities of the prospective supplier. At the time, 1956, French work on enrichment was still nascent (see the discussion on France above). In addition, Israel's choice of reactors took advantage of indigenous uranium deposits, a modest heavy-water production capability, and the research experience of Israeli scientists in France.[34] So, not only was the plutonium route the only technology for which foreign assistance could be procured, it was also compatible with Israel's existing resources and expertise. French involvement in the design and construction of the Dimona complex is believed to have been extensive and should be accorded a leading role in the shaping of the Israeli program.[35]

INDIA

Since its inception, the Indian nuclear program has emphasized electrical power generation.[36] While possessing ample unsafeguarded plutonium and the expertise to assemble weapons, India has disclaimed any interest in deploying nuclear arms. However, India conducted a "peaceful" nuclear explosion in 1974. Research into nuclear explosives is thought to have begun in 1964, following China's first nuclear test, and with the catastrophic 1962 border war against China very much in mind.[37] The plutonium for India's 1974 test came from an unsafeguarded reactor (CIRUS) built in cooperation with Canada and moderated by U.S.

heavy water.[38] CIRUS was touted as a vehicle for developing future power reactors, something India has, in fact, gone on to do.[39]

There seems little doubt that India's nuclear efforts were *not* aimed directly at weapons production at the time of the 1955 CIRUS deal. Then Prime Minister Jawaharlal Nehru was firmly opposed to acquiring nuclear arms.[40] Had weapons been an immediate goal, an Indian test would certainly have come before 1974, considering that the CIRUS reactor became fully operational in 1964 and the Trombay reprocessing facility began operating in the same year.[41] However, the argument of one authority that the possibility of weapons production was recognized, and even deliberately cultivated, at an early date by a leading figure in the Indian nuclear establishment remains plausible.[42] Regardless, the plutonium India used in the 1974 explosion was produced by an infrastructure developed with future civilian power production very much in mind. Further, this infrastructure was deeply influenced by foreign assistance extended precisely because the program was perceived as peaceful in nature.[43]

SOUTH AFRICA

While South Africa's primary motive in seeking fissile material was national defense, commercial and economic concerns helped dictate the choice of material. Research on enrichment began in the late 1960s and was sufficiently far advanced by 1969 to justify the construction of a pilot enrichment plant at Valindaba.[44] The tumultuous decolonization of South Africa's northern neighbors spurred its interest in fissile material. Insurrections were underway in Portugal's African colonies and in Rhodesia by the mid-1960s. That South Africa perceived a threat is clear; defense expenditures increased six-fold between 1961 and 1968. Both the South African prime minister and a member of the Atomic Energy Board hinted at an interest in nuclear weapons at the time.[45]

The development of an uranium program was the result of certain contextual factors specific to South Africa and the world nuclear industry at the time. South Africa has significant uranium reserves and has been a major exporter of uranium since the 1940s. In the late 1960s, the projected global demand for low-enriched uranium (LEU) far exceeded the available supply. In addition, the birth of the South African weapons program was contemporaneous with South Africa's 1968 decision not to sign the Nuclear Non-Proliferation Treaty (NPT) and with mounting international concern over apartheid.

In this context, a uranium program offered benefits beyond weapons production. Enrichment services would add value to uranium exports at a time when global demand for LEU seemed high. (The European commercial enrichment consortiums Eurodif and Urenco started at about this time for similar reasons.) In addition, an indigenous enrichment capability would end South Africa's dependence on supplies of enriched uranium from the United States for its safeguarded SAFARI I research reactor and future power reactors. Fears that the United States would use this leverage to interfere in South African affairs were realized in the mid-1970s; fuel shipments for the SAFARI I reactor were suspended in 1975 due to concerns about South Africa's racial and nuclear policies. A year later, a South African order for two large power reactors from the United States was cancelled.[46] (The two reactors, which require LEU fuel, were later supplied by the French firm Framatome.)

South Africa is reported to have received assistance from the German firm STEAG in developing its aerodynamic enrichment technique.[47] While the availability of foreign assistance may have influenced the course of the program, it is worth noting that prior to the South African experience, aerodynamic techniques had never been realized on any appreciable scale. The South Africans' selection of the untried aerodynamic enrichment process suggests a program motivated by more factors than simply a desire to produce a bomb as quickly as possible. A crash weapons program would have been more likely to use a proven method like gaseous diffusion. South African experiments with centrifuges tell a similar story. Begun in the 1970s, this work was cancelled in 1991 when it became clear that it could not compete commercially with existing European designs.[48]

South Africa did, in fact, investigate developing reactors to produce plutonium. While the full story is not yet known, it appears that the uranium route was preferred. As early as 1969, a plutonium project was cancelled, in part, so as not to drain the uranium program.[49] Later reactor work came under the auspices of the South African Atomic Energy Corporation (AEC). The AEC became increasingly divorced from Armscor, which ran the weapons program, and the reactor effort was cancelled before the development of any infrastructure when the weapons program ceased to fund it through AEC.[50] Throughout the lifetime of the South African program, except perhaps, the earliest stages of research, the uranium route was dominant.

It has recently been argued that material produced in the enrichment plant at Valindaba had been intended strictly for peaceful nuclear explosives until 1977-78, when military roles were also developed.[51] While it may have been literally true that military plans for the use of nuclear weapons *went unstated* until this late date, these arguments merely highlight the fact that nuclear programs in which military applications "figured prominently in the minds of most," to quote France's Goldschmidt, can progress to the brink of weapons production without any formal decision to do so.[52] The formal order to commence research on peaceful explosions came five years after the start of work on the pilot enrichment plant, and the written order for the production of weapons was only issued near to the start of HEU production at the Valindaba plant.[53] Facilities to produce fissile material were also developed by Brazil and Argentina without any commitment to produce weapons but with the option of weapons production very much present.

It has often been noted that the manner in which South Africa intended to use its nuclear weapons influenced the design of the explosives themselves. Because weapons were to be used as leverage for securing Western help in the event of an attack by the Soviet Union's regional allies, large and cumbersome gun-type devices, for which plutonium is unsuitable, were adequate.[54] In addition, more compact implosion designs (for which plutonium *is* suitable) might have required a politically costly test before they could be deployed with confidence. It is incorrect, however, to argue that South Africa's plans for the use of weapons influenced the choice of fissile material. Work on enrichment preceded the formulation of military doctrine and even the most preliminary work on bomb design.

To summarize, security concerns, commercial opportunism, and a desire for energy independence whetted South Africa's desire for fissile materials. While the latter two influences were only of secondary importance in this regard, they were probably of considerable importance in deciding the *route* South Africa would follow to produce fissile material.

PAKISTAN

The motivation for Pakistan's development of fissile material was exclusively military. Defeated and partitioned in the 1971 war with India, Pakistan was unlikely ever to be able to match its giant neighbor's conventional forces. One year after the 1971 war, Prime Minister Zulfikar Ali Bhutto initiated a program to develop atomic weapons.[55] Initially, Pakistan hoped to pursue the plutonium route through a French-supplied reprocessing plant, but intense U.S. pressure slowed and eventually aborted the deal. Interestingly, Pakistan began to develop an interest in centrifuge technology before the start of international pressure over the reprocessing deal. Whether both programs would have matured in parallel in the absence of foreign pressure, or whether the uranium program would have been dropped once the reprocessing contracts were filled is unknown. It has been reported that the Pakistanis, like the Indians, were deterred from initially pursuing enrichment by the higher cost.[56] In any event, the French suspended their contracts in 1977 while the Pakistani uranium program was still gaining momentum. Pakistan's initial preference for the plutonium route is no surprise; together with a 125 megawatt electric reactor already in place in Karachi, the foreign-supplied reprocessing plant would have provided a ready source of fissile material, albeit subject to safeguards. Probably intended as an unsafeguarded backup for the plutonium program, the uranium program was made possible by a combination of historical accident and lax export controls. These two factors rendered centrifuge technology accessible to the Pakistanis.

The subsequent course of the program owes much to the influence of one man: Dr. Abdul Qadeer Khan. Khan, a Pakistani metallurgist, was employed by a contractor to the European Urenco enrichment consortium and had access to Urenco facilities and centrifuge designs. In a 1974 visit to Pakistan (shortly after the Indian nuclear explosion), he argued for the adoption of a centrifuge program and returned for good in 1976 to lead the program that had been created in his absence.[57] Pakistan has since gone on to develop a large, unsafeguarded centrifuge plant at Kahuta.

Pakistan's uranium program relied heavily on equipment and materials acquired from abroad. An entire plant for producing the process gas UF_6 was smuggled from Germany.[58] Naturally, the failures of Pakistan's foreign acquisition attempts have been better documented than its successes. Shipments of inverters, special electronics useful in a centrifuge plant, and maraging steel, a tough alloy suitable for centrifuge rotors, have been stopped. Additional shipments of inverters, vacuum valves, and other useful items were successfully completed. Designs for an enrichment plant were even reported to have been smuggled to Pakistan.[59] Since efforts to acquire equipment continued into the 1980s when the program was well underway, it is important to ask how much of a role the overseas availability of components played in Pakistan's *initial* decision to embark on an uranium program. Khan was familiar with Urenco's suppliers and therefore able to assess the likelihood of procuring equipment from them. Pakistan's ultimate success in acquiring components suggests that Khan would have been well aware of the ease with which parts could be obtained.[60]

BRAZIL

In Brazil, institutional factors played an unusually prominent role in determining the course of technological development. Efforts to develop nuclear technologies were split between a civilian power program and secret projects conducted by the armed services — "the parallel program." In the absence of any over-arching authority, each of the services pursued the technologies most amenable to its interests. The navy program was the first and most successful of the service ventures, and had Brazil decided to develop a nuclear arsenal, the choice of fissile material in that arsenal would have owed a great deal to the navy's institutional concerns.

The navy program originated in a 1978 proposal by a frigate captain who had gone to the United States three years earlier to study nuclear power. The Naval Engineering Board accepted Captain Othon Pinheiro da Silva's proposal to master the nuclear fuel cycle and develop submarine reactors. The navy subsequently began funding a program to enrich uranium with centrifuges.[61] Enriched fuel makes possible more compact reactors suitable for submarines. The navy's efforts culminated in a large and successful centrifuge plant that was eventually headed by da Silva, by that time an admiral.[62]

The production of nuclear weapons may well have been an additional, unstated goal of the navy program. In the mid-to-late 1980s, Brazilian papers routinely referred to the military's interest in such weapons. Earlier, in 1986, the existence of a borehole suitable for testing weapons was disclosed by the paper Folha de Sao Paulo.[63] At the time, the Brazilian government denied that the shaft was intended for a test, but the borehole was filled after President Collor announced that a weapons program had been stopped following his accession to office in March 1990.[64] While the possibility of weapons development may have played an important role in the navy's pursuit of fissile material, the choice of enriched uranium appears to have been motivated by the lure of naval reactors.

The accomplishments of the parallel program were not entirely the product of indigenous effort. The head of the National Nuclear Energy Commission (CNEN) has boasted of Brazil's success in importing components.[65] Brazil also benefited from the increasing openness surrounding nuclear technology. Brazil purchased three centrifuges of an early design in the mid-1950s, and much information about more modern centrifuges was publicly available until its classification in the 1960s.[66] Navy technicians and physicists were trained in the United States, and personnel trained in Germany for work on the civilian program were transferred, most likely to the parallel program.[67] While clandestine acquisitions may have aided the overall progress of the program, their impact on Brazil's choice of fissile material was probably meager.

ARGENTINA

As the French case demonstrates, nuclear programs, even ones with military leanings, can operate in the absence of a formal decision to produce weapons. Technologies will be developed that provide some combination of electric power, nuclear self-sufficiency, prestige, commercial revenue, and military options, depending on their accessibility and the interests of the technocrats directing research and/or the political bodies to which they are beholden. In such an environment, it is no surprise that multiple technologies may flourish.

Such was the case in Argentina; there is no evidence that a decision to make a bomb was ever made. However, until quite recently, Argentina has maintained its right to develop any nuclear technology, including weapons. Argentina has not signed the NPT and for many years declined to ratify the Treaty of Tlatelolco, which bars nuclear weapons in Latin America (though not "peaceful" nuclear explosions). Since a return to civilian rule in

1983, Argentina has moved to defuse suspicions about its nuclear program. A rapprochement with Brazil, Argentina's neighbor and rival, culminated in 1991 with the signing of a joint cooperation agreement that established a mutual inspections regime and barred the production of nuclear explosives.[68] While under military rule (1973-83), however, Argentina's commitment to the peaceful use of nuclear energy was considerably less clear. Consequently, Argentina's technological choices during this period merit study.

From its inception, Argentina's nuclear program has been a source of intense national pride. Furthermore, Argentina has striven to make its program as self-sufficient as possible. While supplied by foreign firms, Argentina's three power reactors incorporate many locally manufactured components. Furthermore, natural uranium-fueled designs were selected, in part, to take advantage of indigenous uranium deposits and avoid dependence on foreign enrichment services. Cheaper bids for designs requiring enriched uranium fuel were ignored in at least one case.[69]

Prior to 1978, Argentina, although possessing a substantial nuclear infrastructure, lacked the means to produce fissile material suitable for weapons. Entirely unable to enrich uranium, Argentina was also ill-equipped to reprocess plutonium. Beginning in 1969, Argentina operated a number of West German supplied hot cells but this small project was shut down in 1972.[70] Furthermore, spent fuel from Argentina's reactors was safeguarded because of either the reactor's or the fuel's foreign origin. Technically, spent fuel could only be reprocessed with foreign permission. Concern that Argentina might develop nuclear weapons has been focused on two unsafeguarded facilities begun in 1978: a reprocessing facility at Ezeiza and a gaseous diffusion facility at Pilcaniyeu.

The Ezeiza and Pilcaniyeu plants were undoubtedly a response to Brazil's gargantuan 1975 purchase of a complete nuclear fuel cycle (enrichment capabilities, reprocessing capabilities, reactors, etc.) from the German firm Kraftwerkunion. (Ultimately, reprocessing technology was not transferred, and the aerodynamic enrichment technique Brazil selected has only proven marginally successful.) Unless Argentina acquired enrichment and reprocessing technology, Brazil, which had previously lagged behind in the nuclear arena, would not only move ahead but also move so far as to hold unchallenged the key elements to developing nuclear weapons. The leader of Argentina's nuclear effort at the time Admiral Carlos Madera has conceded that the desire to keep pace with Brazil motivated Argentina's decision.[71]

In this case however, "keeping up with the Joneses" requires more elaboration. First, sources of fissile material would greatly increase the credibility of Argentina's nuclear weapons option. Second, enrichment and reprocessing plants would close the fuel cycle, implying a considerable degree of technological mastery. The material benefits that accompany this mastery do not appear to be of much utility to Argentina, however. Carlos Madera claimed that reprocessed plutonium could either be sold or mixed with uranium to make more efficient reactor fuel.[72] Though endowed with indigenous uranium reserves, Argentina has also expressed interest in a breeder reactor program of its own.[73] Enriched uranium fuel, while not required for Argentina's power reactors, could increase their efficiency, although whether this would be economical is in doubt.[74] More importantly, the Pilcaniyeu decision coincided with the United States' cut-off of enriched-uranium fuel for Argentina's research reactors (a result of the Nuclear Non-Proliferation Act). Enriched uranium from the Pilcaniyeu plant could be used to fuel these reactors or other research reactors that Argentina was trying to sell abroad.

At no point is there evidence that the Argentines decided to build a bomb. On the other hand, there is clear evidence that they developed the capability to produce fissile material, and hence weapons, when they feared their neighbors would also do so. While not directly aimed at producing a weapon, it is clear that the Argentines not only sought to maintain *the option* of weapons production, but also sought to keep that option as close at hand as their neighbors did. Had Brazil developed weapons in the late 1980s, there can be little doubt that Argentina would have followed suit (and vice versa) without any radical transformation of its program. However, the question remains, why did Argentina's military rulers choose to develop *both* reprocessing and enrichment technologies?

One must answer that a combination of doubt about the success of the projects individually and desire for the prestige and, to a lesser extent, the material benefits that accompany mastery of the technologies motivated the decision. The cut-off of enriched uranium supplies may truly have catalyzed the uranium program in a state looking for sources of fissile material. In addition, the difficulties of the gaseous diffusion process, Argentina's previous experience with reprocessing, and the availability of spent fuel (although under safeguards) also made a strong case for the plutonium route. Given that security concerns were involved (and also given Argentina's past record of choosing expensive technologies that satisfied more intangible national goals), it is not terribly surprising that both technologies were developed. Together, the technologies would match Brazil's anticipated capability and grant a mastery over the fuel cycle similar in principle to that of any first world nation. Finally, while unlikely to turn a profit, sources of enriched uranium and plutonium could both be justified in terms of economic and commercial benefits.

Interestingly, the Argentines chose to develop gaseous diffusion because the technology could be developed indigenously, and they felt that ordering parts for an enrichment system would attract foreign attention. While some components were purchased overseas, tell-tale items such as compressors and barrier material were manufactured locally.[75] In contrast, Pakistan and Iraq chose technologies specifically because items could be purchased abroad, no doubt because of their weaker industrial bases.

IRAQ

Iraq's nuclear efforts were entirely military in nature and guided by the accessibility of the relevant technologies. While recent International Atomic Energy Agency (IAEA) inspections have unearthed a wealth of detail on the hardware used in the Iraqi program, relatively little has been said about the decisionmaking that guided the program. The defining moment of the Iraqi effort was unquestionably Israel's 1981 raid that destroyed the French-supplied reactor at Osirak. Prior to the raid, it appeared Iraq would acquire mastery of the nuclear fuel cycle through the reactor purchase and Italian reprocessing and fuel fabrication equipment.[76] While the reactor was subject to IAEA safeguards and the Italian equipment should have been when put in operation, there is strong evidence that Iraq intended to reprocess spent fuel from the reactor for weapons.[77]

Following the destruction of the Osirak reactor, the Iraqis were faced with the decision whether to continue to pursue plutonium. At the time, Iraq was already operating two small safeguarded research reactors supplied by France and the Soviet Union.[78] Given that Iraq had experience with reactors and still possessed three Italian "hot cells" for reprocessing fuel, the subsequent course of the Iraqi program is something of a surprise: a concentrated effort to enrich uranium.[79] In the absence of any clarifying information, some speculation is in order. What considerations had the most influence on Iraq's decisionmakers? First, Iraq, while possessing considerable wealth from oil sales, probably lacked the industrial infrastructure to develop either plutonium or uranium technologies indigenously. The results of recent IAEA inspections support this conclusion. Second, the publicity surrounding the Osirak bombing and the destruction of the Tammuz cores at La Seyne-sur-Mer probably precluded the secret purchase of another reactor system, if they did not preclude the purchase of any such system altogether. As events have shown, a clandestine program is exactly what the Iraqis wanted and went on to develop.

The enrichment technologies Iraq pursued reveal a great deal about the motivation of their program. Iraq developed electromagnetic separation techniques and centrifugation with considerable success. Research on chemical separation, probably to provide slightly-enriched feed for the electromagnetic separators, made little progress and was abandoned.[80] Iraq also investigated gaseous barrier diffusion but the work was discontinued after a feasibility study indicated that the process would be expensive, highly visible, and *difficult to procure equipment for*.[81]

In contrast, the Pakistanis had ably demonstrated that centrifuge technology could be obtained overseas. Iraq, in turn, not only obtained raw materials and parts for centrifuges but also manufacturing equipment and German centrifuge designs.[82] Electromagnetic separators, known as calutrons, were first developed by the United States during World War II. Calutrons consumed so much power that it was believed no one would choose to duplicate the technology. As a result, much information about these simple machines was declassified. Even so, calutrons exceeded Iraq's manufacturing capability: the magnets had to be ordered from abroad.[83] Nonetheless, the simplicity of the technology and the lack of concern over electromagnetic separation made it easy to acquire parts without attracting attention.

Had Israel not destroyed the Osirak reactor, Iraq would constitute another instance in which a state procured a complete system for producing fissile material from abroad. While the destruction of the French reactor undoubtedly prejudiced the Iraqis against continuing to pursue plutonium, their primary reason for developing an enrichment program and choosing the technologies they did was the ease with which components could be acquired.

LESSONS, "PREDICTIONS," AND THE NORTH KOREAN CASE

An attempt to categorize all the programs discussed earlier according to a primary motivation in their choice of fissile materials must inevitably fail. Programs' decisions often resulted from several factors, and the weight to assign to each is uncertain in some cases (see the chart on the next page). However, loose groupings are discernible. Two programs, those of the United States and Soviet Union, were unquestionably initiated in response to what were perceived as dire outside threats and, in the rush to develop weapons, both the enriched uranium and plutonium routes were pursued simultaneously. Ample resources and the novelty of the technologies also encouraged this approach. Interestingly, the simultaneous pursuit of both paths was contemplated in the United Kingdom and France, but both countries rejected the approach as impractical. While the motivation for producing fissile material was primarily military (*i.e.* directed towards explosives) in the United Kingdom and significantly so in France, neither of these states faced threats as dire as the United States and Soviet Union believed they had faced. Argentina initiated both a uranium and a plutonium program in the face of an imminent external threat, but Argentina's program also had non-military motivations. Pakistan, another country facing a serious external threat, also appears to have briefly pursued both paths. Other programs have developed sources of fissile material with weapons specifically in mind, but have chosen not to develop both metals simultaneously.

A number of programs received sufficient amounts of foreign assistance to greatly simplify the choice of fissile materials. India, Israel, and China fall into this category. In fact, a characteristic of all but the earliest program has been the acquisition of foreign equipment or expertise, sometimes openly, sometimes clandestinely or illegally. It is difficult to define a level of assistance above which the availability of that assistance influences the choice of technology and below which foreign acquisitions are only an added benefit of a technological choice made for other reasons. Pakistan, South Africa, Brazil, and Iraq purchased considerable technology overseas, but probably only in Pakistan and Iraq did the availability of the technology of others conclusively determine their choice of enrichment. One could argue that this was the case in South Africa, but too little is known about German assistance to the South African program to say for sure. The illegal acquisition of foreign technology has been so widespread and so uniform among recent proliferants that, barring a ruthless tightening of export controls, such acquisition should be considered part of the context in which future proliferation takes place. The Pakistani decision to develop centrifuges was also influenced by Dr. Khan, whose helpful presence can only be regarded as an historical accident.

A number of programs were motivated in part by concerns other than producing fissile material for explosives. A distinction could perhaps be made between programs in which the desire for fissile material was whetted by a mixture of military and non-military applications and military programs in which the possibility of non-military applications influenced the choice of fissile materials. France, Argentina, and Brazil reside in the former category, while the United Kingdom and South Africa fall in the latter.

The above discussion indicates that when the original list of examples is pared of states whose choice of fissile material was driven by the urgency of production or the availability of foreign help, considerably fewer cases remain. If this pool is shrunk still further to contain only military programs where questions of accessibility should dominate the choice of routes, the pool is small indeed. Even after broadening the definition of accessibility to take into account the possibility of clandestine purchases of components, the United Kingdom, Iraq, and Pakistan are the only countries sure to remain. Unquestionably though, programs where non-military applications were considered also addressed the question of accessibility. We know accessibility played a key role in the case of France, and therefore our list should be lengthened by one. Brazil and South Africa, however, must remain excluded from our list because in their cases it is only possible to say that the route chosen was *sufficiently* accessible to justify its pursuit.

None of this, of course, is to say that the feasibility of developing enrichment plants or reactors and re-

The Proliferant's Initial Choice of Fissile Materials:

	Enriched Uranium	Plutonium	Motivation for Materials Choices
United States	X	X	urgency of production, technological uncertainty, extensive resources
Soviet Union	X	X**	urgency of production, technological uncertainty, extensive resources, **preference for Pu
United Kingdom		X	technological accessibility, non-explosive applications (very minor)
France		X	technological accessibility, non-explosive applications (far more so than in the United Kingdom)
China	X	**	critical equipment transferred from Soviet Union, **were to have received reactor as well
Israel		X	critical equipment transferred from France
India		X	critical equipment transferred from Canada and the United States, non-explosive applications
South Africa	X*		non-explosive applications, *substantial (?) foreign orders
Pakistan	X*	**	technological accessibility, historical accident, *substantial foreign orders, **sought Pu first
Brazil	X		non-explosive applications, institutional factors
Argentina	X	X	urgency of production (?), non-explosive applications/technological mastery
Iraq	X*	**	technological accessibility, *substantial foreign orders, **sought Pu first
North Korea		X	technological accessibility

processing facilities never entered the minds of decisionmakers in those countries where other forces dictated the choice of fissile materials. It is clear, however, that in the past decisionmakers either have been unsure of the relative difficulty of the two paths or that, in their perception, the difference in cost between paths was less compelling than contextual factors or the attainment of goals beyond weapons production. It must also be noted that technological accessibility is more than the innate difficulty associated with summoning a technology out of the void. The French decision not to pursue enrichment was made, in part, because of a worldwide shortage of uranium. The French pursuit of plutonium was also determined by the course of earlier research. Given that the accessibility of a particular technology depends on the availability of material and intellectual resources, not only will accessibility vary from country to country, but it will also change with time, and for reasons other than technological evolution.

Some general conclusions can be drawn about the nature of proliferation: first, and most obviously, the preferred method for producing fissile materials is through the purchase of complete systems for doing so. This has not been uncommon. India, Israel, and China acquired a weapons capability in this manner, and Iraq and Pakistan tried unsuccessfully to do so. More interestingly, in four of the five cases the equipment in question was for plutonium. In the odd case, China, both uranium and plutonium producing equipment were to be transferred, but by happenstance the uranium plant was completed first.

States developing their own means of producing fissile materials can be loosely divided into two categories. States with a low industrial capacity like Iraq and Pakistan must develop technologies for which parts can be ordered abroad. States with an industrial capacity above some threshold will no longer be heavily dependent on imported technology. Actors like Argentina may pursue technologies where components *do not* have to be purchased abroad in order to maintain the secrecy of their programs.

Some further conclusions concerning the relative accessibility of plutonium and uranium can be drawn *based strictly on the historical record*. For early proliferators working in isolation like the United Kingdom and France, plutonium was the preferred choice. The Soviets also suspected this to be the case. More recently, the proliferation of companies familiar with enrichment technology has meant that bomb builders no longer work in isolation. Parts, designs, and expertise can all be acquired without the assistance of another government. Having failed to procure plutonium production facilities, both Pakistan and Iraq elected to pursue enrichment programs for which *components* could be purchased piecemeal from a number of suppliers, rather than to develop a reactor program indigenously. South Africa and Brazil also found enrichment feasible using some foreign parts.

While it would be bravado to claim that the present state of the North Korean program was predictable, it is at least explainable in light of these conclusions. Frigid foreign relations and intense notions of self-reliance have combined to reproduce in North Korea an isolation similar to that faced by the earliest weapons programs. Furthermore, North Korea possesses a modest industrial capability, suggesting the adoption of technologies that can be developed without significant foreign purchases. The result has been an indigenous plutonium program based on a reactor design well-suited to the North's industrial capabilities. Current concern is focused on an unsafeguarded five megawatt reactor and reprocessing facility at Yongbyon.[84] Thought to have been built without significant foreign assistance, this gas-cooled graphite-moderated reactor requires neither heavy water nor enriched uranium fuel, obviating the need for revealing foreign purchases. The North Koreans overcame by themselves the most difficult hurdle remaining, purification of the moderating graphite.[85] Strikingly, the North Korean's choices of coolant and moderator are the same as those in the French G reactors at Marcoule and an early British station at Calder Hall.[86]

Any assessment of a state's likely choice of fissile material must take into account its motivation in seeking such materials. While technological accessibility also influences the choice of materials, accessibility is in part determined by such intangible and country-specific factors as the willingness of other states to supply equipment, the willingness and ability of the acquiring state to procure equipment clandestinely, and the material and intellectual resources of the acquiring state.

[1] All these programs have either produced weapons or have introduced the *option* of weapons production. This list is not exhaustive.

[2] Richard Rhodes, *The Making of the Atomic Bomb* (New York: Simon & Schuster, 1986), pp. 332, 354.

[3] Quoted in David Holloway, *The Soviet Union and the Arms Race* (New Haven: Yale University Press, 1983), p. 20.
[4] Yuli Khariton and Yuri Smirnov, "The Khariton Version," *Bulletin of the Atomic Scientists* (May 1993), p. 27.
[5] Arnold Kramish, *Atomic Energy in the Soviet Union* (Stanford: Stanford University Press, 1959), p. 109 and Khariton and Smirnov, *loc. cit.*, p. 24.
[6] Kramish, *op. cit*., p. 109.
[7] Quoted in Khariton and Smirnov, *loc. cit*., p. 25.
[8] Kramish, *op. cit*., p. 109
[9] Andrew Higgens, An interview with Yuli Khariton in *The Independent,* June 6, 1993, p. 12.
[10] Holloway, *op. cit*., p. 26. Criticality in a reactor occurs when the chain-reaction of splitting atoms becomes self-sustaining.
[11] Higgens, *loc. cit*., p. 12.
[12] Dan Charles, "In the Beginning was Uranium ... ," *New Scientist* (October 1992), p. 30.
[13] Holloway, *op. cit.*, p. 19.
[14] *Ibid*., p. 26.
[15] Kramish, *op. cit*., p. 110.
[16] *NOVA*, Nazis and the Russian Bomb, #2004.
[17] David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992* (New York: Oxford University Press, 1993), p. 54.
[18] Rhodes, *op. cit.,* p. 494 and Richard Hewlett and Oscar Anderson, Jr., *A History of the United States Atomic Energy Commission, Volume I* (University Park: Pennsylvania State University Press, 1962), p. 624.
[19] Margaret Gowing, *Independence and Deterrence: Britain and Atomic Energy 1945-52,* Volume I, (London: MacMillan, 1974), p. 165.
[20] *Ibid*., p. 166.
[21] British scientists studied gaseous diffusion independently during World War II and had access to early American work. This access was terminated prior to the maturing of the American gaseous diffusion effort, however.
[22] Gowing, *op. cit*., pp. 177-178. Neutrons with high kinetic energy ("fast neutrons") are less likely to induce fission in an uranium atom than neutrons with low kinetic energy. Consequently, the fuel of reactors that rely on fast neutrons must contain higher concentrations of fissile material.
[23] Wilfrid Khol, *French Nuclear Diplomacy* (Princeton: Princeton University Press, 1971), pp. 18-19 and Robert Norris, *et. al*., *Nuclear Weapons Databook Volume 5: British, French, and Chinese Nuclear Weapons* (Boulder: Westview, 1994), pp. 183-184.
[24] Bertrand Goldschmidt, *The Atomic Complex* (La Grange Park: American Nuclear Society, 1982), p. 126.
[25] *Ibid*., p. 125.
[26] Norris, *et. al*., *op. cit*., p. 183.
[27] Goldschmidt, *op. cit*., pp. 125, 270, 271.
[28] *Ibid*., p. 126.
[29] Gowing, *op. cit*., p. 357.
[30] John Lewis and Xue Litai, *China Builds the Bomb* (Stanford: Stanford University Press, 1988), p. 113.
[31] *Ibid*., pp. 119-120. P. B. Sinha and R. R. Subramanian make a similar point in *Nuclear Pakistan: Atomic Threat to South Asia* (New Delhi: Vision Books, 1980), p. 108.
[32] Leonard Spector, *The Undeclared Bomb* (Cambridge: Ballinger, 1988), p. 168 and Seymour Hersch, *The Samson Option* (New York: Vintage Books, 1993), pp. 39, 42-43. The seminal source detailing French involvement in the Israeli program is Pierre Pean, *Les Deux Bombes* (Paris: Fayard, 1982).
[33] Hersch, *op. cit*., p. 39.
[34] *Ibid*., p. 39.
[35] *Ibid*., p. 64.
[36] In the mid 1950s, when India began to develop a nuclear infrastructure, both the prime minister and the head of the Indian atomic energy commission (Jawaharlal Nehru and Homi Bhabha, respectively) were strong advocates of nuclear power. India has gone on to build power stations at Tarapur, Kotah, Kalpakkam, and Narora. G. G. Mirchandani and P. K. S. Namboodiri, *Nuclear India: A Technological Assessment* (New Delhi: Vision Books, 1981), pp. 28-29.
[37] Leonard Spector and Jacqueline Smith, *Nuclear Ambitions* (Boulder: Westview Press, 1990), p. 64.
[38] U.S. Congress, Senate, *Hearing Before the Subcommittee on Energy, Nuclear Proliferation, and Federal Services of the Committee on Governmental Affairs*, 96th Cong., 1st sess., May 1, 1979, p. 1.
[39] Grey Hamilton, "Canada to Help Build Atom Research Reactor for India," *The Globe and Mail*, April 30, 1956, p. 10.
[40] G. G. Mirchandani, *India's Nuclear Dilemma* (New Delhi: Popular Book Services, 1968), pp. 3-7.
[41] The development of reprocessing technology made sense in light of the Indian vision, shared by most other states at the time, of succeeding generations of breeder reactors. G. G. Mirchandani and P. K. S. Namboodiri, *op. cit.*, pp. 33, 71 and Leonard Spector, *Nuclear Proliferation Today*, (New York: Vintage Books, 1984), p. 30.
[42] Spector, *Ibid.,* p. 27.
[43] Hamilton, *loc. cit*., p. 10. Canada offered its assistance at the 1955 Geneva Conference on Peaceful Uses of Nuclear Energy with the condition that any plutonium produced be used for peaceful purposes. No formal safeguards were required, however. Foreign technology may also have been used at the Trombay reprocessing facility. See William C. Potter, ed., *International Nuclear Trade and Nonproliferation: the Challenge of the Emerging Suppliers* (Lexington: Lexington Books, 1990), p. 158 and Spector, *Nuclear Proliferation Today, op. cit*., p. 26.
[44] J. W. de Villiers, *et. al*., "Why South Africa Gave Up the Bomb," *Foreign Affairs* (Nov./Dec. 1993), p. 99.
[45] Spector and Smith, *op. cit.,* p. 270.
[46] *Ibid.*, p. 271.
[47] *Ibid.,* p. 271 and David Fischer, "Reversing Nuclear Proliferation: South Africa," *Security Dialogue* 24 (1993), p. 276.
[48] Albright, Berkhout, and Walker, *op. cit.*, p. 186.
[49] David Albright, "South Africa's Secret Nuclear Weapons," *ISIS Report* (May 1994), p. 4.
[50] *Ibid.*, p. 13.
[51] J. W. de Villiers, *et. al.*, *loc. cit*., p. 99.
[52] Goldschmidt, *op. cit*., p. 126.
[53] J. W. de Villiers, *et. al*., *Ibid*., p. 99.
[54] Fischer, *loc. cit.*, pp. 278-279.
[55] Steve Weissman and Herbert Krosney, *The Islamic Bomb* (New York: Times Books, 1981), pp. 44-5.
[56] Sinha and Subramanian, *op. cit.,* p. 107.
[57] Spector and Smith, *op. cit.,* p. 90.
[58] *Ibid.,* p. 91.
[59] U.S. Congress, Senate, *Hearing before the Subcommittee on Energy, Nuclear Proliferation, & Federal Services of the Committee on Governmental Affairs*, 96th Cong., 1st sess., May 1, 1979. See also U.S. Congress, House of Representatives, *Hearing Before the Subcommittees on Asian & Pacific Affairs and on International Economic Policy and Trade of the Committee on Foreign Affairs*, 100th Cong., 1st sess., July 22, 1987 and Weissman and Krossney, *op. cit.,* pp. 183-191.
[60] Weissman and Krosney, *op. cit*., pp. 182, 184.
[61] *Folha de Sao Paulo*, Sept. 24, 1990, p. A5; in FBIS-LAT-90-188 (27 Sept. 1990), p. 18.
[62] *Folha de Sao Paulo*, Oct. 25, 1990, p. A3; in FBIS-LAT-90-211 (31 Oct. 1990), p. 24.
[63] *Folha de Sao Paulo*, Aug. 8, 1986, p. 6; in FBIS-LAM-86-155 (12 Aug. 1986), pp. D1,D3.
[64] David Albright, "Brazil Comes in From the Cold," *Arms Control Today* (Dec. 1990), p. 13.
[65] *O Globo*, April 9, 1989, p. 9; in FBIS-LAT-89-069 (12 Apr. 1989), p. 40.
[66] David Albright, "Bomb Potential for South America," *Bulletin of the Atomic Scientists* (May 1989), p. 20.
[67] *O Globo*, *loc. cit*., p. 40 and Spector and Smith, *op. cit*., p. 253.
[68] *Gazeta Mercantil*, July 30, 1991, p.14; in FBIS-LAT-91-167 (28 Aug. 1991), p. 38.
[69] Cynthia Watson, "Argentine Nuclear Development: Capabilities and Implications," Ph.D. diss.,University of Notre Dame, 1984, p. 71.
[70] *Ibid*., p. 74.
[71] Spector, *Nuclear Proliferation Today, op. cit.,* p. 206.
[72] *Ibid.,* p. 205.
[73] Albright, Berkhout, and Walker, *op. cit*., p. 182.
[74] Spector, *Nuclear Proliferation Today, op. cit.,* pp. 219-220.
[75] David Albright, president, Institute for Science and International Security, Washington DC, telephone conversation.
[76] Gary Milhollin, "The Iraqi Bomb," *The New Yorker* (Feb. 1, 1993), p. 49.
[77] Spector and Smith, *op. cit.,* p. 187.
[78] *Ibid.,* p. 201.
[79] While Iraq used its existing facilities to separate five grams of plutonium from spent fuel generated by the Soviet supplied research reactor,

there is no evidence that the Iraqis tried to expand their capabilities in this regard. By themselves, the two surviving research reactors are too small to form the basis of a plutonium program. Albright, Berkhout, and Walker, *op. cit*., p. 172.

[80] Diana Edensword, research analyst, Wisconsin Project on Nuclear Arms Control, Washington DC, telephone conversation, Dec. 2, 1993.

[81] Albright, Berkhout, and Walker, *op. cit*., p. 172.

[82] Gary Milhollin, "Building Saddam Hussein's Bomb," *New York Times Magazine* (March 8, 1992), pp. 30-36. See also Diana Edensword and Gary Milhollin, "Iraq's Bomb - an Update," *The New York Times*, April 26, 1993, p. A17 and Albright, Berkhout, and Walker, *op. cit*., p. 171.

[83] Edensword, *loc. cit*..

[84] David Albright and Mark Hibbs, "North Korea's Plutonium Puzzle," *Bulletin of the Atomic Scientists* (Nov. 1992), p. 38.

[85] Joseph Bermudez, "N Korea - Set to Join the Nuclear Club?," *Jane's Defense Weekly* (Sept. 23, 1989), p. 597.

[86] While graphite-moderated, the first British production reactors were cooled by air, not carbon dioxide.