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Stopping the Production of Fissile Materials for Weapons

A halt in producing the essential ingredients of nuclear weapons would be easy to verify. It could therefore contribute to tighter control over the amount of weaponry in the superpowers' arsenals

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Agreements on nuclear-arms control based, like SALT II, on verifiable counts of missiles and other vehicles for delivering nuclear weapons may soon be impossible to devise. The vulnerability of strategic weapons that has come with precision guidance has stimulated a trend toward small, mobile ballistic missiles, such as the proposed U.S. Midgetman, which may be exceptionally difficult to detect. Cruise missiles and many of the other new weapon systems have been designed to carry either conventional or nuclear explosives, impeding an accurate count of deliverable nuclear warheads.

Clearly a new approach is needed to complement the delivery-vehicle counting rules. We suggest a new look at one of the oldest proposals for restraining the growth of nuclear arsenals: an agreement to cut off any further production of the fissile materials that are necessary for the construction of nuclear weapons.

Every nuclear weapon contains at least a few kilograms of chain-reacting fissile material. Fission of about one kilogram of uranium 235 demolished Hiroshima. Nagasaki was leveled by the fission of one kilogram of plutonium 239 in another weapon. The development of thermonuclear, or "hydrogen," bombs in the early 1950's did not eliminate the need for fissile materials, because such weapons require a fission explosion to ignite the hydrogen fusion reaction.

Since fissile material is an essential ingredient in all nuclear weapons, a cutoff would place an ultimate limit on the number of weapons that could be produced. Proposals for a cutoff of production of fissile materials have therefore been on the international arms-control agenda virtually since the invention of nuclear weapons.

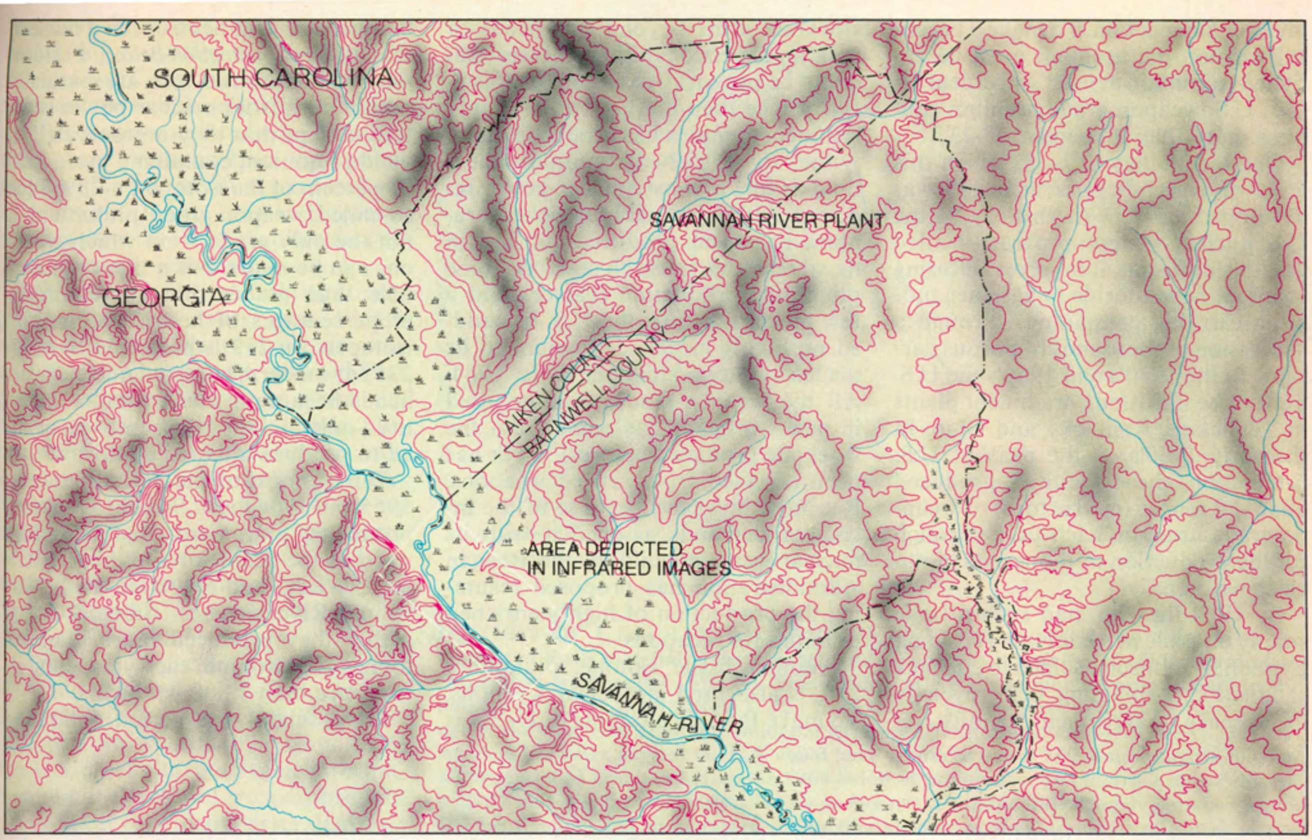
Between 1956 and 1969 a cutoff was repeatedly put forward by the U.S. as a separate arms-control proposal. The Soviet responses were not encouraging, perhaps because at that time the U.S.S.R. had considerably fewer nuclear warheads than the U.S. By the 1980's the two stockpiles were comparable, however, and in 1982 Soviet Foreign Minister Andrei Gromyko suggested that the "cessation of production of fissionable materials for manufacturing nuclear weapons" could be made one of the initial stages of a nuclear disarmament program.

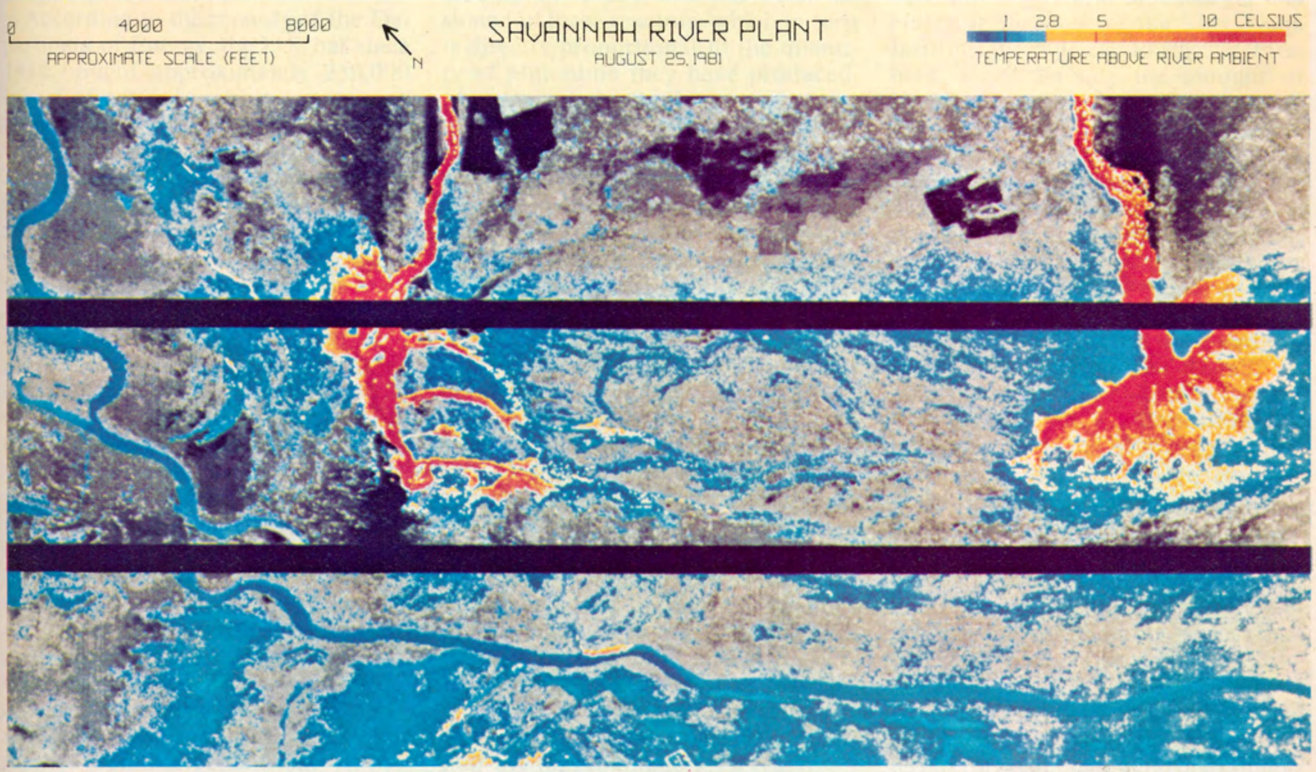
A cutoff would be a natural part of any larger package of mutually reinforcing arms-control and disarmament proposals. For example, to be meaningful any agreement to freeze or reduce the number of warheads would have to contain assurances that new warheads were not being produced.

A cutoff would serve another purpose as well. Continued production of fissile materials for nuclear weapons by the superpowers is severely undermining their efforts to discourage comparable activities by other nations. In the 1950's and 1960's U.S. proposals for a cutoff were often linked to efforts to persuade nonnuclear states to support the Nonproliferation Treaty. That treaty came into force in 1970 and has since been signed by more than 100 states. That the U.S. and the U.S.S.R., the nations that devised the treaty, had not brought their arms race under control resulted in increasingly strong expressions of dissatisfaction with the treaty on the part of the nonnuclear states at the review conferences of 1975 and 1980. The issue can be expected to cause even greater difficulty at the third review conference, which will run from late August through mid-September of this year.

A superpower agreement to cut off the production of fissile materials for nuclear weapons would thus be in the interests of nonproliferation as well as superpower arms control. The purpose of this article is to provide some of the technical background required for a constructive public discussion about the feasibility of a cutoff.

Part of the basis for any such discussion is a description of the nature and availability of the fissile materials themselves. Uranium 235 is the only fissile isotope that exists naturally in more than trace quantities. It is not found in a form that can be used directly in manufacturing nuclear weapons, however. Only .7 percent of a typical sample of natural uranium is U-235. The other 99.3 percent is uranium 238, a heavier isotope that cannot sus-





THERMAL INFRARED IMAGES would help to ensure compliance with a ban on production of fissile materials for weapons. The images shown here reveal discharges of hot water from two U.S. plutonium-production reactors at Savannah River, S.C. In this false-color representation the streams of hot water are red and orange; the cooler background is rendered in blue and gray. The streams are about 100 meters wide until they flow into a swamp, where one spreads out into a delta 1,500 meters wide. These images were made from an airplane flying at an altitude of 1.2 kilometers. Similar images made from satellites could detect hidden reactors.

tain a chain reaction. To make a practical weapon the uranium must be enriched to contain at least 20 percent U-235. U.S. weapon-grade uranium contains more than 90 percent U-235.

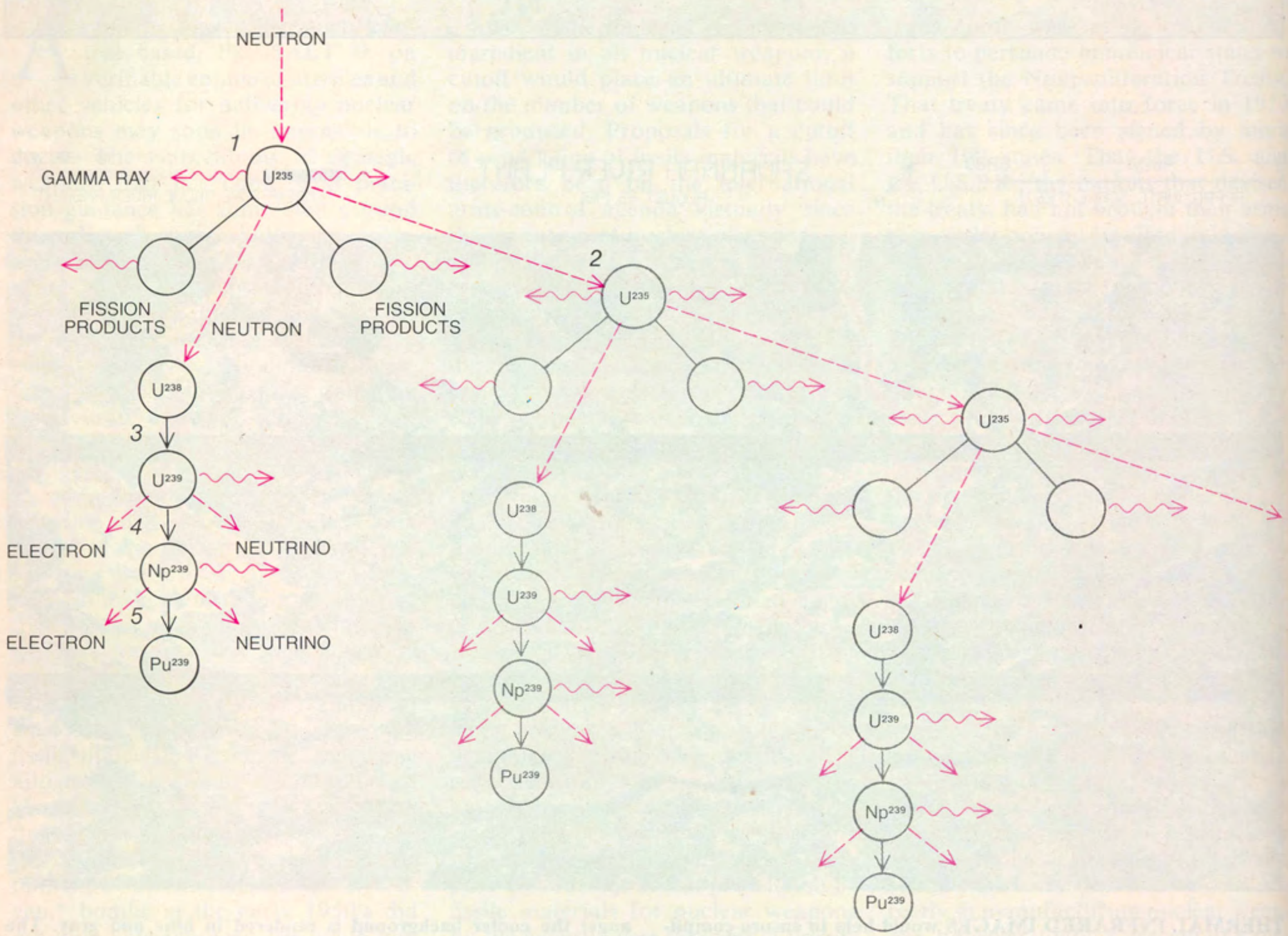
One technology through which this level of enrichment is achieved was developed early in the history of the U.S. nuclear-weapon program. Called gaseous diffusion, it involves diffusing uranium hexafluoride (a gaseous, uranium-carrying compound) through a succession of thousands of porous barriers. In the 1940's and 1950's the U.S. built three diffusion enrichment plants in Tennessee, Kentucky and Ohio. In the early 1960's, at the peak of U.S. production, these facilities produced about 80 tonnes (metric tons) of weapon-grade uranium each year—enough for the production of thousands of nuclear weapons.

By 1964 the U.S. had such a large supply of fissile material that President Lyndon B. Johnson decided to cut back production, explaining that "even in the absence of agreement we must not stockpile arms beyond our needs or seek an excess of military power that could be provocative as well as wasteful." Since then the U.S. uranium-enrichment complex has produced mainly the "low-enriched" uranium that is used as fuel in most nuclear-power reactors. Although highly enriched uranium has been produced for use in naval reactors, research reactors, some plutonium-production reactors and a few power reactors, the U.S. has added no highly enriched uranium to its nuclear-weapon stockpile since 1964. All the weapon-grade uranium used in new warheads has come from the stockpile produced before 1964 or has been recycled from retired weapons. Recently, however, because of the increased demands associated with its nuclear-weapon buildup, the Reagan Administration has proposed resuming the production of highly enriched uranium for weapons.

Another fissile isotope, plutonium 239, is also used in nuclear weapons. To make Pu-239, a sample of U-238 is bombarded with neutrons in a nuclear reactor [*see illustration below*]. Plutonium-production reactors are basically no different from nuclear-power reactors, except that they are operated to yield plutonium containing more than 93 percent of the isotope Pu-239. Such so-called weapon-grade plutonium is not the only grade from which weapons can be made, but it is more desirable than grades that contain higher percentages of heavier plutonium isotopes. Pu-239 is preferred over U-235 for modern, compact nuclear warheads because a much smaller quantity—only a few kilograms—is needed to produce a fission explosion.

During most of the period between 1955 and 1964 the U.S. had 13 reactors producing plutonium. Eight reactors were at the Hanford site, near Richland, Wash., and five were at the Savannah River site, near Aiken, S.C. Together they produced more than six tonnes of plutonium each year, enough for more than 1,000 warheads.

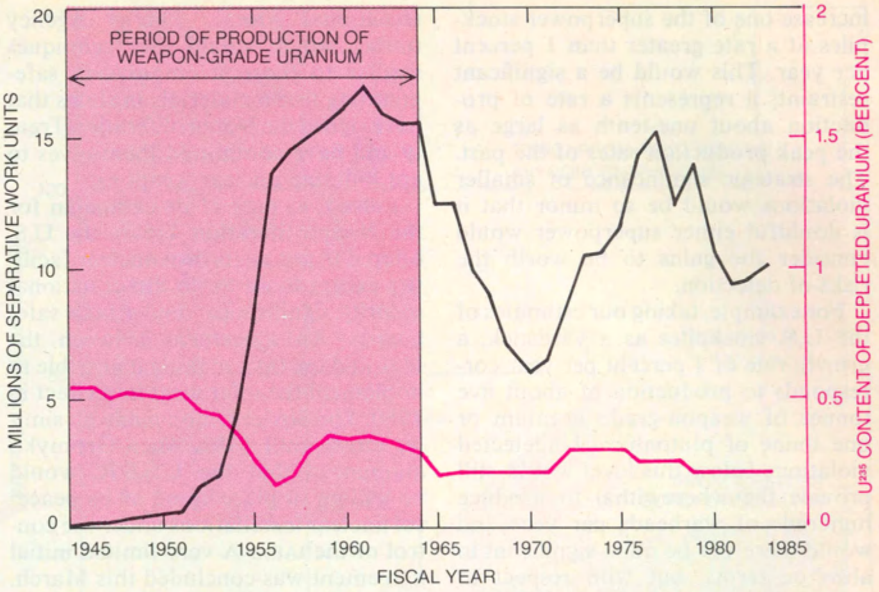
In the eight-year period following



FISSION CHAIN REACTION produces plutonium 239 from uranium 235. When an atom of U-235 is bombarded with a neutron (*1*), it yields intermediate-weight atoms, called fission products, and two or three additional neutrons. One neutron bombards another U-235 atom (*2*), sustaining the reaction. Another is absorbed by an atom of U-238, converting it into U-239 (*3*). The U-239 decays into neptunium 239 by emitting an electron and a neutrino (*4*). Pu-239 is created when the Np-239 emits an electron and a neutrino (*5*).

President Johnson's decision to cut back U.S. production all the Hanford reactors were shut down and two of the five production reactors at Savannah River were mothballed. The other three have remained in operation, along with a newer "dual purpose" reactor, completed in 1964 at Hanford, which generates electric power as well as producing plutonium.

Because of the Administration's plan to produce more than 10,000 new compact nuclear warheads, several projects have been initiated that would increase the rate at which the U.S. stockpile of weapon-grade plutonium grows. These projects include restarting one of the mothballed Savannah River reactors and converting into weapon-grade plutonium some of the 17 tons of fuel-grade and reactor-grade plutonium owned by the Department of Energy.



HISTORY OF U.S. URANIUM ENRICHMENT helps to provide an estimate of the amount of fissile material in the U.S. stockpile. Enrichment activity (*black*) is measured in "separative work units" (SWU's). The number of SWU's is roughly proportional to the amount of energy spent sorting U-235 from U-238. These figures, taken with the percentage of the "depleted uranium" (material left over after sorting out most of the U-235) that was U-235 (*color*), suggest the U.S. could have produced about 750 tonnes (metric tons) of highly enriched uranium before the 1964 cutoff of production. The increase in enrichment activity that began in the early 1970's was due not to production of highly enriched uranium for weapons but to increased production of low-enriched uranium for power plants.

How much fissile material is in the U.S. and U.S.S.R. stockpiles? Enough information is publicly available to allow reasonable estimates of the U.S. stockpile, but public information about the Soviet weapon-production complex is much sparser. It allows only a rough estimate of the size of their plutonium stockpile and yields no clues to the size of their stockpile of weapon-grade uranium.

According to the records of the Department of Energy, the U.S. has since 1944 bought approximately 250,000 tonnes of natural uranium, containing about 1,800 tonnes of U-235. The best way to estimate how much of this U-235 went into weapons is to examine the Government reports that list the annual amounts of "separative work," or enrichment, done in the U.S. uranium-enrichment complex and the associated percentages of U-235 that were left in the "depleted uranium" by-product of the enrichment process. We estimate using these data that the U.S. could have produced up to about 750 tonnes of highly enriched uranium for weapons prior to the 1964 cutoff of production. After estimating the non-weapon-related demands for uranium enrichment through 1964 and subsequent demands for highly enriched uranium, we conclude that there are still at least 500 tonnes of weapon-grade uranium remaining in the U.S. weapon stockpile. Thomas B. Cochran and Milton M. Hoenig of the Natural Resources Defense Council have reached a similar conclusion.

The amount of plutonium in the U.S. weapon stockpile can be estimated from data that have recently been released by the Department of Energy on the heat outputs of its plutonium-production reactors since 1951. Heat output is directly proportional to the amount of U-235 that has been fissioned in these reactors, which in turn is directly proportional to the quantity of plutonium they have produced. (Approximately .9 kilogram of plutonium is produced for each kilogram of U-235 that is fissioned.) On this basis we conclude that the U.S. weapon stockpile contains about 100 tonnes of plutonium. Once again Cochran and Hoenig have made a similar estimate.

Data relating to the amounts of plutonium and highly enriched uranium produced for weapons by the U.S.S.R. have not been made available by that government or by the U.S., but Soviet plutonium production can be gauged from the amount of radioactive krypton 85 that has accumulated in the atmosphere. This isotope, which is produced by fission, is released by facilities that reprocess nuclear fuel. Relatively small amounts are also released by tests of nuclear weapons and by leakage from reactor fuel. Because it is chemically unreactive, Kr-85 accumulates in the atmosphere, where its distribution is nearly uniform because of its long radioactive half-life (approximately 11 years).

Since about 1954 various groups of investigators throughout the world have made periodic measurements of the atmospheric concentration of Kr-85. The most comprehensive and accurate published measurements have been made by Wolfgang Weiss, Albert Sittkus, Helmut Stockburger and Hartmut Sartorius of the Max Plank Institute for Nuclear Physics in Freiberg. By estimating the amount of Kr-85 released in weapon tests worldwide and in fuel reprocessing outside the U.S.S.R. and then subtracting the amount from the total amount of Kr-85 released into the atmosphere, it is possible to estimate how much has been released into the atmosphere by the U.S.S.R. [*see illustration on page 45*]. By this method we estimate that through 1984 the U.S.S.R. had released about as much Kr-85 into the atmosphere as the U.S. If, as in the U.S., most of the Kr-85 was released in reprocessing fuel from reactors that produce plutonium, then the amounts of plutonium in the two countries' stockpiles, like their estimated numbers of nuclear warheads, are roughly comparable. The current rate of plutonium production in the U.S.S.R. appears to be considerably higher than that in the U.S., however.

Suppose the two superpowers agreed to cut off production of fissile materials for weapons. Could one country adequately verify that the other had not violated the agreement? For the purpose of this discussion we shall define adequate verification as the ability to detect within a few years any set of clandestine activities large enough to increase one of the superpower stockpiles at a rate greater than 1 percent per year. This would be a significant restraint; it represents a rate of production about one-tenth as large as the peak production rates of the past. The strategic significance of smaller violations would be so minor that it is doubtful either superpower would consider the gains to be worth the risks of detection.

For example, taking our estimates of the U.S. stockpiles as a yardstick, a growth rate of 1 percent per year corresponds to production of about five tonnes of weapon-grade uranium or one tonne of plutonium. Undetected violations below this level would still provide the wherewithal to produce hundreds of warheads per year and would therefore be quite significant in absolute terms, but with respect to the existing stockpiles such violations would be insignificant.

The problem of verifying a cutoff can be divided into two subsidiary problems. The first is ensuring that significant quantities of fissile material are not diverted to weapons from legitimate activities; the second is ensuring that there are no significant clandestine production facilities.

The U.S. has always assumed that a cutoff agreement would include a system of on-site inspections of facilities that process fissile materials for purposes other than weapon production, in order to ensure that no significant amounts of material were being diverted. Since about 1965 official U.S. statements have suggested that the inspection could be assigned to the International Atomic Energy Agency (IAEA), which would use techniques similar to those it employs in safeguarding fissile materials in states that have signed the Nonproliferation Treaty and have committed themselves to not building nuclear weapons.

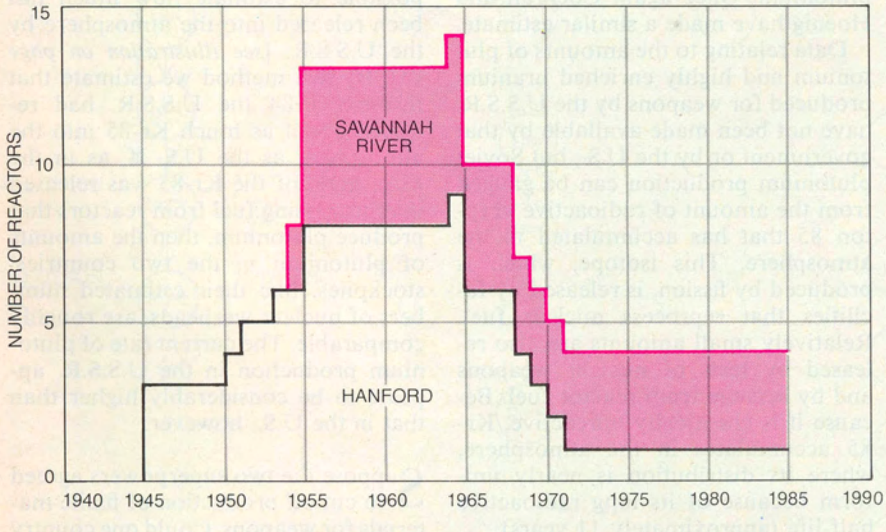
Indeed, as part of its campaign for the Nonproliferation Treaty the U.S. offered to put all its own nuclear facilities except those "with direct national security significance" under IAEA safeguards. An agreement between the U.S. and the IAEA making it possible to implement the offer went into effect in 1980. The Soviet Union made no similar move until 1982, when Gromyko announced that the U.S.S.R. would be willing to place some of its peaceful nuclear installations under the control of the IAEA. A very limited initial agreement was concluded this March, under which the IAEA will be able to safeguard one of the two main classes of Soviet power reactors. Unfortunately, however, the class of reactors that was offered for safeguarding is not the one that could most easily be operated as dual-purpose reactors (like the Hanford reactor that produces both power and weapon-grade plutonium).

The IAEA safeguards are hundreds of times more stringent than those that would be required to verify a superpower cutoff agreement: they are designed to detect within days or months the diversion of enough material to make a single nuclear weapon. The IAEA has specified that the diversion of only eight kilograms of plutonium or 25 kilograms of weapon-grade uranium is significant. Because the nuclear arsenals of the superpowers are already huge, diversions of nuclear material would have to be 1,000 times larger than that to have any potential strategic significance. There is little doubt that the diversion of much less material could be detected. The IAEA safeguards should be able to detect diversions of less than 1 percent of the fissile material flowing through a nation's nuclear-reactor fuel system. In comparison, 5 percent of the flow through the U.S. nuclear-power system or 15 percent of that through the smaller Soviet system would have to be diverted before the diversion amounted to five tonnes of U-235 or one tonne of plutonium per year.

The task of the IAEA safeguards is to confirm, within a specified accuracy, that any fissile material delivered to or produced at a facility is either still there, has been fissioned or has been delivered to another safeguarded location. In this respect the problem of safeguards is similar to the problem of currency safeguards that challenges a bank inspector. Visiting IAEA inspectors periodically check the consistency between actual and reported inventories. Measurements of radiation are used along with other nondestructive measurements on randomly selected nuclear-fuel assemblies to check that there has been no substitution of "counterfeit" fuel.

Where fissile material is in inactive storage the IAEA simplifies its task by applying tamperproof seals to the containers and storage vaults involved so that their contents need not be checked on each visit. Storage areas that cannot be sealed are monitored for suspicious activities by tamperproof cameras. Systems have been developed that make it possible, if necessary, to monitor the pictures being collected by such cameras remotely in real time.

The fuel cycle that is currently most common in U.S. and U.S.S.R. power reactors involves the use of low-enriched uranium in fresh fuel and no recovery of plutonium from spent fuel. In such a fuel cycle there is an additional major barrier to the diversion of fissile material to weapons. Even if enough fissile material could be diverted, a major additional clandestine operation would be necessary to convert it into a form usable for nuclear weapons: fresh reactor fuel would need enrichment to higher levels and spent fuel would need reprocessing to separate plutonium from the highly radioactive fission products. These barriers to diversion will exist as long as the superpowers refrain from shifting their nuclear-power systems to fuel cycles involving the use of



NUMBER OF U.S. PLUTONIUM-PRODUCING REACTORS increased steadily until the mid-1960's. Three reactors at Hanford, Wash., produced the plutonium for the bomb dropped on Nagasaki. Two more were under construction there when the U.S.S.R. tested its first nuclear weapon in 1949. Construction of three more reactors at Hanford and five at Savannah River was approved soon afterward. In 1964 a "dual purpose" reactor, which produces both electric power and plutonium, was completed at Hanford. In that year President Johnson decided to cut back U.S. production of fissile materials for nuclear weapons.

plutonium or highly enriched uranium in the fresh fuel.

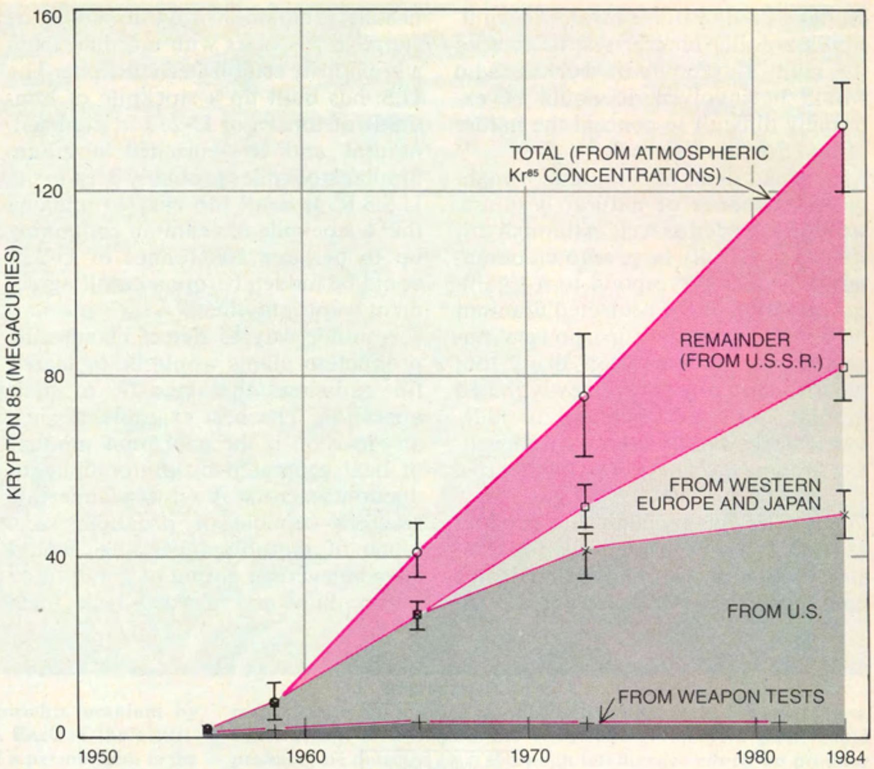
Under a cutoff U-235 would still be used as fuel not only in nuclear-power reactors but also in naval-propulsion reactors. The U.S. and the U.S.S.R. each have more than 100 ships propelled by nuclear reactors. U.S. naval reactors are fueled by weapon-grade uranium and are currently supplied with about five tonnes of U-235 per year. Since the total estimated shaft horsepower of the Soviet nuclear navy is about the same as that of the U.S., and since Soviet ships are at sea a much smaller percentage of the time, it is likely the Soviet navy's demand for U-235 is smaller.

Neither navy is likely to allow international inspectors in its ships or in the facilities that produce fuel for naval reactors. One possible arrangement would be for the superpowers to agree on the amount of U-235 each would be allowed to produce for use in its naval reactors. Under this arrangement the U-235 would be produced entirely at safeguarded plants and an equivalent amount of irradiated enriched uranium would have to be turned in at another safeguarded facility within a certain period of time. These measures would prevent the cumulative diversion of significant quantities of naval U-235 for use in weapons.

The U.S. has about as many research reactors as it has naval power reactors, but their total demand for U-235 is about one-tenth as large. We have no reason to think the corresponding demand in the Soviet Union is much larger. This is a small flow of material (about half a tonne per year) compared with the amount that constitutes a significant violation. In any case, the IAEA has developed thorough safeguards to detect diversions from research reactors.

The final class of reactors whose fuel cycles must be safeguarded are tritium-production reactors. Tritium provides the neutrons that initiate the fission chain reaction and "boost" the fission efficiencies in U.S. nuclear weapons. It is also the source of most of the neutrons produced by the "neutron bomb." Tritium is produced by allowing lithium 6 to absorb neutrons in the same type of reactor that produces plutonium when U-238 is made to absorb neutrons.

Because of its 12-year radioactive half-life, tritium must be replenished even if stockpiles are frozen. This would not call for a very large-scale effort, however. An amount of tritium equal to that in the U.S. stockpile could probably be maintained by a reactor with the capacity of one of the Savannah River reactors. Such a reactor, like any other, could be safeguarded against clandestine production of fissile materials for weapons.



ATMOSPHERIC KRYPTON 85 gives an indication of the size of the U.S.S.R. plutonium stockpile. This isotope is released primarily by nuclear-fuel reprocessing facilities and remains in the atmosphere because it is chemically unreactive. The upper curve, which is based on historical measurements of atmospheric Kr-85 (corrected for radioactive decay), shows the total amount of Kr-85 released to the atmosphere worldwide. The lower curves give the authors' estimates of the contributions to this total originating in weapon tests worldwide and in reprocessing facilities outside the U.S.S.R. The remainder (*color*) represents an estimate of the amount of Kr-85 released by reprocessing facilities inside the U.S.S.R. It is comparable to the amount released by those in the U.S. Most releases from the U.S. and the U.S.S.R. were probably from facilities producing plutonium for weapons, suggesting that the superpowers' stockpiles of weapon plutonium are also comparable.

If legitimate reactors and their fuel cycles can be safeguarded against significant diversion of materials to nuclear weapons, what are the prospects of one side's successfully constructing a clandestine production facility? Under early U.S. proposals for a cutoff of production of fissile materials, each superpower would have deployed roving teams of inspectors to search the other's territory. That approach was unacceptable to the Soviet Union. It was therefore highly significant when, in 1969, the U.S. completely dropped the demand. What brought about such a major change in position?

Part of the answer is that surveillance satellites had given the U.S. Government confidence that it could detect large-scale clandestine production from space. Routine surveillance of the Soviet Union by satellites began in 1961, and by 1969 it had become possible to subject the exterior of every structure on the earth's surface to detailed inspection.

Today indications of the energy intensity of hidden activities can be obtained as well, by telescopes that are sensitive to the infrared radiation emitted by warm surfaces. When the data from such satellite surveillance are analyzed in combination with information culled from internal reports, from intercepted radio and microwave transmission and from interviews with émigrés, the integrated product is stunning. This has been demonstrated convincingly in the Department of Defense's annual publication on Soviet military power.

It is unlikely that either superpower could conceal from such scrutiny the existence of a program large enough to produce one tonne of plutonium or five tonnes of highly enriched uranium per year. There would be many opportunities to discover such a program. For example, the construction of plutonium-producing reactors and their associated fuel-reprocessing facilities would be the equivalent of multibillion-dollar enterprises. In view of the many thousands of workers who would be involved, it would be extremely difficult to conceal the nature of an effort on this scale.

A great deal of uranium, roughly 1,000 tonnes of natural uranium, would be needed as well. Although this is not a physically large amount of material, it does correspond to a significant fraction of the projected uranium flow in either of the superpowers' nuclear-power systems. It is likely that the diversion of so much newly mined uranium would be difficult to hide, particularly if uranium mills were subject to some level of on-site safeguards.

The detection of clandestine production facilities through their associated mining and milling activities has limitations, however, because a clandestine production program could be supplied for years with uranium from a previously established stockpile. The U.S. has built up a stockpile of hundreds of tonnes of U-235 in depleted, natural and low-enriched uranium. Similar stockpiles probably exist in the U.S.S.R. It is all too easy to imagine that a stockpile of uranium containing up to perhaps 100 tonnes of U-235 could be hidden before a cutoff agreement went into effect.

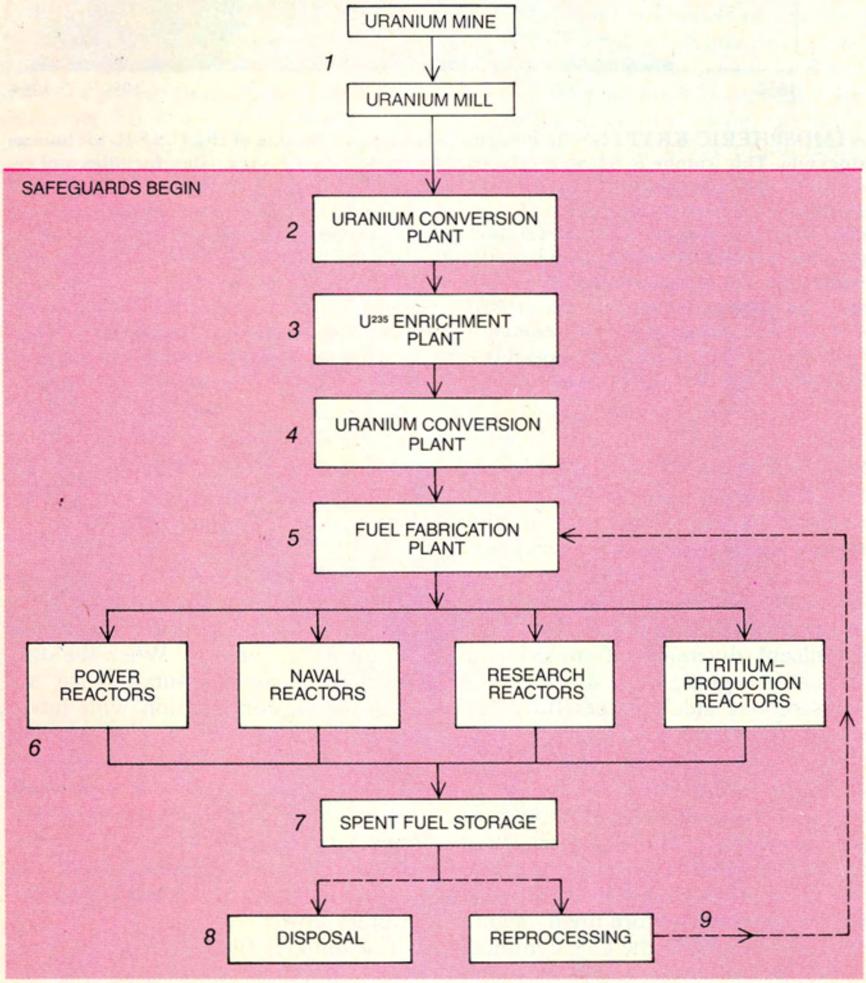
Another way to detect clandestine production plants would be to search for emissions characteristic of their operation. The best example of such an emission is the enormous amount of heat generated by plutonium-production reactors. A set of clandestine reactors capable of producing one tonne of plutonium per year would have an average output of about three million kilowatts of waste heat. Such an amount is about equal to the heat generated by a U.S. city of 300,000 people. It would be hard to dispose of so much heat without detection—sensors exist that can detect from space the presence or absence of ceiling insulation in a single-family house.

The illustration on page 41 shows a thermal infrared image, made from an airplane, of the outflow of hot water from the Savannah River production reactors, each of which has an average heat output of about 1.5 million kilowatts each. Similar images could be obtained at satellite altitudes. Although attempts could be made to reduce the thermal infrared emissions from hot water by, for example, thoroughly mixing it into a large river, the concealment problem would be acute, and the efforts at concealment themselves would provide clues to the nature of the enterprise.

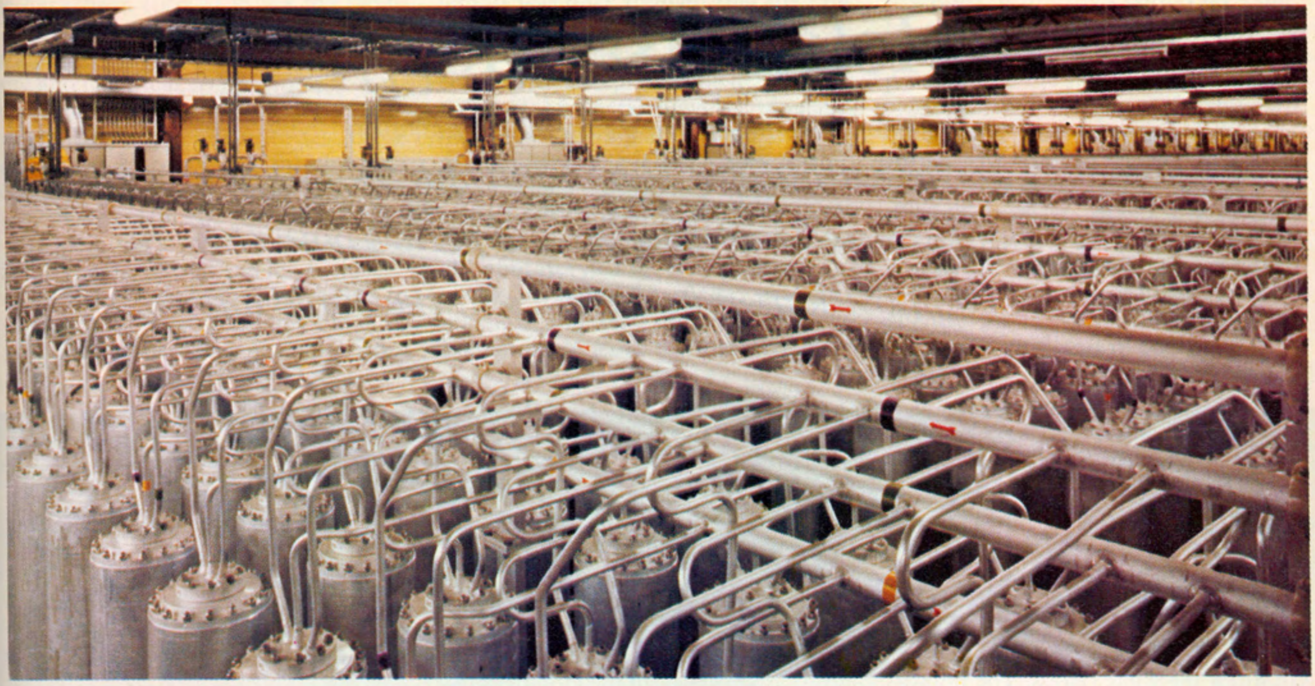
The least conspicuous facilities that are currently able to produce weapon-grade fissile materials are probably the so-called centrifuge enrichment plants. This technology, which is just coming into commercial use, involves spinning cylinders of uranium-carrying gas in centrifuges. Considerably fewer stages are needed in order to reach a given level of enrichment in a centrifuge plant than in a diffusion plant. In addition centrifuge plants are smaller and consume less energy. The appearance of gas-centrifuge plants is much less distinctive than that of diffusion plants, and it might not be possible to identify them from satellite photographs alone. The larger intelligence effort would probably be able to identify them, however, by picking up indications of the enormous effort required to manufacture and install the great number of centrifuges needed to produce five tonnes of highly enriched uranium per year [*see illustration on opposite page*].

The Department of Energy recently announced that its future uranium-enrichment facilities would employ a new technique called laser isotope separation. This technology exploits the fact that the atomic energy levels of U-235 and U-238 electrons are slightly different because of the difference in the masses of the atoms' nuclei. To separate the isotopes a set of lasers are tuned to produce energy that can be absorbed by U-235 atoms (each of which loses an electron in the process) but not by U-238. An electric field then separates the charged U-235 ions from the uncharged U-238 atoms.

An enrichment plant based on laser isotope separation would be smaller than a centrifuge plant; it would therefore be even more difficult to identify



ACTIVITIES TO BE SAFEGUARDED to ensure compliance with a cutoff begin when uranium leaves the mill where uranium oxide is extracted from raw uranium ore (*1*). At a conversion plant (*2*) the uranium oxide is converted into a gas (uranium fluoride) so that it can be enriched (*3*). Then it is converted back into an oxide or a metal (*4*) and fabricated into reactor fuel (*5*). After it has been used (*6*) the spent fuel is stored at the reactor site (*7*). From there it can be shipped to a radioactive-waste depository (*8*) or to a reprocessing plant (*9*), where any fissile uranium and plutonium it contains can be recovered and recycled.



CENTRIFUGE ENRICHMENT PLANT enriches uranium by passing it through a "cascade" of centrifuges. Each of the centrifuges shown (*cylinders*) is roughly the height of a person. This is the least conspicuous type of uranium-enrichment facility now in commercial use. It is smaller and consumes less energy than a diffusion enrichment plant and requires considerably fewer stages of enrichment; it also has a much less distinctive appearance. Nevertheless, construction of a clandestine centrifuge enrichment plant could probably be detected by a thorough intelligence effort. To produce five tonnes of weapon-grade uranium each year (the quantity defined by the authors as representing a significant violation of a cutoff agreement) would require approximately 100,000 centrifuges.

from satellite photographs. Nevertheless, a laser enrichment plant capable of producing five tonnes of weapon-grade uranium per year would still cost the equivalent of hundreds of millions of dollars to construct and would incorporate unusual, high-powered, rapidly pulsed lasers. These features and others would facilitate the detection of such a plant by the larger intelligence effort.

Although each of the means of detection we have discussed could in theory be eluded, the clandestine production of fissile materials would require that the construction and operation of all major facilities involved be concealed successfully for a period of several years. The detection of one suspicious facility by any of the available means of surveillance and intelligence would threaten the entire enterprise.

Ambiguous evidence of clandestine production activities could be brought to a body organized along the lines of the Standing Consultative Commission, which was originally established to discuss questions concerning compliance with the 1972 SALT I treaty. In the absence of satisfactory explanations on-site inspections could be requested, as was agreed by the U.S., the U.S.S.R. and the U.K. in the case of underground nuclear tests, before the suspension of negotiations of a Comprehensive Nuclear Test Ban Treaty in 1980. Systematic obstruction of efforts to obtain answers to legitimate queries would, of course, bring into question the continuation of the cutoff agreement.

The reward for successful concealment of a clandestine production program would hardly be spectacular; it would be a small increase in the size of a stockpile of fissile material that is already unnecessarily large.

If the superpowers are able to reach an agreement banning further production of fissile materials for nuclear weapons, it will be natural to try to extend the ban to include the other states with nuclear-weapon capability and to persuade those states without nuclear-weapon capability who have not signed the Nonproliferation Treaty to do so. A verifiable production cutoff would also lay the basis for verifiable reductions in the quantities of fissile materials already in the arsenals of the nuclear-weapon states.

The obvious way to dispose of fissile materials would be to "burn" them in existing nuclear-power reactors. The weapon-grade uranium would be useless for nuclear weapons after it was diluted with depleted or natural uranium down to the level used in power-reactor fuel. The stockpiles of weapon-grade plutonium would have to be disposed of with greater care, since there is no natural isotopic denaturant for plutonium. One method would be to use the plutonium as fuel in a relatively few heavily safeguarded reactors operated in a "once through" mode (that is, without reprocessing the fuel). Ten large reactors could in this way dispose of all the plutonium currently in U.S. or Soviet weapons in a decade.

Since the superpowers can probably estimate each other's stockpiles of fissile materials reasonably well, there is no obvious reason they could not, on the basis of these estimates, negotiate reductions of 50 percent or so in their weapon stockpiles. When stockpiles had been reduced, small violations would be more important, and so a greater exchange of information and more refined analyses would be necessary in order to lay the basis for further reduction agreements.

There is no reason, however, to delay the actions that could be taken immediately. If the superpowers are willing to accept inspections and other safeguards on their nuclear activities that are not related to weapons, both a cutoff in production of fissile material for nuclear weapons and substantial reductions in the quantities of fissile materials already in the stockpiles could be satisfactorily verified.