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Verified Elimination of Nuclear Warheads

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No nuclear warheads have yet been eliminated by treaty. This paper examines possibilities for verified dismantlement and elimination of nuclear warheads as called for by possible future nuclear disarmament treaties.

After warheads have been removed from missiles, the INF treaty allows each country to retain them, without restrictions.[1] According to present expectations similar conditions will apply to the START treaty now under negotiation to reduce numbers of Soviet and American deliverable strategic ballistic missile warheads by half. Nevertheless, given recent advances in cooperative methods verification, as well as progress in technical capabilities of detection and monitoring, it is reasonable to hope and expect that dismantlement of nuclear warheads, not just the means for their delivery, will be called for sometime in the future. This possibility has prompted a number of studies.[2]

The principal focus of this paper is on procedures to verify that warheads specified by treaty for elimination are, in fact, completely dismantled, their components rendered useless for construction of new warheads, and the contained fissile materials placed under international safeguards or disposed of in such a manner as to make them unusable in weapons.

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THE WORLD'S NUCLEAR WARHEADS

Estimates of the present worldwide numbers of nuclear warheads, as well as the numbers of US and Soviet nuclear warheads of various kinds, are shown in table 1.[3] Estimates of the total quantities of highly enriched uranium, plutonium, and tritium associated with the warheads are also included. More than 90 percent of these materials are accounted for, roughly equally, by the US and the Soviet Union.[4] These estimates are uncertain, especially the quantities of nuclear materials in Soviet warheads. Nevertheless they are helpful in setting the scales of operations needed to dismantle large fractions of the world's present stockpiles of nuclear warheads.

There are only three fundamentally different types of nuclear warheads. Pure fission warheads derive their explosive energy entirely from rapid fission chain reactions. "Boosted" fission warheads incorporate small quantities of deuterium and tritium that release large numbers of neutrons when they react at the temperatures produced by a fission explosion. These neutrons then speed up the rate at which the fission chain reaction proceeds and increase the overall yield of the explosion considerably above what it would be without boosting. Thermonuclear warheads require pure fission or boosted fission explosions to produce the conditions needed to ignite sufficient quantities of thermonuclear fuels to account for a substantial fraction of the overall yield of the warhead.

Warhead weights range from less than 50 kilograms to more than 4,000 kilograms; diameters range from less than 20 centimeters to more than one meter; yields range from much less than 1 kiloton to at least 20 megatons (TNT equivalent).[5]

There are several types of physical couplings between nuclear warheads and their delivery systems. Warheads for land- and sea-based strategic missiles are usually mounted on the missiles, although some warheads may be in storage separately at any given time. Other delivery systems, such as artillery, tactical aircraft and ships, have associated storage facilities for nuclear and conventional warheads. Although such differences can affect some of the details concerning physical means for identifying and containing warheads at specific deployment sites before they are dismantled, the basic principles explored here apply to all cases.

The effect of nonmilitary disposal of fissile materials from dismantled

Table 1: The World's Present Nuclear Warheads

The World's Nuclear Warheads

United States	23,400
Soviet Union	33,000
United Kingdom	700
France	500
China	300
Israel	50–200
South Africa	?
Pakistan	?
India	?
World Total	*about 58,000*

US and Soviet Nuclear Warheads

	US	USSR
Strategic		
Land-based missiles	2,470	7,630
Submarine-launched missiles	5,850	3,970
Bombs	5,170	1,400
	13,490	*13,000*
Nonstrategic		
Aircraft bombs and missiles	3,500	6,370
Land-based missiles	1,805	4,700
Submarine-launched ballistic missiles	0	50
Submarine-launched cruise missiles	150	400
Antiballistic and surface-air missiles	385	4,200
Artillery	2,010	2,000
Antisubmarine	1,760	1,860
Demolition (ADM)	300	?
	9,910	*19,580*

Nuclear Materials in US and Soviet Nuclear Warheads

Material	US	USSR	*Total*
Plutonium	100 tonnes	100 tonnes	200 tonnes
Highly enriched uranium	500 tonnes	400–800 tonnes	900–1,300 tonnes
Tritium	100 kg	100 kg?	200 kg?

warheads would be more symbolic than substantive if further production of these materials for weapons were allowed to continue. But such symbolism may be important politically, contributing to public support for nuclear disarmament. Furthermore, joint development of safe and verifiable procedures for dismantling warheads and transferring recovered materials from military to peaceful use can accelerate confidence in verification aspects of future, more stringent disarmament agreements.

ALTERNATIVES FOR DISPOSAL OF WARHEADS

There are many different ways in which warheads specified under a treaty can be disposed of. Three are considered here.

1. Each nation removes the specified warheads from deployment sites and periodically provides negotiated quantities of fissile materials (plutonium and highly enriched uranium) to an inspection authority. These quantities might be the same for the US and the Soviet Union, and smaller for any other parties to a treaty. Alternatively, they might be proportional to the total numbers of removed warheads of several types. In any case, these quantities should probably be negotiated in the original treaty. The quantities need not reveal the real amounts of fissile materials in each type of warhead, and may correspond to significantly more or less of these materials than are actually present.

2. Each nation removes and retains all fissile materials and thermonuclear fuels (tritium and deuterium, in compounds or as elements) from the warheads for unrestricted use, and the remaining components are verifiably destroyed.

3. Each nation separates the fissile materials and tritium from the other warhead components. The fissile materials are committed for use as fuel supplements for nonmilitary power reactors or for direct disposal in forms that would not be practical for subsequent recovery for use in weapons. The remaining components are verifiably destroyed. Their material residues, including tritium, may or may not be returned to the owner nation.

A variation of this last option would be to negotiate amounts of fissile materials greater than the quantities to be extracted from the warheads to be committed for nonmilitary use or direct disposal. The excess would be supplied from other sources, such as warheads not yet subject to dismantlement by treaty or material stockpiles. The negotiated minimum quantities may differ from country to country, to account for differences in total quantities of weapons materials in national stockpiles. The purpose of such an approach would be to help ensure parity in depletion of fissile materials, considered as fractions of total national stockpiles, as well as parity in giving up specific types of warheads or nuclear weapon systems.

The first option achieves reductions in theoretical maximum numbers of nuclear warheads by reducing the accessibility of key materials that are absolutely required to make nuclear warheads. It is the easiest to implement technically, since it does not require verification of any warhead dismantlement operations. But it offers no verifiable guarantee that all the fissile materials contained in the warheads are relinquished, or that the other parts of the warheads are destroyed.

The second option ensures that the specified warheads are destroyed, but does not deal with the components that are most difficult to produce—the plutonium and enriched uranium.

The third option is the most difficult to carry out technically, but is also the only one that ensures that the specified weapons are destroyed and their contained fissile materials are made inaccessible for weapons. It is considered here in some detail, not because it is evidently the most attractive, but because it raises some especially interesting technical questions that need to be answered in any comparative assessment of these options. Adding fissile materials to those extracted from the warheads to be dismantled, a variation mentioned above, is not analyzed in this paper. Its inclusion would require some minor modifications of the dismantlement process, to allow for safeguarded flows of materials from sources other than the specified warheads.

USE OF WARHEAD FISSILE MATERIALS IN NUCLEAR POWER PLANTS

A worldwide tally of present and projected nuclear power capacity is shown in table 2.[6,7] More than 95 percent of the fuel for power reactors is

Table 2: World Nuclear Power Plant Capacity

	Capacity *GWe* 1988	2000
United States	100	111
France	49	64
USSR	28	85
Japan	27	50
West Germany	19	24
Canada	12	16
United Kingdom	11	11
Subtotal	*246*	*361*
All other	51	99
Total	297	460

uranium of low enrichment (typically about 3 percent uranium-235) or natural uranium. The rate of loading of uranium-235 in a 1,000-megawatt-electric light water reactor fueled with uranium only is about 1,000 kilograms per year. A few reactors are beginning to use recycled plutonium to supplement the uranium-235 (but not in the US).[8] In such cases, the fuel is in the form of mixed oxides of plutonium and uranium, with plutonium accounting for a few percent of the mixture. The annual loading rates of uranium-235 and plutonium in the mixed-oxide reactors are about 670 kilograms of uranium-235 and 350 kilograms of plutonium per 1,000 megawatt-electric-year. Higher plutonium concentrations are possible, but may cause unacceptable reactivity-control problems. The demand for reactor fuel converted from fissile materials taken from weapons will probably be for uranium-235, rather than plutonium, for at least a decade.

The uranium-235 in the world's stockpiles of nuclear warheads is a potential energy resource worth more than $30 billion.[9] This total contributes about 0.5 cents/kWhr to the cost of electric power produced by typical nuclear power plants. Most of this cost could be avoided if highly enriched uranium from warheads were used to supply the uranium-235 needed for power reactors.[10]

It may be argued that warhead plutonium should be stored for use in future reactors that will use recycled plutonium or as core material for plutonium breeder reactors. This option is not considered here, however, since the plutonium might again be used for weapons if there were a major breakdown of disarmament treaty restrictions.[11]

It is therefore proposed here that the warhead plutonium be directly disposed of in ways that make it very difficult to be reused in nuclear weapons. This proposal, however, is not fundamental to the technical possibilities discussed in this paper, most of which would apply equally well if the warhead plutonium were used in reactor fuel.

PROCESS STEPS FOR ELIMINATING WARHEADS

Overview

A system for verifying the elimination of nuclear warheads must ensure that:

1. All warheads and associated payload hardware identified by the owner country and earmarked for elimination are what they are claimed to be.

2. All items earmarked for elimination are destroyed.

3. None of the nuclear material from the warheads to be dismantled is diverted to unauthorized uses.

These guarantees must be provided without the need to disclose sensitive information about the design of the warheads or other associated equipment, such as re-entry vehicles, penetration aids, or shielding against radiation.

All detailed information about the design of specific nuclear warheads is now classified. This includes yields and total weights; quantities of contained materials, including but not restricted to tritium, highly enriched uranium, and plutonium; and dimensions, configurations, and weights of fabricated components. Such information cannot be derived with any confidence from information that is now public. It is therefore assumed here that countries will be unwilling to reveal this information in the warhead dismantlement process.

Two key assumptions about secrecy are inherent in the process descriptions that follow.

The first is that the aggregate quantities of uranium-235, uranium-238, and plutonium of any isotopic composition that are contained in a mix of several different types of warheads can be declassified in the course of future treaty negotiations. This would allow accurate systems for accounting for fissile materials to be set up, without revealing information about the fissile material content of any particular kind of warhead.

The second assumption is that *upper limits* to some of the material quantities, component weights, and dimensions associated with warheads and other payload items can be declassified without national security concerns, provided that the upper limits are sufficiently large compared with their *actual* values. Then each owner nation could mask the true value of quantities it wished to keep secret by adding appropriate items, in unrevealed amounts, to the objects to be dismantled. An example would be the addition of a large weight of sand to each of the containers for some type of warhead, without ever revealing what that weight was.

Having made these assumptions, we can describe a verification system which ensures that all fissile materials in the warheads are accounted for (and made available for inclusion in reactor fuel or direct, permanent disposal) without revealing sensitive design information about specific warheads.

The main steps in the warhead elimination process are shown schematically in figure 1. Broadly speaking, the process provides the following assurances:

1. All materials in the warheads are contained within well-defined boundaries from the time they are placed in shipping containers at the deployment sites until they have been dismantled.

2. Any attempts to divert any of the warhead components to unauthorized purposes will be detected.

3. All major components of the warheads or other payload items are destroyed, in the sense that they would require refabrication to be used in other warheads.

4. All uranium-235, uranium-238, and plutonium in the warheads is accounted for in the measured output of these materials from the dismantlement facility.

5. Substitution of fake warheads for real ones at the deployment sites, before dismantlement operations begin, is likely to be detected.

"Fingerprinting" is a key concept related to detection of substitutions. It covers any method for observing indicators that the contents of all the warhead containers claimed to be of the same type are, in fact, the same. Since these indicators must not reveal sensitive information about the warhead designs, it may be necessary to encrypt them in such ways that they can be compared accurately enough to reveal significant *differences* between the contents of containers without disclosing restricted data.

The process steps and ways to achieve the above assurances are described briefly in the following sections.

Tagging, Sealing, and Shipment of Warheads to Dismantlement Facility

When the dismantlement operations start at a deployment site, all nuclear warheads to be eliminated—possibly along with other attached payload components such as re-entry vehicles and guidance packages—are placed inside shipping containers. The containers are provided by the owner country, which is also responsible for removal of the payloads/warheads from delivery vehicles or storage facilities at the site. The containers are not subject to internal inspection on arrival at the site, since they may contain materials that have been added off-site to mask actual weights of warheads or some of their components (see below). Transfer of payloads/warheads from delivery vehicles or storage to the shipping containers is observed by inspectors. The units may be temporarily covered while being transferred to the shipping containers, to avoid revealing sensitive information about their external appearance.

The inspectors then tag and seal each container. The tags are for unique external identification of each container. The seals are designed to

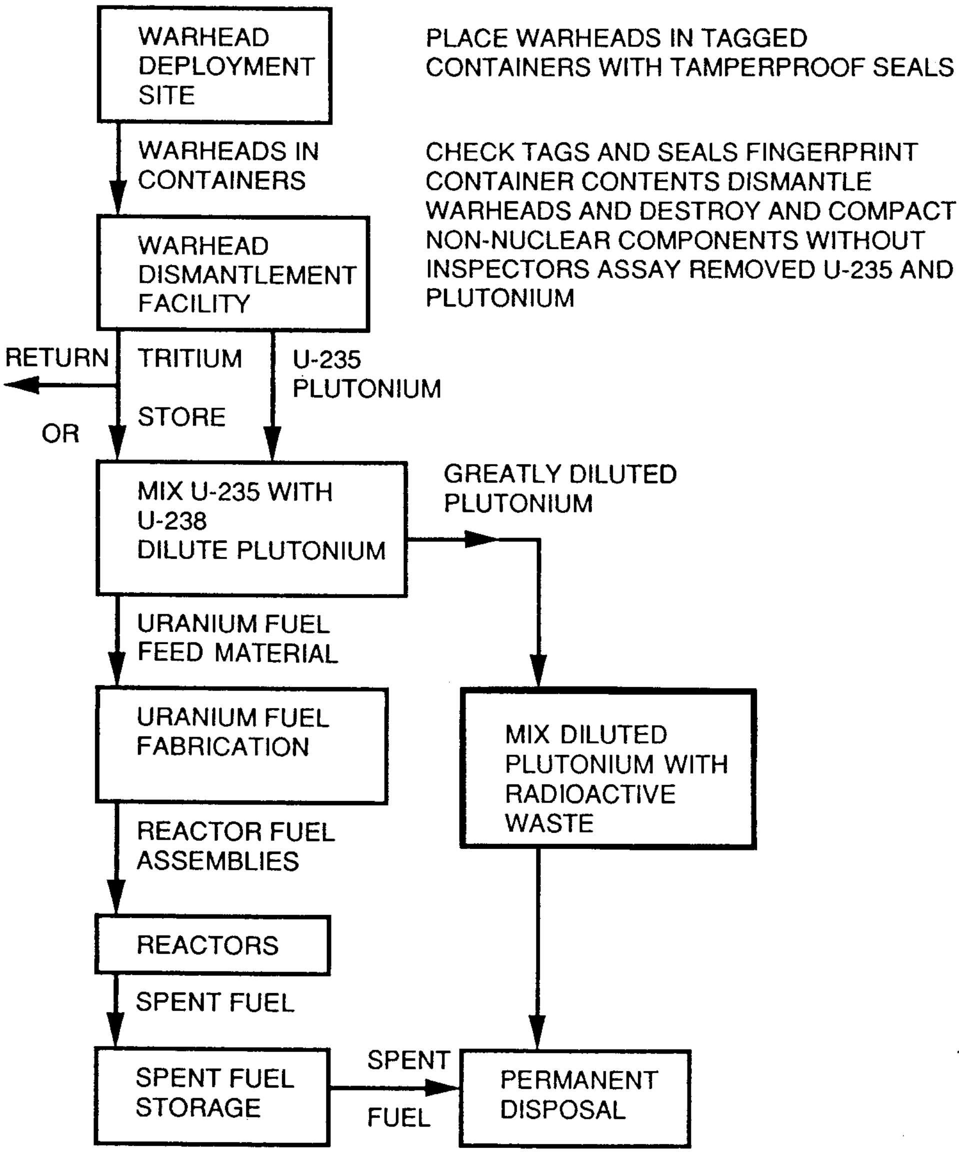

Figure 1: The main steps in the warhead elimination process

reveal any unauthorized opening of the containers.

Methods for tagging the containers include microscopic photography of parts of the outside surfaces or use of spray paint to produce photographed "signatures" that are almost impossible to change or reproduce without detection.

One method of sealing the containers is wrapping them with bundles of optical fibers. Illumination of one end of such a bundle produces a unique and complex pattern at the other end. Before-and-after photographs of these patterns will reveal attempts to remove or cut the bundles of fibers. Such techniques have been used routinely by the International Atomic Energy Agency for safeguarding purposes.[12]

Another sealing option is the spot welding of any removable covers for access to the containers, using the welds themselves as seals. Such seals have unique patterns that can be photographed before and after to reveal unauthorized opening of the containers.[13]

The tagged and sealed warhead containers, which may temporarily be stored at the deployment site, are then shipped to a warhead dismantling and destruction facility in the owner country. At this facility all tagged containers are examined by inspectors to ensure that they have not been tampered with. Inspectors would not need to accompany the shipments in transit, as long as careful accounting for each container is maintained at the deployment sites and the dismantlement facility. After shipment and inspection of the tags, significant numbers of unopened containers would typically be kept temporarily in storage at the dismantlement facility.

Dismantlement of Warheads and Other Parts of Payloads

The announced nuclear weapon states have facilities for dismantling obsolete nuclear warheads to recover nuclear materials or other components to be used in new types of warheads. It is possible that these facilities could be modified to meet the conditions needed for verified dismantlement under a disarmament treaty, especially the need to preserve secrecy concerning some of the warhead design details. This may be difficult in dismantlement facilities that are used both for handling warheads that are not subject to a treaty and ones that are.

This option cannot be assessed without access to detailed information not now public. However, it is possible to describe, in general, proposed process steps in a warhead dismantlement facility, and ways to ensure that the dismantlement and verification objectives are effectively met, whether or not new facilities or modified existing ones are used.

The descriptions provided here are not based on any conclusion that new dismantlement facilities would be preferable to existing ones, even though the latter might have to be significantly altered to allow for appropriate inspection. Decisions whether to modify existing facilities or build new ones for this purpose should follow intensive unilateral and bilateral assessments of the alternatives. Lacking access to descriptions of existing facilities, a hypothetical one is described here.

A schematic illustration of such a facility is shown in figure 2. Enclosures within which inspectors would not be allowed during dismantlement operations are indicated by double lines. These areas could be inspected between dismantlement operations, to ensure that there are no hidden stockpiles of nuclear materials or other sensitive components.

A well-defined boundary surrounds the entire dismantlement facility or area (if it is situated within a production facility). Portals with access through this boundary are all monitored visually and with appropriate equipment to ensure no passage of unauthorized objects, materials, or people. The main function of the portal-monitoring equipment is to detect unauthorized removals of fissile materials from the facility, or introduction of unauthorized items into the facility. The portal to be used for incoming shipping containers with warheads inside is the only one authorized for incoming fissile materials. The only portal authorized for outgoing fissile materials is the one used for removal of fissile materials after extraction from the warheads, for transfer to an adjoining facility for isotopic dilution of the uranium-235 (if needed) and chemical dilution of the plutonium.[14]

The principal inputs to the facility are the tagged and sealed containers with warheads and other payload hardware. All other inputs, such as process materials or new equipment needed for dismantlement operations, are kept to a minimum.

The principal outputs are the following:

- Accurately measured quantities of uranium-235 and -238 mixtures and plutonium (both probably in metallic forms that do not reveal warhead design features), for secure transfer to an immediately adjoining site for dilution.

♦ Tritium, in amounts not to be revealed to inspectors, to be returned to the owner nation or disposed of in a safeguarded manner.

♦ Small containers of radioactive materials used for warhead chain-reaction initiators or functions other than directly releasing explosive energy.

♦ Residues of compaction or incineration of all other components of the warheads or other payload items.

Warhead containers intended for re-use could also be considered as facility outputs. After their contents have been removed for dismantlement, the containers are weighed and inspected, to ensure they are empty. The owner nation is then allowed to place into the containers an undisclosed weight of some common material, such as water or sand, to mask the overall weights of warheads. The containers are then sealed by inspectors (but not weighed), and scanned by an external radiation source to ensure that there is no uranium or plutonium inside.[15] The containers remain sealed until they are externally inspected at a warhead deployment site before they are opened to receive more warheads.

The solid and liquid waste outputs from the site are kept to a minimum and subjected to detailed visual and instrumental inspection before they are removed from the site. A radiation scan of the residue output from each batch of dismantled warheads would ensure that this stockpile of residues did not contain significant quantities of fissile materials.

If the high explosives in the warheads are burned, the waste product is mostly gas. This can be vented from the site after passage through an appropriate gas cleanup system for removing objectionable pollutants.

Vehicles entering or leaving the outer boundary of the facility are kept to a minimum. This can be done by using bulk handling facilities for transfer of the warhead containers or other materials or equipment to the inside enclosures where they are authorized to go. Similar facilities can also be used for all outputs, so that vehicles leaving the site need not be inspected.

The warhead components are dismantled by nationals of the owner nation inside a facility subject to the containment principle that all the outputs from the facility are observed. The high explosives and other

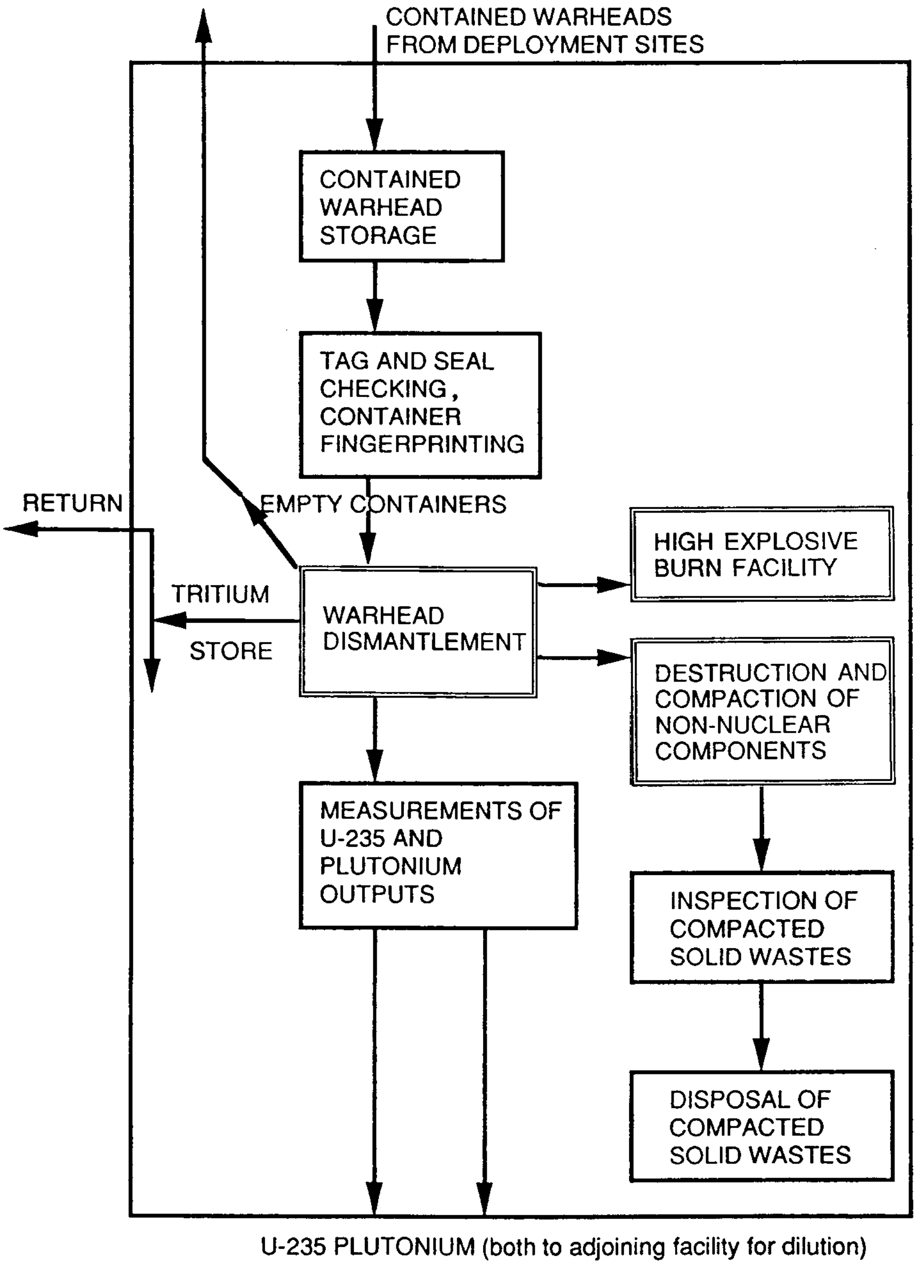

Figure 2: Schematic diagram of a dismantlement facility

non-nuclear components are destroyed in appropriate facilities inside the containment area. The plutonium and uranium are converted, without inspection of the process, to forms (such as metallic "buttons") that will not reveal warhead design features. Equipment appropriate for melting or dissolving the fissile materials and any low-enrichment uranium in the warheads, and then mixing them, are required, along with standard criticality and other safety procedures used in fissile-material processing plants.

Accurate measurements of the quantities and isotopic compositions of the recovered uranium and plutonium are made by inspectors, to obtain the initial data needed for accurate materials-accounting so that the uranium can be subsequently incorporated into reactor fuel and the plutonium disposed of.

In initial stages of nuclear disarmament any tritium might be returned to the owner nation, to avoid having to maintain production to make up for tritium decay (with a 12.5 year half-life) in warheads not yet subject to a disarmament treaty. In this case, the amounts of tritium removed from the warheads need not be revealed to inspectors, since, even for mixtures of warheads, their overall tritium content is likely to be especially sensitive information. Alternatively, the tritium might be placed under safeguards, for possible future use in thermonuclear fusion reactors, or simply allowed to decay. In this case it may be necessary, at least eventually, to reveal the quantities to inspectors.

Tritium containers leaving the site would be scanned to ensure they contain no fissile materials.

Radioactive materials used in the warheads for generators of neutrons for initiating fission chain reactions would be separated from other components and treated as small quantities of high level radioactive wastes to be disposed of at an appropriate facility. The relatively small shipping containers would also be scanned, before leaving the dismantlement facility, to ensure that they do not contain fissile materials.

Deterrents to Substitution of Fake Warheads for Real Warheads

The procedures just described can ensure that objects claimed to be warheads are dismantled, their components destroyed, and all contained fissile materials accounted for. By themselves, however, these procedures cannot completely ensure that fake warheads may not have been substituted for real ones before the dismantlement operation began at the deployment sites.

Objects substituted for the warheads before they are tagged and sealed, might include any of the following:

1. Objects similar in all respects to the real warheads, except that natural or depleted uranium has been substituted for some or all of the plutonium and highly enriched uranium that would have been in the real warheads. The purpose of this substitution would be to withhold significant amounts of fissile materials from the dismantlement process. The fake warheads might or might not be capable of producing a nuclear explosion, depending on the amounts of fissile materials withheld.

2. Objects that might or might not closely resemble the real warheads. In any case, they are much easier to fabricate, to less demanding tolerances, than real warheads. Such objects might include some fissile materials, but substantially less than in the real warheads. The fake warheads might or might not be capable of producing a nuclear explosion. Their function would be to allow unauthorized withholding of complete real warheads.

3. Complete warheads that are being retired from stockpile and that have much less fissile material than the warheads that are supposed to be eliminated.

Several measures can be used to help verify that such substitutions have not occurred, without revealing any secret warhead design information:

1. The specified warheads are tagged and sealed as early as possible, starting with warheads at a few deployment sites randomly chosen from sites specified in the treaty, with a very short time (for example, less than 24 hours) between choice of each site and the arrival of on-site inspectors. Complete substitutions for all warheads would have to be accomplished before the initial tagging and sealing operations begin.

2. Verification techniques are used that will reveal significant differences

between the contents, especially in amounts of fissile materials, of any containers for warheads that are claimed to be of the same type. Thus, if illegal substitutions were made, they would have to be made for all warheads of the same type, rather than for some selected fraction. (Specific ways to carry out this type of verification are discussed below.)

3. Inspectors measure accurately the total quantities and isotopic compositions of mixtures of plutonium or uranium extracted from batches of more than one type of warhead in each dismantlement campaign. Use of this procedure will require that the total plutonium, uranium-235, and uranium-238 extracted from several (e.g. three) types of warheads be declassified.

But it is difficult to see how this could reveal information that is critical to the national security of any announced nuclear weapon states.

4. A few sealed warhead containers of each type are randomly selected for safeguarded storage for an unspecified time. This will preserve evidence of compliance (or non-compliance) with a treaty, in case more effective verification techniques are developed in the future. Present uncertainty about such possibilities could act as a major deterrent to cheating under a current treaty. Furthermore, the selected warheads could be used as standards against which to match very detailed fingerprints. These fingerprints consist of encrypted data preserved in tamper-revealing data processing systems. The only information output is what the comparisons revealed, without disclosing any of the raw data.[16] The number of warheads selected for these purposes might be two or three of each type.

5. The possibility of "whistleblowing" (reporting of treaty violations to a verification authority by nationals of a country whose government orders the violations) is a deterrent that cannot be assessed quantitatively. It may become increasingly important as the universal benefits of nuclear disarmament become more generally apparent and publicized worldwide. Ways to ensure that individuals or groups who report violations can remain anonymous need to be further developed and assessed.

6. None of these measures would reveal restricted information, especially if each owner nation is allowed to add unrevealed weights of common

materials, such as sand or water, to the warhead containers, to disguise the warhead weights or some aspects of their composition. Uranium would not be allowed for this purpose, since introduction of unknown quantities of it into the process would invalidate checks of independent estimates of total quantities of highly enriched uranium that have been produced.[17] The total weights and configurations of any such added materials must be the same for all warheads of a particular type, to ensure that the total contents of all fully loaded containers for each warhead are the same.

Fingerprinting Contents of Warhead Containers

As previously indicated, measurements that will reveal differences between the contents of containers of warheads that are claimed to be of the same type, without revealing secret information to the inspectors, can play key roles in providing assurance that fake warheads have not been substituted for real ones. The term "fingerprint" is used here to mean the totality of such measurements.

There is a wide variety of possibilities for such measurements. They fall into two categories: external measurements, before the warhead containers are opened, and measurements of residues from the dismantlement process. In either case, allowable differences between measured quantities that are nominally for the same type of warhead would have to be negotiated, since such measurements may vary somewhat between warheads of the same type. Examples are the isotopic composition of plutonium and uranium, or weights and configurations of fusing and firing components.

Possibilities for the elements of a fingerprint include the following:

1. Total weight of the contents of each warhead container before it is opened for dismantlement. This weight is derived from the difference between the weight of the loaded container, before it is opened, and the weight of the empty container (after its interior has been inspected, but before unknown amounts of materials have been added by the owner nation). It is specified that the total weight of the contents should always be the same (within negotiated limits) for the same types of warheads. This does not preclude the possibility of substituting fake warheads and changing the weight of added materials to keep the total weight the same.

2. Precise measurements of the aggregate quantities and isotopic compositions of plutonium and uranium extracted from each batch of dismantled warheads consisting of known numbers of several specified types. Isotopic composition of plutonium, especially, can vary significantly between different warheads of the same type, however. Allowable differences in average isotopic compositions, from batch to batch, would therefore have to be negotiated.

The measurements applied to the fissile material outputs are taken here to be the principal basis for fingerprinting. They would reveal use of fake warheads that contain less plutonium, uranium-235, or uranium-238 than in the real warheads, unless fake warheads are substituted for all warheads before they are sealed at the deployment sites. Although they would not necessarily reveal differences in the non-nuclear components of warheads that are supposed to be of the same type, such violations would risk being detected eventually by fingerprinting techniques that might be developed for probing the randomly selected sealed containers that have been placed in safeguarded storage.

Among the many other fingerprinting techniques that might be developed and used in the future are an entire class that would produce extremely detailed raw data concerning the configurations, compositions, and masses of materials in the warheads. The raw data would be withheld from inspectors, but combined in a sealed data processing system that would produce scrambled output data that would reveal no classified information, but reveal significant differences between objects inside the containers. Examples of such measurements include weight distributions along several axes and high-resolution scanning with external sources of gamma rays, x-rays, or neutrons.

Some preliminary analysis by the author has shown that passive radiation scanning is not likely to produce a reliable fingerprint. The external fluxes of gamma rays or spontaneous fission neutrons from warheads of the same type, but with uranium or plutonium of differing isotopic compositions, show credible variations that might *suggest* significant differences in the contents of containers even if they contained what they were supposed to.

Disposal of Warhead Uranium and Plutonium

After accurate measurement of their masses and isotopic compositions by inspectors, the uranium and plutonium would be transferred from the dismantlement facility to an adjoining facility for further processing to prepare them for their ultimate disposal. This facility would also be enclosed by a containment perimeter.

The uranium-235 and uranium-238 mixtures from the warhead dismantlement facility are further diluted as necessary with depleted or natural uranium, to provide uranium with about 3 percent uranium-235 that could be used for fuel for light-water power reactors. For use in heavy-water or graphite reactors fueled with natural uranium, which account for a small fraction of the world's nuclear power, the uranium-235 could be diluted with depleted uranium (about 0.3 percent uranium-235) to a concentration near 0.7 percent. In either case this dilution renders the uranium incapable of sustaining a fast-neutron chain reaction, for which the minimum enrichment required is about 6 percent.

The plutonium would be heavily diluted with materials (such as depleted or natural uranium oxide) that are at least as difficult to dissolve and then separate as typical constituents of fresh reactor fuel, in preparation for its irretrievable disposal. Before final disposal, the diluted plutonium would also be mixed with high-level radioactive wastes.

Unlike uranium-235, plutonium cannot be "isotopically denatured" to render it unusable in nuclear warheads after chemical separation from diluting materials. All plutonium isotopes are capable of sustaining a fast-neutron chain reaction.[18] The best plutonium isotope for nuclear warheads is plutonium-239. Substantial concentrations of plutonium-240 (greater than about 6 percent of the plutonium-239) are undesirable because that isotope spontaneously fissions and releases neutrons that can cause a premature chain reaction in a weapon before it is optimally assembled in an implosion.

Nevertheless, efficient, reliable nuclear weapons, including thermonuclear warheads, can be made with plutonium containing concentrations of plutonium-240 much greater than 6 percent.[19] It is for this reason that chemical dilution, mixing with high level radioactive wastes, and irretrievable disposal at considerable depth in safeguarded geological formations are needed to ensure that warhead plutonium, after disposal, is not practically accessible for making nuclear warheads.

POSSIBLE PARAMETERS FOR A WARHEAD DISMANTLEMENT FACILITY

Possible parameters for a large warhead dismantlement facility in the US are listed in table 3. Its capacity for dismantling eight warheads a day is about as large as may be credibly required for implementing future nuclear disarmament treaties. That is, it would be capable of dismantling all US warheads in less than ten years if operated six days a week. The main characteristics of a corresponding facility in the Soviet Union might be similar.

The average daily outputs of uranium-235, plutonium, and tritium correspond to averages of 20 kilograms, 4 kilograms, and 4 grams, respectively, per warhead (see table 1).

The average weight of a warhead now in the US stockpile is about 350 kilograms.[20] This corresponds to an average daily input of 2,800 kilograms of total warhead weight. The weight of other objects, such as re-entry vehicle structures and guidance packages, in the warhead shipping containers is unlikely to exceed that of the warheads. Additional material in the warhead containers, added to mask the weight of the warheads, might also be as much as another 2,800 kilograms per day, for a nominal total of about 8,400 kilograms removed from the containers each day.

If half the average warhead weight is assumed to be high explosive, the corresponding high explosive input is 1,400 kilograms per day. Most of the residue from burning this will be gaseous products vented, after scrubbing, to the atmosphere.

The remaining average of about 7,000 kilograms per day of non-nuclear materials and thermonuclear fuels not containing tritium could be separated into valuable materials (such as deuterium or beryllium) to be returned to the owner country, and waste materials for direct disposal. In any case, if all these materials were compacted into slabs with a bulk density in the vicinity of 4 grams per cubic centimeter, their total volume would be 1.8 cubic meters per day. A reasonable actual size for each slab might be 1 square meter, with a thickness of 4 centimeters corresponding to an average weight of about 160 kilograms. Each of these slabs (about 40 per day), supported horizontally, could then be conveniently scanned with gamma rays and neutrons to ensure they contained no fissile material or uranium-238.

The warhead and nuclear material storage capacities shown in table 3 correspond to 100 days of average throughput. This is a rough estimate that allows for process holdups and fluctuations.

At less than ten tonnes per day, the facility's daily total input of materials to be processed is similar to that of commercial mixed uranium and plutonium oxide reactor fuel fabrication plants. The capital costs of such plants are several billion dollars. Since none of the final products of a warhead dismantlement facility are components fabricated to exacting tolerances, it seems reasonable to expect that the capital cost of a new dismantlement facility would be lower.

Labor costs for operating such a facility are unlikely to be greater than ten or twenty million dollars per year. A full-time work force of 100 direct labor employees, at $100,000 per person-year (including overhead), would amount to $10 million per year.

It is therefore unlikely that the total costs of dismantling the world's nuclear warheads, and providing the contained fissile materials for use as nuclear fuel or for direct disposal would exceed a few billion dollars.

Table 3: Preliminary Parameters for a US Nuclear Warhead Dismantlement Facility

Capacity	8 warheads/day (25,000 in 10 years)
Average uranium-235 output	160 kg/day
Average plutonium output	32 kg/day
Average tritium output	32 g/day
Storage capacities (100 days throughput)	
Undismantled warheads	800, in containers
Uranium-235	16,000 kg
Plutonium	3,200 kg
Tritium	3.2 kg

TIMING

It is possible that detailed design and construction of facilities needed for eliminating large numbers of warheads may be the pacing items that determine when the complete elimination process can actually begin.

If a treaty calling for elimination of large numbers of warheads comes into force before the needed facilities exist, the warheads could be tagged and sealed in containers, and placed in storage to await completion of the dismantlement facility.

In any case, optimism about new treaties calling for elimination of many warheads should carry with it a considerable sense of urgency about the means for eliminating the warheads. If it is determined that modification of existing dismantlement facilities in the two countries is not appropriate, designing and building new facilities may be necessary.

NEXT STEPS

The concepts and analyses presented in this paper indicate that elimination of identified nuclear warheads that are specified in a nuclear disarmament treaty can be verified with high confidence, without revealing national secrets about warhead designs. Much remains to be done, however, to specify procedures for accomplishing this objective in sufficient detail to provide the basis for negotiated formal protocols and the means for carrying them out.

Two consecutive next steps are therefore proposed.

The first is the establishment of an official joint US-Soviet working group to design and assess specific procedures and corresponding facilities for verified elimination of nuclear warheads. Work by this group should be given high priority by both nations and not require negotiation of further treaties.

The second step is to carry out joint US-Soviet demonstrations of the techniques identified in the first step. These demonstrations would be expected to include some field testing of parts of a warhead dismantlement and verification system. Initial tests could be performed using unclassified mockups of warheads. These could be followed with complete system tests, using warheads from each nation.

Results of these two steps could then be incorporated into negotiated protocols for verification of new treaties.

NOTES AND REFERENCES

1. INF Treaty, protocols for verification, December, 1987.

2. See, for example, J. Taylor, J. Barton, and T. Shea, "Converting Nuclear Weapons to Peaceful Use," *Bulletin of the Atomic Scientists*, February 1985; James de Montmollin, "Some Considerations Involving Verification of New Arms Control Agreements," unpublished report, December 1985, and "Value of Fissile Material from Dismantled Warheads as Reactor Fuel," unpublished report, June 1986; and E. Amaldi, U. Farinelli, and C. Silvi, "On the Utilization for Civilian Purposes of the Weapon-grade Nuclear Material that May Become Available as a Result of Nuclear Disarmament," report of the Accademia Nazionale dei Lincei, Rome, 23–25 June 1988.

3. Robert S. Norris and William M. Arkin, eds., "Nuclear Notebook," *Bulletin of the Atomic Scientists*, June 1988 and July/August 1988. Estimates of the numbers of warheads are much more uncertain for the Soviet Union than for the US. The estimated number of Israeli warheads is based primarily on revelations by Mordechai Vanunu in the London *Sunday Times*, 5 October 1987.

4. Frank von Hippel, David H. Albright, and Barbara G. Levi, "Fissile Materials in US Warheads and Plutonium in Soviet Warheads," *Quantities of Fissile Materials in US and Soviet Nuclear Weapons Arsenals* (Princeton: Princeton University, July 1986), PU/CEES Report No. 168. I have assumed that the uranium-235 and tritium in the Soviet stockpile are each the same as those in the US. Either or both of these assumptions may be far from correct.

5. Derived from Thomas B. Cochran, William M. Arkin, and Milton M. Hoenig, eds., *US Nuclear Forces and Capabilities* (Cambridge, Massachusetts: Ballinger, 1984).

6. For Western capacities: *The Nuclear Power Plant Capacity of the Western World*, (Alzenau, West Germany: NUKEM, April 1987), NUKEM special report.

7. For capacities of USSR, Eastern Europe, and China: "World Survey," *Nuclear Engineering International*, June 1987, pp.28–39.

8. David Albright, "Civilian Inventories of Plutonium and Highly Enriched Uranium," in Paul Leventhal and Yonah Alexander, eds., *Preventing Nuclear Terrorism* (Lexington, Massachusetts: Lexington Books, 1987), pp.265–297.

9. We base the estimate of uranium values on the assumption that the value of uranium-235 (in uranium enriched to about 3 percent in uranium-235) to be used for fuel in the world's nuclear power plants during the next decade is about \$38,000 per kilogram. Of this total, \$19,000 is accounted for by an assumed price of \$66 per kilogram for unenriched U_3O_8; \$2,000 per kilogram by conversion to UF_6 prior to enrichment; and \$17,000 per kilogram for enrichment to 3 percent uranium-235 (with 0.3 percent in the depleted "tails"). Enrichment costs correspond to \$150/SWU. All these costs are consistent with recent average costs presented in *NUKEM Market Report on the Nuclear Cycle* (Alzenau, West Germany: NUKEM, April 1987). Separative work requirements for uranium enrichment as functions of enrichment of product and tails are from *Standard Table of Enriching Services* (Washington DC: DoE).

10. This presumes that worldwide use of nuclear power will continue for several decades and show at least moderate growth. If, for whatever reasons, this should not be the case, and international markets cannot absorb the uranium-235 from nuclear warheads dismantled in the course of vigorous nuclear disarmament, it could be rendered useless for nuclear explosives by dilution with natural or depleted uranium.

11. The estimated global weapon plutonium inventory is about 20 percent of the weapon uranium-235 inventory. Since plutonium-bearing fuel costs much more to fabricate than all-uranium fuel, the value of plutonium per kilogram, as feedstock for reactor fuel, is less than for uranium-235.

12. W. A. Higinbotham, Brookhaven National Laboratory, private communication, 1988.

13. Alex DeVolpi, Argonne National Laboratory, private communication, July 1988.

14. For a summary of portal monitors for detection of fissile materials, see "Portal Monitors," David Albright, Federation of American Scientists, to be published.

15. Fetter et al., "Fissile Material Detection," *Science and Global Security,* to be published. The best approach is probably to use an external, pulsed 14-MeV neutron source to stimulate fissions in plutonium or uranium, and observe delayed fission neutrons or gamma rays emitted from the object being scanned.

16. Richard L. Garwin, private communication, March 1989.

17. Such estimates can be derived from published or estimated aggregate separative work units applied to uranium enrichment, provided the enrichment of tails and products is known. It is possible that sometime in the future further releases of national data of this kind will make such estimates more accurate than they can be today. See "Controlling Nuclear Warheads," Frank von Hippel, Federation of American Scientists, to be published.

18. J. Carson Mark, Theodore B. Taylor, Eugene Eyster, William Maraman, and Jacob Wechsler, "Can Terrorists Build Nuclear Weapons?" in Leventhal and Alexander, 1987, pp.55–65.

19. ibid.

20. Derived from data in Cochran et al. See note 5.