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Verifying the Number of Warheads on Multiple-warhead Missiles through On-site Inspections

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The US and the USSR currently have most of their strategic ballistic-missile nuclear warheads on missiles equipped with multiple-independently targeted re-entry vehicles (MIRVs). START and subsequent strategic arms-control agreements to reduce the numbers of these warheads might alternatively mandate a reduction in the number of missiles capable of carrying MIRVs or in the number of warheads actually deployed on such missiles (or a mixture of both). This latter alternative will be termed "deMIRVing."

In general, reduction in the number of missiles (or, in the case of ballistic-missile submarines, in the number of launch tubes on each submarine) should be the preferred alternative to achieve reductions in the number of ballistic-missile warheads. The danger posed by deMIRVing is that of breakout. It may be possible to quickly restore missiles that have been tested with a large number of warheads, but have since been deMIRVed, to their previous, larger payloads.

The risk of such a breakout is related to the time and effort it would require and to how well any breakout activity could be monitored by other parties. The procedures used in a breakout would probably be similar to those required for maintenance of the re-entry vehicles (RVs) and the "bus" system, which places the re-entry vehicles on their final individual trajectories. With some intercontinental ballistic missiles (ICBMs) this may require only that a missile be lifted slightly from the silo to allow access to the nose-cone region;

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or possibly the maintenance could be done in place. In these cases, the removal of the nose cone and any other protective shrouds, and either the addition of the extra warheads or the replacement of the entire bus and its warheads with another containing more warheads might take little more than a day for a well-trained crew that regularly performs similar work during maintenance. Were this so, several crews might be able to re-equip hundreds of ICBMs with MIRVs in a month or two. In these circumstance, deMIRVing should be regarded, at best, as a temporary measure, pending agreement on less easily reversible reductions.

On the other hand, if it were necessary to remove the missiles from their launchers, as would most likely be the case with submarine-launched ballistic missiles (SLBMs) and missiles carried by mobile launchers, and to take them to a special facility for RV insertion, a week or more might be required to re-equip a single missile, and a breakout involving hundreds of missiles might require several months and would likely be observed. Arrangements might be negotiated as part of a reduction agreement to make breakout still more difficult and time-consuming and visible. In these circumstances, deMIRVing might be a useful part of an arms-reduction agreement.

In this case, methods of counting the number of warheads on a deMIRVed missile must be developed to ensure confidence that the treaty is being observed. The following discussion deals with the technical problem of ensuring that the number of warheads installed is the number agreed upon. A difficulty is that many details of the busing systems and of the re-entry vehicles and the warheads that they contain may be considered secret by the owners; verification procedures must somehow be able to count the number of warheads without revealing these secrets.[1]

The inspection would preferably be by visual means. If it is felt that this reveals too many design details, the use of penetrating radiation might be considered. Radiation emitted by the uranium and plutonium in the warhead could be used or external radiation could be applied for radiography or to increase the output of radiation from the warhead through induction of fission. It will be shown that the most suitable technique using penetrating radiation is radiography.

THE VERIFICATION CONTEXT

Under a deMIRVing treaty, negotiations would limit the number of warheads that could be deployed on each of a declared set of missiles to some agreed value. These missiles would be subject to on-site inspections, both to monitor the elimination of excess warheads and to monitor that the deMIRVing was not later reversed. Monitoring the destruction of excess warheads coupled to safeguards on the recovered fissile material and a cutoff in new fissile-material production for weapons would make breakout more difficult.[2]

The deMIRVed missiles would themselves be subject to random on-site inspections to ensure that they remain deMIRVed. Since any missile found with more than the allowed number of warheads would indicate noncompliance, inspection of a relatively limited number of randomly selected missiles would be likely to expose cheating involving a large fraction of the missiles. If, for example, a party to the agreement cheated by not taking the warheads off of 25 percent of its missiles, it would have a 25 percent chance of getting caught by one random inspection and a 44 percent chance of getting caught by inspection of two missiles. In general, if a fraction C of the missiles are in noncompliance, the probability of catching the violator by inspecting S missiles is approximately $1 - (1 - C)^S$. If some of the deMIRVed missiles were later subject to dismantlement, statistical sampling could also be obtained by selecting randomly the missiles to be dismantled.

Sampling only a few missiles each year would make it easier to arrange for ICBMs to be removed from their silos or SLBMs from their launchers to a facility at which the special access required for x-ray radiography would be easily available. There would also be much less chance of damage to the missile from the inspection apparatus, and radiation barriers could be readily installed to prevent excessive radiation doses to those performing the inspection. In a situation involving inspection of a small fraction of the missiles, even destructive levels of radiation or other measures that might make the missile unusable could be used as part of a procedure to check the number of warheads.

To simplify direct checks of larger numbers of missiles in the field, it is worth investigating the possibility that the missile payload as a whole might have detectable characteristics that change as the number of warheads on the missile is reduced. This may be a pattern of spontaneous radiation, a pattern of induced radiation in response to low levels of neutron or gamma irradiation, a radiation transmission pattern or a pattern of sound waves generated by an inserted acoustic source. A very detailed examination of a single deMIRVed missile might establish both the number of warheads it carried and such a characteristic set of "fingerprints." The fingerprints then could be used as a template in examining other missiles of the same type to determine whether they had been modified in accordance with the deMIRVing agreement.

Tagging and sealing could also be very helpful. If each of the missiles were inspected at the time that it was deMIRVed, and if it were then tagged and sealed, there would be no need for further inspection except to see that the missiles were still tagged and sealed. This would be a particularly useful alternative if there was concern that the high levels of radiation used in repeated active examinations might cause damage. For such a system to work, however, it would be necessary that access to the interior of the sealed volume for maintenance be required very infrequently. An alternative suggested by Garwin[3] is to tag and seal dummy re-entry vehicles in the locations of the missing ones. This would allow regular maintenance of the approved RVs without breaking any seals.

It might also be appropriate in some circumstances to tag missiles before deMIRVing. Each of the missiles could then be moved into a controlled area, entering as tagged with the original number of re-entry vehicles. The re-entry vehicles to be removed would be withdrawn from the controlled area in conformable canisters that would be checked to confirm that each contained a warhead. The deMIRVed missile would then be tagged and sealed and returned to its launcher.

METHODS OF ON-SITE INSPECTION

The four methods for counting warheads during an on-site inspection considered in this paper are:

- Visual inspection after removal of the nose cone
- Detection of the penetrating radiation spontaneously emitted by the fissile material[4]

- Use of neutron or x-ray radiography to reveal warheads through the dense core of absorptive fissile material that each warhead contains
- Irradiating the warhead region with high-energy neutron or x-ray beams to excite fission in the fissile cores thus increasing their emission of penetrating radiation.[5]

As indicated the first method requires removing the nose cone of the missile. The remaining three methods do not.

Visual Inspection

The best verification system is one with minimal technical complexity. This would be to remove the nose cone of the missile and any other protective shrouds, and to directly count the number of RVs by visual observation. In spite of the design information that might be made available by this procedure, it is not an unlikely scenario. Pictures of US RVs and delivery buses already exist in the open literature. If the Soviet Union maintains its present attitude toward verification, it is likely that it would agree to visual inspection.

Even if complete visual inspection is not acceptable, a restricted inspection might be. After removal of the nose cone, a conformal cover could be placed over the RVs to allow a view of them that is adequate for counting but does not give away detailed information about the design of the RVs or their delivery bus but made clear the absence of those that had been removed. These methods seem best suited to delivery-bus designs with all the RVs mounted in a single plane.

This sort of restricted visual inspection would, in most cases, require good access to the missile payload region. For silo-based ICBMs it should be possible to use those access methods normally used for ICBM maintenance whether at the silos or in special facilities to which the missiles are moved for servicing. Submarine-based ballistic missiles and mobile ICBMs would probably fall into the latter category.

These visual methods of inspection might not work if any slots of the delivery bus are occupied by heavy decoys designed to look identical to the real RVs. Some detail of the decoy might distinguish it from the RV but knowledge of the distinction might also reveal information that would help to distinguish it from the RV when in flight. Such decoys would either have to be counted as re-entry vehicles, or techniques such as those discussed below would have to be used to check whether they contained fissile material.

Passive Inspection

An attractive method for counting nuclear warheads would be to use the penetrating radiation that is spontaneously emitted by the uranium or plutonium isotopes that they contain. The effectiveness of this method depends critically, however, on the materials from which the weapons are constructed.

A combination of neutron and gamma-ray detectors should be able to detect the radiation from warheads containing kilogram quantities of plutonium and/or uranium-238 at a distance of a few meters. Shielding to prevent detection would be impractical, given the limited space and launch mass capacity of strategic ballistic missiles.

Fetter et al.[6] make estimates of the radiation from four possible fission warhead designs. With three of the designs, which incorporate either large quantities of gamma-radiation–emitting uranium-238 in the tamper or significant percentages of neutron-emitting plutonium-240 in a plutonium core, passive detection was found to be possible. In the case of a weapon using a core of weapon-grade uranium (WgU) and a tungsten tamper, however, the radiation emitted—a total of 20 neutrons and 30 gamma rays per second—is so small that it could be undetectable in the presence of other signals and background.

The examples given by Fetter et al. are not actual weapon designs but conform to estimates of the average amount of fissionable material used in warheads, on known sizes and weights of ballistic-missile warheads, and on a general "public" understanding that in the fission trigger of a strategic nuclear warhead, the fissionable materials are formed into a spherical shell, which is then compressed by explosive charges to start the chain reaction. The numbers derived are probably accurate to better than an order of magnitude. They relate only to the fission trigger of fusion weapons. Actual weapons might produce much more radiation than that given in these estimates, if uranium were used in the fusion component of the warhead or if there were present highly radioactive contaminant isotopes such as the uranium-232 which was detected in a Soviet cruise missile warhead in the "Black Sea Experiment."[7] For the purpose of verification, however, it is best to assume that, if cheating were done, there would be a great effort to use low-radiation–emitting materials. It is therefore important to note that it is possible to reduce significantly the emission of neutrons from plutonium weapons by using highly purified plutonium-239 instead of ordinary weapon-grade plutonium, which is 6 percent plutonium-240. The use of very pure plutonium-239 in combination with a tungsten tamper would make this type of weapon almost undetectable. The additional cost of the processing required might be of the order of $1 million per kilogram[8]—a significant cost but not out of the question.

Using the spontaneous radiation emitted by warheads to count the number carried by a missile is much more difficult than merely noting the presence of radiation. The radiation from the approved warheads can produce a very large background making essential a collimated detector and a reasonably large signal from the hidden warheads.

Radiographic Inspection

The specific objective for radiographic inspection can be defined as counting the number of high-density, heavy-metal concentrations within the missile nose cone. Because of payload weight limitations, there is no plausible nonweapon purpose for such masses on a ballistic missile. Any high-density concentration averaging 7 g/cm^3 or more[9], distributed over a volume with a radius of roughly 10 centimeters, would be considered to be part of a nuclear warhead.

Both high-energy neutrons and gammas can penetrate moderate quantities of normal structural materials, including aluminum, steel, carbon, and plastics, and give good transmission contrast for weapon-like configurations.

This method of examination would place the source of a neutron, gamma-ray, or x-ray beam[10] on one side of the nose cone and detectors on the other (figure 1). Both source and detector would then be rotated around the missile nose cone to produce projected radiographic "images" of the warheads by

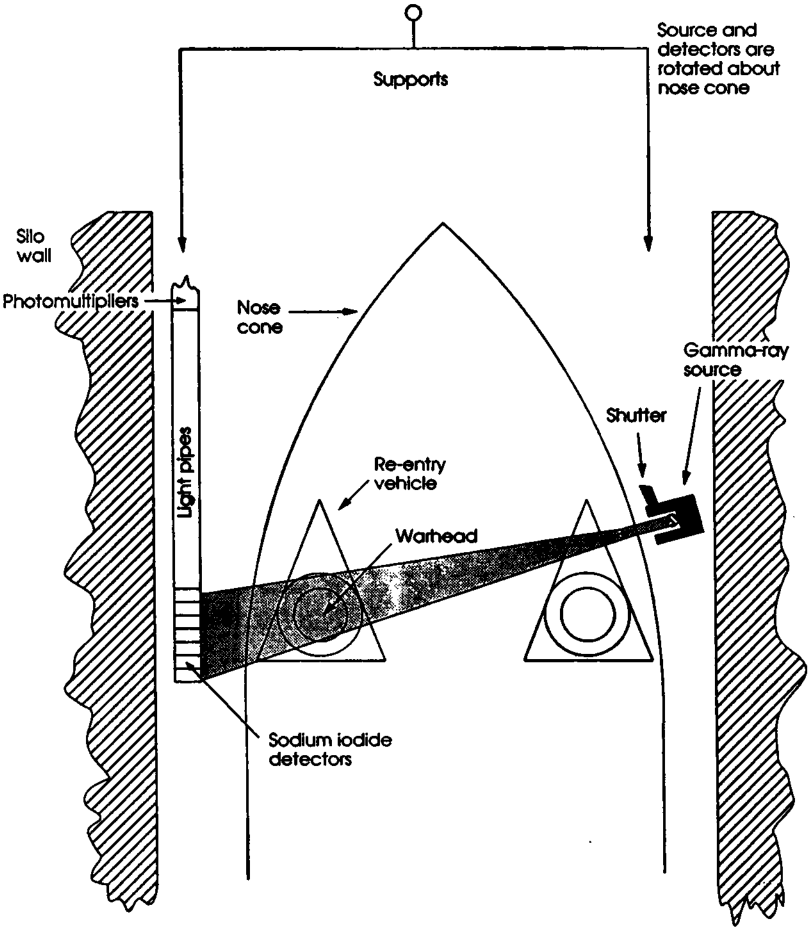

Figure 1: Radiographic examination of missile warheads in silo

showing the absorption produced by the fissile material.[11,12]

Although neutron and x-ray accelerator sources can be made small in size and allow some choice of the beam particle energy, isotopic radioactive sources may be more convenient and less expensive[13]. Their use might also be more reassuring to the inspected group because of the inherent limits on the maximum intensity that might be generated "accidentally."

The detection scheme shown in figure 1 uses a 1-MeV gamma-ray source. This could be a radioactive isotope enclosed in a well-type container with a remotely operated opening and a collimator. At a greater cost and complexity, an electron accelerator could be used to gain greater penetrating power and control of both intensity and energy.

A very strong cobalt-60 source of about 1 curie would emit 300,000 gammas per second into a solid angle of about 10^{-4} steradians. On the other side of an approximately 2-meter–diameter missile nose cone a 20 × 20–centimeter array of sodium iodide detectors would be more than adequate to register the transmitted beam. The sodium iodide detectors could be made sensitive only to the highest-energy gamma rays so that scattered gamma rays, which would always have lower energies, could be ignored. The resolution obtained would be slightly smaller than the size of the individual sodium iodide crystals used.

A diagrammatic cross section of a hypothetical WgU-tungsten warhead can be seen in figure 1 of "Detecting Nuclear Warheads" (this issue) while figure 2 of the present paper shows in high resolution the attenuation of 1-MeV gamma rays passing through this warhead as a function of the beam's lateral radial distance from the center.[14]

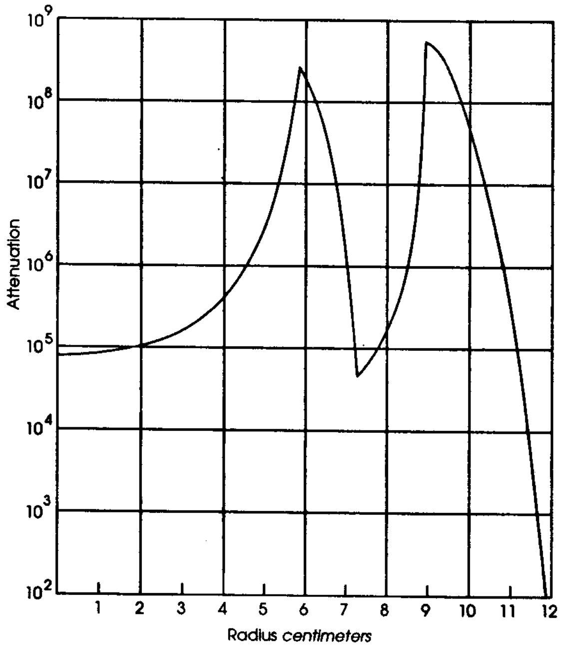

Figure 2: Attenuation of transmitted gamma-ray intensity from radiographic examination (resolution comparable to diameter of warhead tamper)

To prevent the inspection from revealing sensitive design information, the spatial resolution could be limited by controlling the detector size, the length and diameter of the collimator, the number of scan increments, the source strength, and the counting time. Data from the radiation detectors could be delivered at the same time to both host and inspection teams. A preinspection test of resolution could be carried out at the site with a slug of heavy metal (for example, depleted uranium). Radiation-dose monitoring would also be needed to avoid damage to sensitive components.

It would also be possible to produce an algorithm to allow the examination to be performed using a computer interface to restrict the detail of the image presented to the verification team of the object scanned. A possible method would have the computer search for large attenuation recorded by a group of sodium iodide detectors and then signal to those persons operating the system that the detector system had shown the presence of an absorbing object at a specified location. The computer program could be jointly produced and monitored by both the verifying and host groups and could be tested on mock-ups.

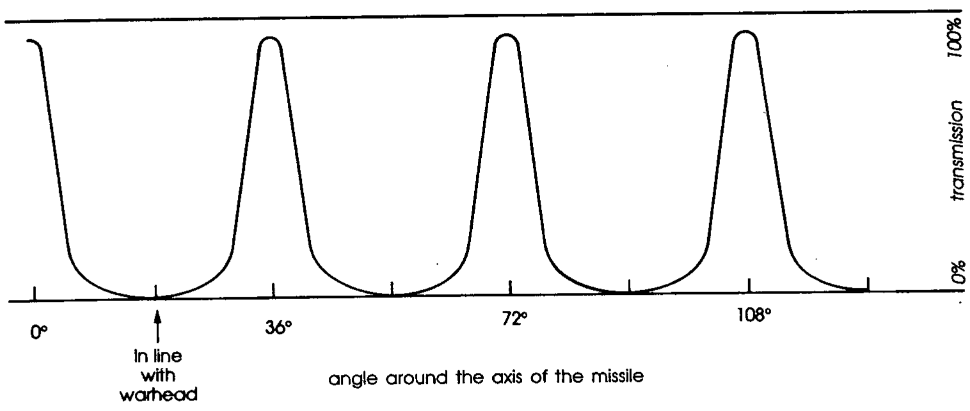

Figure 3: Transmitted gamma-ray intensity from radiographic examination of a missile with 10 warheads arranged in a circle observed as source and detector are rotated about its nose cone. The resolution (10 centimeters) is comparable to diameter of warhead the tamper. Note that the beam line is at an angle so that it is assumed to intersect only one warhead core at a time.

Figure 3 shows the absorption from a circle of warheads of the type shown in "Detecting Nuclear Warheads" with a resolution just equal to the diameter of the tamper. Only about 10 photons in a million incident would pass through the central region intercepted by the fissile material. The tamper alone causes attenuation by a factor of about 50,000 when the beam passes through the tamper far enough from the center of the warhead that it does not pass through the fissile material. Passage through the thickness of conventional explosive, by contrast, attenuates the beam by less than a factor of 10. Although nuclear warheads may differ from the hypothetical design, they will contain comparable concentrations of heavy metals.

Although a very large cobalt-60 source would be required to allow inspection of a nose-cone region in a reasonable time (an hour), its beam at a distance of a meter would be depositing less than 10^{-5} rads per second and at 10 centimeters less than a millirad per second. This is dangerous for human exposure but far too small to damage sensitive weapon components.

Neutrons interact differently from gamma rays, and comparing the transmission of neutron and x-ray beams would allow more information to be obtained about the materials present in the object being examined. This is not necessarily desirable in a verification tool, however, because the missile's owner may wish to keep such information secret. Collimating neutron sources is also more difficult than collimating gamma-ray sources and the measurement of neutron energy would not seem practical in this type of operation. Gamma rays therefore appear more suitable for the present purpose.

A fundamental difficulty with the use of transmission inspection in the field is that there may not be space to place the radiation source on one side of the missile nose cone and the detectors on the opposite side. In particular in the environment of some silos, it might be feasible to place equipment only above the nose cone. In this case it would be necessary to raise the missile from its normal position and perform the inspection above the silo or launch tube. It is probable that access to service some silo-based missiles is obtained by raising them in this way. Using radiography to inspect missiles carried by submarines may require removal of the missiles from their launch-tubes and moving them to a nearby facility where radiography could be conveniently accomplished. Similar arrangements may be appropriate for missiles on land-mobile launchers.

Detection Through Induced Fission

In those situations that do not allow transmission examination, inducing fission with external neutron or gamma beams might be considered as an alternative means of locating masses of fissile material. A possible arrangement of equipment for generation of a gamma-ray beam and detection of induced neutrons is shown in figure 4.

If "activation inspection" is used to search for extra undeclared warheads on a deMIRVed missile, however, the presence of the declared warheads may

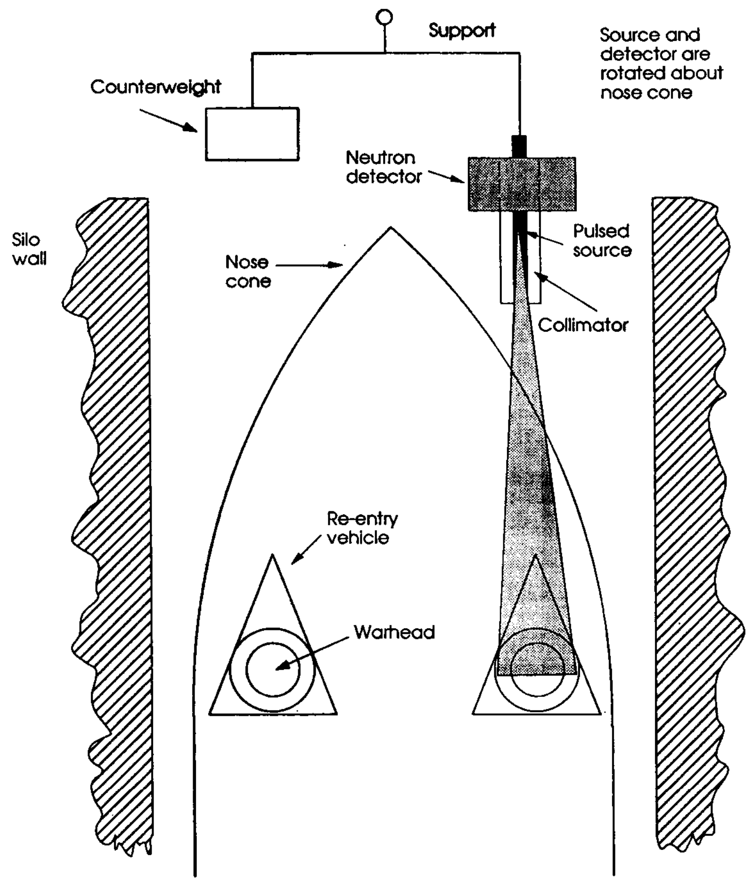

Figure 4: Search for a hidden warhead by fission excitation

cause a severe background. In particular, if the declared warheads have cores containing about 4 kilograms of ordinary weapon-grade plutonium (6 percent plutonium-240), they will be emitting about 400,000 neutrons per second.[15] A large number of fissions would have to be induced in any undeclared warhead in order for it to become detectable against this very large background.

The most effective particle for producing fission is a neutron, but a neutron beam will be difficult to use in the presence of declared warheads because the neutrons in the beam can scatter to these warheads and increase still further the background fission signal from warheads not directly illuminated. The low-energy neutrons scattered from the incident beam would be even more effective in causing fission than the higher energy ones present in the original beam.[16] With excellent collimation of the detector, these effects can be reduced but the use of an energy-sensitive neutron detector would still be required to make possible the rejection of low-energy neutrons scattered into the collimator.[17] An alternative would be to use an electron accelerator to produce an x-ray (bremsstrahlung[18]) beam of 10–15 MeV peak energy. Such an x-ray beam can be collimated to prevent its hitting areas other than that at which it is directed. Its energy would be high enough (over 5 MeV) to stimulate fission and could be varied to give information about backgrounds due to nonfission nuclear reactions. In contrast to neutrons, once a photon has scattered at a large angle it will lose enough energy that it can no longer stimulate fission.

Unfortunately, the cross section for high-energy x-rays producing fission in fissile materials is about a thousand times smaller than that for high-energy neutrons. This small cross section can be readily compensated by increasing the intensity of the photon beam from a linear accelerator, but at the cost of more radiation damage.

The particles used to detect induced fission must be different in some characteristic from those of the beam and from those produced by nonfission nuclear reactions caused by the beam. Table 1 shows some possible combinations. It would not be possible, for example, to use the detection of prompt gamma rays as evidence of x-ray induced fission because there are too many other sources of such gamma rays. They can come from other gamma interactions in the material examined and from neutron-induced interactions (the

Table 1: Combinations of source beam and resulting radiation useful in detecting fissionable material

Source beam	Detected radiation
Low-energy neutrons	High-energy neutrons
X-rays	Neutrons
Pulsed neutrons	Delayed neutrons or gamma rays
Pulsed x-rays	Delayed neutrons or gamma rays

neutrons coming from spontaneous fission in the declared warheads). Similarly, although the prompt-neutron signal from photofission would be quite strong, the cross section for x-rays to produce neutrons from reactions with nonfissile nuclei could be 10 times larger.

The most distinctive signal from photofission would be delayed neutrons. Although there are less than 1 percent as many delayed neutrons from fission as prompt ones, almost no delayed neutrons are produced by a photon beam through nonfission reactions. Nonfissile nuclei excited by the photon beam can also produce delayed gammas.

We therefore assume a procedure in which a pulsed photon beam is scanned over the nose cone from above and the delayed fission neutrons are detected by a partly collimated detector (figure 5).

It is so easy to produce a well-collimated x-ray beam using a linear accelerator that the distance from the linear accelerator source to the missile nose cone is not important. The beam can readily be made so small as to hit only the area subtended by the fissile material in a single warhead. In estimating the delayed-neutron signal from a warhead illuminated by such a beam, we therefore assume that the x-rays are all incident in a useful region.

An x-ray beam created by the collision of 15-MeV electrons with a dense target material is assumed: such a bremsstrahlung beam contains photons of all energies with approximately equal total photon energy per MeV from 0 to 15 MeV individual photon energy. Only photons with energies above 5 MeV would induce fission. The ratio of the fission cross section to the total cross section gives the fraction of the incident photons that are usefully absorbed in the fissionable material. In the hypothetical warhead discussed above, the major absorber for the incident x-rays before they reach the fissionable material will be the tungsten tamper. (If a depleted uranium tamper were used, it would be a source of induced fission neutrons.) The 3 centimeters of tamper would transmit only about 5 percent of 5–15-MeV x-rays. In the fissile material, an absorption length by electromagnetic interactions is about 1 centimeter and about 1 in 20,000 of the photons reaching the fissile material would cause fission in it. Of those photons with energy greater than 5 MeV incident on the warhead, one in 4×10^5 would cause fission. As delayed neutrons occur at a rate of somewhat less than 1 percent per fission, the total number of incident photons per delayed neutron would be of the order of 40 million.

If a SLAB[19] neutron detector with an area of 0.56 square meters and efficiency of 7 percent were located about 3 meters away from a possible hidden warhead, it would detect 1 in 3,000 neutrons emitted by the warhead. The background from the declared warheads could easily be about 400,000 neutrons per second per warhead. If we assume the presence of three of these warheads—also at a distance of about 3 meters from the detector—it would count about 400 of their emitted neutrons per second. To obtain a five-standard deviation effect above this background[20] the signal would have to be five times larger than the square root of the integrated background count.

An examination of the time delays for emission of delayed neutrons shows that about half of all neutrons would be observed in about 10 seconds. Unless there are rate-dependent radiation-damage effects, a good inspection procedure would be to stimulate the fission using a very short beam pulse. The time could be as short as a microsecond. One would then observe the delayed neutrons for about 10 seconds.

To express the situation algebraically, $S = 5\sqrt{B}$ where S is the signal and B is the background,

$$S = \frac{A \varepsilon N_s t}{4 \pi r^2}$$

with A the area of the detector, ε its efficiency, N_s the average number of delayed neutrons emitted per second from the stimulated material, t the observation time in seconds and r the distance to the detector,

$$N_s t = IaFDd$$

with I the number of incident photons with energy greater than 5 MeV aimed at the suspected warhead, a the attenuation factor of the beam before it reaches the fissile material in the warhead, F the fraction producing fission, D the fraction of delayed neutrons per fission and d the fraction of the delayed fission neutrons emitted in the time t,

$$B = \frac{A\varepsilon N_B t}{4\pi r^2}$$

where N_B is the number of neutrons emitted by the declared warheads. (It is assumed that the distance r to the declared warheads is the same as that to any hidden ones.) The general neutron background is negligible in comparison.

From these relationships we can derive the following expression for I, the number of photons with energy greater than 5 MeV in the x-ray beam:

$$I = \frac{5\sqrt{N_B t \, 4\pi r^2}}{aFDd\sqrt{A\varepsilon}}$$

Using the following values of the parameters:

$N_B = 1.2 \times 10^6$
$t = 10$ seconds
$r = 300$ centimeters
$a = 0.05$
$F = 5 \times 10^{-5}$
$D = 0.01$
$d = 0.5$
$A = 5{,}600$ square centimeters
$\varepsilon = 0.07$

we obtain $I = 7.4 \times 10^{13}$ incident photons with energies above 5 MeV to produce a detectable number of delayed neutrons from an undeclared warhead. In the energy region between 5 and 15 MeV a bremsstrahlung spectrum with a peak energy of 15 MeV would contain approximately 1 photon per 15 MeV of energy in the total spectrum (ln[15/5] =1.1). Therefore $7.4 \times 10^{13} \times 15$ MeV or approximately 10^{15} MeV will be deposited by the number of photons needed to make a detectable signal. If the beam irradiates an area equal to the size of the fissile material in the warhead—about 150 square centimeters in the example shown in figure 1—and penetrates to a depth of 20 g/cm^2, a mass of about 3,000 grams will be irradiated, and the energy deposited per gram will be about 4×10^{11} MeV. Since 1 MeV per gram = 1.6×10^{-8} rads this would give a radiation exposure of about 6,000 rads. If the same beam intensity were aimed at a smaller area, as might be appropriate for a plutonium core, the radiation exposure would be even higher. The inspection procedure could easily double or triple this value. If there was concern about the possible presence of additional shielding, 10–100 times more radiation might be required. Such high exposures would cause radiation damage to sensitive electronics.[21]

CONCLUSION

In a nuclear-weapon reduction agreement, the achievement of warhead reductions through reductions in the number of warheads carried by existing missiles would be inadvisable if the deMIRVing could be rapidly reversed. However, if this breakout problem can be reduced to manageable proportions, there are several methods for verifying the deMIRVing. Visual methods of inspection would be the most straightforward but may not always be applicable. The other techniques investigated in this paper employ penetrating radiation. The most suitable of these appears to be the use of radiography. It is possible to design warheads that are very difficult to detect by their spontaneously emitted radiation while the use of neutron-induced fission to increase radiation output is complicated by the likelihood that the radiation background will also be increased through induced fission in the allowed warheads. The use of x-ray induced fission may result in unacceptable large radiation doses to the electronics of the missile.

The choice of system to be used also depends on the available access to the nose-cone area, the structure of the bus system involved (in particular whether it carries more than one layer of warheads), the procedures planned for deMIRVing (whether the missiles will be removed from their launchers during this process), and the confidence placed in tagging and sealing systems. Therefore, in order to determine the methods most appropriate for verification in each specific case, negotiations must provide for some preliminary inspection of the launchers and missiles before the choice of verification system is settled.

NOTES AND REFERENCES

1. As part of the Strategic Arms Reduction Talks, Soviet and US negotiators have agreed to allow inspection of each other's strategic ballistic missiles to help establish procedures to verify that the missiles hold no more than a declared number of warheads. The Soviets were scheduled this spring to inspect the warhead bus for the US MX missile in a visit to Warren Air Force Base in Cheyenne, Wyoming; inspections of the US Trident II missile and the Soviet SS-N-23 are planned. *Aviation Week & Space Technology*, 29 January 1990, p.17

2. Theodore B. Taylor, "Verified Elimination of Nuclear Warheads," *Science & Global Security* **1**, 1–2 (1989).

3. Richard L. Garwin, "Tags and Seals for Arms Control Verification," 1 August 1988, pp.11,12 (unpublished manuscript).

4. This method was previously discussed in Alex De Volpi, "Expectations from SALT," *Bulletin of the Atomic Scientists*, April 1970, p.6.

5. Ibid.

6. Steve Fetter, Valery A. Frolov, Marvin Miller, Robert Mozley, Oleg F. Prilutsky, Stanislav N. Rodionov, and Roald Z. Sagdeev, "Detecting Nuclear Warheads," in this issue.

7. See "Occasional Report: The Black Sea Experiment," this issue.

8. Fetter et al.

9. In g/cm^3 the density of aluminum is 2.7; iron, 7.9; lead, 11.3; plutonium, 16–18 (depending on crystal structure); and uranium, 19.

9. In g/cm^3 the density of aluminum is 2.7; iron, 7.9; lead, 11.3; plutonium, 16–18 (depending on crystal structure); and uranium, 19.

10. It is conventional to describe a high-energy photon (energy of the order of 1-MeV or more) as being a gamma ray if it comes from a radioactive nucleus and an x-ray if it is created in a collision of a high-energy electron with a target.

11. Alex De Volpi, *Fast Neutron Radiography with National Security Applications* (Argonne National Laboratory). Summary for submission to ANS Washington DC meeting November 1986.

12. Alex De Volpi, "Applications of Cineradiography to Nuclear Reactor Safety Studies," *RSI*, **55**, 1197 (1984).

13. T. Gozani, *Active Non-destructive Assay of Nuclear Materials, Principles and applications*, (Washington DC: US Nuclear Regulatory Commission, NUREG/CR-0602) pp.109–120 (gamma-ray sources), pp.83–107 (neutron sources).

14. To a first approximation, a photon or neutron beam passing through a material is attenuated exponentially. Thus, if given thickness of material reduces the beam intensity to one half, twice the thickness will reduce it to a quarter.

15. Fetter et al.

16. The fission cross section for a very-low-energy "thermal" neutron can be hundreds of times higher than that for a high energy neutron.

17. Development work is being done on a double scattering neutron detector capable of obtaining angle and efficiency information concerning incoming fission neutrons. If efficiencies of the order of 1 percent and angular resolution of 10° can be obtained, such a detector could significantly reduce backgrounds and would be very useful in fixed installations. W. Sailor, R. Byrd, Y. Yariv, A. Gavron, R. Hammock, M. Leitch, P. Mc Gaughey, W. Sondheim, and J. Junier, *A Neutron Source Imaging Detector for Nuclear Arms Treaty Verification*, LA-UR-90-581 (Los Alamos, New Mexico: Medium-Energy Physics Group, Los Alamos National Laboratory).

18. A German word that means "braking radiation." High-energy electrons release x-rays when they are stopped by collisions.

19. The SLAB detector is described in Gozani, p.218.

20. The natural background radiation would be negligible by comparison.

21. See, for example, G.C. Messenger and M.S. Ash, *The Effects of Radiation on Electronic Systems*, (New York: Van Nostrand Reinhold, 1986).