Nuclear Disengagement in Europe

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Paper 12. Technical feasibility of the detection of nuclear weapons

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I. Introduction

When one contemplates the possibility of nuclear weapon-free zones, or a future total ban on nuclear weapons, reliable methods for detecting nuclear weapons become essential. In general, this would imply a number of procedures and techniques; some of them will be similar to those used in verifying other arms control agreements, but specific methods will also be required. If it is possible to get close enough in the verification process, the fact that all nuclear materials used in nuclear weapons (uranium, plutonium, etc.) are radioactive can be taken advantage of.

Because of the numerous applications of radioactive materials, many problems associated with their detection have already been studied [1,2]. However, the nuclear explosive materials used in nuclear warheads are usually much less spontaneously radioactive than, for example, the kind of materials involved in the civilian nuclear fuel cycle. The detection of nuclear weapons containing weapon-grade plutonium or uranium is thus a rather difficult problem.

From among the various techniques that could be used to detect weapon-grade nuclear materials, this paper will concentrate on the so-called passive methods. Such passive methods were used in October 1981, when ^{238}U was detected on board a Soviet submarine which had run aground in Swedish waters. In that particular case, the radioactivity measurements were of necessity improvized so that only limited evidence for the presence of nuclear weapons on board could be provided. Some details of these measurements were published [3], and will be used to illustrate the kind of difficulty involved in the detection of nuclear weapons.

The main conclusion of this introductory work is that, in ideal conditions, it should be relatively easy to detect the presence of some types of nuclear weapon, especially those containing plutonium, within a range of a few metres, unless they are heavily shielded. However, some others, especially those containing very highly enriched ^{235}U, would be quite hard to detect by even a sophisticated detection system. The main practical difficulty would come from the presence of background radiation. In particular, the natural radioactivity from the soil can in some cases render the measurements extremely difficult or even impossible if the detector is too far away from the source. Finally, some difficulty would come from the possible interference from other nuclear materials that could be on board the carrier. For example, this would be the case for ^{238}U, which has several non-nuclear military applications but is extensively used in some nuclear weapons as well.

II. Nuclear materials detection methods

The main technical means for detecting nuclear materials are well known. Rassmussen [1], for example, discusses the principal methods proposed for safeguarding and identifying nuclear materials. The non-destructive techniques of interest in our case would generally depend upon the measurement of nuclear radiations from the weapon. These methods are commonly divided into two general types: active and passive.

In passive methods, the detected radiations are emitted spontaneously from the weapon as a result of radioactive decay processes. In the case of active methods, the detected radiation is stimulated by radiation from an external source.

Passive methods

Passive methods make use of the natural decay processes characteristic of all radioactive materials. These decays result in the emission of various nuclear radiations, but only the neutral particles emitted will have a substantial probability of being detected at some distance from the radioactive material. This is why gamma rays and neutrons are the only kinds of radiation one would expect to detect at some distance from a nuclear warhead.

Passive gamma ray method

In this method, one measures the gamma rays from the radioactive decay of the nuclear materials in the warhead.

The salient feature of this method is that each kind of radioactive nucleus emits a set of gamma rays with energies and relative intensities unique to that nucleus. Therefore, the measurement of the gamma ray spectrum emitted by an unknown source enables one in principle to find out exactly what kinds of radioactive material it contains and in what relative proportions.

However, gamma rays are very easily absorbed by heavy materials such as lead, and even more by nuclear materials like uranium and plutonium. The absorption of the gamma rays by the radioactive material that emits them is called *self-absorption*. Because of this process, only the most energetic gamma rays emitted by nuclei located very close to the surface may escape from the material and have a chance of being detected. Table 12.1 gives the energies of the gamma rays that are the most suitable for gamma ray detection. The table also shows the self-absorption half-length in the respective materials, as well as, for comparison, the corresponding absorption half-lengths in steel. (The absorption half-length is defined as the thickness of material which reduces the number of gamma rays by one-half. A thickness of two such half-lengths would reduce this original number to one-quarter, and so on.)

As can be seen from the table, self-absorption is particularly large in ^{235}U but not quite as large in ^{239}Pu. On the other hand, the 1 001 keV gamma ray characteristic of ^{238}U (which in fact is emitted by ^{234}Pu, a daughter product of ^{238}U), suffers much less self-absorption. Uranium-238 is thus the easiest one to detect by the gamma ray technique. As far as the shielding by light- or medium-weight materials is concerned, the figures for steel show that the gamma rays of interest can traverse several centimetres of steel before being substantially attenuated. Shielding by light materials is thus not an essential limitation of this method.

Table 12.1. Characteristics of gamma rays of nuclear weapon materials

	^{235}U	^{238}U	^{239}Pu
Gamma ray energy (keV)	185	1 001	414
Self-absorption half-length (cm)	0·03	0·5	0·15
Absorption half-length in steel (cm)	0·5	1·5	1·0

Source: Notea and Segal [2].

The kind of detector needed for the detection of gamma rays in the energy range of interest is easily available. For quick detection of the proximity of a gamma ray source a portable detector can be used. For the precise identification of the kind of gamma ray emitter involved, a more complex system comprising a high-resolution detector and a multi-channel spectrum analyser will have to be used.

Passive neutron method

In this method, one measures the neutrons emitted in the spontaneous fission of the fissile materials used in a nuclear weapon. The total number of spontaneous fission neutrons emitted per second and per gramme for each of the most important nuclear materials is as shown in table 12.2.

Table 12.2. **Spontaneous fission neutron rates of nuclear weapon materials**

	^{233}U	^{235}U	^{238}U	^{239}Pu	^{240}Pu
neutrons (s^{-1} g^{-1})	0·002	0·0007	0·017	0·03	1300

Source: Rassmussen [1].

Except for ^{240}Pu these rates are relatively low. Fortunately, 'weapon-grade' plutonium contains 3 to 5 per cent ^{240}Pu, which is sufficient to make a plutonium weapon detectable because of the number of neutrons leaking out of it.

In the case of a uranium weapon, highly enriched uranium with a ^{238}U content of less than 7 per cent is generally used. The number of spontaneous fission neutrons from such a warhead is small and not easily measurable, unless a neutron detector can be set up very close to the weapon. In actual fact, most of these neutrons would come from the decay of ^{238}U and not from ^{235}U. From the table, one can see that natural or depleted uranium has a spontaneous neutron emission rate about 20 times greater than pure ^{235}U. For this reason ^{238}U can be detected by neutron counting, but only if a sufficient quantity is present.

There is a major difference in the physical processes affecting the leakage of gamma rays and neutrons from a nuclear weapon: for gamma rays there is a severe self-absorption effect, whereas for neutrons there is virtually no self-absorption correction. Furthermore, whereas gamma rays are strongly attenuated by all materials heavier than steel, neutrons can traverse these materials relatively easily. On the other hand, neutrons are strongly attenuated by light materials, and in particular by organic compounds like plastics or engine fuels which contain a lot of hydrogen. However, even accounting for the high explosives used to trigger the nuclear weapon, or materials such as beryllium that can be used as a tamper, there is normally not enough light material surrounding the core of fissile material to absorb more than a fraction of the spontaneous fission neutrons.

The detection of neutrons is unfortunately more difficult than that of gamma rays. For example, simple hand-portable neutron detectors are typically 10 to 1 000 times less sensitive than portable gamma ray detectors. Efficient neutron detectors suitable for the application considered here are available; however, their use is not as widespread as the kind of gamma ray detector required for the gamma ray detection method.

Active methods

The obvious advantage of the passive methods is that they can in no way affect the nuclear weapon or the vehicle that is containing it. Active methods are also non-destructive. They require, however, an external radiation source that can be either a small accelerator or some appropriate radioactive material. This external radiation source will generate a low-intensity beam of neutrons or gamma rays, and this beam directed towards the possible location of the nuclear weapon will induce various nuclear reactions inside the fissile material. The neutrons and gamma rays from these induced reactions may then be recorded by detectors similar to those used in the passive methods. The techniques using neutron or gamma ray beams are called neutron or gamma ray interrogation.

In theory, the *ideal method* for detecting nuclear weapons would be one that would respond exclusively to the special nuclear materials ^{235}U, ^{239}Pu or ^{233}U which, contrary to ^{238}U, can sustain an explosive chain reaction because they are fissionable with low-energy neutrons. A method approaching this ideal condition is the so-called *sub-threshold neutron interrogation*. This technique requires a beam of neutrons with energies below the fission threshold of ^{238}U. When such a beam is aimed at some nuclear explosive material, a certain amount of low-energy fission will be induced, and the detection of secondary gamma rays or neutrons would be an unambiguous signature of its presence.

If the location of a possible nuclear weapon can be determined with sufficient accuracy, and if it is possible to approach it within less than a metre or so, sub-threshold interrogation becomes feasible by some rather simple means using, for example, an intense californium neutron source [1]. Californium-252 has a very large spontaneous fission rate and is thus a copious source of fission neutrons. By suitably moderating these neutrons, a low-energy neutron beam can be prepared. With such a system it should be easy to verify, for instance, the presence or the absence of fissile ^{235}U behind a ^{238}U shield or tamper.

Shielding

To avoid detection, the obvious countermeasure is shielding. In passive methods the radiations emitted by the fissile material have first to emerge from the weapon by going through its various components, and then to leak through the shield and other materials before reaching the detector. In active methods, the interrogating gamma rays or neutrons would have first to reach the fissile material, and thus the shield would intervene twice.

In principle it is possible to design shields that would easily make it impossible to detect nuclear weapons of all kinds behind them, either by active or by passive methods. The counting rate estimates made by the author show that for both gamma rays and neutrons a shielding factor of 100 to 1 000 would definitely make detection of all kinds of nuclear weapon very difficult.

For gamma rays, the most compact shield would be provided by a very heavy material. However, for the relatively high-energy gamma rays of interest here, the mass-absorption coefficient becomes essentially a function of the total mass of the shield. For a shielding factor of 100, that is, a 100-fold reduction in the number of gamma rays, 10 cm of steel would be adequate.

For the neutrons, the shielding is more complicated. The reason is that the neutrons have first to be slowed down before they can be captured by a neutron-absorbing material. A shielding factor of 100 is achieved with 30 cm of polyethylene [4] or water.

An optimum multilayer shield providing a shielding factor of 100 for both gamma rays and neutrons would probably require an arrangement compounding about 5 cm of steel and 20 cm of polyethylene. In other words, effective shielding can only be obtained by the addition of considerable weight and volume. Such a shield behind which any kind of nuclear weapon could be hidden would be difficult to install on aircraft or other light carriers. However, as will be seen, several kinds of nuclear weapon may escape simple detection methods by much less shielding. Furthermore, some possible nuclear weapon carriers, such as battleships, tanks or self-propelled howitzers, would naturally offer a substantial gamma ray shielding factor because of the thickness of their steel structure. Finally, any kind of fuel tank or densely packed ammunition storage of 20 cm in thickness or more would efficiently attenuate any neutron signal from a nuclear weapon and make neutron interrogation very difficult.

III. Detection of nuclear weapons

The problems of detection and verification

The overall problem of verifying a complete ban on nuclear weapons from a given region is, of course, much more than just a technical one. However, at some point or another in the verification process it may become necessary to be able to detect nuclear weapons in order to ensure with a high level of confidence the total absence of such devices.

A nuclear weapon-free state, for instance, would have to guarantee that under no circumstances would nuclear weapons enter or make transit through its territory. This would require some technical means of verification, for example, at civilian or military airfields where aircraft possibly carrying nuclear weapons might be landing. This would also be the case at various border check-points or harbours. Further need of verification would arise for nuclear weapon-free countries which are members of an alliance. They would have to ensure that no vehicle of the ally that could possibly deliver a nuclear weapon would come into the free zone with a nuclear warhead.

In such cases, if there is some reason to believe that a nuclear weapon might be located inside some carrier or other inaccessible closed space, a standard detection procedure could consist of four steps, as follows:

Check list

1. Preliminary check.
2. Passive check.
3. Active check.
4. Inspection.

Each of these successive steps would ensure with a higher degree of confidence the absence of nuclear weapons. For instance, the fact that no radioactive signal was registered at the preliminary or passive check level does not mean that there was no nuclear weapon. It would be up to the inspecting party to decide whether the negative results of these simple checks were sufficiently reassuring to make more elaborate checks unnecessary. Ultimately, if active checks were to be negative one would have to envisage physical inspection of the *inside* of the carrier or space suspected of containing a nuclear weapon.

From the point of view of the inspected part, levels 1 and 2 would probably be acceptable as they would be passive and absolutely non-destructive. Active checks with gamma ray or neutron interrogation may on the contrary be more difficult to accept as it can be argued that even a very low level of radiation might be unacceptable to the crew or other people inside the carrier and to sophisticated or delicate electronic equipment. Finally, the question of the acceptability of the inspection of the inside of an enclosure likely to contain a nuclear weapon goes beyond the purely technical level of this paper and will not be further discussed.

Nuclear weapon detection procedure

In order to discuss the technicalities and the effectiveness of the first three levels of checking, one has to make some assumption on the design of nuclear weapons and the minimum amount of shielding that would be naturally provided by the possible nuclear weapon delivery systems to be checked. With such assumptions, a very simple but reasonable model has been used to calculate the strength of the radioactive signals passively generated by nuclear weapons, and the specifications of the equipment required to detect them.

The following discussion will concentrate on carriers such as aircraft which would not provide large shielding factors unless special measures were undertaken. Finally, it will be assumed that the only detectable sources of radioactivity will be the fissile material in the fission bomb or the hydrogen bomb trigger.

Preliminary check

The preliminary check would involve the use of two simple but highly sensitive radiation counters, one for the gamma rays, the other for the neutrons. Calculations by the author show that the gamma and neutron counters should have similar sensitivities and be capable of detecting reliably a few counts per second or less. This would not be very easy for the neutron counter, and some precautions might have to be taken because of cosmic rays or other possible backgrounds.

With such counters, plutonium warheads would most certainly be detectable from a distance of a few metres, and in a few minutes, possibly by both kinds of counter if there is no heavy material to stop the gamma rays or no thick fuel tank to absorb the neutrons. A lightly shielded weapon containing very pure ^{235}U would be very difficult to detect, but a sufficient amount of ^{238}U would be detectable at several metres because of its characteristic high-energy gamma ray.

At this level several complications may already arise. Of course, any radioactive source on board would trigger the detectors. This would be the case with any substantial amount of depleted or natural uranium used because of its attractive non-nuclear properties: uranium, like tungsten, is a very heavy material (its density is almost twice that of lead), but it is cheaper and more easily processed. It is therefore often used as a counter-weight in aircraft and on armour penetrator in anti-tank artillery rounds, etc. If such sources of radiation cannot be removed from the inspected vehicle, they might radiate sufficient background to make more elaborate measurements difficult.

The second major difficulty would come from the natural radioactivity. This background is due mainly to cosmic rays and to the radioactivity of materials in the immediate surroundings. The soil and most construction materials are usually slightly radioactive, and this radioactivity may be similar in intensity to that of a nuclear weapon located at a distance of several metres. The natural background thus sets the limit to the distance at which the signal from a nuclear weapon can be measured.

Passive check

By recording counting rates, the preliminary checks can locate the point where the strength of the signals is maximum. A high-resolution gamma ray detector and spectrum analyser would then be set up at this point together with a low-background, well calibrated neutron detector. The information from both counters would then be used to identify the radiation source and, hopefully, within a few tens of minutes, provide a reasonable estimate of the total amount of radioactive material. Calculations by the present author have shown that the capabilities of such a combined system are as follows:

1. Uranium-238 can be identified and its total amount estimated from both the gamma ray and neutron signals.
2. Plutonium-239 cannot be identified if there is a heavy material shield absorbing its gamma ray signal. A plutonium weapon can, however, be detected by the neutrons emitted by the ^{240}Pu it contains. If there is a thick ^{238}U shield, the neutron signal from plutonium should in general be much higher than the neutron signal from ^{238}U. The gamma ray identification of ^{238}U associated with a strong signal would be the signature of a plutonium weapon with a ^{238}U tamper, or of a hydrogen bomb with a plutonium trigger and a ^{238}U reflector.
3. Uranium-235 cannot be detected if it is surrounded by a heavy material shield a few millimetres or more thick. Its gamma ray signal would be essentially suppressed and one would have to rely on its neutron signal which, for a warhead containing 10 kg of ^{235}U, would be approximately equivalent to the neutron signal generated by 1 kg of ^{238}U. As ^{235}U is always mixed with some amount of ^{238}U, it would be very difficult to use this information to ascertain the presence of ^{235}U with such a passive check alone.

As with preliminary checks, we see that the detection of ^{238}U is ambiguous. This is because ^{235}U has both a low-energy gamma ray signature and a low spontaneous fission rate relative to ^{238}U. On the other hand, plutonium weapons are much more readily detectable through their strong neutron signal, which, unlike a clean gamma ray spectrum, is merely indirect evidence for the presence of this material.

Active check

Sub-threshold neutron interrogation holds the promise to provide an unambiguous method for detecting nuclear weapons. In particular, it should be able to resolve the ambiguity associated with the detection of ^{238}U. The use of ^{238}U as a tamper or reflector in a fission or fusion warhead with a uranium trigger would then be indicated by the strong increase of secondary radiation that would occur as the neutrons from the interrogator interacted with the warhead.

The Swedish experience

The account of the attempt to detect nuclear weapons on board the Soviet submarine which had run aground in Swedish waters in October 1981 provides us with a practical example of the difficulties encountered in such a task [3].

The detection procedure followed in that event was similar to the one considered above. The preliminary measurements were made with portable gamma ray and neutron counters. The sensitivity of the gamma ray detector was 0·1 microröntgen per hour. This corresponds to a detection threshold of two gamma rays per second of 1 001 keV energy. This is adequate and, indeed, easily led to the source of this radiation. On the other hand, the sensitivity of the neutron detector was about 0·1 milliröntgen per hour. The neutron detection sensitivity was thus 1 000 times smaller than the gamma ray detection sensitivity. This illustrates the difficulties encountered in neutron detection and it is thus not really surprising that no neutrons were detected.

The passive check was made with a standard high-resolution gamma ray detector and a multichannel spectrum analyser. Such a system is perfectly adequate for the kind of measurement undertaken and consequently led to the identification of ^{238}U. Should there have been a uranium or plutonium nuclear weapon *without* a ^{238}U tamper and no other heavy material shield in the way, ^{235}U or ^{239}Pu could have been detected just as well. The information available on the measurements [3] indicates that after four hours of counting, a near to 100 per cent confidence level in the identification of ^{238}U was reached. Such a figure corresponds to the present author's calculations for 10 kg of ^{238}U at a distance of 1 m, under the assumption that this amount of ^{238}U has the general shape of a nuclear weapon. This assumption on the shape is crucial because of the large effect of the gamma ray self-absorption. For example, the gamma ray intensity from a 10 kg sphere of ^{238}U is essentially the same as the intensity radiated by a 2 cm thick plate weighing only 2 kg.

In view of the success of detecting gamma rays from ^{238}U, the information from a good neutron detector would have been very valuable. However, it seems that it was not possible to set up a better neutron counter. A reliable neutron count would have enabled the unambiguous detection of a plutonium warhead, for instance. And in the case of ^{238}U, it would have considerably helped the determination of the total amount of depleted uranium by providing an independent measurement which depended less on the shape of the material.

Similarly, it appears that the conditions could have been adequate for a sub-threshold interrogation with a moderated californium source. However, because of lack of time and equipment it was not possible to do this. Therefore, the problem of the detection of some neutrons from this source by the nuclear radiation monitors on board the submarine did not arise.

A favourable circumstance in this event was that the natural radioactivity background was low, as it usually is above water relative to on land. This must have played some role in the success of the preliminary checks and facilitated the identification of the ^{238}U.

IV. Conclusion

We have discussed the feasibility of detecting nuclear weapons by taking advantage of the radioactivity of the fissile material they contain. In good background conditions this seems possible, provided that the detector can be placed close enough, and that the radiation from the warhead is not attenuated by some shielding material. However, even if these requirements can be met, and thus lead to the detection of some radioactive material, there still remains the question that such materials could also be used for other purposes. The practicality of the passive detection methods described here and of other methods, including active ones, in a variety of circumstances, should thus be further investigated.

Notes and references

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