Verification of Nuclear Disarmament
Challenges and Prospects

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Executive summary

This commission has been assigned the task of analysing the challenges and prospects regarding verification of nuclear disarmament. This verification is desirable to both the host and the inspectors as it builds confidence and trust between the two.

The main problem is trying to balance between attaining high confidence of dismantlement verification and the disclosure of sensitive information prohibited by the Non-Proliferation Treaty (NPT) and national security. The via the NPT, IAEA safeguards dictate what information on nuclear weapons cannot be passed between nations. This limits the ability to verify, for instance, the mass of fissile material, as host nations would not give out such information.

The mechanism with which to restrict the amount of information between the host and the inspectors is known as the information barrier. Its extent is agreed upon by all the member states of the ratified treaties: the capabilities of the equipment and an example procedure. The treaties outline what information should and should not be shared with the inspectors; the implementing equipment and procedure are the technological or economic constraints not inside the scope of the treaties. The information barrier is most likely implemented as a computer program sitting between the statistical analysis and the simplified output.

The dismantlement process begins with the separation of the components of the warhead. This includes separating the primary physics package, comprising of the fissile material, from the warhead. In addition, the explosive package and the firing mechanism are extracted. The firing mechanism is crushed after being separated until it is considered militarily unusable. The fissile material may be down-blended and used as a fuel in commercial nuclear reactors.

Verification describes the process of determining if a nuclear warhead presented for dismantlement is indeed nuclear. For verification to be achieved with a high confidence it must be possible to confirm that all the nuclear material has remained throughout the dismantlement process, but also be able to recognise other eventualities such as nuclear material being smuggled as non-nuclear material.

To attain this, a host of verification methods have been developed at institutions such as the Lawrence Liverpool National Laboratory (LLNL), and this commission has been convened to review a selection of these methods and determine if it possible to confidently verify dismantlement with the information that is currently declared.

This commission proceeded to review radiation detection methods. These include neutron and gamma ray detection, as well as muon tomography – a new technology currently in development. Tags, seals, and containers are currently utilised in all verification regimes to deter tampering. However all seals are vulnerable to rapid, low-tech attacks that will defeat the seal.

This commission advocates the use of passive detection over active detection because it is less intrusive and safer. The confidence level expected to be attained, however, should vary according to the total number of weapons being dismantled. An interesting suggestion would be to limit the number of weapons within a given range of a dismantlement facility. This would be relevant in the case of Russia and the US eager to demonstrate the transparency a Nuclear-Weapon State (NWS) with a smaller stockpile could attain. However this requires further review as the security burdens may increase. but this could be addressed in the case of US and Russia by limiting the transportation range of the weapons by type.

In summary, all of the reviewed detection methods are vulnerable to forgery and evasion. If

employed alone, they are weak and would introduce uncertainty of the verification, and thus reduce the level of confidence. By using a combination of all the detection methods, it is possible to compensate for each method's limitations. Such a strategy is recommended to increase the confidence level of dismantlement.

Purely conventional methods including seals and tags are not recommended because they are vulnerable and are liable to deceit. Therefore this commission recommends that unconventional methods, such as pit-stuffing, be used in conjunction with the conventional approaches. These proposed methods include the use of military GPS, anti-evidence seals and the "town crier" method.

Contents

1 Background

Weapons-grade nuclear materials explode just by putting them together. The limits at which the material begins to sustain the chain reaction required for explosion, also known as criticality, is extremely sensitive to slight changes in the environment. The late Feynman from the Manhattan Project had been able to salvage the Uranium refinement plant from exploding a hundred times over. He noted that, even after briefing about the sensitivities and some numerical limits, policy makers continue to formulate dangerous policies.[1] The gravity of the situation is difficult to convey. It is imperative that reports on nuclear policy include the basic physics for safety reasons. This report, at various points, depends upon the model of the nuclear weaponry used, and the model discussed follows the preliminary physics required for informed decisions. Rough information about the monetary costs are provided wherever appropriate.

This report had been commissioned mainly for the formation of policy; a brief overview of the current political background relevant for decision making is also provided. The disarmament and verification process is directly affected by the various barriers to the free flow of information. Although these barriers have been erected to prevent dissemination of rightfully sensitive information, this commission argues that the current restrictions cripple the verification process and should be pushed back.

1.1 Preliminary Physics

Nuclear weaponry cause destruction by releasing parts of the large amounts of energy dormant in the nucleus of atoms over a short period of time. This process is the most efficient that current technology has access to. Different types, or elements, of atoms behave differently in this process. Lighter elements

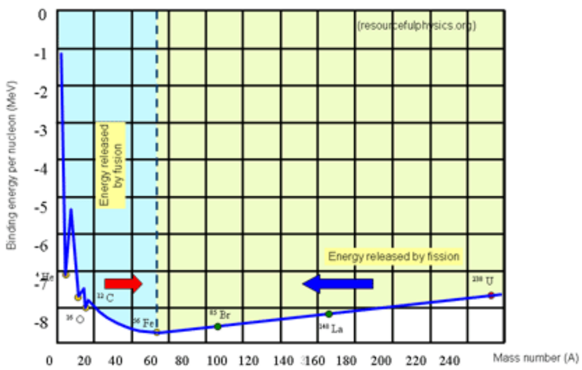


Figure 1: Graph of nuclear binding energies per nucleon as a function of number of nucleons in a nucleus of an atom.[2]

can release energy when they fuse together to make heavier elements, whereas the heaviest elements release energy by breaking apart, by fission. Figure 1 shows a simplified view of the separation; the horizontal axis roughly corresponds to the size or weight of the elements while the vertical axis maps quite well to the energy. In simple terms, imagine a ball on this ramp; no matter on the left or the right sides, the ball tends to roll towards the centre region where the energy is least. The vertical distance between the initial and final states is the energy released by the reaction.

There are some relevant complications to the simplified picture. The type of element that mainly defines the atom's properties is the number of protons in the atom. This is known as the atomic number (Z) of the element. For each given Z, there can be some variation on the number of neutrons, N, in the atom, and each variation is known as an isotope of the same element. It is chemically difficult to tell the variations of N apart. Since the masses of protons and neutrons are similar, the mass number (A), roughly defined by $A = N + Z$, is a good measure of the weight of each individual atom. Note that, although only as an approximation, A and the bulk material mass density of an element grows together. For the most part of this report, the important elements are Uranium ($Z_{\text{Uranium}} = 92$) and Plutonium ($Z_{\text{Plutonium}} = 94$). Their respective important isotopes have A equal to 235, 238, 239 and 240. This report follows chemistry notation by writing them as ^{235}U, ^{238}U, ^{239}Pu and ^{240}Pu respectively.

One of the notable complications is that, although all four of these isotopes are fissionable, only the odd numbered versions are fissile. Fissionable means that these isotopes can be made to release energy via fission, and it is not immediately obvious why is it that not all fissionable materials are also fissile. It turned out that the oddness and evenness of the number of neutrons and protons in an atom had such a great influence on the energy of the nucleus that it causes the difference. As such, ^{238}U and ^{240}Pu fail to have enough energy to sustain a chain reaction and are thus not fissile. This is one manifestation of the sensitivities of the nuclear process to environmental conditions.

The above consideration also explains why there is a need to refine nuclear material when making a bomb – Non-fissile isotopes hinder the energy extraction from the nucleus. Naturally occurring Uranium, for example, mainly consists of ^{238}U. Uranium is said to be enriched when the percentage of ^{235}U is increased to above 20% by the process of isotope separation, whereas weapons-grade Uranium (WgU) consists of above 90%.[3] Weapons-grade Plutonium (WgPu) is 93.5% ^{239}Pu and 6% ^{240}Pu whereas reactor grade Plutonium is 58% ^{239}Pu and 24% ^{240}Pu.[4] To make a normal fissile bomb, it is estimated that around 12 kg of WgU or 4 kg of WgPu would be needed.

Another manifestation of the sensitivities that is by now thoroughly understood is the criticality under many conditions. Feynman had already pointed out above that water and other substances can dramatically shift the criticality limits around.[1] The criticality of these materials are so well understood that, by 1946, dangerous criticality experiments were performed: separating two hemispheres of Plutonium with just a screwdriver in the hand of a scientist at Los Alamos.[5] Fermi had, reportedly, warned these scientists to stop their dangerous behaviour before they killed themselves, but after an accident that's exactly what happened. However, their ability to precisely determine the point of criticality to even *attempt* the experiment shows the efficacy of our physical knowledge. That knowledge, however, requires rather complete information to be of *any* use; an issue this report will come to address.

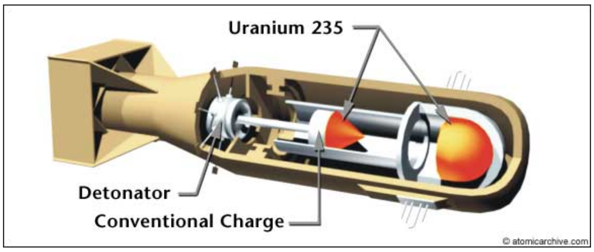


Figure 2: A typical "gun-type" fission bomb.[6]

From the above consideration, it is obvious that a bomb could be made by simply assembling two near-criticality pieces. This is the essence of the "gun-type" nuclear fission bombs. The design, however, is incredibly inefficient TODO:CITATION, requiring a lot of extremely expensive highly enriched nuclear material, and most of it is wasted in the explosion. The explosion would disperse the nuclear material too quickly for much of a reaction to happen. Hence, this design is absent from current stockpiles. Thus, there will be further discussion of this type of weapon.

A simple way to increase efficiency is to increase the length of time whereby the nuclear chain reaction effectively occurs. Such an increase is usually achieved by providing the nuclear materials with momentum to congregate

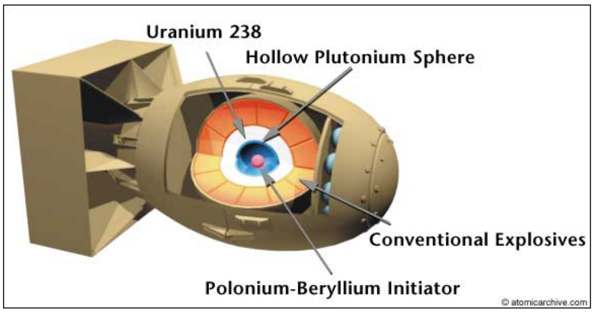


Figure 3: A typical implosion-type fission bomb.[7]

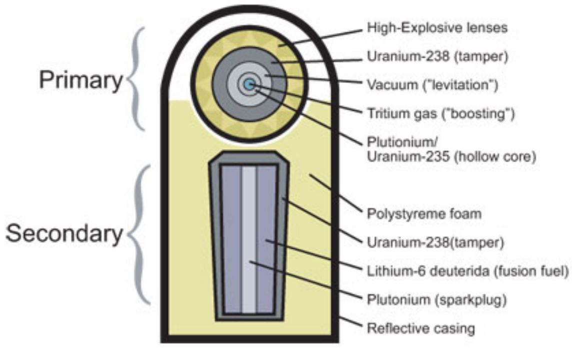


Figure 5: A fusion bomb of the Teller-Ulam design, featuring the implosion-type fission first stage.[9]

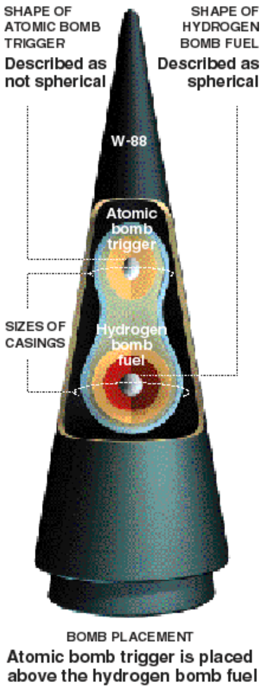


Figure 4: The Trident Ballistic Missile: An example of a fusion-boosted fission warhead. Note the inclusion of the implosion-type fission first stage.[8]

– the explosive reaction has to then spend some time to reverse the momentum before the nuclear materials dissipate. Currently, all nuclear bombs employ this method albeit with variations, and this report focuses upon the detection of this mechanism. Another reason for focusing upon the detection of this mechanism is the fact that it provides a unique and certain signature that is different from all the other possibilities. The fusion parts of fusion bombs and all of the non-nuclear conventional bombs, for example, are not easily detectable and/or differentiable. The method of providing the nuclear material with congregating momentum is known as compression, and the bomb would be of the implosion type.

Before a detailed discussion of the issues surrounding the detection of the nuclear material in the implosion type bomb, a few nomenclature introductions and the possibility of nuclear fusion being involved should be addressed. The original atomic bomb used only the nuclear fission reaction for its explosive impact. Bombs of this type are known as fission bombs or weapons. To achieve nuclear fusion, a lot of energy is required, and current technology is only capable of delivering the required energy via nuclear fission. i.e. For any bomb

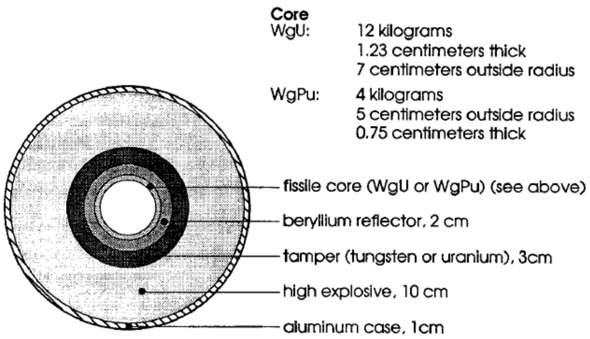


Figure 6: Hypothetical weapon model as used in Fetter et al.[10]

that relies upon nuclear fusion to derive its energy, nuclear fission must be employed. Such combination bombs are known as thermonuclear weapons.

The categorisation of nuclear weapons is further complicated by other factors. For the purposes of this report, issues like the type of destruction maximised (electromagnetic radiation, neutrons or conventional heat) and so on are irrelevant. This commission, however, would like to mention that fusion weapons can be further classified by the usage of the fusion process: If the nuclear fusion is only employed to increase the efficiency of the nuclear fission process, then the bomb is a fusion-boosted fission weapon. If the nuclear fusion is the main process providing the energy, then the regular name suffices. The difference is small enough that confusion is of little consequence. The part of the nuclear weapon where the nuclear material belongs is known as the physics package.

1.1.1 Working Model

As can be seen from all of the cross-sections provided, nuclear weapons have a relatively unchanged component, the fissile part. It has been mentioned before that this provides a unique, undeniable and unmistakable way for the detection of a nuclear bomb. The working model consists of a fissile core, reflectors to concentrate the neutrons near the core, and a massive tamper that does not actually react but serves only to push the core inwards using momentum.

This report mirrors the paper by Fetter et al.[10]; the original is recommended for a more complete discussion. The paper considered four different variations on the same simulated model by changing the material used in the core and the tamper. The four choices are: either WgU or WgPu for the core, and either depleted Uranium or Tungsten for the tamper. It is stated very early in the paper that the point of the exercise was to stretch the boundaries. Of the four designs, the Uranium/Tungsten combination is virtually undetectable. The group themselves did not believe that it is within reason for Nuclear-Weapon States to utilise such a devious combination for the fact that the design is much more expensive and inefficient than is required. The Plutonium/Uranium combination, which is much more detectable, is closer to what they would expect. The point of the unreasonably difficult Uranium/Tungsten combination is to set a meaningful lower bound, which would turn out to have remarkable consequences. TODO:CROSS-REF

It should be noted that Uranium bombs would require 12 kg as compared to the 4 kg Plutonium ones. This is a huge difference in efficiency and cost that almost ruled out the use of Uranium in space-constrained warheads.

1.2 Politics

There is currently no known opposition to the consensus that nuclear weapon stockpiles are too large, at least among the developed countries. This commission believes that this agreement is based on solid foundations for a number of reasons, of which, only risk management

Country	Active	Total	CTBT
US	1950	8500	S
Russia	2430	11000	R
UK	160	225	R
France	290	300	R
China	180	240	S
India		90	N
Pakistan		100	N
North Korea		<10	N
Israel		140	S

Table 1: Number of nuclear warheads, active and total, by country. Status of ratification of the Comprehensive Test Ban Treaty (CTBT) is also shown. S denotes Signatory, R means Ratified and N for Non-Signatory.[11]

and economics are considered in this report. The relevant arguments and numbers are presented in section TODO: CROSS-REF.

To have a more meaningful discussion about the subject, a brief outline of the current Nuclear-Weapon States (NWS) and political situation has to be given. The International Atomic Energy Agency (IAEA), will be introduced as the standard organisation. Because the problem is one of worldwide cooperation, international treaties form the foundation upon which disarmament verification is performed. It shall be shown that the treaties of relevance lead to the formation of information barriers, and their consequences are briefly touched upon. Finally, some non-political issues that are of importance are iterated. TODO: TRUST; TERRORISM. Notes?

1.2.1 Nuclear-Weapon States (NWS)

Although exact numbers are not known, there are around 20 000 to 40 000 nuclear weapons in the world.[11;12]

From the viewpoint of risk management, each nuclear weapon represents a risk of accidental detonation that has to be weighed against the potential benefits that its ownership may bring: mainly deterrence and diplomatic power. As can be seen in Table 1, the current stockpiles, in at least the United States (US) and Russia, are much too big to support either of the two arguments. Thus, they provide great risk for negligible benefits and should rightly be lowered. Terrorists present a complication to the decision-making process, but the judgement of excess is not altered. The changes needed to discuss terrorism are discussed in section TODO: CROSS-REF.

The arguments presented deserve further scrutiny on many counts. Table 1 can be roughly separated into groups: US and Russia who are certainly overloaded with nuclear warheads, states with hundreds to thousands of nuclear weapons, and “Rogue” states of varying degrees of destructive probability. Diplomatically, this way of grouping the states seems to make sense – the “Rogue” states group enjoy an increase in diplomatic power thanks to their ownership of nuclear weaponry; of the states in the middle group, only China is threatening to increase her stockpiles, and is thus the only one to leverage off the diplomatic power. China’s excuse for doing so is the overly large stockpiles by US and Russia; Indeed, low or non-nuclear weapon states like North Korea and Iran cite the same excuse among other reasons.

However, the grouping may be misleading. India and Pakistan, on the borderline of “rogue-ness” may be better considered as “mischievous” since they do not pose a serious threat to developed countries. The tensions between those two countries, on the other hand, are real. In a similar way, Israel possesses nuclear warheads for deterrence reasons and is thus not considered as rogue by the developed countries, a designation that will certainly be disputed in the Middle East. For China that does pose a real threat, there may be some pressures to apply the rogue label. That, however, is not justified because, whatever threat

China poses, she is unlikely to be a nuclear threat from deterrence theory (large target; a lot to lose).

When considered from the perspective of deterrence, the grouping does an even worse job at being relevant. The standard argument is that the spreading of nuclear weaponry would deter conflict through considering Mutually Assured Destruction (MAD). By that argument, every NWS should have joined in so as to deter every other state, and groupings should not occur, or should at least occur similar to the Allied-Axis split of World War II. In reality, policymakers have had to take each country's unique circumstances and targets into account.

The above sets the political context but cannot be sustained for a valuable contribution towards the verification discussion. However, policymakers should be aware of the issues surrounding deterrence theory. Although the US administration is still firmly centred upon deterrence, the theory had neither been proved nor proved applicable.[13–15]

The consensus to dismantle is also based on economic motivations. In the 21st century around $50 billion a year, or 10% of the annual US military budget, is spent on nuclear weapons.[16] The US spent $5.8 trillion on nuclear weapons between the early 1940s and 1996. Trident, the UK's nuclear weapons system, costs up to $4 billion a year to run, and plans to replace it will cost $154 billion. It has been estimated that worldwide costs exceeded $1 trillion for 2010–2011.[17] This should be compared to the estimate that the cost of implementing a dismantlement program for processing Plutonium and Highly Enriched Uranium (HEU) into non-weapons-grade material would cost just $7 billion per year for ten years.[18] This minimal amount, in comparison, is equivalent to less than half of unaccountable spending in the Pentagon over the last decade, 0.09% of current world military spending, or 25% of the $28 billion spent every year to keep nuclear weapons secure.

1.2.2 International Atomic Energy Agency (IAEA)

The IAEA is an international organisation established on the 29th of July 1957 as an autonomous organisation through its own international treaty, the IAEA Statute, and reports to both the United Nations General Assembly and Security Council. It serves as an intergovernmental forum for scientific and technical cooperation in the peaceful use of nuclear technology and nuclear power worldwide. The programmes of the IAEA encourage the development of the peaceful applications of nuclear technology, provide international safeguards against misuse of nuclear technology and nuclear materials, and promote nuclear safety (including radiation protection) and nuclear security standards and their implementation.

The missions of the IAEA are decided upon based on the needs and interests of its Member States, strategic plans and the vision embodied in the IAEA Statute. There are three main areas that the IAEA works in: Safety and Security, Science and Technology, and Safeguards and Verification. Within these areas the IAEA has, as its core missions and objectives, been encouraging member states to use nuclear power peacefully, introducing and enforcing safeguards to verify that nuclear energy is only used for non-military purposes, and promoting high standards for nuclear safety.

The IAEA executes these missions by inspecting existing nuclear facilities to ensure their peaceful and safe use, providing information needed to ensure the safety and security of nuclear facilities, and acting as a hub for the various fields of science involved in the peaceful applications of nuclear technology.

Because there is only one international organisation dealing with nuclear technology, and that everything related to nuclear technology links to it, the IAEA is easily able to deliberate on any technical issues. Issues do not need to be sent across many different organisations and hence do not incur inefficiencies of bureaucratic red-tape. Policymakers also like the fact that it is easy to secure and monitor the central organisation against the leakage of sensitive information.

However, the centralisation is not without disadvantages. Being a large and monolithic organisation, it is difficult to check if internal information barriers are working. Furthermore, the IAEA is an overstretched and underpowered organisation. Mainly a civilian outfit, it is difficult for the IAEA to command any influence in military affairs, a tight bind that is worsened by the political quagmire in the United Nations General Assembly and Security Council that the IAEA relies upon. Understaffed and underfunded on top of underpowered, there had been calls for alternative organisations to be established in order to lessen its load. For the purposes of disarmament verification, this commission is without preference between empowerment of the IAEA and establishment of new organisations, as long as the problem is not allowed to fester in the status quo. Sadly, this commission is not under any illusions that the abandonment of the status quo is likely.

1.2.3 Treaties

As had been mentioned, disarmament verification is mainly an international cooperation problem. As such, international treaties form a substantial part of any serious attempt at a solution. Central to the discussion of nuclear treaties is the fact that NWS consider the implementation of nuclear weaponry as national security secrets and thus are reluctant to divulge. These concerns lead to the formation of information barriers that are enshrined in the treaties.

There are two treaties that are most relevant to the disarmament verification process today. Namely, they are the Non-Proliferation Treaty (NPT) and the Comprehensive Nuclear Test-Ban Treaty (CTBT) discussed below. A brief historical overview of the various treaties is provided in TODO: Appendix.

There is also no known opposition to the erection of information barriers in the context of nuclear weaponry. It shall be seen, however, that the height of the information barriers (summarised in TODO: CROSS-REF) are set so high as to effectively cripple the disarmament verification process.

1.2.3.1 Non-Proliferation Treaty (NPT)

The NPT is a landmark international treaty whose objective is to prevent the spread of nuclear weapons and weapons technology, to promote cooperation in the peaceful uses of nuclear energy and to further the goal of achieving nuclear disarmament and general and complete disarmament. The NPT represents the only binding commitment in a multilateral treaty to the goal of disarmament by the NWS. There have been several other treaties with the aim of encouraging disarmament, with varying degrees of success.

Limited success was achieved with the signing of the Partial Test Ban Treaty in 1963, which banned nuclear tests in the atmosphere, underwater and in space, but neither France nor China signed it. However, after an 80 to 19 vote in the US Senate meant that the treaty was still ratified by the United States. Opened for signature in 1968, the NPT entered into force in 1970. On 11$^{\text{th}}$ May 1995, it was extended indefinitely. A total of 190 parties have joined the NPT, including the five NWS. More countries have ratified the NPT than any other arms limitation and disarmament agreement, a testament to the significance of NPT. Recalling the determination expressed by the Parties to the 1963 Treaty banning nuclear weapons tests in the atmosphere, in outer space and under water in its Preamble, its goal is to achieve the discontinuance of all test explosions of nuclear weapons for all time and to continue negotiations to this end.

Other goals of the NPT include the easing of international tension and the strengthening of trust between States in order to facilitate the cessation of the manufacture of nuclear weapons, the liquidation of all their existing stockpiles, and the elimination from national arsenals of nuclear weapons and the means of their delivery pursuant to a Treaty on general and complete disarmament under strict and effective international control.[19]

The NPT was a major step towards the non-proliferation of nuclear weapons. This particular treaty decreed the prohibition of possessing, manufacturing or acquiring nuclear weapons or other nuclear explosive devices for non-nuclear weapon states. It committed all signatories, including nuclear weapon states, to the goal of total nuclear disarmament. However, India, Pakistan and Israel have declined to ratify the NPT. Their grounds for doing so were that the treaty is fundamentally discriminatory; it places limitations on states that do not have nuclear weapons but does not attempt to restrict weapons development by those who are declared nuclear weapons states.

1.2.3.2 Comprehensive Test-Ban Treaty (CTBT)

On 10th September 1996 the CTBT was adopted by the United Nations General Assembly; on the 24th of September 1996 it then opened for signature in New York, when it was signed by 71 States, including five of the eight then nuclear-capable states. As of January 2012, 156 states have ratified the CTBT and another 26 states have signed but not ratified it, including China, Egypt, Iran, Israel and the US. India, North Korea and Pakistan have yet to sign it (see Table 1).

Due to the political climate of the next few decades after the signing of the NPT, very little progress was made in nuclear disarmament until 1991. But, that year, an amendment conference was held to discuss the proposal of converting to a treaty that bans all nuclear-weapon tests. The UN General Assembly gave it strong support, leading to negotiations for the CTBT beginning in 1993. It took three years of intense effort and work to draft the CTBT text and its two annexes, but a consensus could not be reached on the adoption of the text in the Conference on Disarmament (in which negotiations were being held). Under the direction of the Australian Prime Minister John Howard and Foreign Minister Alexander Downer, the text of a draft resolution was submitted to the United Nations General Assembly in New York. The CTBT was finally adopted by a large majority, exceeding two-thirds of the General Assembly's Membership on the 10th of September 1996.

1.2.4 Important Notes

There are some notable omissions in the above discussion that need to be addressed. One of which is the new emphasis on terrorism that many are acutely concerned with. Another omission that has to be filled in is an overview of the information barrier set up by the treaties. Finally, this commission emphasises the original reason for the entire disarmament verification process: Trust.

Public attention has recently gathered around terrorism, thanks to the September 11th attacks. There are benefits and problems with this new-found emphasis. One problem that stands out is the unbalanced attention it is receiving. Terrorism is neither a new threat nor an unknown one. Traditional risk management techniques have already taken it into account: Usually under random risks, even if it is not especially noted. As such, the issue brings little change to the national security strategies that countries already use.

On the other hand, the attention on terrorism has already brought much needed critical evaluations to the strategic decision-making process. The numbers used in traditional risk management to account for randomness and terrorism have not been justified nor really studied, since not much is known about the issue. New security challenges are also presented by the fact that non-state terrorist groups in possession of nuclear weapons are conceptually outside the bounds of a deterrent strategy. The sudden increase in the criticisms of deterrence theory is particularly hinting; Whether it is hinting at a fad or a failure of the collective decision-making process to critically evaluate risk, this commission shall not speculate.

There are, however, other aspects of terrorism that are relevant to this commission. For one, the likelihood that non-state terrorists will come into possession of nuclear weaponry is increasing, so the need for disarmament is also increasing. As mentioned before, each nuclear weapon presents itself as a liability in this case. Not only is this the case, each place in which nuclear materials are handled, be it production, storage, inspection or equipment, represents a risk. This interferes with the deterrence theory in yet another disastrous way. On one hand, deterrence theory dictates that nuclear weaponry be spread out over many small pockets so that they cannot be easily deactivated by enemy forces. On the other hand, many small pockets make it probable that accidents and slip-ups occur.

TODO: Information barrier description. How many bombs.

Finally, this commission would like to remind policymakers of the central reason for the purpose of disarmament verification. Whereas this report has already outlined many reasons in favour of disarmament, none of the above manage to describe the true reason for disarmament *verification*. By considering the fact that there is no real obstacle for countries to unilaterally disarm their stockpiles, it is obvious that the sole reason for verifying disarmament is to convince other countries to do the same i.e. to gain their trust. There are many other pressures in the decision-making process relevant to disarmament verification, and policymakers should take care not to jeopardise the accumulation of trust.

Indeed, just like the sensitivities of the nuclear process, it is difficult to convey the seriousness of the threat to the accumulation of trust. TODO: Show information barrier is untrustworthy.

TODO: sectionise the 3 points?

1.3 Summary

TODO: Summary of Background.

2 Process

3 Introduction

3.1 Facts on Nuclear Weapons

Nuclear weapons are devices that generate a massive amount of energy from nuclear reactions, used to create mass destruction. These weapons come in two forms of bomb: nuclear fission or a combination of fission and fusion (thermonuclear). Weapons where the entire explosive output is generated by a fission reaction are called atomic bombs. The majority of their energy occurs in fission reactions where a piece of sub-critical material is “shot” into a mass of fissile material with a super-critical mass. This begins an exponentially increasing chain reaction, releasing energy. Another method uses compression of the subcritical sphere of fuel, by using an explosive to implode the sphere. The two most commonly used fissile materials for atomic bombs are (enriched) Uranium-235 and Plutonium-239. Uranium is said to be enriched when the percentage of Uranium-235 is increased to above 20% by the process of isotope separation, whereas weapons grade consists of above 90%.[3] Weapons-grade Plutonium is 93.5% Pu-239 and 6% Pu-240 whereas reactor grade Plutonium is 58% Pu-239 and 24% Pu-240.[4]

The second type of nuclear weapon is the thermonuclear (or hydrogen) bomb, and these utilise fusion reactions. The fusion reaction typically occurs with Deuterium and Tritium to release energy, but this is first triggered by a fission reaction to heat the fusion fuel. There are six countries purportedly that have conducted thermonuclear weapons: the United States, Russia, United Kingdom, The People's Republic of China, France and India.

Nuclear weapons were essential to maintaining international security during the Cold War because they were a means of deterrence. The end of the Cold War made the doctrine of mutual Soviet–American deterrence obsolete. Deterrence continues to be a relevant consideration for many states with regard to threats from other states. But reliance on nuclear weapons for this purpose is becoming increasingly hazardous and decreasingly effective, in such a way that nuclear weapons have no real legitimate purpose in todays world. They are immoral to use, would cause genocide, and their use is illegal due to inevitable civilian casualties. These weapons kill everything in their path and also cause additional death through radioactive fallout. The effects of detonating a weapon can spread for hundreds of miles, causing long-term health problems for people not killed in the explosion.

In the 21$^{\text{st}}$ century around $50 billion a year, or 10% of the annual US military budget, is spent on nuclear weapons.[16] The US spent $5.8 trillion on nuclear weapons between the early 1940s and 1996. Trident, the UK's nuclear weapons system, costs up to $4 billion a year to run, and plans to replace it will cost $154 billion.

The likelihood that non-state terrorists will come into possession of nuclear weaponry is increasing, so the need for disarmament is also increasing. In today's war waged on world order by terrorists, nuclear weapons are the ultimate means of mass devastation. New security challenges are presented by the fact that non-state terrorist groups in possession of nuclear weapons are conceptually outside the bounds of a deterrent strategy.

There is also an economic incentive to dismantle nuclear weapon stockpiles – it has been estimated that worldwide costs exceeded $1 trillion dollars for 2010–2011.[17] This is in comparison to the estimate that the cost of implementing a dismantlement program for processing Plutonium and highly enriched Uranium into non-weapons grade material would cost just $7 billion per year for ten years.[18] This minimal amount in comparison is equivalent to less than half of unaccountable spending in the Pentagon over the last decade, 0.09% of current world military spending, or 25% of the $28 billion spent every year to keep nuclear weapons secure.

Disassembly can last from a few days to a period of a few weeks, depending on the bomb or type of warhead.[20] Ideally once the dismantlement has taken place, the individual parts would be disposed of or incinerated, so that they could not be reused. The difficulty in the dismantlement process comes from verification of whether the weapon is genuine without compromising sensitive national security information.

Inspectors would not be allowed to know details of the size, shape and composition etc. of

Country	Active	Total	CTBT
USA	1950	8500	S
Russia	2430	11000	R
UK	160	225	R
France	290	300	R
China	180	240	S
India		90	N
Pakistan		100	N
North Korea		<10	N
Israel		140	S

Table 2: Number of nuclear warheads, active and total, by country. Status of ratification of the Comprehensive Test Ban Treaty (CTBT) is also shown. S denotes Signatory, R means Ratified and N for Non-Signatory. TODO:CITATION

the warhead. The quantity of fissile material in a nuclear warhead is typically classified, so techniques have to be used by the inspectors to ensure nothing is hidden when they are not able to measure it in detail themselves.

One certainty of the dismantlement process is the problem of dealing with the hundreds of tons of Plutonium and thousands of tons of highly enriched Uranium that the warheads contain. A way to deal with this would be to build a specialised nuclear power reactor that could use the Plutonium and Uranium as fuel. This process would generate electric power and convert the fuel into a form that cannot be used in nuclear weapons again.[21–23]

3.1.1 Nuclear Weapons States

Although exact numbers are not known, there are around 20 000 to 40 000 nuclear weapons in the world.[11;12] These weapons have the capability to destroy entire cities, murdering hundreds of thousands of people in the process. These devices have no place in a peaceful world and bring limitations to human development.

3.1.2 International Atomic Energy Agency (IAEA)

The International Atomic Energy Agency (IAEA) is an international organisation established on 29 July 1957 as an autonomous organisation through its own international treaty, the IAEA Statute, and reports to both the UN General Assembly and Security Council. It serves as an intergovernmental forum for scientific and technical cooperation in the peaceful use of nuclear technology and nuclear power worldwide. The programs of the IAEA encourage the development of the peaceful applications of nuclear technology, provide international safeguards against misuse of nuclear technology and nuclear materials, and promote nuclear safety (including radiation protection) and nuclear security standards and their implementation.

The missions of the IAEA are decided upon based on the needs and interests of its Member States, strategic plans and the vision embodied in the IAEA Statute. There are three main areas that the IAEA works in: Safety and Security; Science and Technology; and Safeguards and Verification. Within these areas the IAEA has its core missions and objectives; encouraging member states to use nuclear power peacefully, introducing and enforcing safeguards to verify that nuclear energy is only used for non-military purposes, and promoting high standards for nuclear safety.

The IAEA executes these missions by inspecting existing nuclear facilities to ensure their peaceful and safe use, providing information needed to ensure the safety and security of nuclear facilities, and acting as a hub for the various fields of science involved in the peaceful applications of nuclear technology.

3.1.3 Non-Proliferation Treaty (NPT)

The NPT is a landmark international treaty whose objective is to prevent the spread of nuclear weapons and weapons technology, to promote cooperation in the peaceful uses of nuclear energy and to further the goal of achieving nuclear disarmament and general and complete disarmament. The Treaty represents the only binding commitment in a multilateral treaty to the goal of disarmament by the nuclear-weapon States. Opened for signature in 1968, the Treaty entered into force in 1970. On 11 May 1995, the Treaty was extended indefinitely. A total of 190 parties have joined the Treaty, including the five nuclear-weapon States. More countries have ratified the NPT than any other arms limitation and disarmament agreement, a testament to the Treaty's significance. Recalling the determination expressed by the Parties to the 1963 Treaty banning nuclear weapons tests in the atmosphere, in outer space and under water in its Preamble, its goal is to achieve the discontinuance of all test explosions of nuclear weapons for all time and to continue negotiations to this end.

Other goals are to further the easing of international tension and the strengthening of trust between States in order to facilitate the cessation of the manufacture of nuclear weapons, the liquidation of all their existing stockpiles, and the elimination from national arsenals of nuclear weapons and the means of their delivery pursuant to a Treaty on general and complete disarmament under strict and effective international control.[19]

3.1.4 Comprehensive Test Ban Treaty (CTBT)

On 10 September 1996 the treaty was adopted by the UN General Assembly; on 24 September 1996 it then opened for signature in New York, when it was signed by 71 States, including five of the eight then nuclear-capable states. As of January 2012, 156 states have ratified the CTBT and another 26 states have signed but not ratified it, including China, Egypt, Iran, Israel and the United States. India, North Korea and Pakistan have yet to sign it (see Table 1).

There have been several other treaties with the aim of encouraging disarmament, with varying degrees of success. Limited success was achieved with the signing of the Partial Test Ban Treaty in 1963, which banned nuclear tests in the atmosphere, underwater and in space, but neither France nor China signed it. However, after an 80 to 19 vote in the United States Senate meant that the treaty was still ratified by the United States. In 1968 the Nuclear Non-Proliferation Treaty (NPT) was signed, which was a major step towards non-proliferation of nuclear. This particular treaty decreed the prohibition of possessing, manufacturing or acquiring nuclear weapons or other nuclear explosive devices for non-nuclear weapon states. It committed all signatories, including nuclear weapon states, to the goal of total nuclear disarmament. However, as mentioned previously, India, Pakistan and Israel have declined to ratify the NPT. Their grounds for doing so were that the treaty is fundamentally discriminatory; it places limitations on states that do not have nuclear weapons but does not attempt to restrict weapons development by those who are declared nuclear weapons states.

Due to the political climate of the next few decades, very little progress was made in nuclear disarmament until 1991, but that year an amendment conference was held to discuss the proposal of converting the Treaty into one banning all nuclear-weapon tests. The UN General Assembly gave it strong support, leading to negotiations for a comprehensive test-ban treaty beginning in 1993. It took three years of intense effort and work to draft the Treaty text and its two annexes, but a consensus could not be reached on the adoption

Figure 7: General internal components of a fission bomb.[24]

Figure 8: Basic components of a thermonuclear weapon.[27]

of the text in the Conference on Disarmament (in which negotiations were being held). Under the direction of the Australian Prime Minister John Howard and Foreign Minister Alexander Downer, the text of a draft resolution was submitted to the United Nations General Assembly in New York. The CTBT was finally adopted by a large majority, exceeding two-thirds of the General Assembly's Membership on 10 September 1996.

US President Barack Obama in April 2010 called for the world's nuclear weapon arsenal to be vastly reduced. He labelled the thousands of remaining weapons "the most dangerous legacy of the Cold War." For this to be achieved would require cooperation because the Nuclear Weapon States (NWS) and a trusted verification and dismantlement process.

3.1.5 Nuclear Weapon Components

Using the so called 'gun' method is probably the easiest for purely fission reaction bombs. These derive their energy from the splitting of heavy nuclei that are bombarded by neutrons to decay into lighter elements, releasing energy. This then begins a chain reaction. For fission bombs, at least 8kg of Plutonium-239 is needed, or 25kg of HEU are needed to build weapons.[25] To start the reaction in the gun method, about 44kg of TNT are necessary[26] for the explosive charge, which is placed behind a 'bullet' that forms the moving part. This is what strikes the physics package. This physics package comprises of two halves of the fuel shaped into hemispheres, separated by approximately 4cm. The method relies on the separation to keep the system from reaching criticality and blowing. When the bullet interacts with the halves, they are brought together to start the chain reaction, going supercritical for an explosion to occur.

Thermonuclear weapons utilise technology from fission bombs to create enough heat for fusion that then releases more energy. Initially the fission bomb implodes, releasing energy. The fusion fuel in the primary core is then compressed beginning a nuclear fusion reaction. This then releases more neutrons to further the nuclear fission reaction. This entire process increases the efficiency of the weapon. The energy from these initial stages transfers further to the secondary stage of the fusion reaction, again compressing the fuel (Deuterium, Tritium) and a 'sparkplug', causing it to go critical, creating another chain reaction and heating the Deuterium to even higher temperatures, prompting further fusion. This then generates neutrons to fuse the lithium in the fuel.

3.1.6 bits to add in

Information barriers can be used which would confirm the agreed amount of radioactive material is correct in the container. These barriers would be separately built by each country. Main Objectives Before dismantlement the total quantities of weapons grade Plutonium and Uranium need to be determined for each NWS. Dismantle process begins with the warheads being split into their individual components which include the arming or firing mechanism, the primary physics package, the secondary physics package. The warhead needs to be destroyed by crushing the part until it is rendered militarily useless. Weapons-grade Plutonium is 93.5% Pu-239 and 6% Pu-240 whereas reactor grade Plutonium is 58% Pu-239 and 24%

Pu-240. TODO:CITATION Ideal conditions for a transparent international dismantlement facility would include a neutron source that could obtain the mass of Plutonium or Uranium used to an accuracy of 5%, and would log this separately for each weapon. The facility would ideally be brand new and observed under construction and shown to have no basements. This means the facility could be checked for nuclear material before a weapons dismantlement began. Care is needed when handling hazardous materials such as beryllium.

4 Political Background

4.1 Treaties

After the Second World War, people started to realise that nuclear weapons were too powerful, dangerous and needed to be controlled. They started to develop constraints for development of nuclear weapons. The most general one of these is the NPT.[28] The NPT is an international treaty whose goals are to prevent the spread of nuclear weapons and weapons technology, to promote cooperation in the peaceful use of nuclear energy and to further the goal of achieving nuclear disarmament. The treaty was penned for signature in 1968 and became effective in the year 1970. A total number of 190 countries has committed to this treaty. And on 11 May 1995, the Treaty was extended indefinitely.

America and Russia played important roles in the global nuclear disarmament act as they have the most nuclear weapons. The starting point of such an act can be chased back to 1969: The Strategic Arms Limitation Talks, known as SALT.[29] This referred to two rounds of negotiations conducted between the Soviet Union and America on the purpose of arms control.

SALT I led to a five year interim between the United States and the Soviet Union in which the ABM treaty was created. This treaty will be discussed later in this report. After the success of SALT I, SALT II was proposed and reached an agreement in 1979, but the United States chose not to implement the treaty due to the invasion of Afghanistan by the Soviet Union, which happened later in the year. Eventually, the US withdrew from the treaty in the year 1986.

Even though SALT II failed, the incident led to the birth of the Strategic Arms Reduction Treaty (START).[30] START was a bilateral treaty signed between the United States and the Soviet Union. It focused on the reduction and limitations of strategic offensive arms. The treaty was signed in 1991 and came into force in 1994. The treaty gave limitations to the number of nuclear warhead ICBMs, submarine-launched ballistic missiles, and bombs. At the end, it managed to get rid of eighty percent of all the nuclear weapons existed. It is the largest and most complex arms control treaty in history.

START II is the follow up of START I. It forbids the use of multiple independently targetable reentry vehicles (MIRVs) on intercontinental ballistic missiles (ICBMs).[31] However, it is not currently in effect because Russia withdrew from the treaty on 14 June 2002 in response to US withdrawal from the Anti-Ballistic Missile Treaty (ABMT). This treaty was signed in 1972 between the United States and the Soviet Union. It focused on limiting the anti-ballistic missile (ABM) systems that were used to defend areas against missile-delivered nuclear weapons.[29]

And then there is START III. Its objective was to reduce the deployed nuclear weapons arsenals of both countries and to continue the weapons reduction efforts that had taken place in the START I and START II negotiations.[32] The negotiation process started in 1997, however, the treaty was never signed because the negotiations broke down.

Between the failed START III negotiations in June 2003 and the New START treaty that finally came into force in February 2011, there was this other treaty that focused on the arms reduction between the US and Russia. Its name was the Strategic Offensive Reductions Treaty (SORT).[33] In the SORT, both countries agreed to limit their number of nuclear weapons to between 1700 and 2200 operationally deployed warheads each. However, each country could withdraw from the treaty upon giving three months written notice to the other.

New START was signed on 8 April 2010 in Prague and, after ratification, entered into force on 5 February 2011. It is expected to last at least until 2021.[34] New START is a combination of the START I treaty, the proposed START II treaty, and the START III. According to the terms in the treaty, the number of strategic nuclear missile launchers will be reduced to half. Also, a new inspection and verification regime will be established, replacing the SORT mechanism. However, the treaty does not give limitations to the number of inactive stockpile that America and Russia each still have a few thousands of.

The new inspection and verification regime was built based on the Trilateral Initiative.[35] This was a six-year (1996–2002) effort conducted trilaterally by America, Russia and IAEA. This program allows America and Russia to submit their nuclear weapons for verification and monitoring. In this Trilateral Initiative, they looked into one very important concept called the "information barrier" which will be discussed in length in the following section.

4.2 Nick's Stuff

Verification may take place at any point along this chain. A Nuclear Weapon State may declare numbers and types of weapons in storage sites for example, and it is the job of the inspector to confirm or refute this information. However inspectors do not enjoy the unrestricted right to freely examine the weapons; they must do so behind the veil of an information barrier because the act of inspection incurs the risk of spreading weapon information.

4.2.1 Information Barrier

In support of several ratified and pending nuclear material control agreements, technical representatives from the US and Russia have recognised the necessity for assurances against the release of sensitive information to be put in place. The majority of these agreements involve storing nuclear materials and components from stockpile weapons within specially designed containers.

Strategies for monitoring the agreements include measuring the neutron and gamma radiation signature to verify declared attributes of the Plutonium or HEU. If these measurements are accurate enough to serve for this verification purpose, then they are accurate enough to contain information about the design of the component being monitored. Subsequently safeguards have been designed to prevent the disclosure of that information. Hardware, software and procedural measures containing the sensitive data will only present the relevant results required for verification.[37]

In the interest of transparent monitoring, inspectors may witness or perform restricted measurements on controlled items. The information barrier is designed to mitigate the intrusiveness of taking these measurements, and the proliferation knowledge it would pass on to the inspector. Wolford and White[37] highlighted three objectives that hardware, software, and human procedures should fulfil in order to be an effective information barrier: "Prevent the unintended release of sensitive information during an inspection; Display a sim-

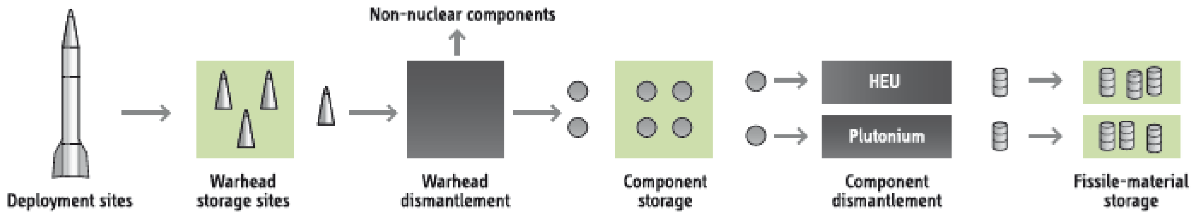


Figure 9: Overview of the dismantlement process from deployment to disposal. [36]

ple but reliable and useful result to the inspector; Allow checks on the integrity of the internal operations not visible during an inspection." However in applying the barrier, the person monitoring may lose the assurance that the internal operations proceeded as intended. Fortunately it can be shown that thoughtful design elements can help recover some of that lost assurance for the human operator.

4.2.2 Design Elements

An actual information barrier must be adapted to the measurement instrument it accompanies. However there are certain design elements that must be implemented no matter what type of measurement is being performed. The DoE–DoD information Barrier Working Group has provided guidance for 10 design bases which, when grouped into functional categories, fall into 3 top-level elements:

1. "A barrier to conceal the sensitive information gathered in a measurement, and from which the physical attributes of an inspected item are derived. This consists of some combination of hardware, software, and human procedures, and must work in both directions, shielding unintended signals originating both outside and inside the measurement system.

2. "A simplified display that indicates clearly the selected results of the measurements as defined in the agreement, and nothing more. Accordingly, the display should be no more complex than is necessary to convey the result to the inspector.

3. "Enough autonomy to compensate for the lack of a human operator, both in monitoring the measurement and in safeguarding the data. The instrument must assure the reliability of its own measurements as well as protect the data resident during an inspection. In the event of failure or signs of tampering, this mechanisms should erase all traces of sensitive data from the instrument and halt the inspection." [38]

TODO: Shift to implementation. Example: Information Barrier for Gamma Ray Measurements Gamma ray measurements can infer a lot of information about the object being measured including, constituents abundances, a lower bound for the masses, and the amount of intervening material. Also in a neutron-emitting source such as Plutonium, the presence of other elements can be inferred from the evidence of activation products. Clearly much of this information lies outside that demanded of transparency agreements and fortunately a full spectrum is not required to derive the most useful attributes.

Programmers have an opportunity to protect most of the information. At Lawrence Livermore National Laboratory software was created that used Plutonium lines between 630 KeV and 670 KeV to compute a ratio of 240Pu

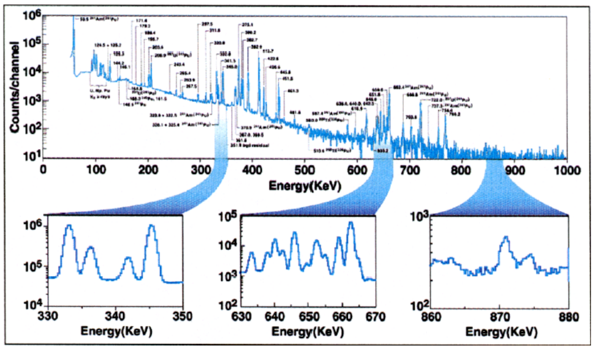


Figure 10: Plot of the gamma ray spectrum from a non-sensitive sample of Plutonium containing several isotopes and decay products. The details illustrate the relatively narrow subintervals containing the spectral lines used in the attribute calculations known as Pu300, Pu600 and Pu900 respectively.[37]

to 239Pu which distinguishes weapon-grade Plutonium from non-weapon grade. The tool, called Pu600, was adapted and enhanced for the requirements of the Trilateral Initiative. Programmers at Lawrence Livermore National Laboratory developed similar methods called Pu300 for determining the time since separation, and Pu900 for determining the amount of oxide present in a sample.

5 Overall Process

5.1 Chain of Custody

Chain of custody refers to the system of routines used to provide a high confidence level that a nuclear warhead will be delivered from its field deployment or storage location to the dismantlement facility and that the recovered nuclear material will be monitored until its disposal to make sure that it will not be reused.[35] Chain of custody includes the use of photography (X-ray or gamma ray images, optical pictures), seals and tags, visual surveillance or video, warhead authentication (detection and confirmation of nuclear or non-nuclear warhead) and information processing (data transmission and relay, data compression, encryption and decryption etc.). There are two categories of chain of custody: limited chain of custody of a specific dismantlement facility and full range chain of custody with continuous knowledge of the disarmament process and the total number of nuclear warheads.[39]

5.1.1 Seals and Tags

A tag is a unique characteristic ('fingerprint') of an object or container that is used to unambiguously identify it. A seal or tamper-indicating device is a device or material that records unauthorised access and leaves inerasable evidence behind. There are two categories of modern seals: passive and active. Passive seals do not need electrical power to work and they are inexpensive but they can only be used once. Active or dynamic seals require electrical power to work, either internally or externally. They are more expensive than passive seals but they are typically reusable.[40]

Seals used in verification of nuclear disarmament need some unique attributes such as transparency and negotiability. If the inspected facility provides and controls the seals, then the inspectors will be suspicious and think that the seals have been tampered with. If the inspectors provide and control the seals, then the inspected facility will worry about espionage devices such as microphones being embedded in the seals. High tech electronic seals could be less comfortable to both parties due to tampering, safety and espionage concerns. Also some weapon containers cannot accommodate extra seals so the seals for nuclear disarmament will have to coexist with seals for safeguards and internal security.[40]

Current technologies and technologies under development:[35]

VACOSS fibre optic seal

The first IAEA electronic seal which consists of a loop of fibre optic cable that is actively checked for integrity by the seals electronic system. Remote reading of the seal is also possible. They are no longer supported by the manufacturer and are being replaced by the EOSS seal which is more secure.[41]

Electronic Optical Sealing System (EOSS)
It is intended for long duration surveillance with high reliability. It uses a seal for enhanced authentication, smart power management system, tamper indication and encryption. A tamper indicating enclosure protects the electronics and a microwave foil protects the complete housing against drilling. It can be coupled with surveillance systems and can be remotely interrogated.[41]

Reflective Particle Tags (RPT)
Reflective particles are mixed into glue that is applied to the object being tagged. If the tag is illuminated by a point light source, particle reflections form a unique pattern to that tag and incident angle. A tag reader records the pattern of individual pictures using a camera and forms a set of fingerprints unique to that tag. The object can be uniquely identified by reading its tag.[42]

Ultrasonic Intrinsic Tags (UIT)
A sample is scanned ultrasonically and a hand-held scanner collects sub-surface structure data. A computer performs the alignment and correlation functions. These tags are resistant to surface changes and counterfeit.

Surface feature tags
A unique fingerprint of an item by examining its surface using scanning electron microscopy, holographic interferometry and micro-videography.

Shrink-wrap seals
They consist of a plastic film that shrinks tightly around the safeguarded object. A unique pattern is produced by multiple layers of geometrically patterned film and its photographed for verification.

Cobra seals
Consist of a loop of fibre optic cable and a polycarbonate sealing body. A unique light pattern is created when a blade cuts the cable. The Cobra seal reader photographically records this unique pattern and uses it for future comparison.

E-type cup wire loop seals
Consist of two metal cups which snap together and cover the crimped ends of a wire loop. The inside of the cups are covered with melted solder and this is scratched to create a unique pattern that is recorded for future comparisons.

E-tag mechanical seals
Similar to E-type cup wire loop seals but also contain an electronic chip that contains a unique identification number that can be verified without opening the seal.

Pressure-sensitive adhesive seals
Use pressure-sensitive adhesives to attach fragile labels to an object. Unique reflective patterns are created by microscopic glass beads.

T-1 Radio-Frequency seals and tags
Consist of a fibre optic seal, case tamper switches, motion detector and low and high temperature indicators.

Acoustic tags
Based on the unique resonant properties of an object when scanned using sound waves of a specific frequency.

Radio-Frequency (RF) tags
: Emit a unique identification number and can be scanned using a RF device.

VNIIEF smart bolts
: A small reader is used to read the unique electrical properties and the digital identification of the seal. The electrical properties of the bolt change if its unscrewed and that indicates tampering.

5.1.2 Surveillance technologies

Surveillance is another important element in the chain of custody and comprehensive surveillance can also increase the security status of the monitored nuclear warheads. Comprehensive surveillance provides a high confidence in the dismantlement process and establishes mutual trust between the involved countries. Comprehensive surveillance combined with seals and tags can constitute an in depth inspection system. Several technologies can be used for comprehensive surveillance such as video monitoring, sensor monitoring, photograph comparing, intrusion detection and satellite imaging.[39]

Video monitoring is widely used in international safeguards and domestic security and it plays an important role in preventing illegal activities and proving treaty compliant activities. It is one of the most widely used containment and surveillance techniques by the IAEA.[39] Modern digital imaging used by the IAEA includes single camera digital surveillance units such as the All-in-one System (ALIS), All-in-one Portable System (ALIP), Digital Single Camera Optical Surveillance System (DSOS) and multi-camera digital surveillance systems such as the Server Digital Image Surveillance System (SDIS) and the Digital Multi-camera Optical Surveillance System (DMOS). These systems were developed to replace aging videotape based systems and the SDIS can be used for remote and unattended operation. The General Advanced Review Station Software (GARS) was developed to review all digital image surveillance records of the IAEA using a desktop computer.[43] The newest system is the Next Generation of Surveillance System (NGSS) and it will be used in 2012. It is scalable to any number of cameras, has solid state storage media, low power consumption, advanced security features and is highly reliable under harsh environmental conditions. It can be configured as a single all-in-one camera system or as a scalable multi-camera system. It supports various trigger signals from electronic seals and sensors, high resolution and coloured images, remote monitoring and picture taking rates of one image per second. Four different fields of view can be recorded simultaneously by a single NGSS camera.[41]

Figure 11: Picture of the Next Generation of Surveillance System (NGSS) with 24 cameras.[41]

Sensor monitoring is another effective method used to track and authenticate nuclear warheads. Various sensors such as motion/acceleration, weight, acoustic, radioactive, magnetic, thermal, temperature/humidity, impact force sensitive and vibration sensors can be combined to monitor nuclear warhead reduction and provide a high confidence. Most of these sensors are commercially available and can be used in an integrated monitoring system which is easy to understand, technically transparent and applicable by all parties.[39]

Photograph comparing is used to carefully examine recorded images of the objects being monitored and detect tamper activities. Drawing random marks or images near the monitored object and then photographing it from all angles can enhance the photograph comparing method. It can easily raise disputes because it requires specific interpretation, either algorithmic or artificial, and the picture taking process can be also affected by environmental elements so it is never used on its own. It is often embedded into tamper-indicating monitoring methods and used as a complimentary technique in nuclear disarmament.[39]

Intrusion detection is used in guarding nuclear warheads and uses microwave, capacity sensitive, weight detection, infrared beam and motion/acceleration sensors to detect unauthorised access. The technologies and intrusion detection methods are being continuously developed to increase the efficiency and reliability of intrusion detection.[39]

Satellite imaging is used to detect change of large facilities or objects and requires advanced space and electronic sensor technologies. It can integrate visual, multi-spectra, synthesised aperture radar (SAR), thermal/infrared and other photographic technologies into a comprehensive system to provide a meaning full picture of a specific area or object.[39]

5.1.3 Vulnerability in Chain of Custody

The Vulnerability Assessment Team (VAT) at the Los Alamos National Laboratory has extensively researched issues associated with nuclear safeguards in the areas of transport security, intrusion detection and vulnerability assessments.[44]

All seals appear to be vulnerable to simple, rapid, low tech attacks. Attacking a seal means to trying to gain access to whatever the seal is protecting without being detected. Defeating a seal means opening the seal without being detected or leaving evidence of entry, or repairing any damage and erasing evidence of entry, or replacing the entire seal or parts of it with counterfeits. The most comprehensive seal vulnerability study has been undertaken by the VAT. In 1997 they analysed 94 different seals and defeated them for a total of 132 times. All of the defeats were implemented using low tech attacks with tools and supplies that in some cases can be easily carried in a person's pockets. The time taken for successful attacks varied from 3 seconds for several seals to 125 min for the most difficult seals. The mean time taken to complete the 132 defeats was 4.3 min and the mean cost of the defeats was \$56.[45] As of the 28$^{\text{th}}$ February 2012, 244 seals have been analysed and defeated by the VAT. Half of these seals are used for critical applications and 19% are used in nuclear safeguards.[46]

Most organisations ignore or underestimate the security risk posed by employees, also known as insider threat.[44] Motivations for an insider attack include revenge, greed, ideology, terrorism, social engineering or even mental illness and periodic background checks should be used to reduce the insider attacks. Common mistakes that organisations make regarding the insider threat are thinking that low-level employees are not a threat, not testing if employees can be bribed, thinking that only employees are insiders and having overconfidence in the polygraph test.[47] The IAEA does little or no background checks on its employees either before or after hiring, including nuclear inspectors. The IAEA must trust its inspectors judgement on whether treaty violations are occurring and the lack of background checks puts the reliability of inspections at risk. Also IAEA inspectors are granted diplomatic privileges and the position of an inspector could attract people who want to exploit diplomatic status for terrorist or criminal activities.[44]

Another security risk is the fact that people are poor observers and they don't realise it. Perceptual blindness, also known as inattentional blindness, is the phenomenon of not being able to perceive things which are in plain sight if you are focused on a specific visual task. Change blindness, which is also a kind of perceptual blindness, is the phenomenon of observers failing to notice changes, including blatant changes, even when they are expected. This has serious implications for inspectors and security guards who inspect seals, watch video monitors, operate safeguards equipment and guard gates. Inspectors and security guards should be educated and trained on this and technology could be used to cover for perceptual weaknesses in humans.[47]

Confusing inventory with security leads to bad security. Inventory is concerned with the counting and locating of stuff. The methods employed in that field can detect innocent errors by insiders such as sending a shipment to the wrong location, but it is not designed to detect spoofing and deliberate nefarious attacks by insiders or outsiders.[48] Security is meant to counter nefarious adversaries, both insiders and outsiders.[47] Inventory systems should not be used as security systems. Examples of inventory systems used as security systems in nuclear safeguards include using the Global Positioning System (GPS) for cargo security and using contact memory buttons (CMBs) or radio frequency identification devices (RFIDs) for nuclear material control and accounting (MC&A).[48] Almost all nuclear applications use the civilian GPS signals and not the military signals. The civilian GPS signals are unauthenticated, unencrypted so they are not secure and were never meant to be used for security applications. GPS receivers can be easily spoofed or jammed using widely available commercial GPS satellite simulators which can be easily purchased, rented or stolen. CMBs and RFIDs are very useful for inventory but they are not designed to deal with nefarious adversaries. They are very easy to lift, counterfeit, tamper with the reader or spoof the reader from a distance.[44] On the other hand nuclear MC&A may look like an inventory function since it involves counting and locating nuclear assets but it is a security function meant to detect nuclear theft, tampering, diversion or espionage. A nuclear MC&A program or system should make significant attempts to deter or detect spoofing by a nefarious adversary.[48]

5.1.4 Unconventional approaches to chain of custody

Conventional tamper detection methods are fundamentally flawed. A conventional seal must store the information indicating that it has been opened until it is inspected but it is too easy to hide or erase this information or even make a counterfeit seal. A much better approach is to use the "anti-evidence" method. Information that tampering has not occurred (the anti-evidence) is stored at the beginning when the seal is first installed.[44] If tampering is detected, this information, which is usually 1 byte in length for electronic anti-evidence seals, is being erased.[49] The inspector will look for anti-evidence during inspection and if it is missing or incorrect then tampering has occurred. If the anti-evidence is intact then the seal has not been opened. Only the people who installed the seal will get to know the anti-evidence information, and it is different for each seal. It even changes if the seal is reused. The attacker will not know the anti-evidence information so he cannot counterfeit, erase or hide anything.[44] It is also theoretically possible for the inspected party to check the anti-evidence seal and send the anti-evidence to the inspectors without them being present there.[49] This is very useful because inspectors might not be allowed to handle nu-

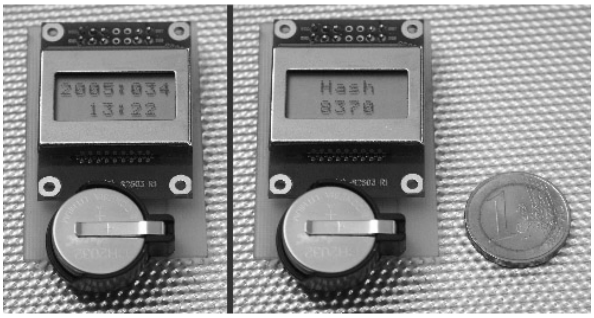


Figure 12: Working Time Trap prototype showing entry occurring at 13:22 on 3rd February 2005. The picture on the left shows the time that intrusion was detected and the picture on the right shows the hash for that time. If the hash value is wrong or missing or the time is different by a few minutes, then tampering has occurred. An on-board programmable microprocessor controls this anti-evidence seal and the entire device cost $8.[44]

clear material or weapons and might be limited to observing the facility personnel installing or removing the seals. An example of an anti-evidence seal is the Time Trap, shown in Figure 12, which can be placed on the hasp of a door or container. It turns on its liquid crystal display when entry has occurred and the display will alternate between the time that the entry has occurred and the hash for that time. Each time has a different hash and only the people who installed it know the correct hash for future times. When the seal detects entry, the future hash values are instantly erased so the attackers cannot counterfeit the seal because they do not know what hash it should display.[44]

The anti-evidence method can be used for real-time monitoring of nuclear material, including during transport and this approach is called the "Town Crier" method. It does not send out an alarm when intrusion is detected because the alarm signal can be easily blocked or jammed. Instead it sends a periodic "ALL OK" byte called the bingo number. Only the monitoring system and the people listening in know the correct bingo number at any given time and if the bingo number fails to arrive on time, it indicates trouble. The probability of guessing one bingo number correctly is 1/256 (0.4%) and the probability of guessing two correctly is 1/65536 (0.002%) so the attackers cannot counterfeit the bingo number. It is a simple, low cost method that uses a very low bandwidth of 1 byte per minute, one-way communication and provides high security since attackers gain nothing by blocking the signal.[49]

Another method that could be used is colorimetry because colour is very difficult property to accurately reproduce. Inexpensive commercial colour sensors can measure colour accurately and they can be used as change detectors for seals. Inspectors could also use them to check if the walls of a camera enclosure have been cut open, then repaired and repainted to hide the intrusion.[49]

5.2 Pit stuffing

'Pit-stuffing' was developed at Los Alamos National Laboratory to ensure that warheads that had been internally evaluated to be unsafe would not accidentally go off. Pit-stuffing makes it possible to disable thousands of nuclear warheads, quickly, cheaply, and irreversibly; in a verifiable manner.

Implosion-type nuclear weapons have a "pit" which is a hollow sphere of Plutonium or HEU, as can be seen in Figure TODO:CROSS-REF. For fusion-boosted bombs, the hollow part is to be filled with Tritium. To do that, a tiny tube is drilled into the sphere. Depending on the specific model, this hole may be drilled into fission bombs that do not already have one. If some other appropriate material is fed through this small tube until the inside of the pit is "stuffed", the Plutonium would no longer be

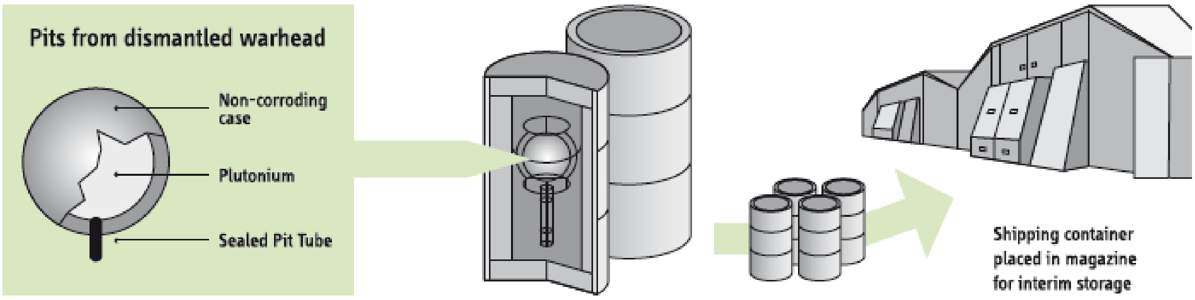


Figure 13: Storage arrangements for US Plutonium warhead "pits" at the Pantex warhead dismantlement facility in Amarillo, Texas.[36]

able to be compressed enough to cause the explosion.

At Los Alamos there had been discussions as to what would be the most suitable material. Aluminium powder and epoxy were suggested, however powder could be made to fall back out the tube, and organic material within the vicinity of Plutonium could trigger chemical radiations and thus threaten the safety.

The best considered option is to use bits of metal wire that are shaped so that they cannot be removed via the fill tube. If this were achieved the only way to make the weapon functional again would be to dismantle it, remove the pit and cut it open to take the wire out; then re-manufacture the pit and reassemble the weapon. This would be an expensive process, especially compared to the minimal time it takes to fill the pit. The physical act of stuffing the pit would about a minute; therefore a single inspection visit could be very productive, even if additional time is spent carrying out necessary safety procedures. Verifying that the pit had indeed been filled could be confirmed by incorporating micro-curie quantities of Cobalt-60 in the stuffing wire. One set of gamma-ray counters aligned to view the pit from one side would give a few simultaneous counts with another gamma-ray detector orientated in a perpendicular direction. This is because Cobalt-60 gives two simultaneous high-energy gamma rays. Such measurements could not be mimicked by gamma-ray sources that are not in the interior of the pit.[35] However further measures may have to be taken against the host merely inserting minimal amounts of Cobalt-60 without inserting the wire, or semi-inserting the wire with a view to remove it after the inspection. Also, because pit-stuffing depends on certain details of warhead design and fabrication, it might not be an approach that can be blindly administered.

The practicalities of this approach are encouraging for the cause of verified dismantlement because of the speed and minimal cost. The intrusiveness in principle could be low, if there was assurance that the wire had been inserted and could not be removed. The host could then be free to complete the dismantlement in privacy, removing the need for foreign verification during transportation which is currently a considerable expense.

After the dismantlement, the inspectors would return and be shown the canisters containing the stuffed pits. Again a gamma-ray spectrum could confirm that the containers enclosed hollow spheres of Plutonium stuffed with wire. The inspector could be very confident that these were the same pits observed before the dismantlement as it would be very expensive and cumbersome to manufacture thousands of hollow Plutonium spheres stuffed with wire.[50]

This method would work for US warheads, but needs to be evaluated for Russian warheads that may have a different design.[35] However pit-stuffing as a verification technique might not get its opportunity to be utilised because of the asymmetry between the sensitivity of classified items between Russia and the US. The years 2000-2002 saw dramatic global change, including the changing of American and Russian leaders. This meant that the enthusiasm for implementing initiatives negotiated in the late 1990s was not sustained. The Russian Federation decided that it would melt its pits into 2-kilogram balls and pack two Plutonium balls into each specialised AT-400R container before submitting the material for US or IAEA verification. The US and Japan provided AT-400R's are the standard containers designed for Russia's Mayak Fissile Material Storage facility. Russia maintained that the isotopic composition of its weapon Plutonium in the 2-kg balls was classified.[51]

Although political decisions on declarations might stand in the way of pit-stuffing as a universal verification technique, further work, perhaps similar to the 2011 UK–Norway Initiative Workshop on Nuclear Disarmament Verification, could be done to address some of the technical issues discussed as it could prove to be a useful tool to verify the US.

5.3 Dismantlement

A joint exercise between UK and Norway described a possible dismantlement and verification process was conducted near Oslo in 2009. A ^{60}Co sample was used to mimic a physics package. A single nuclear weapon was moved into a dismantlement facility, where screwdrivers were used to open a side panel and remove the physics package. It was placed in a separate container. Everyone entering or leaving the dismantlement room was checked for radioactive material. Inspectors then confirmed that radioactive material was present in the container. It was stored overnight in a sealed room with CCTV surveillance. Seals used on items were of low technology. The doors on the overnight storage room had a purple adhesive down the hinge which would change colour if disturbed. The adhesive strip itself was identifiable with a cluster of glitter suspended in transparent glue. Upon application and removal of the adhesive strip, the glue tag was photographed to check if it had been replaced; the exact configuration of suspended pieces of glitter would be near impossible to replicate. A simple technology like this seemed to provide a reliable way of detecting alteration on a door or package seal. The following day the physics package was moved to the "hot cell" where it was dismantled. Using an "information barrier" device, the amount of material in the package can be measured without revealing the quantity to the inspectors. It gives a green light if the result was the same as the last measurement. Both countries independently developed and built their own detectors. Using this method the package could be inspected at multiple points to ensure that no material had been siphoned off. Once the weapon had been dismantled the nuclear material was taken away for storage.[52]

The magazine transparency system is a proposed method of storage to monitor and maintain the inventory of a "magazine", a storage area containing nuclear warheads or nuclear fissile materials during dismantlement verification operations.

A system like this has been demonstrated at the Pantex dismantlement facility in Texas. The weapon itself has only passive tags and seals placed upon it to eliminate problems associated with battery life. The MagTag blanket is simply a tarp containing permanent mag-

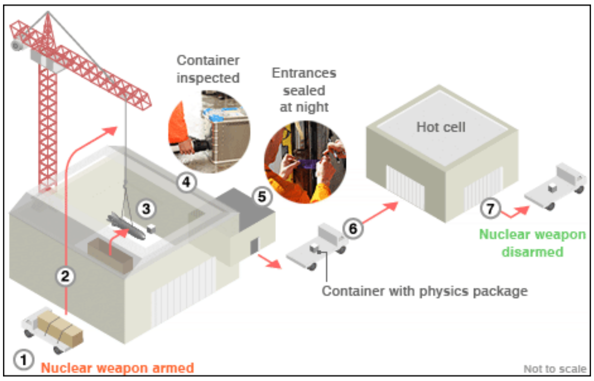


Figure 14: Nuclear Disarmament Process.[52]

1. Nuclear weapon transported to disarmament facility
2. Weapon is hauled by crane into storeroom and dismantled
3. Physics package is removed and placed in separate container
4. Inspectors use device to confirm radioactive material is present in container
5. Container is then sealed in a side-room overnight with CCTV
6. Next day physics package is transported to a hot cell for dismantling
7. Radioactive material is removed safely and put into storage

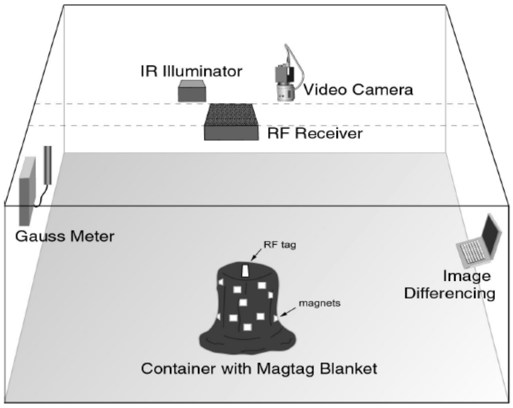


Figure 15: A schematic of the Magazine Transparency System (MTS) showing the primary components.[53]

nets in random orientations, so as to make it unique. The system has a high resolution magnetometer to detect changes in the position or characteristics of the blanket. The bar-code reader records the bar-code on the seal of each container when the magazine is emptied or filled. This data is stored on an integrated notebook computer which can transmit to a central monitoring station. The RF receiver transmits the unique RF tag number on each weapon/storage vessel to the notebook. Low light video cameras also send video straight to the notebook for processing. With all of this information, Gauss readings, video, RF tag and so on, the notebook computer sends an "all okay" signal once every second assuming no anomalous activity is detected from any of the sensors. The notebook computer records no Non Proliferation treaty sensitive information. In the event of anomalous activity in an MTS during disarmament verification operations, the notebook is immediately given to the inspectors who can determine what kind of activity took place.[53]

Many weapons are dismantled without foreign verification by nuclear weapon states.

This is done to reduce the size of the stockpile or to dispose of older outdated weapons. In the US, the national nuclear security administration (NNSA) is "responsible for the management and security of the nation's nuclear weapons, nuclear nonproliferation, and naval reactor programs"[53] Part of this management is weapon dismantlement. Design laboratories work with production facilities to identify and mitigate any risks associated with dismantling a particular design of weapon. A plan is formulated to safely dismantle the weapon and it is taken to the Pantex Plant in Texas. The time required to dismantle a warhead ranges from "a few days to a few weeks" depending on the complexity of the design.[54] With the weapon dismantled, the high explosives and other non-nuclear materials are processed on site at Pantex and a few other facilities. The special nuclear materials are then dismantled at the Y-12 National Security Complex.[55] Here nuclear materials are down blended to reduce the enrichment and render the Uranium useless for military application. Down blended Uranium is then used to fuel nuclear power plants. According to the US DoE 10% of the electricity used in the United States is produced using former Russian nuclear weapons.[56] Uranium "pits" that are not down blended can be stored in a "sealed insert" system. Leak-tight stainless steal vessels are placed into steel storage over pack drums.

5.4 Monitoring

Monitoring nuclear weapons is of two varieties, there are non-treaty stockpile maintenance operations, and operations that are stipulated from treaty regimes. For practicality it should be made possible for these operations to be carried out simultaneously at the same facility; however the two activities cannot drastically interfere. With this consideration, researchers at Los Alamos National Laboratory designed

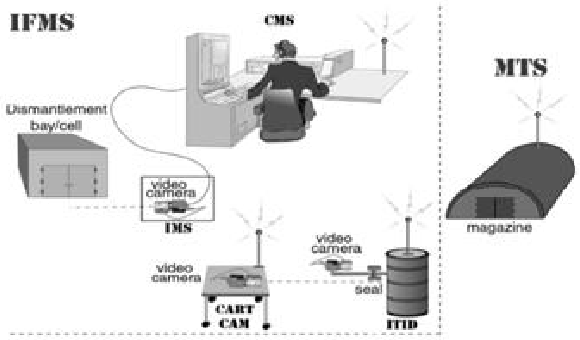


Figure 16: The Integrated Facility Monitoring System and its four sub-systems. The Magazine Transparency System is shown to also pass "All Okay" signals to the Central Monitoring System.[53]

two monitoring systems that minimise the interference, while promoting high levels of negotiability and mutual confidence. The systems are known as the Magazine Transparency System (MTS) – which has been discussed previously, and the Integrated Facility Monitoring System (IFMS). Although the systems were designed for the now defunct START III, they are currently back on the agenda following the ratification of New START on the 5$^{\text{th}}$ February 2011.

5.4.1 Integrated Facility Monitoring System (IFMS)

The IFMS uses widely available hardware and custom Los Alamos software to track nuclear component containers during the dismantlement process. It uses a combination of live sensors, video cameras, tags, tamper-indicating seals and a computer system to track treaty-limited components and weapons. The system consists of four components which are: the Central Monitoring System; the Integrated Tamper-Indicating Device; the Cart-Cam; and the Integrated Monitoring System.

The Central Monitoring System (CMS) is

the analysis and control room for all the monitoring instruments. Dismantlement activities that are subject to verification can be viewed in real-time, and archived unclassified data can be reviewed. The video signals are processed by NTVision, software that was developed at Los Alamos to only store video footage in which motion occurs. This reduces the amount of video that the foreign inspectors must review.

An expert system to integrate sensor information with "disassembly protocols" was also developed. This means that an inventory of treaty-limited items is maintained to assure compliance, and, for example, the system can detect excess time of movement between processing stages.

The CMS could also be used for data sent from the Magazine Transparency System which is used to monitor temporary or long-term storage of weapon containers.

A suitable Integrated Tamper-Indicating Device (ITID) would be attached to every container that housed a declared treaty-limited component or weapon. The powered device would consist of a seal, a unique infrared tag, a miniature video camera focused on the tag and seal, and a wireless video transmitter. An infrared illuminator and filter are also utilised to block ambient room light; this aids the NTVision software to ignore the motion of shadows.

This uninterrupted surveillance is clearly more efficient and effective than periodic checks of seal integrity

The Cart-Cam (CC) consists of a small pinhole video camera, wireless transmitter, battery, and LCD monitor. It is used to help assure the remote inspectors that the ITID had been installed and removed correctly. The Cart-Cam could be made remote-controlled, however it is safer to simply move it around manually at the dismantlement facility.

The Integrated Monitoring System (IMS) is sensor module that would be placed at the en-

Figure 17: Photo of the Integrated Tamper-Indicating Device. The video camera monitors the seal, its barcode, and a portion of the container. The video transmitted and IR tag are not featured.[53]

Figure 18: The Cart-Cam that transmits a close-up video to the CMS when the Integrated Tamper-Indicating Device is attached or removed from a container.[53]

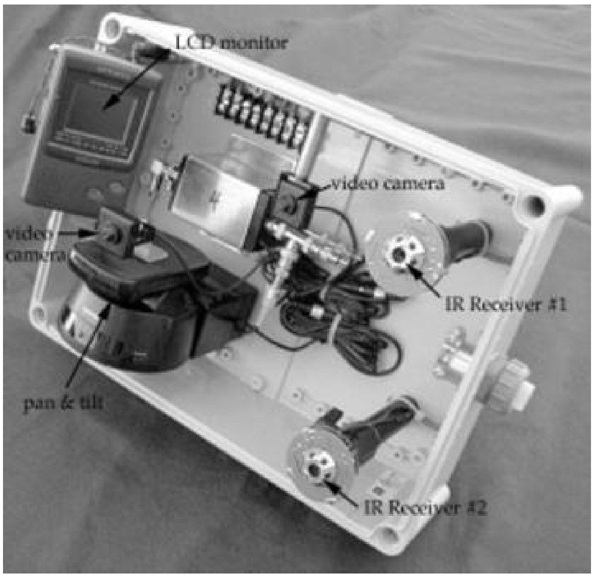


Figure 19: Photo of the Integrated Monitoring Station module (cover removed for better view). They are placed outside each dismantlement bay and monitor activities taking place.[53]

trance of the disassembly bays allocated for treaty verification. The constituents are two pinhole video cameras, two infrared tag receivers, and an LCD monitor. The cameras may pan and tilt, and this improved visibility may be exploited to "live verify" the on-going procedures.

5.4.2 Live Verify and Local Verify

The Integrated Facility Monitoring System and the Magazine Transparency System offer an alternative to using information barrier devices that rely on encryption and analysis algorithms. Also some of the vulnerable human elements of inspecting are removed. For example, with the ability to review surveillance footage and additional aids from software systems, the chances of catching out a cheater are no longer limited to how observant the inspector is. In the early 1990s, inspection standards had dropped when the manuals became less instructive in order to give the inspector autonomy in case of disagreements.[57]

However, for IFMS and MTS the procedures and expectations from both sides are clearly defined and this maintains the credibility of the inspections. The video signals themselves can be verified to be live and local. The need to do this is analogous to assuring that the encryption method of the information barrier is functioning correctly, only that it is much easier to perform.

IFMS Live Verify: There are high- and low-tech ways to verify that the footage is in fact live, though the developers of the IFMS system maintained that the low-tech methods should suffice. From the CMS, inspectors could unexpectedly call the dismantlement operations to a halt – much akin to a fire drill. The inspector would then request a specific employee to perform some arbitrary action in front of the camera, a waving gesture for example. This and other potential requests could verify that the footage originates from the facility of interest, and that there is no switching or splicing of different video signals. However in principle it would be very difficult for the host to perform such a trick because the illumination, shadows, and pixel-grains seen in the different frames would not match exactly. A simple comparison would be likely to yield anomalies. Greater confidence could be achieved by the inspector asking to pan or tilt the camera. A stereoscopic scene of a dismantlement facility would be even more difficult to forge than a 2D image. In order to use this method, a small amendment to the New START treaty would be required to place a limit on the number of times that inspectors can ask the host to perform arbitrary gestures.

IFMS Local Verify: The local verify test could be carried out without the facility personnel having to stop what they are doing, or even be involved. The finite speed of electronic signals can be used to determine that the IFMS video signals are approximately local. In 1999 the IFMS system was demonstrated at Pantex. The Integrated Monitoring Station module used for the demonstration carried a small curved mirror, making it possible to view a LCD monitor to which a known video signal was broadcast. The bandwidth of video signals can be used to measure the time between selected pixel intensity information; the video signal could even be a local broadcast TV program. The same could be achieved by hard-wiring an LED that the inspector would control and then time the delay, however simply using wireless transmission would be more efficient.[53]

5.5 Disposal and Containment

5.5.1 Storage of Fissile Materials/Nuclear Weapons

Assuming confidence in the dismantlement of a warhead, for real progress to made, storage is important. Fissile nuclear materials, especially of the weapons-grade variety, need to be stored under international or bilateral monitoring, to prevent the construction of new weapons and also safeguard against theft.

5.5.2 MPC+A, Material Protection Control and Accounting

This program is an example of bilateral efforts to safely and securely store nuclear materials. Funded initially by the DoD and then by the DoE, its goal was to improve security on hundreds of buildings at 40 sites in Russia to prevent theft or loss of nuclear materials. 600 tons of material was found to be at "risk". In 2001, a report detailed that so far 81 buildings housing 81 tons of fissile material had received upgraded security systems. In 1998 the program was predicted to finish upgrading the storage facilities by 2020.[58]

5.6 Down-Blending

Down-blending is the opposite of enrichment; excess Highly-Enriched Uranium (HEU) can be blended down to Low-Enriched Uranium (LEU), which can then be used commercially in nuclear fuel. Natural Uranium is comprised of three main isotopes, ^{234}U which is 0.01% by weight, ^{235}U which is 0.71% by weight and ^{238}U which is 99.28% by weight. Of the three naturally occurring constituents ^{235}U is the only fissile isotope. Uranium that is enriched enough to be used in nuclear weapons is typically >90% ^{235}U whereas in commercial reactors this enrichment is 3-5% ^{235}U. HEU is defined by having a ^{235}U content of greater than 20%. HEU can only be used in nuclear weapons and in research reactors.

The surplus of HEU from dismantled nuclear weapons can be blended down to LEU so that in can be used in commercial nuclear power plants. An example of this is the "Megatons to Megawatts Program" that converts ex-Soviet WgU to fuel for US commercial power reactors. From 1995 to mid-2005, 250 tonnes of HEU (enough for 10 000 warheads) was recycled into LEU. The goal is to recycle 500 tonnes by 2013. The decommissioning programme of Russian nuclear warheads accounted for about 13% of total world requirement for enriched Uranium leading up to 2008.[59] The United States Enrichment Corporation has been involved in the disposition of a portion of the 174.3 tonnes of HEU that the US government declared as surplus military material in 1996. Through the US HEU Down-blending Program, this HEU material, taken primarily from dismantled US nuclear warheads, was recycled into LEU fuel, and used by nuclear power plants to generate electricity.

In the process of blending down, HEU is to be blended to a concentration of 3-5% ^{235}U so that it is then LEU and can be used as nuclear reactor fuel. For this purpose, there are two techniques that can be implemented – blending into uranyl nitrate solution and blending into Uranium hexafluoride.

Converting Uranium into uranyl nitrate is considered appropriate to produce LEU material. When Uranium is dissolved in nitric acid, an aqueous solution of uranyl nitrate [$UO_2(NO_3)_2 \, . \, xH_2O$] is formed. The preferred Uranium compound used for this is U_3O_8 in powder form, as it has a high surface-area-to-volume ratio, thus enhancing dissolution. The rate at which Uranium is fed into the process can be monitored and metered allowing the whole reaction to be well regulated.

This process can produce a wide variety of compounds of purified Uranium. When LEU is required for waste disposal by way of down-blending procedures, the mixed LEU UN solution is converted to U_3O_8. The concentrated LEU UN solution is then thermally decomposed to produce UO_3, which can then be oxidised producing impure LEU U_3O_8 powder.

The downblended LEU produced (either UNH crystal or U_3O_8) is packaged and delivered to either a reactor fuel fabrication facility or a LLW disposal site. In the United States the US Department of Transportation (DoT) allows these LEU compounds to be shipped overland in approved packaging containers.

Uranium into Uranium hexafluoride is the other process achievable for downblending. The UF_6 blending process described here is favoured for diluting the ^{235}U isotope abundance in HEU being blended for use as reactor fuel.

If subsequent blending operations are to be performed, any excess HEU feed material needs to be converted to UF_6, as most of the surplus HEU being downblended for use as reactor fuel will be either in oxide compounds or metal form. No fluorination process is required for the diluent stream, as low-concentration UF_6 can easily be made available from previously existing inventories and domestic facilities.

In order to convert Uranium metal and oxide compounds into UF_6, many methods can be employed. One such method uses two separate hydrofluorination and fluorination reactions to convert UO_2 into UF_6. Provided they are first processed for conversion to UO_2, this method can also be used for Uranium metal and UO_3.

Hydrofluorination is the first step in this process, and it occurs in a fluid bed reactor where hydrogen fluoride (HF) is reacted with the UO_2 resulting in the production of Uranium tetrafluoride (UF_4):

$$UO_2 + 4HF \rightarrow UF_4 + 2H_2O$$

Fluorination is the second step, and this occurs in a vertical tower reactor where fluorine (F_2) is reacted with UF_4, producing UF_6:

$$UF_4 + F_2 \rightarrow UF_6$$

There is a series of cold "traps" in the equipment for capturing the UF_6 gas and it can be sublimed into a solid. Any gaseous UF_6 that gets past these cold traps is caught by sodium fluoride (NaF) trap.

Both hydrofluorination and fluorination produce exhaust substances, which are passed through a further series of filters in order to trap any remaining HEU material. The substances passing through these filters is carefully monitored to verify the absence of Uranium and in order to prevent any HF or F_2 from being released the exhaust substances are then scrubbed with Potassium hydroxide (KOH).

There is also a single, direct fluorination method that allows to conversion of Uranium metal into UF_6. The Uranium metal is sealed in a tube furnace with a gaseous mixture of F_2 and a diluent such as nitrogen. The heat from the furnace initiates the fluorination reaction, but excess F_2 must be added for the reaction temperature to be sustained:

$$U + 2F_2 \rightarrow UF_4$$

The UF_6 gas is then collected and the exhaust gases filtered as in the two-step hydrofluorination/fluorination method described previously.[60]

5.7 Information Barrier Technology

The process of dismantlement verification involves large amounts of classified information. However, the NPT specified that it is illegal to reveal nuclear weapon information to other countries. Information that can be considered as classified include isotope ratios in the warhead, size of nuclear weapon or design of the nuclear weapon. But in order a have a confident dismantlement result, some certain classified information must be accessed. Therefore the scientists have to develop a way to provide a confident verification process without violating the NPT.

In the past, such requirement was achieved by exchanging less information, restricted onsite inspection and so on. But these extra constraints not only made the inspection process very complicated and long, but also reduced the confidence level of the inspection.

The Trilateral Initiative looked into a concept called "Information Barriers". The Information Barriers are most likely implemented as a computer program sitting between the statistical analysis and the simplified output. It would permit unrestricted measurements on a secure basis. The results would be compared to unclassified parameters in a way that questions could be answered in a pass-fail manner.[61] For example, the measured ratios of the key isotopes would be compared to a limit. If less than the limit, the answer would be "pass", and conversely, if greater than the limit, then "fail". An information barrier system that is accepted by both the host and the inspecting country can be extremely useful in the verification process. It simplifies the whole inspection process and increases the confidence level. Most importantly, it prevents the transmission of classified information to inspectors.

In the past few years, people have done quite a lot of research on information barriers. The Atomic Weapons Establishment (AWE) from the UK cooperated with the Institute for Energy Technology and the Norwegian Defence Research Establishment from Norway. A limited prototype device to be used on a radiological source has been designed. This prototype has been used in an experiment conducted between Norway and UK.

In June 2009, the UK and Norway went through a full-scale exercise mocking up non-nuclear state verification of nuclear warhead dismantlement. During the experiment, the mock weapon was in a container – the inspectors could only see the red/green light on the black box located on a table next to the weapon container. The light turned green after roughly 30 minutes, indicating the presence of the mock fissile material. This means that advanced seals need to be placed on the container.

The detection mechanisms and the information barriers can be regarded as a black box. Measurement and data analysis are conducted inside the box (protected) while display output of the final result transmitted outside. All of the sensitive information generated from the measurement system stays inside the box. There are three possible ways for sensitive information to pass through such an information barrier:

- Some sensitive information may accompany the useful results out of the box.
- Regular maintenance of the hardware that go through the information barrier (cables, power supply) could be a potential method for the leaking of sensitive information.
- Radiation emitting from inside the box

(e.g. sound waves, electromagnetic waves) might carry sensitive information.

The concept of information barriers can be extended to cover the whole inspection process. Each area of the inspection process can have a uniquely designed information barrier system. Examples include:

- Using Hash functions in the case of exchanging sensitive information.[62] TODO: VAGUE
- Using different kinds of information barrier systems for different kind of detecting methods.
- Placing the nuclear weapon in separate room from the inspectors.

There is also a kind of information barrier specially designed for the on-site inspection.

The design of the information barriers should obey the following principles:

1. Only the information needed will be accessed without any possibility of leaking out. e.g. In the inspection activity of Threshold Test-Ban Treaty (TTBT), both sides uses the CORRTEX (Continuous Reflectometry for Radius versus Time Experiments).[63] They all agreed that the initial stage of the nuclear explosion is confidential, so they eliminated information contained in the first 15 micro seconds. This kind of system is called Anti-Intrusiveness Device (AID).
2. The information barrier system should be strong, simple and cheap, capable of recognising a radioactive source (representing the warhead) to a specified level of confidence, based on agreed attributes.
3. The information barrier system should be designed in a way that information contained within in it cannot be modified or passed to other parties.
4. The information barriers should be something "that will be credible and mutually acceptable to all parties under future disarmament treaties".[64]

TODO:questions As mentioned above, the information barrier system needs to be credible and mutually accepted. Most likely, the information barriers are designed by the host. How could the inspection side be sure that it's the actual system that they are looking for? How could they be sure that the data contains in the system meets the requirement? This suggests that the information barrier system itself needs a verification process. It will only work once it passes the verification process.

Possible methods of achieving this are:

1. The host should guarantee that the information barrier system is reliable and provide accurate measurements. The design of the system meets the requirements and it does not contain a hidden switch.
2. The host should have few sets of identical system that could be randomly chosen by the inspection side. For those expensive systems, they should at least have few sets of the key hardware parts that can be randomly chosen.
3. Run tests on some well known templates.

The success of the information barriers makes the dismantlement process reliable and efficient. It resolved lots of thorny problems in the past years. So, the development of the information barrier system is extremely important to nuclear disarmament. It should be one of the main priorities at this stage.

6 Detection Schemes

6.1 Background

Nuclear warhead detectability is reliant upon four factors. These factors are: the warhead design, the technique used for detection, the sensitivity of the detectors, and any material between the warhead and detector that functions as a shield for the radiation.[65]

In order for detectors to accurately identify special nuclear material (SNM), they need to be able to accurately isolate the true signal (for example, the gamma ray spectrum) from noise (background radiation). That is, the detector needs to have a high signal-to-noise ratio. A detector's ability to obtain a true signal depends on its efficiency and spectral resolution.[66]

The efficiency of a detector is a measure of its ability to detect radiation and the rate at which the detector is able to record data.[66;67] SNM emits radiation in all directions; however its intensity decreases with distance. Therefore, to improve efficiency, the detector should be large or close to the SNM. It should also record data as fast as possible so as to reduce the time spent waiting for the scan to take place.[66]

Spectral resolution describes the sharpness of peaks in a gamma ray spectrum. Since a radioactive isotope releases radiation at certain energies, an ideal detector would record the spectrum as vertical lines corresponding to those energies. However, detectors are not ideal, thus the energy is recorded as a bell shaped curve. The closer the curve is to a vertical line, the more beneficial the data is.[66]

The features of materials which allow them to be detected or identified are:

1. Atomic Number and Density: The atomic number Z is the number of protons in the nucleus of the atom; it is unique to every element. Density is described as mass per unit volume. Plutonium has an atomic number which is slightly higher than Uranium but its density varies from slightly more to slightly less than Uranium.[66]

2. Radioactivity: Atoms which are radioactive are unstable and give of different types of radiation in order to become stable. The types of radiation used in nuclear detection are gamma rays and neutrons. Gamma ray spectra are unique to each isotope, thus, it is fairly easy to determine the gamma ray radiation that is emitted from an isotope.[66]

3. Photon Opacity: The impenetrability of a material to a photon beam depends on three things: the amount of material presented to the path of the beam, the energy of the photons and the atomic number and density of the material. Gamma rays are able to travel through low Z materials without any problems, however, high Z materials absorb and deflect them. On the other hand, neutrons are able to pass easily through high Z materials but are absorbed and scattered by low Z materials.[66]

6.1.1 Gamma Ray Detection

Gamma rays are produced from within the nuclei of radioactive atoms.[67] To detect gamma rays, a scintillation detector is used. A scintillation detector consists of a scintillator and photomultiplier tube (PMT). A scintillator is a material which converts the energy deposited by the gamma ray into optical photons (pulses of visible light). The optical photons are picked up by the PMT which has two functions: conversion of the optical photons into an electrical signal and amplification of the signal so that it can be measured. The PMT consists of a photocathode, dynodes and an anode. The photocathode emits electrons when struck by the optical photons. The electrons are attracted to the first dynode which amplifies the electrons into more electrons that are then accelerated to the second dynode which produces even more electrons, and the process contin-

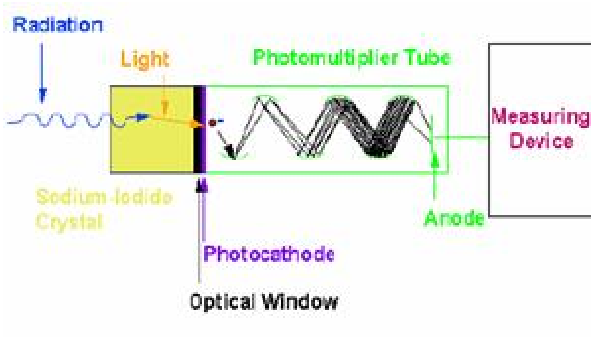


Figure 20: A scintillation detector.[68]

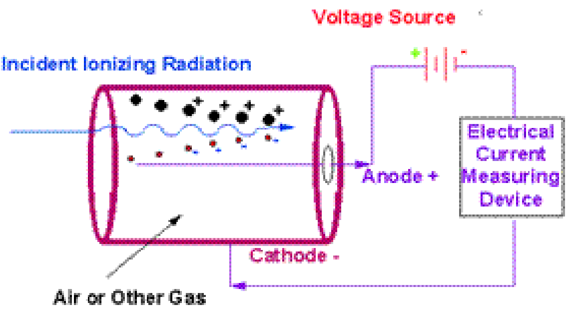


Figure 21: A neutron detector.[68]

ues until the electrons reach the anode. This is done so that a measurable current pulse can be detected. The voltage of the current pulse is proportional to the number of low energy photons which in turn is proportional to the energy of the gamma ray. Each pulse height produced from the PMT is analysed by a device called a Multi-Channel Analyser (MCA). When the MCA receives a voltage pulse, it sorts it into a bin depending on the energy and increases the counts in that particular bin by one. A histogram representing the gamma ray spectrum of an isotope is then drawn based on the information in the different bins.[66;67]

An alternative detector which can be used to measure gamma rays is a semi-conductor detector. A voltage is placed between two terminals on opposite sides of the semiconductor crystal.[67] When a gamma ray strikes the crystal, its energy is given to the electron which is then able to escape from the crystal. The electron is then attracted to the positive electrode. When enough electrons are able to escape from the crystal, a current will flow. The electric current has a voltage proportional to the energy of the gamma ray. The voltage is then sorted into a bin in the same way as the scintillation detector.[66;67]

6.1.2 Neutron Detection

Neutrons are uncharged particles. To detect neutrons, helium-3, an isotope of helium is a good material to use. A tube consisting of helium-3 gas linked to a power supply is a conventional neutron detector. The tube contains charged plated or wires that are positive and negative. When a low energy neutron strikes the detector, it is absorbed by a helium-3 atom. Energetic charged particles are then produced which lose their energy by knocking off other helium-3 atoms. Positively charged particles are attracted to the negative plate and the electrons are attracted to the positive plate. This movement causes a small electric current to be generated which is then recorded. Neutron detection cannot be used to identify isotopes because they do not have characteristic lines that correspond to discrete energies and they lose energy as they interact with a low Z-material, thus their spectra is blurred.[66;67]

6.1.3 Passive Detection

There are two techniques used for detection. These are passive and active detection. The simplest detection method is passive detection which involves detecting any and all radiation (gamma rays and neutrons) that are spontaneously emitted by the warhead.[65] The advantages of passive detectors are: they require less electrical output, they are not very expensive, they are easy to build and do not add any additional health risks to workers. However, they are not without their disadvantages. The major disadvantage is that the signal emitted from a nuclear warhead needs to be greater than the background signal in order for it to be recognised. As a result, there is a very good chance that passive detection systems can easily be fooled if the radioactive material is shielded to prevent measurable amounts of radiation from reaching the detector.[69]

The passive methods that are used to detect the presence of Plutonium depend on the emission of both neutrons and gamma rays from its isotopes. The gamma rays emitted from the Plutonium isotope are of relatively low energy and attenuate greatly as they travel through the warhead, thus gamma ray detection is not a reliable method to use. The best technique to use is to look for neutrons emitted by the ^{240}Pu isotope. The fissile isotope of Plutonium is ^{239}Pu; however, ^{240}Pu is active also.[4] This isotope spontaneously fissions and typically emits about 106 neutrons per second with a characteristic energy of 1 MeV.[4] In spite of the attenuation that these neutrons undergo as they travel through the warhead, approximately 10% emerge from the weapon and can be detected. It has been estimated that a warhead containing 4kg of ^{239}Pu contaminated by 6% of ^{240}Pu could reliably be detected with a detector 1m from the warhead in only 1 second.[4] The most important advantage of using this method is that a well-defined image of the warhead is not observed because the neutrons are scattered repeatedly as they travel through the weapon to the outside, thus only the grainiest geometrical information is revealed.[4;70] A drawback of using this method is that the emerging neutrons can be shielded without any difficulty. These factors suggest that this neutron detection technique is best used in examinations in which nuclear material is expected to be present, for example, to verify that the warheads earmarked to be dismantled are indeed nuclear.

The passive detection of Uranium can be carried out by measuring the high energy gamma rays that are emitted from the ^{238}U isotope. ^{238}U emits about 1MeV hard gamma rays at the rate of about 7.5 per gram per second with 1MeV energy.[4] Depleted Uranium (almost all ^{238}U) also emits gamma rays at this rate but HEU emits gammas at a rate of 0.5 gammas per gram-second with 1MeV energy. The amount of depleted Uranium and HEU determines the amount of gamma rays escaping from the warhead. When a simple model of a nuclear warhead is used to estimate this flux, the result is about 100 gamma rays per second which is easily detectable.[4] The primary advantage of this technique is that the counting rate (the number of gamma rays detected in a particular time) is generally high. One disadvantage of this technique is that the radiation signature of HEU is relatively small; hence it quickly attenuates.[71] A second disadvantage is that ^{238}U is used for other applications in which a high Z material is essential, therefore there could be a lot of false positives (from ^{238}U used in something that is not a nuclear weapon) if the method was used at questionable sites.

6.1.4 Existing Detection Equipment

Some of the existing detection technologies available are:

1. Radiation pagers: These are able to detect radiation at close distances. They are lightweight and inexpensive, but are unable to ascertain the source emitting the radiation.[66]

2. Radioactive isotope identification devices: These devices are able to identify radioisotopes based on their gamma ray spec-

Figure 22: A radiation pager.

Figure 23: A radioactive isotope identification device.

Figure 24: A radiation portal monitor.

trum. These devices are mainly handheld but heavy and delicate. They need to be cooled with liquid nitrogen or by mechanical means, thus their usability in the field is limited. They have a relatively short range for detecting radiation sources with low radioactivity, notably shielded HEU, making them unsuitable as the primary method of screening cargo containers.[66]

3. Radiation portal monitors: Many of these devices use large sheets of plastic scintillator material, such as polyvinyl toluene (PVT), to detect radiation coming from a vehicle. However, PVT cannot identify the source of radiation. However, there are lots of items in everyday trade that contain radioactive material. As a result, some produce many false alarms, which may require considerable effort to resolve, delaying the flow of commerce. Newer versions have some isotope identification capability.[66] They are primarily used for security purposes at checkpoints and borders.[71]

6.2 Active Detection

6.3 Muon Tomography

6.3.1 Cosmic Rays

Cosmic rays are a flux of high energy particles that bombard the earth's atmosphere. They are produced in other parts of the universe and approximately 98% of these particles are protons or heavier nuclei and 2% are electrons. These cosmic rays collide with air molecules and produce a shower of particles that include protons, neutrons, electrons, positrons, photons, kaons and pions (both neutral and charged). These particles interact by the nuclear and electromagnetic forces to produce additional particles in a cascade process. Pions will interact with air molecules via the strong force but some will spontaneously decay via the weak force into a muon plus a muon neutrino or an anti-muon neutrino.[72]

$$\pi^+ \to \mu^+ + \overline{\nu}_\mu$$

$$\pi^- \to \mu^- + \nu_\mu$$

6.3.2 Muons

Muons are the most abundant charged particles at sea level. They are produced high in the atmosphere, typically 15 km and lose about 2 GeV before reaching the ground due to ionisation. The mean energy of muons at the ground is 4 GeV.[73] They interact with matter via the weak and electromagnetic forces but not with the strong force. They decay via the weak force into an electron plus an electron neutrino or an anti-electron neutrino.

$$\mu^- \to e^- + \overline{\nu}_e + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$$

The muon flux at sea level is about 1 muon cm^{-2} min^{-1} [74] or 10000 muons m^{-2} min^{-1}. They are highly

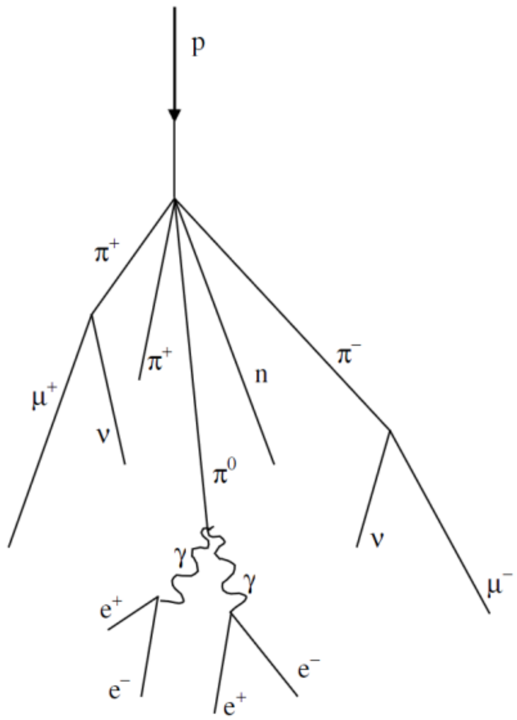


Figure 25: Cosmic ray cascade induced by a cosmic ray proton striking an air molecule nucleus.[72]

penetrating charged radiation. A typical cosmic ray muon of energy 3 GeV can penetrate more than 1000 g cm^{-2} (e.g. 10 m of water). As muons pass through matter they either scatter if they have high energy or are absorbed if they have low energy. The angle at which they scatter depends on the atomic number Z of the material. As the atomic number of the material increases, the scattering angle increases. In a layer 10 cm thick, a 3 GeV muon will scatter with an angle of 2.3 mrad in water, 11 mrad in Iron and 20 mrad in Lead.[75]

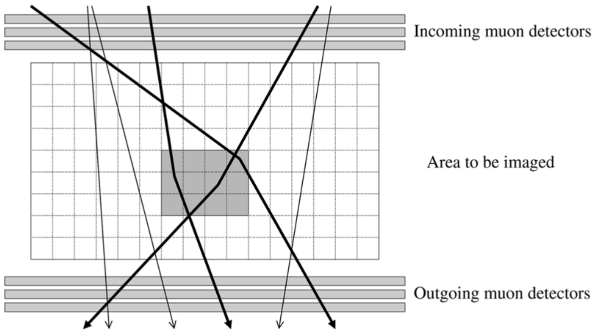


Figure 26: Muon tomography concept. The grey tracks are the muons going through air and the black tracks are the muons that penetrate a dense object.[74]

6.3.3 Limitations of X-rays

X-ray radiography is successful in many areas but has limitations. X-rays are unable to penetrate dense objects that have a high atomic number. Multiple projections are needed in order to resolve a three-dimensional structure using X-rays and they also pose health risks from radiation. In X-ray radiography, absorption and scattering cause attenuation of the incident beam which determines the intensity of an image pixel. The maximum mean free path of photons is about 25 g cm^{-2} for all materials which corresponds to 2 cm of Lead.[75] Even the most penetrating gamma rays are attenuated by an e-folding in 2 cm of Lead. A very large incident dose of radiation is needed to penetrate thicker objects and that is harmful for living organisms.[76] A different type of radiography must be used for thicker objects and it must be based on the interaction of charged particles with matter by multiple Coulomb scattering.[75]

6.3.4 Muon tomography concept

Muon tomography is based on the multiple Coulomb scattering of muons as they pass through a material. Radiographs of objects of any thickness can be produced by using multiple scattering. Cosmic ray muons are passive and harmless radiation and allow radiograph of dense objects with no artificial dose of radiation such as X-rays or gamma rays. The scattering of muons differs significantly in three different groups of materials: low Z (water, plastic, concrete), medium Z (Iron, Copper) and high Z (Lead, Tungsten, Uranium).[77] Each muon carries information about the objects it has penetrated and the properties of these objects can be determined by measuring the scattering of multiple muons. High Z objects can be detected amongst typical low Z and medium Z objects.[74]

The muon tomography concept is illustrated in Figure 26. The position and angle of incoming muon tracks are provided by a set of two or more planes of muon detectors above and below the object. These detectors only detect vertically oriented muons. Side detectors could be used to detect horizontally oriented muons. The detectors above the object measure the position of incident muons in two orthogonal coordinates. The scattering of the muons that pass through the material depends on the type of the object. The detectors below the object measure the positions and angles of the scattered muons. The scattering angle of

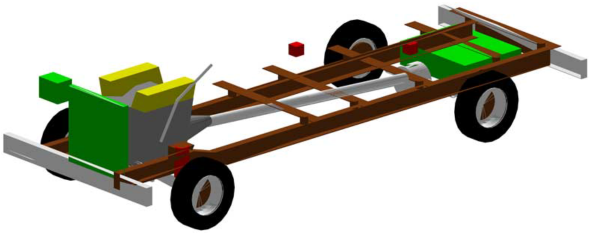


Figure 27: Illustration of major objects in a simulated passenger van using GEANT4. The red block in the centre represents a $10 \times 10 \times 10$ cm^3 solid piece of Tungsten which is a high Z threat object.[74]

each muon is calculated from the corresponding incident and scattered measurements. The momentum is calculated from the slight scattering of muons in the detectors themselves.[74]

6.3.5 Simulations of muon tomography

Simulations of muon tomography are very promising and results can be obtained within a very short exposure time of approximately 1 min. The GEANT4 Monte Carlo package is used for the simulations because it implements a complete, accurate and validated model for multiple scattering. A detailed GEANT4 simulation of a passenger van has been produced and reconstruction was achieved using two different methods: mean and median.[74]

The mean method of reconstruction shown in Figure 28 contains red spots scattered over the image. The median method shown in Figure 29 does not contain these effects. The denser components of the van (engine, battery, drive train) are shown as green (low Z) or blue (medium Z) but the high Z threat object stands out as red. The median method is clearly better.[74]

A ray crossing algorithm has been developed that highlights locations where strongly scattered muons cross paths. The basis of the ray crossing algorithm is the fact that a

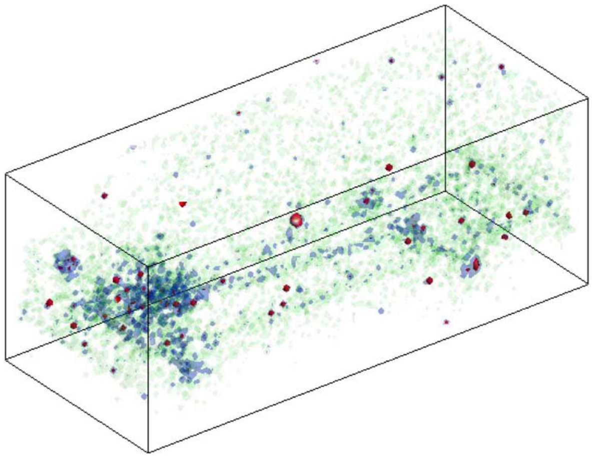


Figure 28: Reconstruction of 1 min of simulation muon exposure of the passenger van using the mean method.[74]

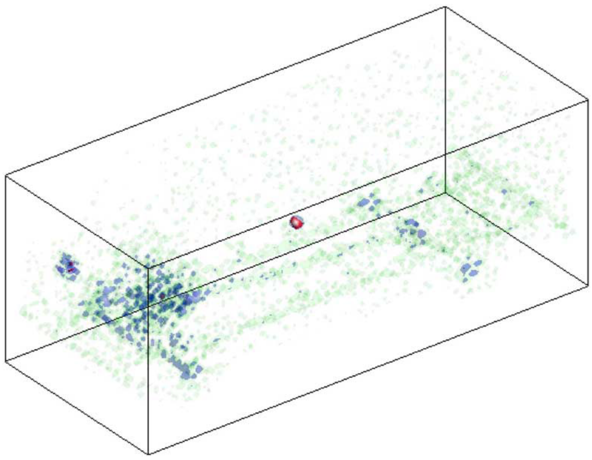


Figure 29: Reconstruction of 1 min of simulation muon exposure of the passenger van using the median method.[74]

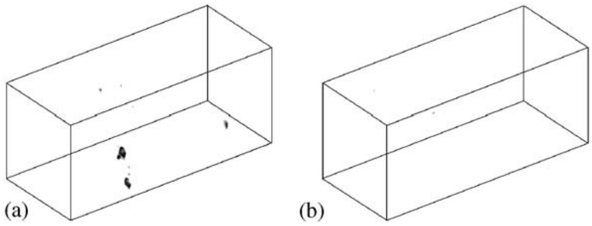


Figure 30: Ray crossing algorithm reconstructions of 1 min of simulated muon radiography of a $6 \times 2.4 \times 2.4\ \mathrm{m}^3$ cargo container filled with 12 tons of iron and three $9 \times 9 \times 12\ \mathrm{cm}^3$ Uranium bricks (a) and without the Uranium bricks (b).[77]

high Z object produces many highly scattered rays which intersect in a small volume. A large depth of medium Z material can also produce highly scattered rays but these rays will spread over a larger volume. The algorithm was applied to a simulated scene of a $6 \times 2.4 \times 2.4\ \mathrm{m}^3$ cargo container filled with 12 tons of iron and three $9 \times 9 \times 12\ \mathrm{cm}^3$ Uranium bricks were buried within the iron. A cosmic ray exposure of 1 min was simulated and the tracks were processed using the ray crossing algorithm. The results are shown in Figure 30.[77]

All three Uranium bricks are clearly identified in Figure 30a. The image without the Uranium bricks is empty of any signal as shown in Figure 30b. The ray crossing algorithm shows great promise in eliminating the scattering background.[77]

Other simulations were also produced using a Monte Carlo simulation code and the results are shown in Figure 31.

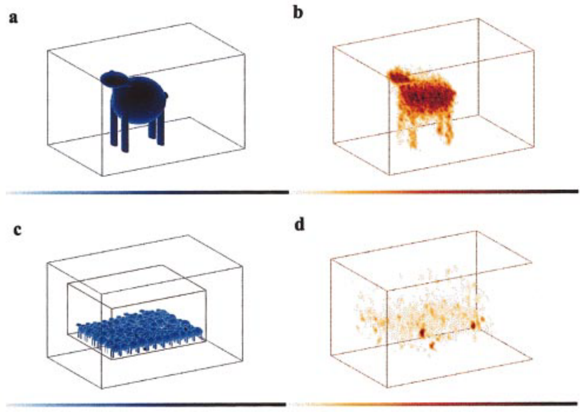


Figure 31: Muon radiograph of a complex target in a volume of $9 \times 3 \times 5.5\ \mathrm{m}^3$. The first object (a) is a large complex Lead sculpture. The reconstructed image (b) shows much of the detail of the object and its based on 1 min of exposure. The second object (c) consists of a $4 \times 2.4 \times 2.4\ \mathrm{m}^3$ container with walls of thickness equivalent to 3 mm of steel. There are 69 sheep made of water (shown in blue) inside the container with a body size of $60 \times 30 \times 40\ \mathrm{cm}^3$ and three Uranium bricks of size $9 \times 9 \times 12\ \mathrm{cm}^3$ (shown in black). The reconstructed image (d), based on 1 min of exposure, shows that the 3 Uranium bricks stand out. The colour intensity in the two reconstructed images corresponds to the significance of the signal.[76]

6.3.6 Experimental results of muon tomography

There are a few prototype experimental muon tomography detectors that show excellent results which are consistent with the simula-

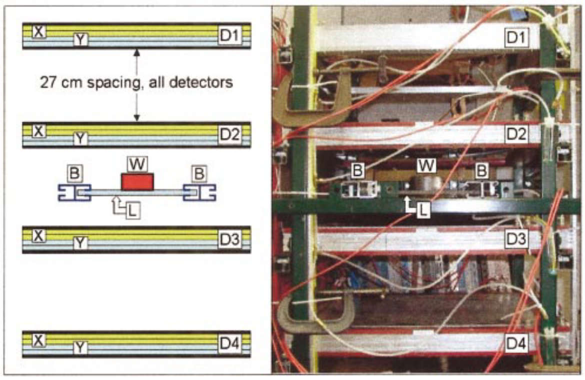


Figure 32: Picture of experimental apparatus at the Los Alamos National Laboratory in 2003. There are four muon detectors labelled D1-D4 with a vertical spacing of 27 cm. The detectors determine the positions and angles of the muons in two orthogonal coordinates (X and Y). The test object (W) was a Tungsten cylinder of radius 5.5 cm and height 5.7 cm. A thick Lexan (L) plate of dimensions $35 \times 60 \times 1$ cm^3 and steel support beams (B) were used to support the test object.[76]

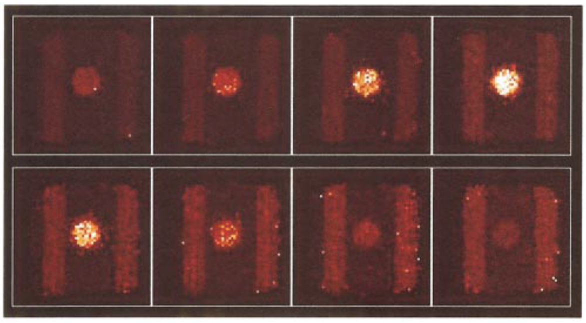


Figure 33: Test object reconstruction using 100 000 muons. A volumetric image of $1 \times 1 \times 1$ cm^3 voxels was reconstructed. The eight planes are horizontal slices near the middle of the volume, moving from top to bottom. Both the Tungsten cylinder and the steel support beams are clearly visible.[76]

tions. A small scale experimental detector system was developed in 2003 at the Los Alamos National Laboratory, Los Alamos, New Mexico.[76] A picture of the detector is shown in Figure 32.

Eight X and eight Y locations were measured for each muon by four ionising radiation detectors contained in the detector stack. The two detectors on top measure the incoming muon track while the two detectors at the bottom measure the scattered track. Each delay line drift chamber detector had an active area of 60×60 cm^2. The detector was calibrated with no test object to determine the precision of the position measurement. A Windows based acquisition program was used to collect the data. The reconstruction was approximated using the following simple technique. Multiple scattered tracks were approximated to have only a single scattering event and the point of scatter was located by extrapolating the incident and scattered rays. A maximum likelihood technique was used to assign voxels (3D pixels) to each scattered muon. The reconstructed 3D image of the Tungsten test object is shown in Figure 33.[76]

The data for Figure 33 were collected over several hours because the detector was not fully optimised. An optimised detector with 100% tracking efficiency and large solid angle could acquire the same data in approximately 30 min. The test object and the test support beams can be clearly resolved using this long run. Considerably shorter runs could be used for a simple yes/no detection.[76]

Another sub-scale prototype was built at the Los Alamos National Laboratory in 2006 called the Large Muon Tracker (LMT) which is 20' tall. The design of this detector is very similar to the previous detector. It consists of 6 top and 6 bottom planes of drift tube detectors for each X and Y dimensions (24 planes in total) on a flexible frame. The top and bottom sections are separated by 1.5 m to allow a large sampling region. X and Y tracks are fit-

Figure 34: The Large Muon Tracker (LMT) prototype at the Los Alamos National Laboratory in 2006. The precise positions of muon tracks above and below the sampling region are determined by the overlapping X and Y detector planes. The new redundant detector planes will be used improve the tracking efficiency and quality.[78]

Figure 35: Photograph of a car engine in the LMT at the Los Alamos National Laboratory in 2008.[79]

ted separately to find the slope and intercept of each dimension and combining them yields the 3D trajectory of the muon. A picture of LMT is shown in Figure 34.[78]

The prototype of LMT was completed and tested in 2008. A simple reconstruction technique was used to process the data. The sample volume of $1.5 \times 1.5 \times 1.0$ m^3 was segmented into $2 \times 2 \times 2$ cm^3 voxels. The median scattering angle was calculated for all muons whose trajectories intersected a voxel with an adjustable distance. The prototype was tested using a $10 \times 10 \times 10$ cm^3 Lead cube that represented the threat object and it was placed in the LMT along with a car engine and transmission. A photograph of the engine in the LMT is shown in Figure 35.[79]

Data were collected for approximately 160 min and have been analysed to reconstruct the images shown in Figure 36. The mean scattering angle is plotted for all trajectories that pass through each voxel.[79]

Another muon tomography prototype is located at the INFN National Laboratories of Legnaro, Padova, Italy. A volume of 11 m^3 can be inspected using the prototype which is ideal for cargo inspection. A picture of the prototype is shown in Figure 37.[80]

Two Muon Barrel drift chambers of dimensions $300 \times 250 \times 29$ cm^3, built for the CMS experiment at CERN, were used for the experiment, separated by 160 cm. A concrete and iron structure is supporting the chambers. There are two additional drift chambers underneath the bottom detector that will be used in the future as a momentum filter. The reconstruction procedure uses a List Mode Iterative Algorithm (LMIA) that processes events one at a time instead of grouping similar events together.[80]

The experiment was repeated using two Lead blocks of dimensions $10 \times 10 \times 20$ cm^3 and two iron blocks of dimensions $10 \times 20 \times 20$ cm^3 placed on a support structure 65 cm in the vertical direction. The 3D reconstruction of this layout is shown in Figure 39.

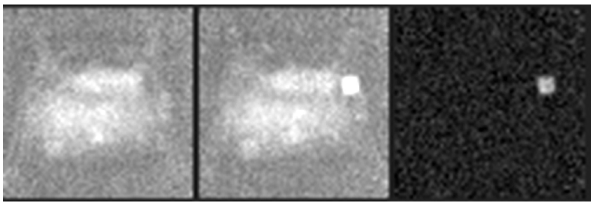


Figure 36: Mean scattering angle for a slice through the scene 50 cm above the base plate. The left image shows the car engine, the middle image shows the engine with the Lead cube and the right image shows the difference of the other two images. The Lead block stands out dramatically.[79]

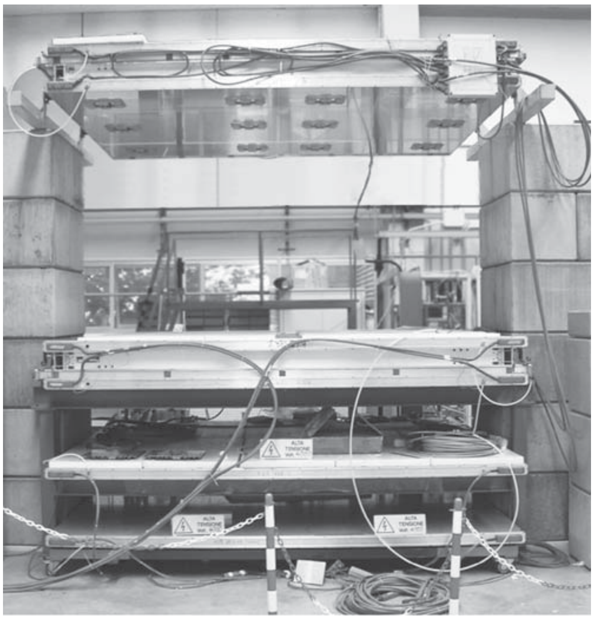


Figure 37: Muon tomography system prototype located at the INFN National Laboratories of Legnaro.[80]

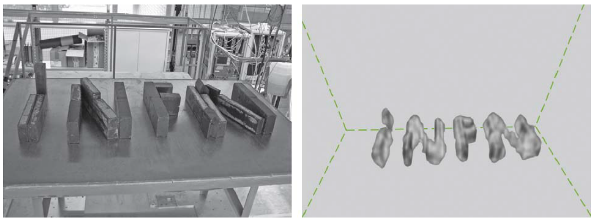


Figure 38: Test of the imaging capability of the prototype. The picture on the left shows the layout of iron bricks forming the word INFN and the picture on the right shows the result of the data analysis using the LMIA. The reconstructed image is very clear.[80]

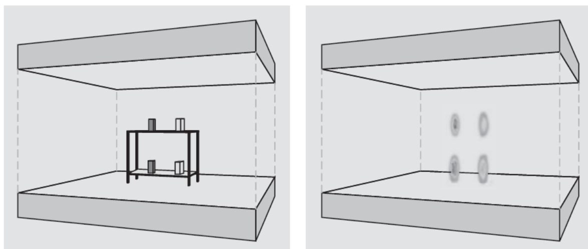


Figure 39: The left image is a sketch of the layout with the two Lead and the two iron blocks. The darker blocks are the Lead blocks. The right image shows the 3D view of the reconstructed image using the LMIA.[80]

The position of the blocks is reproduced correctly but there is finite spatial resolution in the reconstruction especially in the vertical direction. The reconstructed scattering density of the Lead blocks is greater than that of the iron blocks. Its straightforward to discriminate low Z or medium Z materials from high Z materials using this method. The problem with this method is that discrimination between high Z materials denser than iron is more difficult because of the non-linearity in the reconstructed scattering density. This means that the muon momentum has to be measured as well to allow a better material recognition and increase the statistical precision of the density measurement.[80]

6.3.7 Applications of Muon Tomography

Muon tomography could be used to protect the rail network from terrorism. The idea is to equip train stations with large muon detectors above and below. Density images can be produced very fast in a time scale of minutes. High density objects such as nail bombs and fissile materials will be easily identified.[81]

It could also be used as a detection method of nuclear devices or material in vehicles and containers. An automobile sized counting station could be used to scan vehicles at border crossing. This would allow examination of every vehicle and shipping container crossing a border. It will require enough detectors to handle the traffic at the borders. The total traffic crossing the US – Mexico and the US – Canada borders in 2008 was 1.3×10^8 vehicles. Assuming a single muon tomography detector could analyse a vehicle within 1 min and operates for 12 hours per day, then 500 detectors would be needed to handle the entire border crossing traffic. This would cost a total of \$1.5–\$2 billion but its negligible compared to the consequences of the detonation of a nuclear bomb.

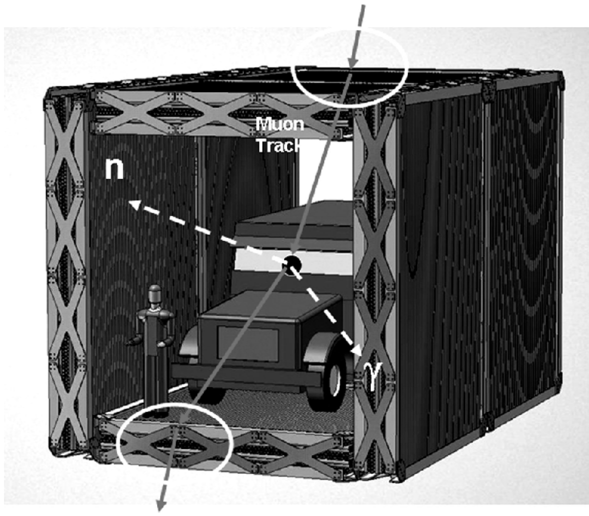


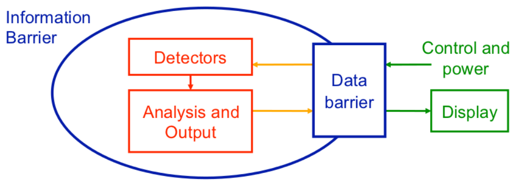
Figure 40: Schematic view of how a counting station might look. Vehicles would have to stop for approximately 20 seconds for the scan.[79]

A picture of how it could be implemented at a border crossing is shown in Figure 40.[79]

Both methods could be used for nuclear dismantlement verification. The vehicle transporting the bomb for disarmament could be scanned at several stations during its journey to the dismantlement facilities. A single muon tomography detector at the dismantlement facility could be used to verify a small quantity of nuclear bombs. If there is a large number of bombs queued for verification then the idea of the train stations could be used. A room with muon detectors on the flood and the ceiling could be used to scan all of them at the same time.

7 Confidence and National Security

When talking about dismantlement of nuclear warheads, the scale of the dismantlement must be taken into account. The limit for any process to work is for there to be a very high chance of discovering if anyone is cheating. It



is useful to make a broad categorisation here between the dismantlement of the Russian and American stockpiles and the possible dismantlement the rest of the nuclear weapon states (NWS) might undergo.

Russian and American stockpiles are in the thousands and so the dismantlement process to reduce these will need a very low confidence level to ensure a high chance of discovering cheating. When thousands of warheads are being dismantled, a confidence percentage in the single digits would be enough. Other NWS have warheads in the low hundreds and so any dismantlement here would be much more difficult to achieve. The benefits to both individual nations' security and international security of dismantling at this level is also very debatable. Taking this into account it seems pertinent to focus on the Russia/America dismantlement.

As already mentioned in other sections, the verification of the dismantlement procedure needs to balance confidence with information barriers, to ensure no NPT information is released. It also seems that the information barriers required by America and Russia are so severe as to be a red/green light pass/fail system.

From earlier sections, it is clear that this sort of system can be technically achieved. There are ways of maximising the confidence level of such a system:

- Both parties developing the design of the dismantlement facility and components together
- Both parties being familiar with the equipment and understanding the procedure
- Observation of construction
- Random selection of components for both measurement and validation

The validation procedure can be particularly useful here. The procedure is as follows:

1. Several identical components are presented
2. Two are randomly chosen, one for measurement by the host, one for validation by the observer
3. The component for validation can be checked by the observer. If shown to be proper, then it can be assumed the measurement component is also correct.

This validation allows the observer to be sure that the components are indeed identical, even with a low number of components to randomly choose from, because the process will be repeated for each warhead. If this is used, the design must be such that the observer is sure that the measurement component is at no point switched.

These measures may not be able to assure the required confidence, if one party is determined enough to cheat. Whilst the component validation system is useful, it cannot be entirely relied upon. A dismantlement facility may be able to be designed such that it appears to the observer to be of correct design, but actually allows the host to circumvent the measures mentioned before.

In order to analyse this fully, the motivation to cheat must be considered. If one party can maintain its own stockpile whilst the other dismantles, then it has a significant first strike advantage. This is a strategy of surprise attack, to attempt to wipe out enough of the opponent's nuclear capability to be able to survive the retaliation. This motivation however must be balanced against the statistical likelihood of a nuclear accident, whilst maintaining a large warhead stockpile. If the repercussions of a nuclear accident could be as severe as repercussions of nuclear war then it is easier to advocate dismantlement. Whilst it may be possible to quantify the chance of a nuclear accident, it is harder to quantify the chance of nuclear war, so it is difficult to properly balance these two risks. It is also useful to consider whether political establishments in these two countries will take both risks into account properly.

With this clear motivation to cheat it is difficult to design a foolproof system. However, it may be worth advocating reducing the motivation to cheat, to improve confidence in dismantlement. This could be in the form of both countries improving their second-strike capabilities, so that preemptive strike is less appealing. If second-strike capabilities were considered to be enough to assure mutually assured destruction, even with a much lower stockpile than an opposing nation, it helps to alleviate the motivation to cheat for both parties, and thereby helps the dismantlement process. This is the policy taken by many of the other NWS e.g. UK, France.

8 Conclusion

This commission recommends the setting up of a department within the IAEA that would be responsible for designing a universal nuclear weapon dismantlement facility and overseeing the dismantlement process. Nations wishing to dismantle nuclear weapons in these facilities would have neutral inspectors observing the construction and the dismantlement, for verification purposes. The initial costs would be high, but there would be a long term benefit to dismantlement and countries would not have to pay for nuclear weapon storage facilities and the costs of security for them. It is very important for a neutral organisation to observe the construction of the dismantlement facility inside the host nation as this minimises the opportunity for the host nation to build basements and other modifications that would be able to deceive the verification process. In addition, this commission recommends that the NPT be re-drafted to allow for neutral UN and UN-affiliated representatives to be allowed to observe sensitive nuclear weapon information.

Before dismantlement, the total quantities of weapons grade Plutonium and Uranium need to be determined for each nuclear warhead. This can be compared with any information already given for the weapon by the host. Next, the dismantling process begins with the warheads being split into their individual components. This includes the arming or firing mechanism, the primary physics package and the secondary physics package. Safe procedures would need to be devised for the removal of the physics package. A suggested method could be to insert a steel wire containing a Cobalt-60 signature between the two Plutonium hemispheres, to prevent accidental ignition. Other than the nuclear material, which is disposed of safely, the rest of the warheads components need to be destroyed by crushing the parts until they are rendered militarily useless.

Inspectors would be responsible for following the dismantlement procedure presented by the host. The process initially begins with the transportation of weapons from their storage facility to the disarmament facility. It is recommendable to start the chain of custody from the warhead storage facility in order to increase the confidence by allowing the inspectors to witness the transport of the warhead to the dismantlement facility. To ensure that the weapons are not tampered with during transportation, anti-evidence seals are suggested which electronically erase memory when tampered.

Inspectors and host employees would need to have regular background checks to increase confidence from participation nations and reduce the risk of the insider threat. As mentioned before, inspectors could be trained to counter perceptual blindness and use technology to aid them. During the transportation of weapons, military GPS should be used to increase the accuracy and the security since it is encrypted and is less likely to be spoofed or jammed. The town crier method is also a very useful and cheap method to avoid the failure to detect any tampering with the nuclear warhead. Inspectors can use perimeter portal monitoring to count the number of warheads entering and the number of fissile materials leaving the dismantlement facility by monitoring one or more portals

It is recommended that the inspectors visit the dismantlement facility prior to the dismantlement monitoring visit to familiarise themselves with the facilities and the dismantlement timeline. The inspectors and the host should agree on which inspection activities are permitted and the control measures by the host during this visit.

A room within a low security area should be provided, where the inspectors can review documentation, perform data analysis related to the dismantlement and write their reviews. The inspectors should be able to work with a minimum number of restrictions there but they should be careful when moving information and equipment between their room and the dismantlement facilities. The usage of electronic equipment or notes to monitor access to nuclear materials is recommended by this commission. In the probable event that the host does not approve their use, written notes or photographs of seals are proposed as inferior alternatives.

All of the main equipment is usually supplied by the host; the inspectors would not be allowed to use their own equipment inside the dismantlement facility. The inspectors would be responsible for authenticating any equipment supplied by the host. Both parties could work together to establish a joint tags and seals development project enabling the inspector team to take full custody of all supplied and bring them to the dismantlement facilities. It is highly recommended for the host to prepare for and allow new technologies to be used.

The host should carefully manage access to sensitive facilities and nuclear weapon components to prevent the disclosure of any sensitive information related to NPT or national security. They should be responsible for checking the identity of the inspectors before and during the meeting and use metal detectors to check for any unauthorised materials. The inspectors should be escorted and guarded at all times in the dismantlement facility and any high security areas that could compromise NPT and national security information should be shrouded to the inspectors. The host should make sure that it has enough staff to escort the inspectors in order to prevent any unsupervised measurements by the inspectors. The escort staff should include both security guards and facility staff for technical inspection activities. The inspectors should be allowed to photograph some items as evidence of their inspection.

CCTV cameras should be used at agreed areas where there is no sensitive information, such as ceilings and entrances, to provide a direct visual confirmation to the inspectors that no material or personnel had entered or left the facility when the inspectors were not present.

At the end of each day the inspected item should be stored in a secure storage area with video surveillance and anti-evidence seals to ensure that no tampering or any diversion activities have occurred. After the dismantlement, the fissile material should be transported to a secure storage facility.

The involvement of a Non-Nuclear Weapon State (NNWS) is vital in creating an international acceptance and trust of a proposed verification regime.

To prevent the inspectors from obtaining excessive information, inspectors must examine the weapons behind the veil of an information barrier. This is because the act of inspection incurs the risk of spreading weapon information. For the verification of weapons, passive detection is a non-intrusive method that ensures that the host will not lose classified information.

However, these detectors can easily be deceived if the warhead is shielded to reduce or hide the radiation signal, which reduces the confidence level in this type of detection. The spoofing is possible in the other direction too with care, it is plausible to strengthen the radiation signals where some material had been removed. In order to increase confidence whilst preserving the classification of sensitive information, this commission recommends the creation of an effective passive detector, one that is able to passively detect both neutrons and gamma rays from the warhead. Strategies for monitoring the agreements include measuring the neutron and gamma radiation signature to verify declared attributes of the plutonium or HEU. This is essential for verification, and both methods are necessary, as it is difficult to shield both neutrons and gamma rays than either of these separately. Finally, safeguards would need to be designed to prevent the disclosure of that information. Hardware, software and procedural measures containing the sensitive data would only present the relevant results required for verification. To prevent the unintended release of sensitive information during an inspection, the software would display a simple but reliable and useful result to the inspector. Inspectors would be allowed to check equipment when not in operation, to improve integrity of the operations not visible during an inspection.

Uranium disposal is necessary as it demonstrates that the fuel cannot be reused in weapons. There are two methods that would be acceptable for Uranium disposal: blending as Uranyl nitrate solution and blending as Uranium hexafluoride. These possibilities would follow the suggested process in the above section. The Uranium from these processes can then be transported from the facilities to be used in nuclear power plants, although the economics suggests against such manipulations.

As a sign of trust, the two biggest weapon states, United States and Russia, could work together and move all unwanted nuclear weapons to a shared storage facility waiting for dismantlement. They could also place all of their excess HEU and Plutonium under IAEA monitoring. This would set an example for the other nuclear weapons states.

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