Nuclear Disarmament Verification

Aldridge, Barritt, Christodoulou, Lu,
Moors, Rajroop, Theodorou, Xiao,
Department of Physics and Astronomy,
University College London,
London WC1E 6BT,
United Kingdom

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Executive summary

The Context

Why do we Verify? We verify to assure confidence. We have a declaration, our verification methods, and our confidence. If we are too intrusive with our verification methods there is the threat of the spread of proliferation information which could in turn lead to a breakdown of the declaration agreements alongside an increased risk of mass devastation. If the verification methods employed are too feeble, the uncertainty in the confidence will be high and inspectors may fail to detect anomalous behaviour in the hosts disarmament activities.

This balance is known as the information barrier and it is spawn from the consideration of ratified treaties, the capabilities of the equipment and the feasibility of the procedure. The treaties outline what information should and shouldn't be shared with the inspectors; the equipment and procedure are the technological or economic constraints.

*A chart of time, treaty and declaration information or disarmament rates, there should be an inflection at 2002 *

Summer's treaty review Nick's information barrier in the context of treaty Luke's weapon introduction Jack's confidence in verification

The Process

What do we verify? Luke's weapon introduction Nick's brief overview Ralph's dismantling process Valentino's chain of custody / Containment and surveillance of dismantlement Luke's Blending down

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Final Summary

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1 Introduction

1.1 Facts on Nuclear Weapons

Nuclear weapons are devices that generate a massive amount of energy from nuclear reactions, used to create mass destruction. Their energy is derived from two methods of bomb: nuclear fission or a combination of fission and fusion. Weapons where the fission reaction generates wholly the explosive output 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 supercritical mass. This begins an exponentially increasing chain reaction, releasing energy. Another method uses compression of the sub-critical sphere of fuel using an explosive to implode the sphere. The two most commonly used fissile materials for atomic bombs are (enriched) uranium-235 and plutonim-239. Uranium is said to be enriched when the percentage of uranium-235 is increased by the process of isotope separation.

The other type of nuclear weapon – utilising the fusion reaction, is the thermonuclear bomb (also known as hydrogen bombs). 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, such that nuclear weapons have no real legitimate purpose in todays world. They are immoral to use, would cause genocide, and their use is illegal because civilian casualties would be inevitable. These weapons kill everything in their path and also cause additional death through radioactive fallout. The effects of denonating a weapon can spread for hundreds of miles, causing long-term health problems for people not killed in the explosion.

In the 21st century around \$40 billion a year, or 10% of the annual US military budget, is spent on nuclear weapons. The US spent \$5.8 trillion on nuclear weapons between the early 1940s and 1996. Trident, the UKs 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 get their hands on nuclear weaponry is increasing, increasing the need for disarmament. In today's war waged on world order by terrorists, nuclear weapons are the ultimate means of mass devastation. And non-state terrorist groups with nuclear weapons are conceptually outside the bounds of a deterrent strategy and present difficult new security challenges.

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 [ref] 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. 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. [ref]. 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 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 certain 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.[ref]

1.1.1 Nuclear Weapons States

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

Country	Active Warheads	Total Warheads	CTBT Status
United States	1950	8500	Signatory
Russia	2430	11000	Ratifier
United Kingdom	160	225	Ratifier
France	290	300	Ratifier
China	180	240	Signatory
India		90	Non-Signatory
Pakistan		100	Non-Signatory
North Korea		<10	Non-Signatory
Israel		140	Signatory

1.1.2 International Atomic Energy Agency (IAEA)

TheInternational Atomic Energy Agency(IAEA) is an international organization that seeks to promote the peaceful use ofnuclear energy, and to inhibit its use for any military purpose, includingnuclear weapons. The IAEA was established as an autonomous organization on 29 July 1957. Though established independently of theUnited Nationsthrough its own internationaltreaty, the IAEA Statute, the IAEA reports to both the UNGeneral Assemblyand Security Council.

The IAEA serves as an intergovernmental forum for scientific and technical cooperation in the peaceful use ofnuclear technologyandnuclear 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 andnuclear materials, and promotenuclear safety(includingradiation protection) and nuclear security standards and their implementation.

The IAEA's mission is guided by the interests and needs of Member States, strategic plans and the vision embodied in the IAEA Statute. Three main pillars – or areas of work – underpin the IAEA's mission: Safety and Security; Science and Technology; and Safeguards and Verification

The IAEA executes this mission with three main functions: the inspection of existing nuclear facilities to ensure their peaceful use, providing information and developing standards to ensure the safety and security of nuclear facilities, and as a hub for the various fields of science involved in the peaceful applications of nuclear technology.

The IAEA is generally described as having three main missions: Peaceful uses: Promoting the peaceful uses of nuclear energy by its member states, Safeguards: Implementing safeguards to verify that nuclear energy is not used for military purposes, and Nuclear safety: Promoting high standards for nuclear safety

1.1.3 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. [ref]

1.1.4 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 are yet to sign it (see table about 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 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 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.

U.S. 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.

1.1.5 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. http://www.fas.org/irp/agency/dod/jason/dismantle.pdf 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.

2 Political Background

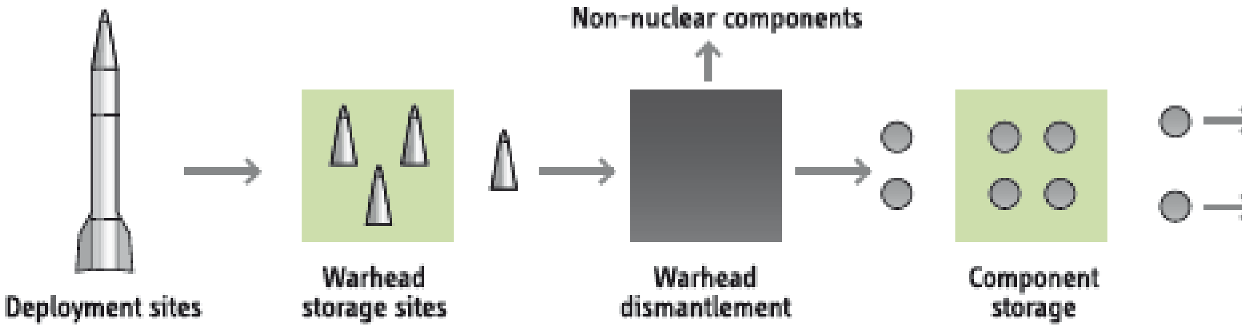
2.1 Treaties

2.2 Nick's Stuff

The Verification process seeks to ensure consistency with declaration, and that disarmament has been achieved with a degree of irreversibility. The challenge facing proponents of Nuclear disarmament is to ensure that measures have been taken to safeguard against a Nuclear Weapon State attempting to cheat against the international agreements that have been put in place. The foundations for confidence are essentially built upon two key principles: Declaration and Verification. The interplay between the two is what establishes the iterative development towards Nuclear disarmament; because a more complete declaration can lead to greater confidence in the verification, and successful verification can lead to a decision to release a more complete declaration. However there is a third consideration that mediates between the two and also governs what should be done with the sensitive information that may emerge from the verification measurements – the "information barrier"; the foundations of which shall be discussed in section ??.

What do we verify? – Nicks brief overview Nuclear warhead dismantlement starts with the removal from warheads from the deployment areas to the storage areas. The warheads are then transported to the dismantlement facilities where the "Physics package" is removed and then stored to await further dismantlement. Lastly plutonium and Highly Enriched Uranium re-emerge in an unclassified form ready for final disposition.

[dismantlement process.png] [Fig ?? : accompanying text] [Global Fissile Material Report 2009: A Path to Nuclear Disarmament, IPFM Annual report, Acton et al., p67] 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.



2.2.1 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.

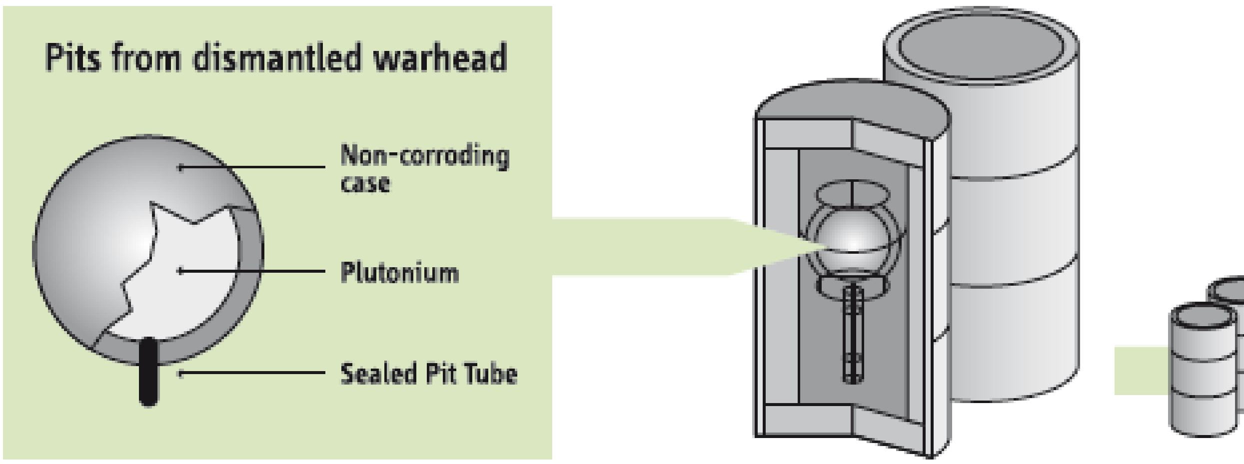
Strategies for monitoring the agreements include measuring the neutron and gamma radiation signature to verify declared attributes of the plutonium or HEU. If these measurements are accurate enough to serve for this verification purpose, then they are accurate enough to contain information about the 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.

[Progress in Gamma Ray Measurement Information Barriers for Nuclear Material Transparency Monitoring", Wolford and White, Lawrence Livermore National Laboratory Library, 2000] 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 (2000) highlight three objectives that hardware, software, and human procedures should fulfill in order to be an effective information barrier: "Prevent the unintended release of sensitive information during an inspection; Display a simple 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.

2.2.2 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.” [THE JOINT U.S. DOD-DOE INFORMATION BARRIER WORKING GROUP, Functional Requirements for Information Barriers, PNNL-13285, Pacific Northwest National Laboratory, Richland, WA, May 1999.]

How do we verify? – Nicks 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.



[Pits.png Fig??] Figure 5.3. Storage arrangements for U.S. plutonium warhead “pits” at the Pantex warhead dismantlement facility in Amarillo, Texas.217 [Global Fissile Material Report 2009: A Path to Nuclear Disarmament, IPFM Annual report, Acton et al., p71] Modern implosion-type nuclear weapons have a “pit” which is a hollow sphere of plutonium or highly-enriched uranium, with a tiny tube through which the tritium is passed into the hollow sphere. If an appropriate material is fed in through this small tube until the inside of the pit is stuffed, and the plutonium can no longer be compressed enough to reach the critical mass to sustain a nuclear chain reaction as it would encounter the fill on the way.

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 remanufacture 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 microcurie 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. [R. Garwin, Technologies and procedures for verifying warhead status and dismantlement, Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions edited by Nicholas Zarimpas, 2001] 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 an approach that can be administered entirely blindly.

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.

['Pit-Stuffing': How to Disable Thousands of Warheads and Easily Verify Their Dismantlement, Bunn, Federation of American Scientists Public Interest Report, volume 51, issue 2, pages 3-5, 1998] This method would work for US warheads, but needs to be evaluated for Russian warheads that may have a different design. [R. Garwin, Technologies and procedures for verifying warhead status and dismantlement, Transparency in Nuclear Warheads and Materials: The Political and Technical Dimensions edited by Nicholas Zarimpas, 2001] 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 specialized AT-400R container before submitting the material for U.S. or IAEA verification. The US and Japan provided AT-400Rs are the standard containers designed for Russias Mayak Fissile Material Storage facility. Russia maintained that the isotopic composition of its weapon plutonium in the 2-kg balls was classified. [Global Fissile Material Report 2008, p. 70]

Although political decisions on declarations might stand in the way of pit-stuffing as a universal verification technique, further work* could be done to address some of the technical issues discussed as it could prove to be a useful tool to verify the US.

*(perhaps similar to the UK Norway Initiative Workshop on Nuclear Disarmament Verification 7-9 December 2011) 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 LLNL software was created that used plutonium lines between 630 KeV and 670 KeV to compute a ratio of 240Pu 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 and the FMTT program. Programmers at LLNL developed similar methods called Pu300 for determining the time since separation, and Pu900 for determining the amount of oxide present in a sample.

[Progress in Gamma Ray Measurement Information Barriers for Nuclear Material Transparency Monitoring", Wolford and White, Lawrence Livermore National Laboratory Library, 2000] [Fig??: The gamma ray spectrum for a non-sensitive sample of plutonium containing several isotopes and decay products. The three narrow intervals of spectral lines are what is used in the attribute calculations Pu 300, Pu600 and Pu900.]

2.2.3 Ideas for conclusion

The United States has stated the need to protect the host's warhead design information overrules the need to provide confidence to the inspecting party regarding the accuracy and reproducibility of the measurements; in case an inspection is carried out in the absence of any agreement to share classified nuclear weapon design.

We could recommend that this shouldn't be the case for Non-Nuclear weapons states like Iran, where their proliferation information is obviously less developed than that of the US or Russia. Talking about info barrier.. The greatest potential for improvement in the transition from generic laboratory instrumentation to more special purpose inspection equipment, and the greatest challenge is to move away from stored programs and microprocessors towards pure hardware solutions. The technology of information barriers is primitive compared to the technology of radiation detection and data reduction. Nevertheless, relatively

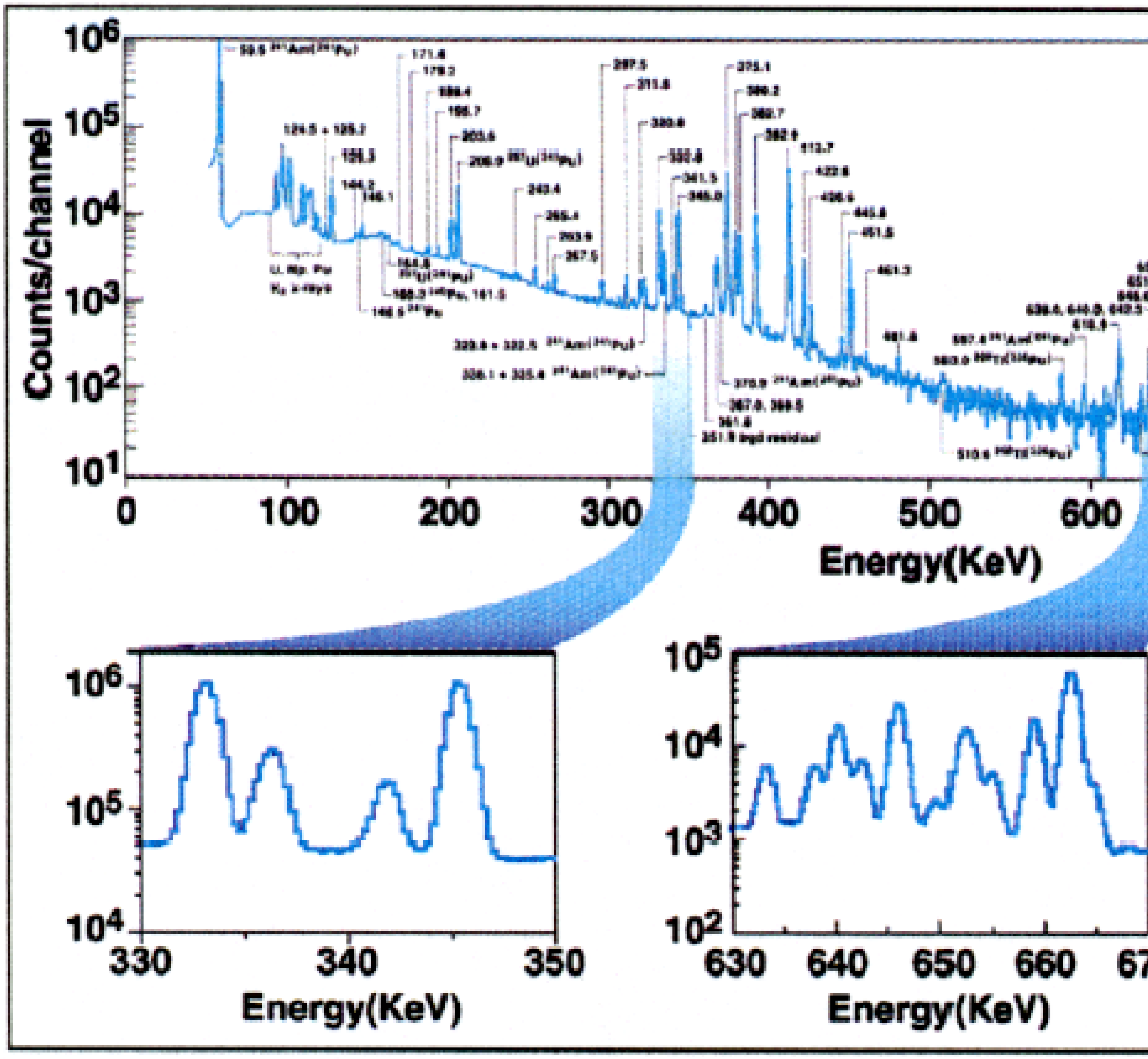


Figure 2. Plot of the gamma ray spectrum from a non-sensitive sa
isotopes and decay products. The details illustrate the relativel
spectral lines used in the attribute calculations known as Pu300,
courtesy of Thomas B. Gosnell, LLNL.)

simple systems such as those described above and in the references have provided sufficient assurance to sustain negotiations. The specific implementation of an information barrier system will depend on the requirements of the inspection regime. Nevertheless the three elements introduced here will always form its basis. More specific design influences include decisions about equipment origin and custody and the number and type of physical attributes to be collected. [Progress in Gamma Ray Measurement Information Barriers for Nuclear Material Transparency Monitoring", Wolford and White, Lawrence Livermore National Laboratory Library, 2000]

The treaty should challenge the Host facility to demonstrate compliance: Change the emphasis of the verification procedure. Consider that a Nuclear Weapon State intends to cheat the disarmament agreements that are in place. "Winning" if them is if they manage to fool the inspector. However if the onus were on host, it would be their duty to convince the inspector they are abiding by the agreements; for the cheat "winning" would be managing to convince the inspector. This approach addresses the underlying psychology between inspector and host facility more positively.

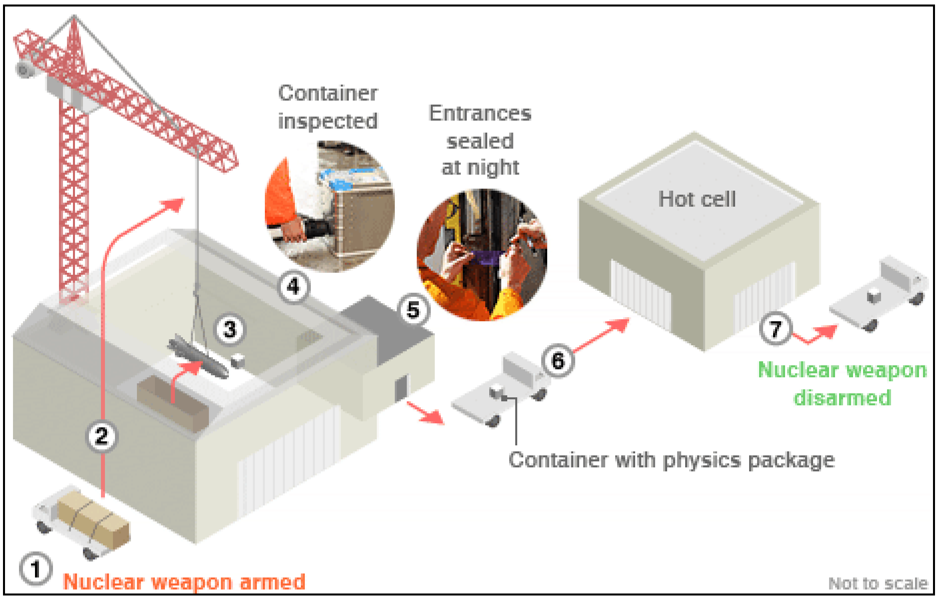
3 Overall Process

3.1 Dismantlement

Joint exercise between UK and Norway describes a possible dismantlement and verification process, conducted near Oslo in 2009. Cobalt 60 sample used to mimic physics package. A single nuclear weapon was moved into a dismantlement facility, where screwdrivers are used to open a side panel and remove the physics package. It is placed in a separate container. Everyone entering or leaving the dismantlement room is checked for radioactive material. Inspectors then confirm that radioactive material is present in the container. It is stored overnight in a sealed room with cctv. Seals used on items are low tech. The doors on the overnight storage room had a purple adhesive down the hinge which would change colour if disturbed. The adhesive strip itself is identifiable with a cluster of glitter suspended in transparent glue. On application and removal of the adhesive strip, this glue tag is photographed to check it has not been replaced, the exact configuration of suspended pieces of glitter would be near impossible to replicate. A simple technology like this seems to provide a reliable way of detecting tampering with a door or package seal. The following day the physics package would be moved to the "hot cell" where it would be 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 detector. Using this method the package can be inspected at multiply points to insure no material has been siphoned off. Once the weapon has been dismantled the nuclear material is taken away for storage.[1]

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 magnets 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 etc... the notebook computer sends an "all ok" 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. [2]

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" [2] Part of this management is weapon dismantlement. design laboratory's 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 reqired to dismantle a warhead ranges from "a few days to a few weeks" depending on the complexity of the design.[3] 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. [4] 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 department of energy 10% of the electricity used in the United States is

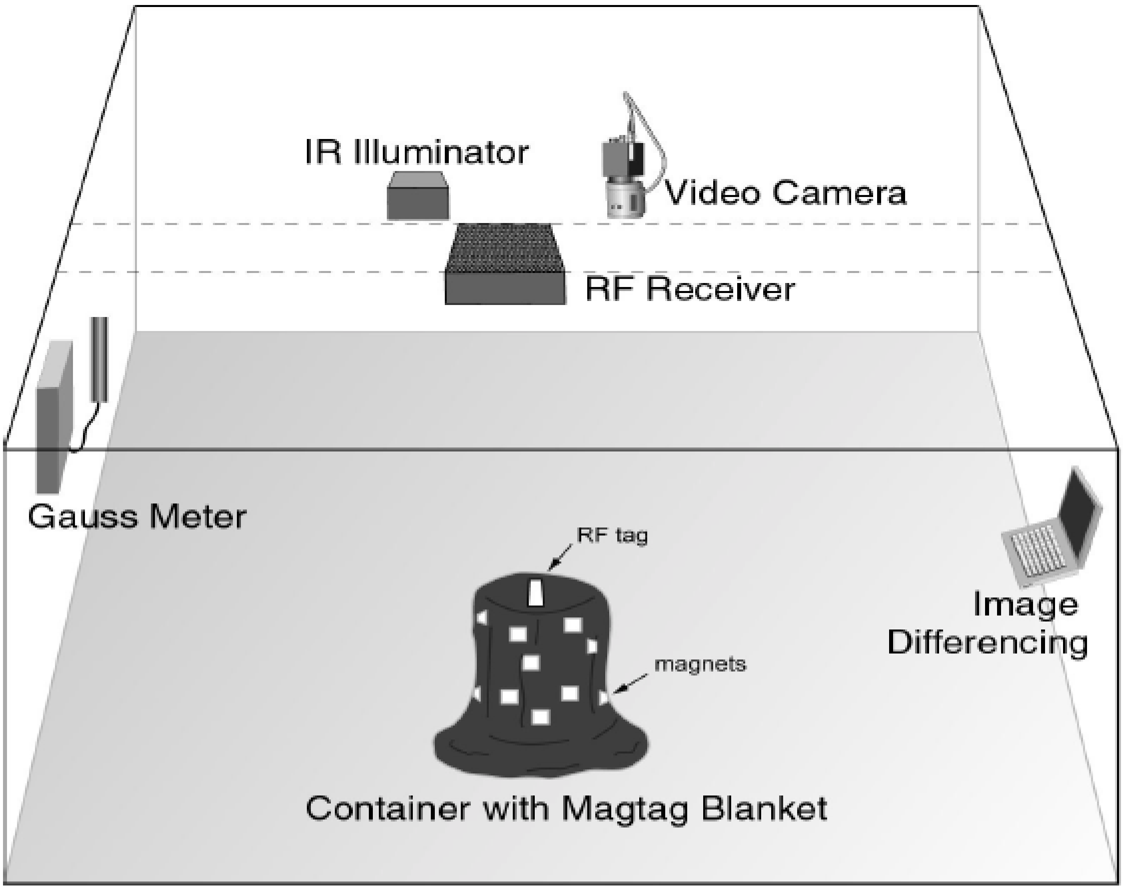


Figure 1: A schematic of the Magazine Transparency System (MTS) showing the primary components.

produced using former Russian nuclear weapons.[5] 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.

3.1.1 Downblending Uranium

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

The suplus of HEU from dismantled nuclear weapons can be downblended to LEU so that in can be used in commercial nuclear power plants. An example of this is theMegatons to Megawatts Programconverts ex-Soviet weapons-grade HEU to fuel for U.S. commercial power reactors. From 1995 through mid-2005, 250 tonnes of high-enriched uranium (enough for 10 000 warheads) was recycled 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 [http://www.asx.com.au/asxpdf/20080410/pdf/318j6y3ctr TheUnited States Enrichment Corporationhas been involved in the disposition of a portion of the 174.3 tonnes of highly enriched uranium (HEU) that the U.S. government declared as surplus military material in 1996. Through the U.S. HEU Downblending Program, this HEU material, taken primarily from dismantled U.S. nuclear warheads, was recycled into low-enriched uranium (LEU) fuel, used by nuclear power plantsto generate electricity [http://www.usec.com/company/mission-and-values]

During the downblending process, HEU is needed to be blended to a concentration of 3-5% U-235 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 as uranyl nitrate solution and blending as 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 downblending 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 oxidized 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 U.S. 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 U-235 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 converts 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 of 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 desublimed 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. [ref]

3.1.2 Storage of Fissile materials/nuclear weapons

Assuming confidence in the dismantlement of a warhead, for real progress to made storage is equally important. Nuclear weapon fissile materials need to be stored under international or bilateral monitoring, to prevent the construction of new weapons and also safeguard against theft.

3.1.3 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 facility's by 2020. [6]

3.2 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 disposition to make sure that it will not be reused [1]. 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. [2]

3.2.1 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. [3]

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. [3]

Current technologies and technologies under development: [1] 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. [4] 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. VACOSS fibre optic seal: The first IEAE 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. [5] 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. [5] 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 is covered with melted solder and 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 radio-frequency device. VNI-IEF 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.

3.2.2 Vulnerability of seals

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 Vulnerability Assessment Team (VAT) at the Los Alamos National Laboratory. They analysed 94 different seals and defeated them for a total of 132 defeats. All of the defeats were implemented using low tech attacks with tools and supplies that in some cases can be easily carried in a persons 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. [6]

3.2.3 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. [2]

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. [2] 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. [7] 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. [5]

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. [2]

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 photograph 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. [2]

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. [2]

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, synthesized 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. [2]

Figure 2: Picture of the Next Generation of Surveillance System (NGSS) with 24 cameras [5].

3.2.4 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.

4 Detection Schemes

4.1 Passive Detection

Nuclear warhead detectability is reliant upon 4 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. [1]

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 detectors ability to obtain a true signal depends on its efficiency and spectral resolution.[2]

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. [2][3]. 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. [2]

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. [2]

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 [2]. 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 [2]. Gamma ray spectra are unique to each isotope, thus, it is fairly easy to determine the radiation that is emitted from an isotope. 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.

4.1.1 Gamma Ray Detection

Gamma rays are produced from within the nuclei of radioactive atoms. [3] 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 continues 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. [2][3]

(FIGURE 1: PICTURE OF A SCINTILLATION DETECTOR)

An alternative detector which can be used to measure gamma rays is a semiconductor detector. A voltage is placed between two terminals on opposite sides of the semiconductor crystal. [3] 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. [2][3]

(FIGURE 2: PICTURE OF A NEUTRON DETECTOR)

4.1.2 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. [3]

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. [1] 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 measureable amounts of radiation from reaching the detector [4]

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 plutonium-240 (Pu-240) isotope. The fissile isotope of plutonium is plutonium-239 (Pu-239); however, Pu-240 is active also [5]. This isotope spontaneously fissions and typically emits about 106 neutrons per second with a characteristic energy of 1 MeV [5]. 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 Pu-239 contaminated by 6% of Pu-240 could reliably be detected with a detector 1m from the warhead in only 1 second [5]. 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. [5][6]. 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 uranium-238 (U-238) isotope. U-238 emits about 1MeV hard gamma rays at the rate of about 7.5 per gram per second with 1MeV energy [5]. Depleted uranium (almost all U-238) 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 [5]. The primary advantages of this technique are 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 [7]. A second disadvantage is that U-238 is used for other applications in which a high Z material is essential, therefore there could be a lot of false positives (from U-238 used in something that is not a nuclear weapon) if the method was used at questionable sites.

4.1.3 Existing Detection Equipment

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. [2] 2. Radioactive isotope identification devices: These devices are able to identify radioisotopes based on their gamma ray spectrum. 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. [2] 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. [2] They are primarily used for security purposes at checkpoints and borders. [7]

4.2 Active Detection

4.3 Muon Tomography

4.3.1 Cosmic Rays

Cosmic rays are a flux of high energy particles that bombard the earths 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. [1]

$$\pi^+ \to \mu^+ + \overline{\nu}_\mu \tag{1}$$

$$\pi^- \to \mu^- + \nu_\mu \tag{2}$$

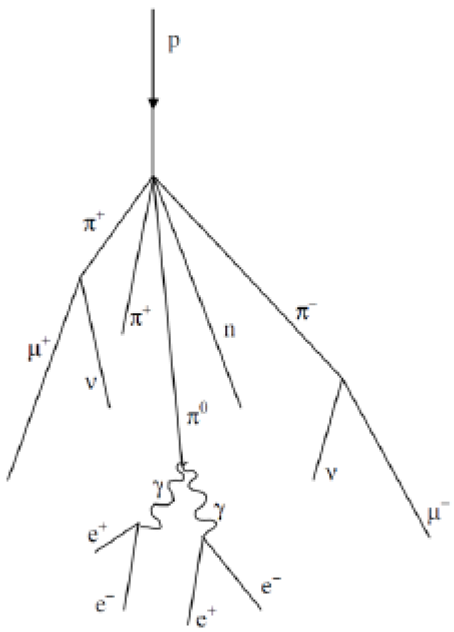


Figure 3: Cosmic ray cascade induced by a cosmic ray proton striking an air molecule nucleus. [1]

4.3.2 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 ionization. The mean energy of muons at the ground is 4 GeV [2]. 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.

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu \quad (3)$$

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu \quad (4)$$

The muon flux at sea level is about 1 muon cm^{-2} min^{-1} [3] or 10000 muons m^{-2} min^{-1}. They are highly penetrating charged radiation. A typical cosmic ray muon of energy 3 GeV can penetrate more than 1000 g cm^{-2} (eg. 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 (number of protons) 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. [4]

4.3.3 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 [4]. 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 [5]. 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 [4].

4.3.4 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) [6]. 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. [3]

The muon tomography concept is illustrated above in Figure 4. 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

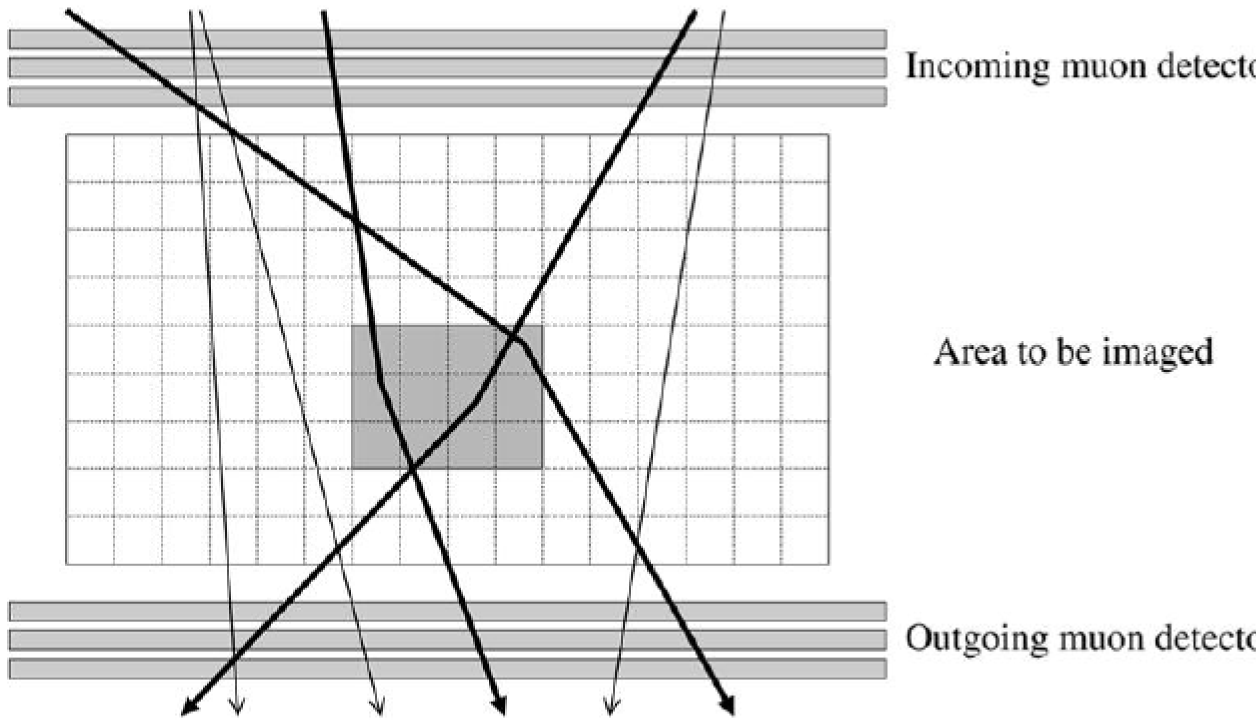


Figure 4: Muon tomography concept. The grey tracks are the muons going through air and the black tracks are the muons that penetrate a dense object. [3]

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 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. [3]

4.3.5 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. [3]

The mean method of reconstruction shown on Figure 6 contains red spots scattered over the image. The median method shown on Figure 7 does not contain these effects. The denser components of the van (engine, battery, drive train) are shown as green (low Z) or blue (medium) but the high Z threat object stands out as red. The median method is clearly better. [3]

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

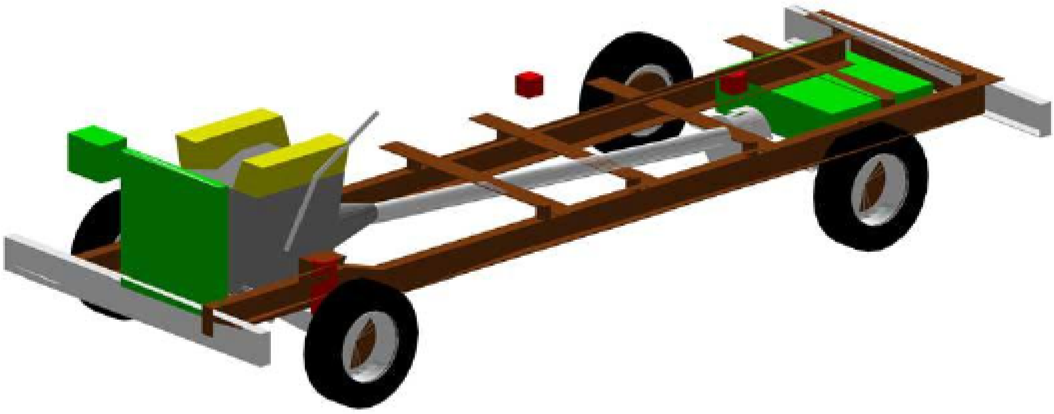


Figure 5: Illustration of major objects in a simulated passenger van using GEANT4. The red block in the centre represents a $10 \times 10 \times 10$ cm^3 solid piece of tungsten which is a high Z threat object. [3]

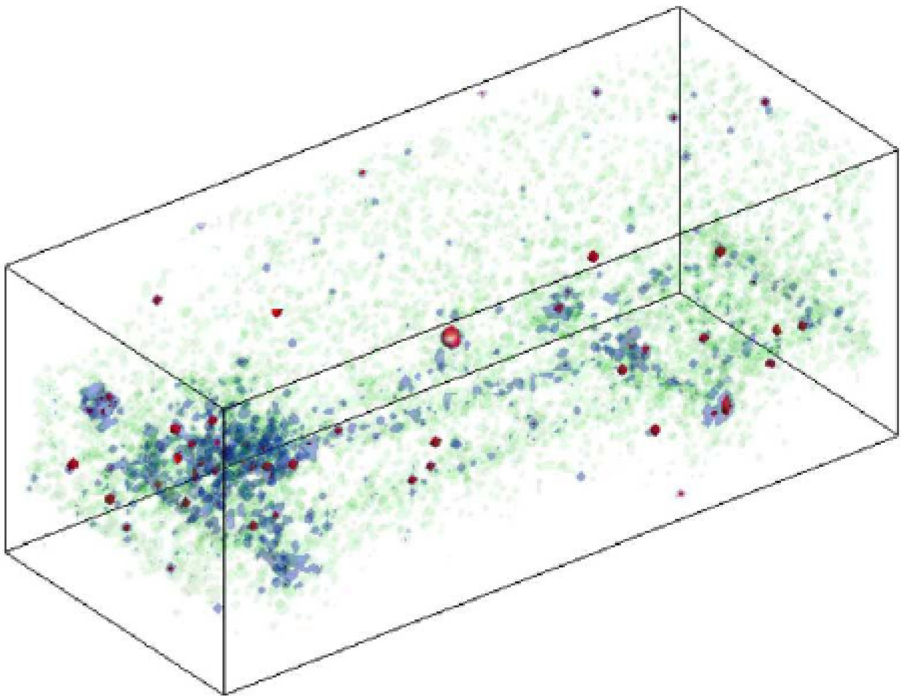


Figure 6: Reconstruction of 1 min of simulation muon exposure of the passenger van using the mean method. [3]

is the fact that a 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 $6 \times 2.4 \times 2.4$ m^3 cargo

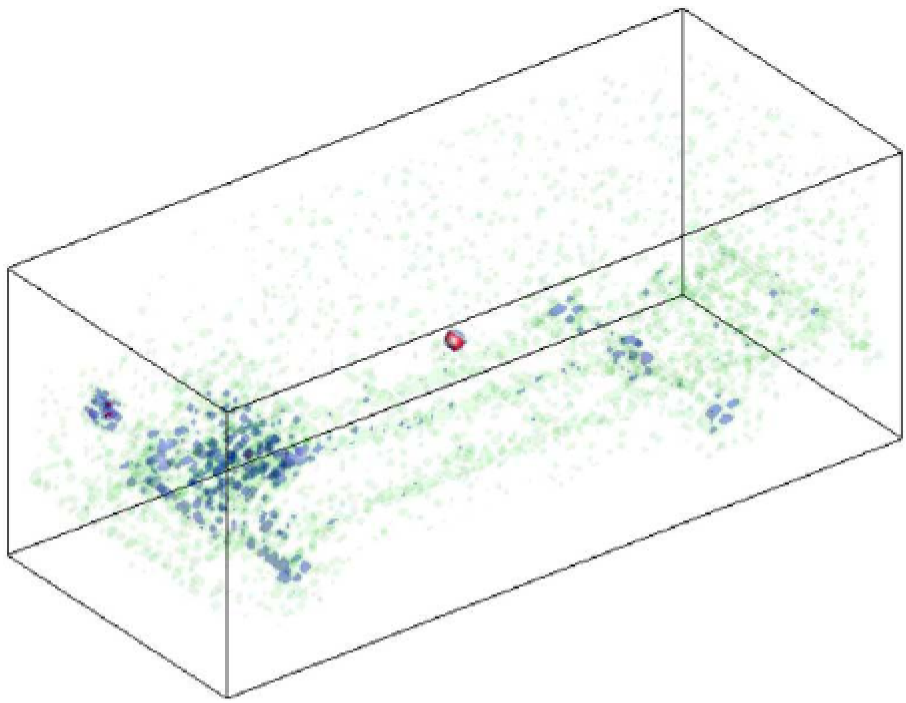


Figure 7: Reconstruction of 1 min of simulation muon exposure of the passenger van using the median method. [3]

container filled with 12 tons of iron and three $9 \times 9 \times 12$ 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 below on Figure 8. [6]

All three uranium bricks are clearly identified on Figure 8a. The image without the uranium bricks is empty of any signal as shown on Figure 8b. The ray crossing algorithm shows great promise in eliminating the scattering background. [6]

Other simulations were also produced using a Monte Carlo simulation code and the results are shown below on Figure 9.

4.3.6 Experimental results of muon tomography

There are a few prototype experimental muon tomography detectors that show excellent results which are consistent with the simulations. A small scale experimental detector system was developed in 2003 at the Los Alamos National Laboratory, Los Alamos, New Mexico [5]. A picture of the detector is shown below Figure 10.

Eight X and eight Y locations were measured for each muon by four ionizing 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

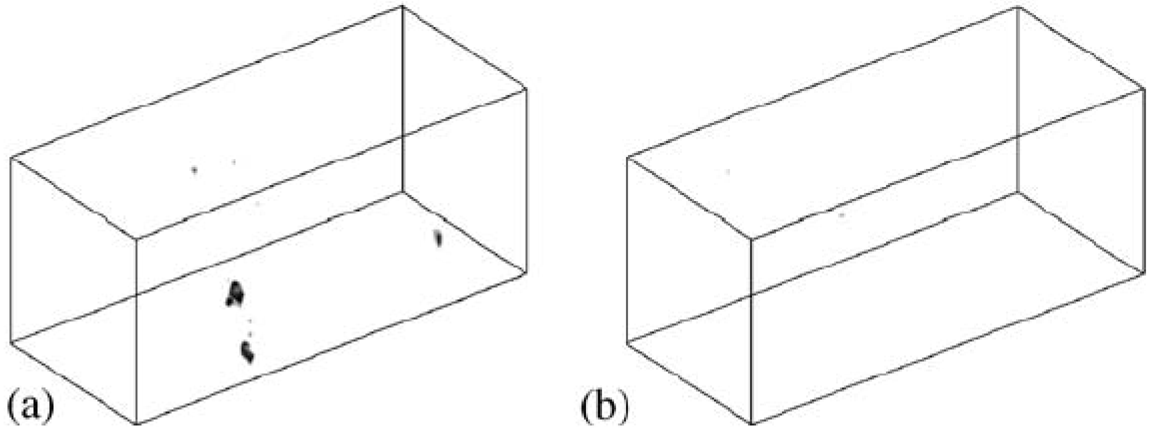


Figure 8: Ray crossing algorithm reconstructions of 1 min of simulated muon radiography of a $6 \times 2.4 \times 2.4$ m^3 cargo container filled with 12 tons of iron and three $9 \times 9 \times 12$ cm^3 uranium bricks (a) and without the uranium bricks (b). [6]

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 below on Figure 11. [5]

The data for the above image 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. [5]

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 fitted 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 below on Figure 12. [7]

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

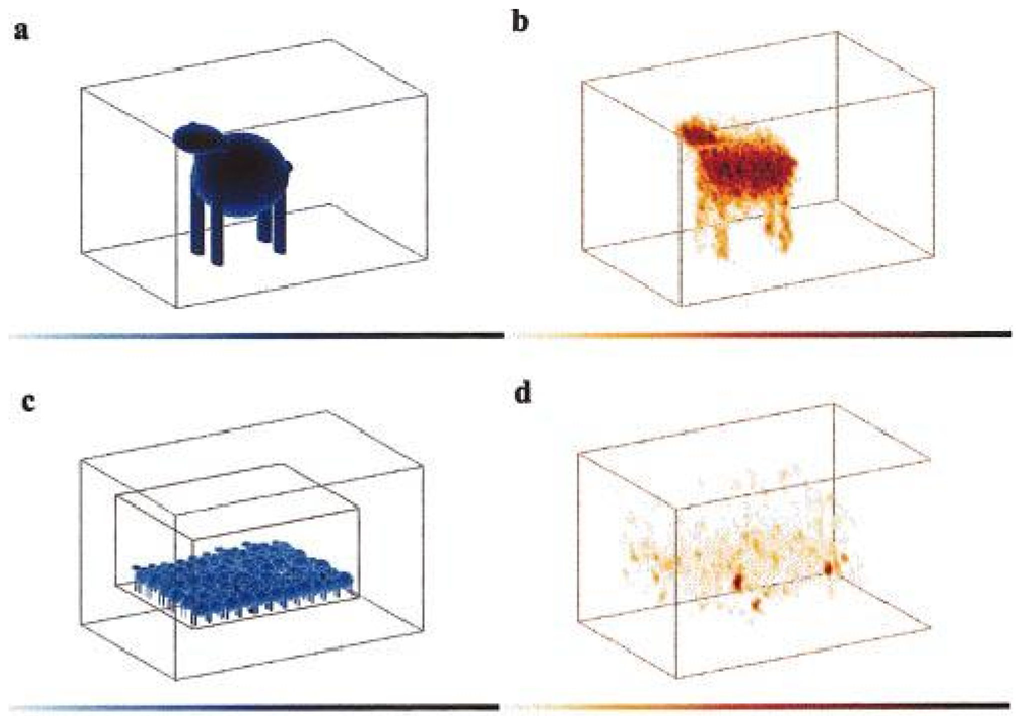


Figure 9: Muon radiograph of a complex target in a volume of $9 \times 3 \times 5.5$ m^3. The first object (a) is a large complex lead sculpture. The reconstructed image (b) shows much of the detail of the object and its based on 1 min of exposure. The second object (c) consists of a $4 \times 2.4 \times 2.4$ 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 $60 \times 30 \times 40$ cm^3 and three uranium bricks of size $9 \times 9 \times 12$ 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. [5]

with a car engine and transmission. A photograph of the engine in the LMT is shown below on Figure 13. [8]

Data were collected for approximately 160 min and have been analysed to reconstruct the images shown below on Figure 14. The mean scattering angle is plotted for all trajectories that pass through each voxel. [8]

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 below on Figure 15. [9]

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 process events one at a time instead of

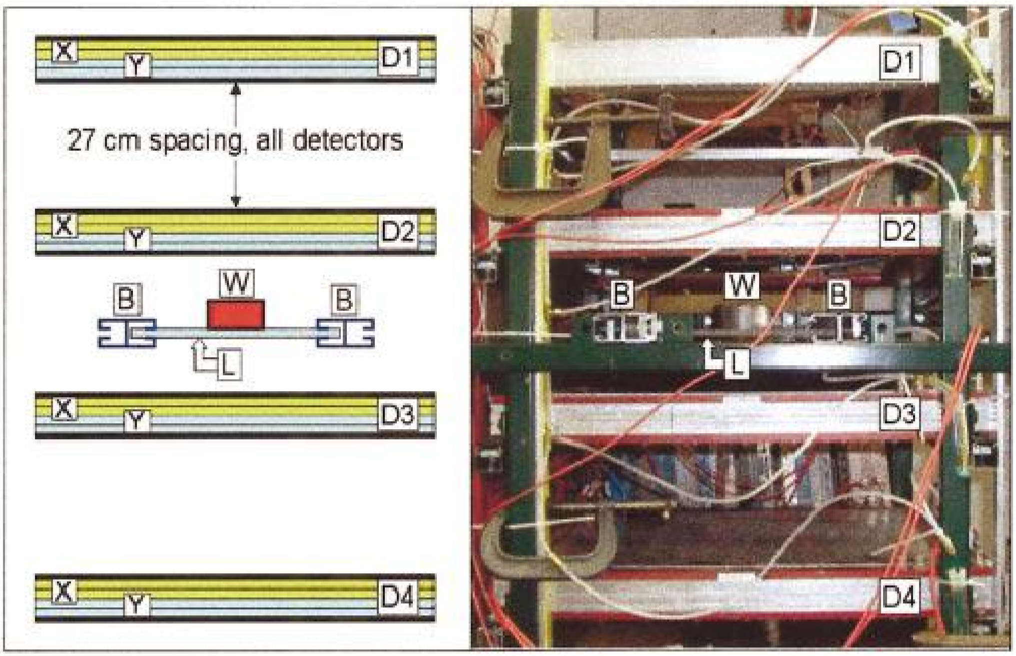


Figure 10: Picture of experimental apparatus at the Los Alamos National Laboratory in 2003. There are four muon detectors labelled D1-D4 with a vertical spacing of 27 cm. The detectors determine the positions and angles of the muons in two orthogonal coordinates (X and Y). The test object (W) was a tungsten 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. [5]

grouping similar events together. [9]

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 below on Figure 17.

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. [9]

4.3.7 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.

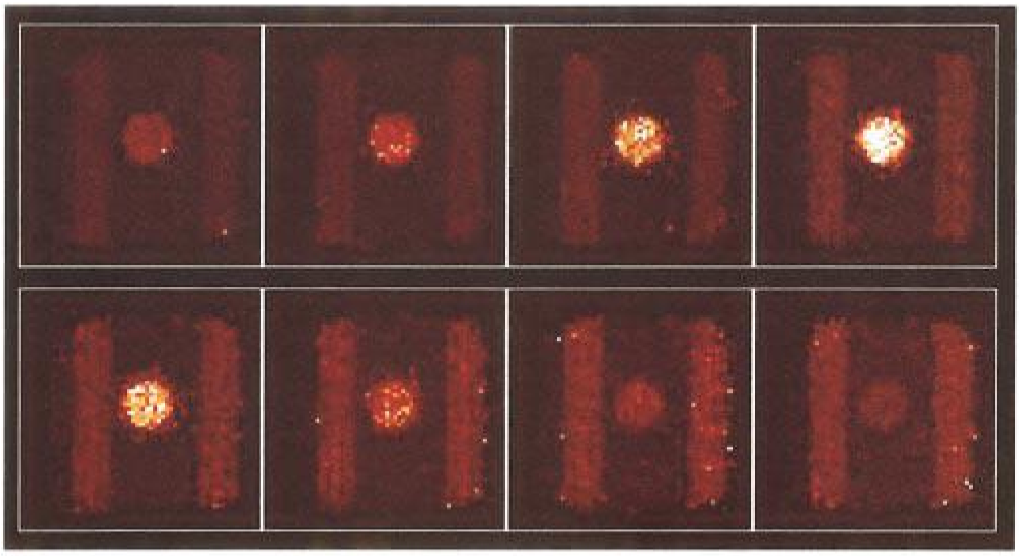


Figure 11: Test object reconstruction using 100 000 muons. A volumetric image of $1 \times 1 \times 1$ cm^3 voxels was reconstructed. The eight planes are horizontal slices near the middle of the volume, moving from top to bottom. Both the tungsten cylinder and the steel support beams are clearly visible. [5]

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. [10]

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 to 2 billion dollars but its negligible compared to the consequences of the detonation of a nuclear bomb. A picture of how it could be implemented at a border crossing is shown below on Figure 18. [8]

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.

Figure 12: 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. [7]

Figure 13: Photograph of a car engine in the LMT at the Los Alamos National Laboratory in 2008. [8]

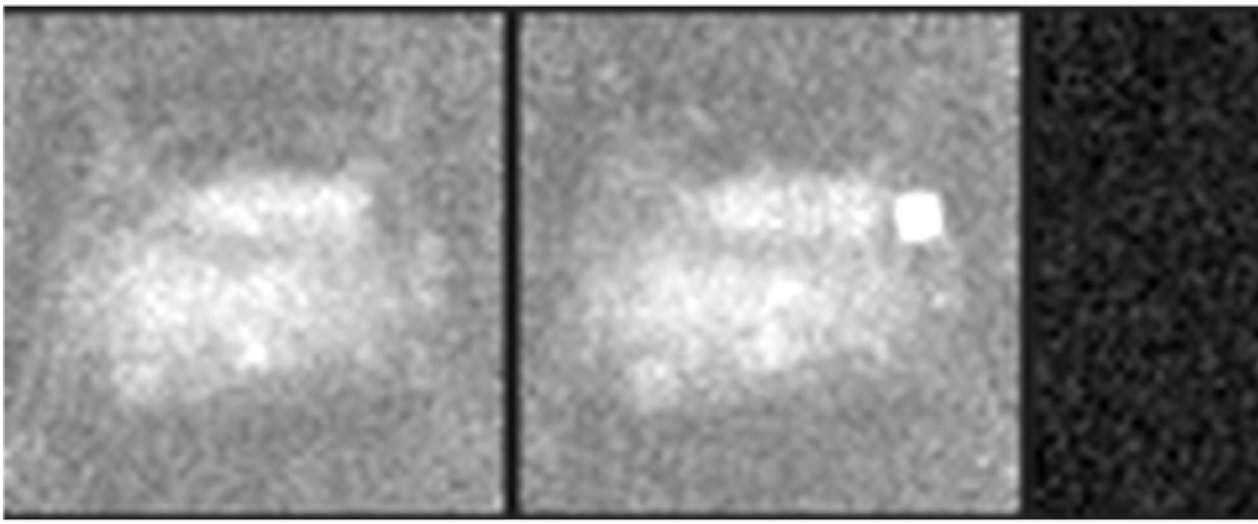


Figure 14: Mean scattering angle for a slice through the scene 50 cm above the base plate. The left image shows the car engine, the middle image shows the engine with the lead cube and the right image shows the difference of the other two images. The lead block stands out dramatically. [8]

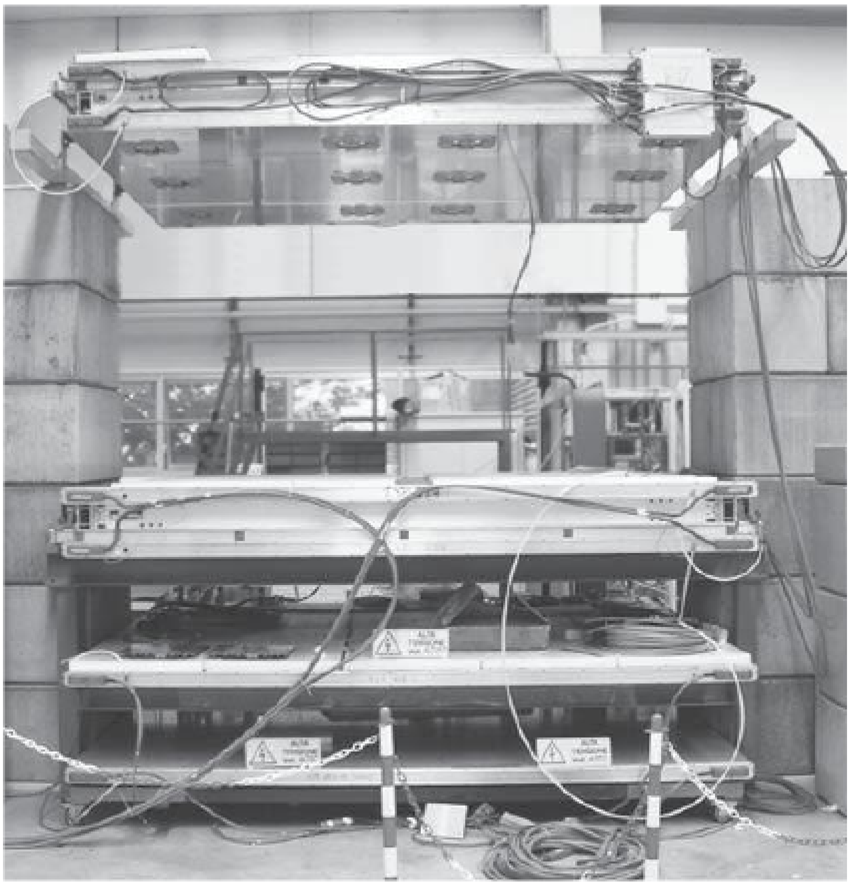


Figure 15: Muon tomography system prototype located at the INFN National Laboratories of Legnaro. [9]

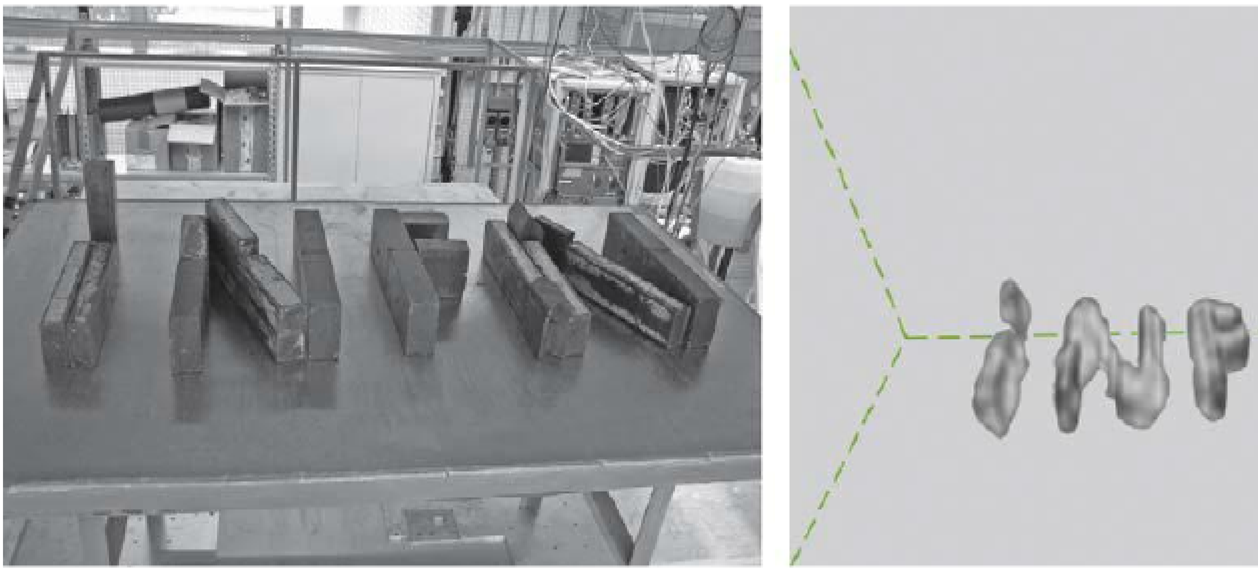


Figure 16: Test of the imaging capability of the prototype. The picture on the left shows the layout of iron bricks forming the word INFN and the picture on the right shows the result of the data analysis using the LMIA. The reconstructed image is very clear. [9]

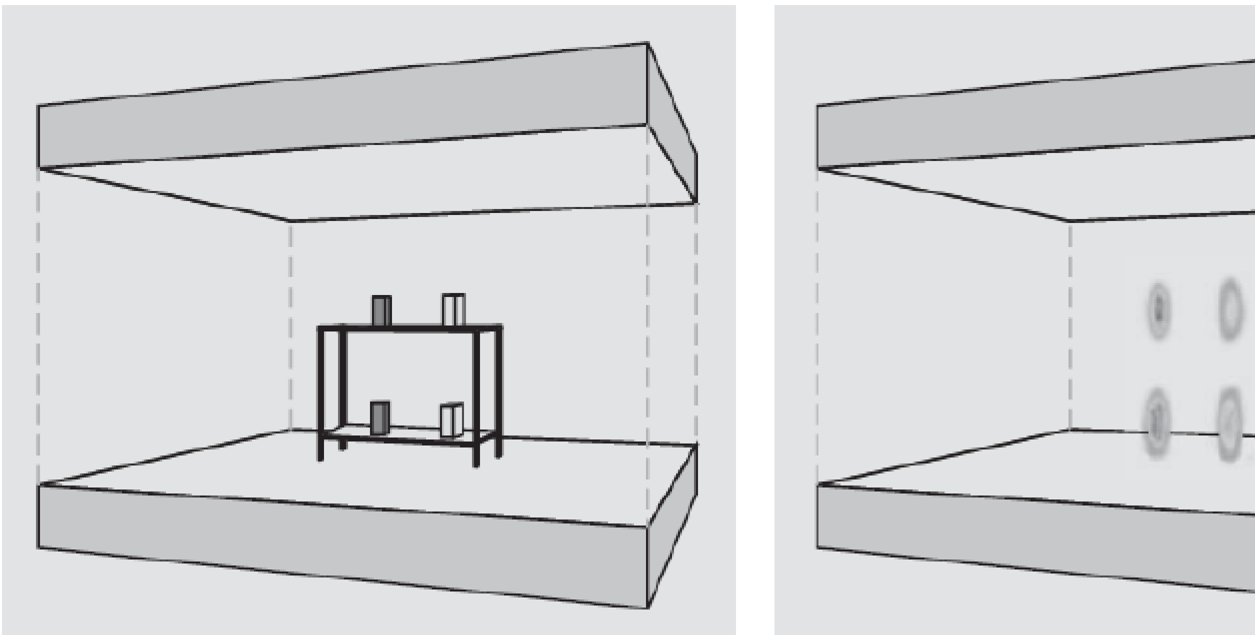


Figure 17: The left image is a sketch of the layout with the two lead and the two iron blocks. The darker blocks are the lead blocks. The right image shows the 3D view of the reconstructed image using the LMIA. [9]

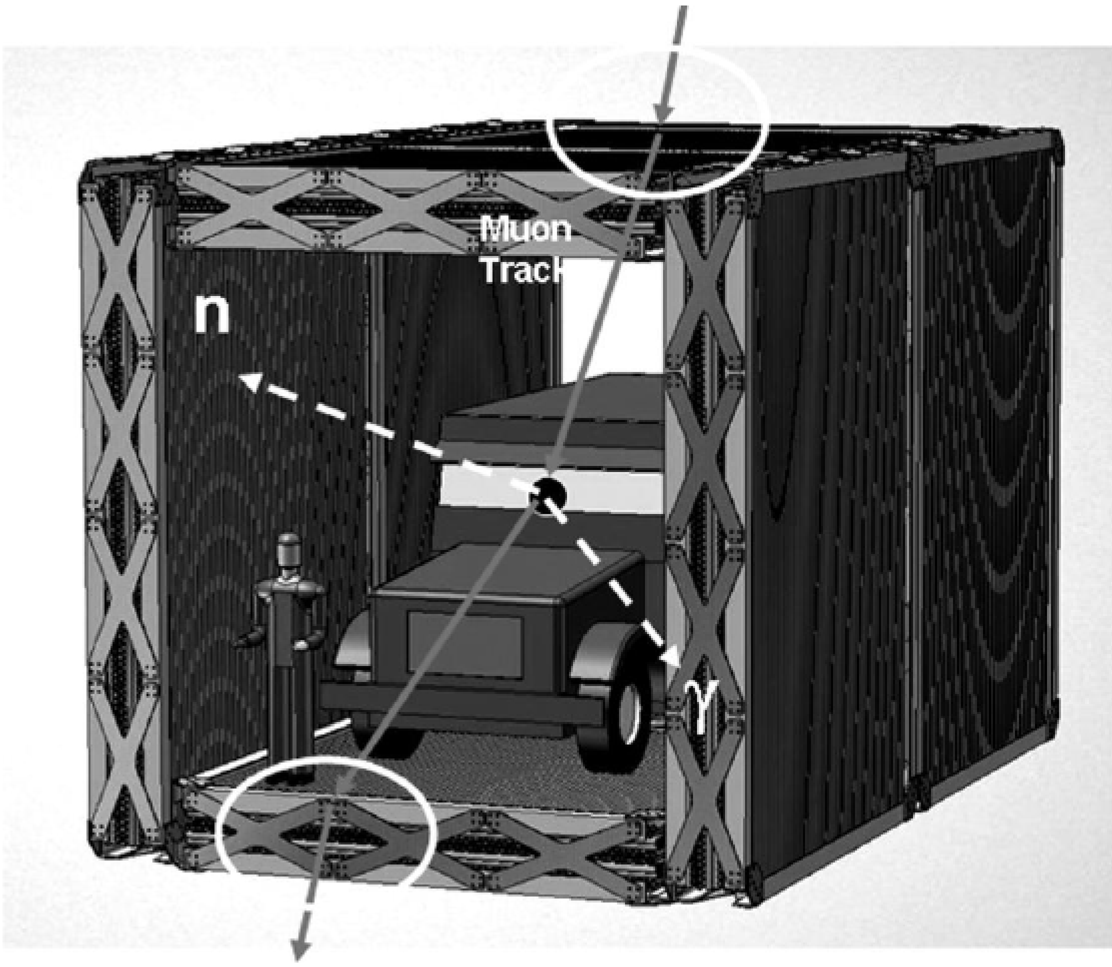


Figure 18: Schematic view of how a counting station might look. Vehicles would have to stop for approximately 20 seconds for the scan. [8]