Verification of Dismantlement of Nuclear Warheads and Controls on Nuclear Materials

S. Drell, Chairman
C. Callan
J. Cornwall
F. Dyson
D. Eardley
N. Fortson
R. Garwin
D. Hammer
S. Koonin
N. Lewis
C. Max
R. Muller
W. Panofsky
W. Press
S. Ride
M. Rosenbluth
M. Ruderman
J. Sullivan
S. Treiman
P. Weinberger
H. York
F. Zachariasen

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JASON
The MITRE Corporation
7525 Colshire Drive
McLean, Virginia 22102-3481
(703) 883-6997

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S. Drell, Chairman et al.

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The MITRE Corporation
JASON Program Office A10
7525 Colshire Drive
McLean, VA 22102

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This study addresses the question of verification of future agreements with respect to dismantlement and destruction of nuclear warheads, bans on the production of additional quantities of plutonium (Pu) and highly enriched uranium (HEU) for nuclear weapons and agreements on the end-use or ultimate disposal of special nuclear materials (SNM) i.e., Pu and HEU from warhead dismantlement. We consider national technical means (NTM) both as a stand-alone means for monitoring and also in conjunction with aerial overflights ("open skies") and other cooperative technologies and procedures.

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EXECUTIVE SUMMARY

GENERAL APPROACH

This study addresses the question of verification of future agreements with respect to dismantlement and destruction of nuclear warheads, bans on the production of additional quantities of plutonium (Pu) and highly enriched uranium (HEU) for nuclear weapons and agreements on the end-use or ultimate disposal of special nuclear materials (SNM) — i.e., Pu and HEU — from warhead dismantlement. We consider national technical means (NTM) both as a stand-alone means for monitoring and also in conjunction with aerial overflights (Open Skies) and other cooperative technologies and procedures. Our approach is to consider specific technologies and cooperative procedures of monitoring compliance, and to analyze the standards of verification that can be achieved for the following five missions:

1. Determine the total quantities of SNM and the total number of warheads in the current nuclear arsenals of the United States and Russia.

2. Dismantle warheads, defined as separating warheads into their individual parts, i.e., arming/firing mechanisms, primaries, secondaries, and airframes.

3. Destroy warheads, defined as crushing the parts to render them militarily useless.

4. Cut off the production of new SNM.

5. Secure, store, and eventually dispose of the SNM.

It is assumed in all cases that the United States and Russia will retain nuclear weapons at a level that is significant in comparison to the other overt nuclear states (e.g., United Kingdom, France, China), and that both states will retain an operating nuclear weapons complex to refurbish weapons in their forces, to disassemble weapons for internal inspection, and to reassemble and, possibly, remanufacture weapons.

Monitoring requirements will vary depending on the agreement, and the desired and necessary standards of verification must be carefully evaluated in terms of their value for United States national security. In any conceivable dismantlement/disarmament/cut-off regime, verification will of necessity be less than perfect. Therefore, a decision as to whether a particular informal agreement, or formal treaty *is* in the United States national interest must rely on difficult political/strategic judgments, as well as technical ones, as to its risks and benefits.

We have to consider two very different objectives in evaluating the expected advantage of any bilateral agreement between Russia and the United States; these two objectives imply different standards and procedures for assuring an adequate monitoring capability. One is to provide confidence to the United States of detecting a strategically significant Russian violation. The second is to provide assurance that any dismantlement agreement will detect leakage of only a few warheads or kilograms of SNM to other countries seeking to acquire a nuclear weapons capability.

The primary focus of this report is on the first of these two objectives in a bilateral U.S.-Russian context. The resulting cooperation with Russia toward achieving this goal will form an essential basis for progress toward the second one.

Finally we observe that, in the near term, the safe and secure removal of the strategic nuclear weapons still remaining in Belarus, Ukraine, and Kazakhstan, and the return of these weapons to Russia to initiate their dismantlement, is a matter of overriding priority with verification considerations treated as a secondary issue.

CONCLUSIONS

We present our conclusions and recommendations in terms of the technical capabilities for monitoring agreements to dismantle or destroy nuclear weapons and/or to store and dispose of SNM. We also offer several concluding observations of a more political nature.

1. NTM alone are inadequate for verification of warhead dismantlement and SNM production. However, they are important as part of a larger verification system including cooperative procedures for monitoring activities and changes. They can raise suspicions and trigger the application of Open Skies and other more detailed inspections, overt and cooperative or covert, of suspect sites and activities. They are very valuable for monitoring the shut-down of declared facilities and for providing early indications of large scale construction.

   This conclusion agrees with that of the Robinson Report,[1] which identified the limited value of NTM for detecting and monitoring warhead dismantlement and materials production signatures and for detecting clandestine activities by the Russian weapons complex. We emphasize, however, that working together with cooperative procedures, NTM give the United States a greatly strengthened ability to monitor indicators

[1]Report to Congress: "Verification of Nuclear Warhead Dismantlement and Special Nuclear Material Controls" (July 1991) by the Technical Advisory Committee on Verification of Fissile Material and Nuclear Warhead Controls (Ambassador C. Paul Robinson, Chairman).

of the production of special nuclear materials, the transport of weapons, and the construction of new facilities. We also note that, while a determined and highly disciplined evader could undertake clandestine production of weapons or special nuclear materials without being detected by NTM, real-world lapses of discipline are most likely to leave traces of any sizable activity that NTM could detect. This is especially true of activities in Russia in its currently unsettled conditions, and given the extensive disillusionment and emigration of former Soviet functionaries.

Looking ahead, NTM capabilities for monitoring activities and detecting changes are making important progress at the R&D level.

2. Open Skies is a new and potentially valuable component of the verification system. We are just beginning to test and analyze its full potential. Viewing with multi-spectral sensors — visible, infrared (IR), laser radar (LIDAR) and SAR — and from closer range than NTM, it can help clarify ambiguities and provide useful triggers for raising challenges concerning suspected non-compliance. Open skies is of unique value in that it can be used to provide an overt signal of suspicious activities that we may have learned of from sources and methods, perhaps covert or involving advanced and secret technological capabilities, that we do not wish to disclose.

   The prospective enhancement of Open Skies to allow additional sensors that collect air samples for gas and particulate analysis will increase its value in identifying clandestine activities.

3. Cooperative verification includes a very broad range of technologies and operational procedures; altogether these can be very effective in uncovering and hence deterring covert activities. However, we face a tension in setting standards and requirements for monitoring activi-

ties by cooperative inspection: with more comprehensive and intrusive procedures we learn more about the other party and increase the probability of detecting a violation. At the same time, however, they may be able to learn more about us, including sensitive information, and because comprehensive procedures take time to set up, we both may lose opportunities for valuable progress during the currently open window of opportunity. We may also incur substantial costs for only a marginal improvement in verification capability.

There are several important elements to keep in mind in setting standards and requirements for detecting clandestine activities. One is the new transparency in Russia as a result of extensive emigration and contacts with present and former members of the military, intelligence, and nuclear establishments. Secondly, in today's world the disadvantage to Russia if we detect a violation is considerably greater than any benefit to them should they escape detection. Finally, successful cooperation between the two countries — on a personal, technical and business level, as well as government to government — will, in time, lead to higher confidence.

RECOMMENDATIONS

1. Continue strong R&D support for space-based sensors and systems for monitoring activities and changes.

2. Develop and support a strong R&D program for identifying and characterizing source signatures and multi-spectral optical, IR, LIDAR, SAR, and air-sampling sensors for Open Skies observations of activities.

3. Develop an effective monitoring system that integrates cooperative procedures with Open Skies and NTM without requiring unnecessary and

unwanted intrusive and comprehensive procedures so that we can take full advantage of the current favorable circumstances for working with Russia to reduce the nuclear danger by dismantling/destroying warheads and ceasing production of SNM.

Finally, we note that many of the NTM techniques (both existing and future) most useful for monitoring nuclear weapons dismantlement and SNM materials controls *within* Russia would also be applicable for detection of weapons proliferation. Advances in technologies can considerably enhance capabilities for monitoring both non-proliferation and dismantlement.

1 INTRODUCTION

1.1 Study Charge

This study addresses the question of monitoring future agreements between the United States and Russia with respect to dismantlement and destruction of nuclear warheads, bans on the production of additional quantities of plutonium (Pu) and highly enriched uranium (HEU) for nuclear weapons, and agreements on the end use or ultimate disposal of special nuclear materials (SNM) — i.e., Pu and HEU — from warhead dismantlement. We consider NTM both as a stand-alone means for monitoring and also in conjunction with aerial overflights (Open Skies) and other cooperative technologies and procedures.

Our work builds on an earlier study,[2] commonly known as the Robinson report after its study chairman, Ambassador Paul Robinson. The Robinson report was completed in July 1991 in response to a Congressional mandate contained in Section 3151 of the National Defense Authorization Act of 1991. In the relatively brief time since the Robinson report was completed, there have been remarkable changes in the world. The Soviet Union has ceased to exist. The United States has withdrawn all its ground-based tactical nuclear weapons from Europe and removed all nuclear weapons from its surface ships. Tactical nuclear weapons have been withdrawn to the Russian Federation from all other republics of the Former Soviet Union (FSU). Ukraine, Kazakhstan, and Belarus, the only republics of the FSU aside from Russia

[2] Report to Congress, op. cit.

containing strategic nuclear weapons, have agreed to the complete elimination of all nuclear weapons on their territories under START mandated reductions, and the same republics have agreed to sign, at an appropriate time, the Nuclear Non-Proliferation Treaty as non-nuclear states. Considerable progress in the development of cooperation between the United States and Russia and the other republics of the FSU has occurred generally. In particular, the signing of the Open Skies Treaty on March 24, 1992, has created a new and potentially valuable cooperative verification regime. Most recently, the Washington agreement signed by Presidents Bush and Yeltsin on June 17, 1992, calls for removing an additional combined total of 8,000–9,000 strategic warheads below the levels mandated by START during the coming decade.

There now exist new opportunities for reducing arsenals of nuclear warheads and inventories of SNM that are beyond the usual framework of formal treaties and their elaborate frameworks for monitoring activities and verifying compliance. President Bush initiated the more flexible approach of reciprocal unilateral reductions on September 27, 1991, and then-President Gorbachev quickly responded in kind six days later. Their initiatives led to the de-commissioning of large numbers of tactical systems and the removal from alert status of elements of the long-range strategic forces. More recently the Russians proposed selling large quantities of their HEU to the West for cash in order to help alleviate their economic crisis, and an outline of such an agreement was released by the White House on September 1, 1992. If such a deal is consummated, it will lead to direct and automatically confirmed major reductions of their nuclear threat to us. Indeed, if these sales are made to private corporations — as has also been proposed — it will amount to expanding the cooperative monitoring or inspection regime beyond government-to-government arrangements by including extensive contacts in the commercial sector as well. Such a development would be most important for future exploitation in trying to reduce the nuclear threat and bring it under secure control.

This study addresses the possibilities and prospects for government-to-government monitoring of the more traditional approach of bilateral U.S.-Russian accords. We give our primary emphasis to the potential value of Open Skies overflights, as recently negotiated, and to cooperative inspection technologies and procedures applied in concert with existing and prospective NTM systems.

Our approach is to consider the specific means of monitoring and analyze the standards of verification that can be achieved, assuming different degrees of intrusiveness in the inspection process, for the following five missions:

1. Determine the total quantities of SNM and the total number of nuclear warheads in the current arsenals of the United States and Russia.
2. Dismantle warheads, defined as separating warheads into their parts, i.e., arming/firing mechanisms, primaries, secondaries, and airframes.
3. Destroy warheads, defined as crushing the parts to render them militarily useless, aside from the value of the SNM itself.
4. Cut off the production of new SNM.
5. Secure, store, and eventually dispose of the SNM.

A bilateral agreement between the United States and Russia would call for one or more of the above steps, depending on its purpose. The following are possible examples:

1. A limited agreement ensuring that nuclear warheads removed from delivery systems eliminated under treaties, or under matched unilateral statements, are not available for reuse on other delivery systems or for use by terrorist or dissident groups without some level of reassembly/remanufacture.

2. An agreement of a similar nature as (1) but requiring full destruction of a specific number of warheads along with the requirement that special nuclear materials removed from warheads be placed in secure storage.

3. An agreement to retain all, or some agreed-upon amount, of the weapons-grade SNM now in national stockpiles in secure storage as an interim measure prior to an agreed disposal or denaturing step, or as a longer-term measure, pending future agreement on ultimate disposition.

4. An agreement establishing a verified bilateral cutoff on the production of new weapons-grade fissile materials (HEU and Pu^{239}).

5. An agreement not to manufacture new nuclear warheads.

6. A more comprehensive agreement combining several of the above provisions.

It is assumed in all cases that the United States and Russia will retain nuclear weapons at a level that is significant in comparison to the other overt nuclear states (e.g., United Kingdom, France, China) and that both states will retain an operating nuclear weapons complex to refurbish weapons in their forces, to disassemble weapons for internal inspection, and to reassemble and, possibly, remanufacture weapons. Remanufacture might be subject to restrictions or forbidden altogether according to the terms of the particular agreement under consideration.

Monitoring requirements will vary depending on the agreement, and the desired and necessary standards of verification must be carefully evaluated in terms of their value for U.S. national security.

We recognize that in the near term, the safe and secure removal of strategic nuclear weapons still remaining in Belarus, Ukraine, and Kazakhstan, and return of these weapons to Russia to initiate their dismantlement, are matters of overriding priority, with verification considerations currently being of secondary importance. This report looks to the longer-term issues; in particular, our analysis and findings should be viewed as being applied bilaterally to the United States and Russia. In any conceivable dismantlement/disarmamant/cutoff regime, verification will of necessity be less than perfect. Therefore, a decision as to whether a particular informal agreement, or formal treaty *is* in the U.S. national interest must rely on difficult political/strategic judgments, as well as technical ones, as to its risks and benefits. For example:

- How great are the advantages to the United States if agreements are complied with by the Russians, relative to the risks the United States faces if it fails to detect a violation?
- From the point of view of the Russians, how great are the advantages if they successfully evade detection relative to the disadvantages if they are detected violating an agreement?

- How does a successful agreement benefit U.S. security relative to having no agreement at all? For example, how valuable is it in keeping nuclear weapons or special nuclear materials out of the hands of terrorists or dissidents in the former Soviet Union?

- What risks might intrusive verification measures pose to U.S. interests, such as the possibility of Russia learning certain features of U.S. nuclear warhead design or collateral information? Is the United States willing to share restricted data with Russia, and perhaps the other overt nuclear nations, under defined circumstances in order to strengthen verification, while retaining the present barriers against other countries?[3]

1.2 The Verification Equation

The following qualitative "equation" provides a useful way of evaluating the expected advantages that might motivate the Russians to violate an agreement to dismantle/disable weapons or to cut off production of SNM. For a statement of this problem, we introduce B_R, the benefit perceived by

[3]The following sections of the Atomic Energy Act are pertinent to the question of declassification of restricted weapons data. Section 11 (y): "The term 'Restricted Data' means all data concerning (1) design, manufacture, or utilization of atomic weapons; (2) the production of special nuclear material; or (3) the use of special nuclear material in the production of energy, but shall not include data classified or removed from the Restricted Data category pursuant to section 142." Section 142: "(a) The Department [of Energy] shall from time to time determine the data, within the definition of Restricted Data, which can be published without undue risk to the common defense and security and shall thereupon cause such data to be declassified and removed from the category of Restricted Data." "(c) In the case of Restricted Data which the Department [of Energy] and the Department of Defense jointly determine to relate primarily to the militarization of atomic weapons, the determination that such data may be published without constituting an unreasonable risk to the common defense and security shall be made by the Department [of Energy] and the Department of Defense jointly, and if the Department [of Energy] and the Department of Defense do not agree, the determination shall be made by the President." We thank George Bunn of the Center for International Security and Arms Control, Stanford University, for this reference.

Russia if it successfully evades detection, and D_R, the disadvantage to Russia if a violation is exposed. B_R and D_R include military, as well as economic and political benefits and risks. Let P denote the probability that the United States will detect a violation and $\bar{E}$ denote the expected advantage of a successful violation of the agreement to the Russians, which we can write symbolically

$$\bar{E} = (1-P)B_R - PD_R \quad . \tag{1-1}$$

In this case verification is a deterrent to cheating by the Russians if

$$\bar{E} < 0 \tag{1-2}$$

or

$$P > \frac{1}{1 + (D_R/B_R)} \quad . \tag{1-3}$$

Equation (1–3) puts a lower bound on the required probability of detection in terms of the ratio

$$\frac{D_R}{B_R} \quad . \tag{1-4}$$

If this ratio of disadvantage to benefit is large, even a small probability of detection will eliminate the expected gain from a contemplated violation.

Whereas the probability of detecting a violation is largely under U.S. control and is affected by improvements in its verification technology and operational procedures, B_R and D_R are not. They depend largely both on intentions and psychology of the Russians. With Russia in a cooperative state, as at present, and eager for economic aid and political acceptance from the rest of the developed world, the ratio (1–4) is high, and it is relatively easy to satisfy (1–3). Should Moscow revert to confrontational policies, this may no longer be the case. However, such a transition back to policies and strategies reminiscent of the Cold War would be readily detectable through public information channels, and would presumably lead to a reassessment of any treaty. With this in mind, it is appropriate to assess the inequality (1–3) and the ratio (1–4) on the basis of U.S.-Russian cooperation, while simultaneously retaining in the United States a capacity to strengthen verification measures and also to initiate a rebuilding of nuclear forces should the need arise.

Prior to the end of the cold war, P was determined primarily by NTM. For the kinds of missions (listed above) we are concerned with in this study, we shall find that (P^D_{NTM}), the detection probability based on NTM alone, will be inadequate to satisfy (1–3). However with the much greater transparency present in Russian society today, we can rely on more intrusive technology and cooperative procedures to *supplement* NTM for detecting violations. This means we need only rely on NTM to trigger a suspicion of non-compliant activities or installations.

Using NTM to trigger suspicion of non-compliant activities coupled with follow-up cooperative measures — either by Open Skies, in-place inspection, or an on-site visit — can result in an overall probability of detection that will be much higher. Furthermore, a quota of challenge inspections independent of NTM can add further to the probability of our detecting a violation. Symbolically we write

$$P = P^D_{NTM} \oplus P^S_{NTM} P_F \oplus P_C \quad , \qquad (1-5)$$

where P^S_{NTM} denotes the probability of a suspicion resulting from NTM P_F, denotes the probability of detecting a violation in a follow-up investigation, P_C denotes the probability of an independent challenge inspection detecting a violation, and $\oplus$ in expression (1–5) means that the probabilities are compounded, i.e., each term increases the probabilities of detection [4] although

[4]Note also that the probability of detecting violations increases with the number of

they are not literally "added." An additional advantage of cooperative procedures, including open skies, is that they allow a follow-up investigation of a suspicion that may have been triggered by a source or method we choose not to reveal (i.e., advanced satellite signals, emplaced sensors, or humint sources). With evidence in hand from follow-up inspection, the United States can then proceed to request clarification or register a challenge without compromising its covert methods.

The point of all this is that, while the monitoring of an agreement on dismantling or destroying warheads or a cutoff on the production of SNM may be inadequate if it relies on NTM alone, other tools are available. Monitoring becomes much more effective when cooperative and other verification techniques are added to NTM. Moreover, by means of the economic and political carrots and sticks that are now available to the West, the ratio (1–4) can be made favorably large. (*This general framework also applies to would-be* nuclear proliferators.)

We may thus very well come to different conclusions about the value of such an agreement if NTM only were available, or if the ratio (1–4) were much smaller as it was during the Cold War.

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incidents of non-compliance.

2 MEANS OF VERIFICATION

For the kinds of agreements that we consider in this study, verification by NTM *alone* is generally inadequate. Adequate verification requires NTM in conjunction with more intrusive technologies, including aerial overflights (Open Skies) and further cooperative procedures. In this section, we discuss these possibilities and describe in general terms how they might be applied. The subsequent sections consider the applications of verification systems in more detail for each of the five specific missions listed in Section 1.1.

2.1 National Technical Means

NTM can play a significant role in attempting to monitor violations of agreements to dismantle nuclear weapons, cut off production of SNM, and securely store or dispose of this material. They are also valuable for monitoring nuclear weapons proliferation. As the technology of satellite instruments advances, so will the kind of information they can provide: broader spectral ranges, improved spectroscopic analysis, and improved data processing. More frequent observations would seek early indications of major construction, sudden changes in activities or power consumption around facilities, telltale emissions, or suspicious shipments on roads or railways, any of which could be followed up by more capable, usually more intrusive, means such as Open Skies.

For visible or near-visible imagery, some of the interesting features require only modest spatial resolution of one to two meters. These include cooling towers, ponds, and stacks of spent fuel casks at production reactors, fuel casks and seep ponds at reprocessing plants, storage bunkers at fabrication plants, large transport vehicles appearing at such sites, large excavation projects including disposition of the excavated material, and areas of vegetative or other environmental damage from chemical poisoning around certain facilities. As in LANDSAT imagery, using several spectral bands can enhance the capability of identifying smaller, unresolved features.

Thermal radiance at $5 - 10\mu$m, averaged over 30-meter surface resolution elements, could reveal the temperature of cooling towers and ponds at production reactors, possibly yield a monthly average energy throughput, and detect very hot items of smaller size (smokestacks, transformers, etc.) at any facility.

A small interferometer of modest capability reaching to a wavelength of 10μm with a resolving power $\equiv \lambda/\delta\lambda \cong 1{,}000$, radiometric accuracy of order 1 percent, and a surface spatial resolution of 10 km forms a small instrument package of about 25 kg in weight requiring power of about 30 watts. It could be targeted to detect gases such as halogen mixtures emitted from enrichment facilities, freon or nitrogen oxides from reprocessing plants, and volatile solvents from weapons material processing or device fabrication sites. An important research area is to assess the overall utility of remote sensing (of both emitted gases and particulates) as a means of detecting proliferation activities, and also the degree of resolution and complexity of the instrumentation required.

We describe here several new and newly developing technologies that can extend U.S. capabilities for overhead surveillance and thereby improve the means of monitoring activities. The concepts described will require detailed engineering and system analysis in order to evaluate them more fully. In this brief discussion, we draw liberally on the 1989 JASON report on *Verification Technology*[5] and on the 1992 Summer Study Report on *Precision Strike*.[6]

Improvement in activity monitoring from space can come from three general approaches. One is by deploying a constellation of relatively small and inexpensive photo reconnaissance satellites in low earth orbit (LEO) ($\sim 300 - 600$ km altitudes). The attractiveness of such a system is that it enhances our capability for activity monitoring by making frequent overflights of all sites of potential interest. In order to keep the optical systems and satellites themselves relatively simple and light, we settle for moderate ground resolution ($\sim 1 - 2$ m) imagery, which is adequate for many surveillance purposes that emphasize activity monitoring for treaty verification. A second approach is to achieve longer dwell times over target by deploying one or a few large optical observing platforms at high altitudes ($\geq 5,000$ km). A third approach is presented by the possibility of equipping surveillance satellites with lasers (LIDARs) or radars (SARs) to illuminate the ground.

2.1.1 Small Satellite Reconnaissance Fleet

Technological developments leading to miniaturization of sensors and communications links and to reductions in required power levels have the potential to reduce the cost and size of essential components of reconnaissance satellites. As examples[7] of such progress achieved in a number of programs, we mention fiber-optic gyros with < 0.1 deg per hr drift, star trackers accu-

[5] JSR-89-100A; Chapter 7.
[6] JSR-92-170.
[7] JSR-89-100A, op. cit.

rate to 100μrad with a 60 deg field of view, on-board computing power in the range up to 100 MIPS, laser diode arrays producing 5 to 10 watts per array at 30 percent overall power efficiency and CCD arrays with of the order of 10^6 pixels of individual dimension $10\mu m \times 10\mu m$. These advances lead us to consider a constellation of relatively small and simple reconnaissance satellites that achieve medium ground resolution (1–2 m from LEO ($\sim 300 - 600$ km).

Atmospheric drag limits how low an altitude such a system can operate at economically. A minimum altitude of H = 300 km is consistent with a two-year life time for a satellite weighing $\approx 1,100$ pounds during periods of maximum sun spot activity.

Key issues include the number of satellites and of the total data transmission rate as a function of the frequency of overpasses and the fraction of available imagery returned. For definiteness we assume the satellites are at an altitude of 600 km and have optical apertures of 30 cm. With these parameters, a diffraction limited ground resolution of about 2 m can be achieved for visible imagery out to a slant angle of 45 deg, and a resolution of about 30 m is possible for thermal imagery at 10μm wavelength. A constellation of 10 such satellites revisits any spot on earth in roughly 2 hours. The performance of larger or smaller optics in different orbits would be scaled accordingly.

As illustrated in the Reference listed in Footnote 5, if such a system were limited to handling a data rate of nGbit per sec it could produce $\sim n$ hundred frames per sec with each frame covering 4 km^2 in 10 sec of viewing at a ground resolution of 2 m. A reasonable choice of detector for these satellites would be a square array of 1,000 $\times$ 1,000 pixels of $10\mu m \times 10$ μm CCDs. Operating at shot noise conditions, they would receive enough photons — 2×10^7 photons per sec per pixel — to measure pixel to pixel contrast of 3 percent in less than 10^{-4} sec dwell time per pixel. A telescope with a focal length of 4 m would focus a 2 m $\times$ 2m resolution element on one CCD. (Further generic system considerations are found in the Reference listed in Footnote 5.)

2.1.2 High-Altitude Large Aperture Systems

Frequent looks in order to monitor activities can also be achieved from geosynchronous (GEO), or near-GEO, orbits by a single large aperture optical system. For example, a diffraction limited 20 m aperture at GEO can give 1–2 m resolution. One way to achieve this in practice would be with a sparse optical aperture — i.e., with the aperture largely unfilled — that incoherently superposes successive images. In practice, knowing the modulation transfer function of the optical system, this can be done by adding the Fourier components of the scene obtained successively from different viewing configurations.[8] Issues that remain to be studied for this approach include the required amount of image processing to make the resulting pictures readily interpretable.

2.1.3 Active Sensors

The physical parameters of radars and lasers in space, and of SARs and LIDARs are well studied. Little can be said here beyond noting some general

[8]For other suggestions for high-altitude optical large aperture systems see the Reference listed in Footnote 5.

features and future possibilities.

SAR imagery would of course provide all-weather day and night coverage of items and activities otherwise revealed in visible imagery, thus reducing the required revisit rate or guarding against covert operations by night.

The concept of a radar in GEO orbit for observing objects and activities on the ground has been explored in other JASON studies (JSR-89-900, JSR-92-170). The basic idea is that the GEO radar serves as a transmitter only, with receivers mounted on LEO satellites or on aircraft at much shorter than GEO range from the illuminated targets. If coverage and revisit time capabilities call for a fleet of a substantial number of LEO satellites, the savings that arise from elimination of transmitters and power sources on the LEO satellites can be considerable.

Clearly the most interesting space-based radar is a SAR, with its promise of high spatial resolution. The price paid for high resolution is measured in transmitter power, which goes as the inverse cube of the resolved pixel length (two of the three powers coming from the power needed on the pixel cross-section, the third from the bandwidth, inversely proportional to the range resolution, to which the receiver noise power is proportional). In JSR-92-170 a GEO transmitter with 1 m resolution and a prime power of ~ 30 kW is discussed. To illuminate an area on earth as small as 200×200 km requires some 25 m^2 of transmitter antenna (either MMIC phased-array or a klystron-fed reflector). Such a transmitter, powered by a solar array, is well within the capabilities of a Titan-4 launch to GEO. Further details can be found in the report cited above. If better resolution is needed (not likely in the verification/dismantlement context), solar arrays for GEO transmitter prime power would not be feasible. For example, scaling the resolution of the SAR discussed above to 1 ft, or 0.3 m, would require, according to the inverse-cube law, roughly 30 times the power, or nearly 1 MW. In JASON reports JSR-89-900 and JSR-89-100A, we have discussed MW-class GEO transmitters that are powered from antenna farms on the ground (an inverse Solar Power Station), as shown in Figure 2.1 taken from the latter report. An X-band antenna farm 10 $\times$ 10 km in size has a main lobe of 200 m at GEO (plus substantial side lobes if the farm is an unfilled array). A reflector dish this size, plus some equipment to maintain or correct the dish figure based on a ground reference beacon and to do a modest amount of beam steering, could be launched to GEO with today's heavy launch vehicles. Another possibility is to use a ground-based laser to illuminate photo detector arrays on satellites; again MW-class power can be transmitted from earth to space.

It is not clear that a GEO transmitter and a LEO receiver fleet is the optimum arrangement. A few transmitters at half-synchronous altitude, with a smaller fleet of receivers at several thousand kilometers altitude, may be a more economical choice, or one might even find that collocated transmitters and receivers work best. There is nothing sacred about using GEO to station a satellite receiving microwave power from Earth; at lower altitudes the duty cycle for power transmission goes down because of the geometry, but in return, the satellite can be made smaller.

Equipping satellites with lasers for illuminating the ground would extend their optical viewing capability to the night time, a particularly important advantage at higher latitudes during winter. Major issues are the laser power needed to produce useful imagery, perceived intrusiveness over foreign territory, and eye-safety on the ground.

The same telescope could be used to image the ground in the daytime by

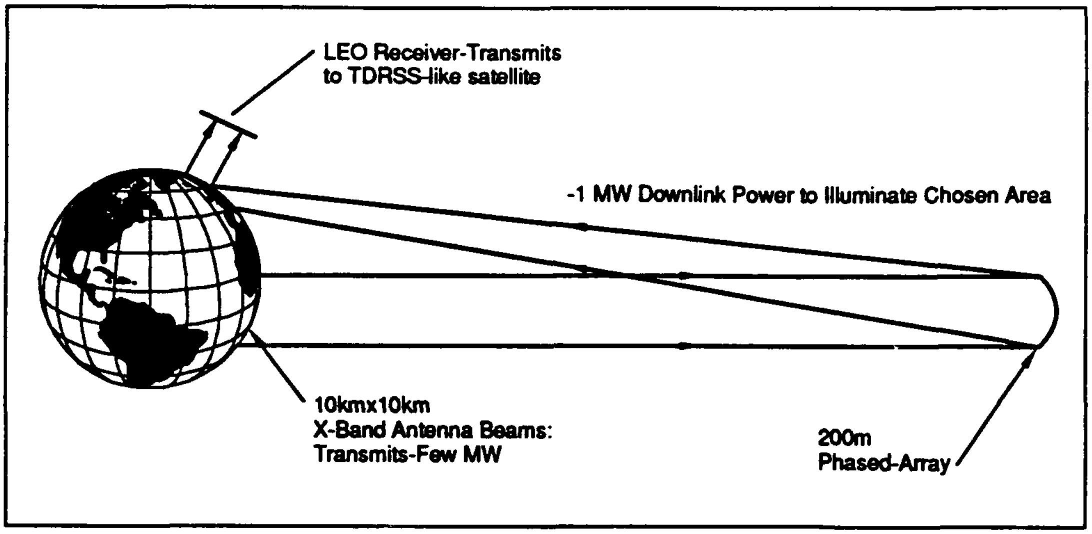

LEO Receiver-Transmits
to TDRSS-like satellite
-1 MW Downlink Power to Illuminate Chosen Area
10kmx10km
X-Band Antenna Beams:
Transmits-Few MW
200m
Phased-Array

Figure 2.1

sunlight and at night by laser light. With laser illumination, an alternative to using a conventional telescope is to obtain images by processing unfocused (pupil-plane) signals. This is an active area of research at present.

The prospects for using laser illumination have been enhanced considerably by recent improvements in laser diode technology, especially the development of coherent laser diode arrays. Compact arrays are now readily available with a power output of 5 watts, and overall efficiency of 30 percent. Gallium arsenide lasers diodes produce light in the 0.7 – 0.9μm region where Si CCD detectors have maximum efficiency.

As described in the Reference listed in Footnote 5, laser diode arrays in the 0.7 - 0.9μm region now make laser illumination a promising satellite reconnaissance tool for optical viewing at night. Questions of eye safety were considered in the Reference listed in Footnote 5 and shown to be manageable.

2.2 Open Skies

The recently signed Open Skies Treaty constitutes an important step toward increased transparency in the military activities of participating nations. Current signatories include the United States and its NATO allies, Russia, Belarus, Ukraine, Georgia, and all states of the former Warsaw Treaty Organization. The treaty sets up quotas for permitted aerial observation flights by any one signatory over the territory of other signatories, with the stipulation that no areas may be closed for national security reasons. Of special interest here, the treaty may open up the possibility of useful new measures for nuclear verification.

There are four contexts in which the Open Skies Treaty is of interest for this purpose: (1) surveillance capabilities provided by the treaty as now agreed; (2) improved surveillance capabilities that may become available as the treaty is upgraded; (3) the treaty as a model for more intrusive aerial inspections by aircraft equipped with specialized sensor suites for the purposes of verifying specific bilateral agreements between the United States and Russia; and (4) as a model for international inspection procedures that might be invoked to supplement present IAEA safeguard inspections as part of a nuclear/biological/chemical non-proliferation regime.

2.2.1 Current Treaty

Under terms of the Open Skies Treaty, each country agrees to an annual quota of observation flights it is willing to accept, and each is entitled to conduct as many flights as it receives. Details of the requested flight path must be specified 24 hours in advance by the observer party, after a generalized overflight request has been registered at least 3 days earlier. On any one flight path , a given site may not be overflown more than once. Data from any flight must be shared immediately by both parties and may be purchased by other parties to the treaty. The currently permitted sensors comprise video, panoramic and framing cameras for daylight photography, infrared line scanners, and SARs. Current maximum resolution limits are: 30 cm for visible wavelength sensors, 50 cm for infrared devices, and 3 m for SARs. (In an initial three year phase-in-period, not all of the above features are permitted.) The minimum flight altitude is currently set at 30,000 ft.

It is clear that, even under its current resolution limits, the treaty allows recognition of buildings; loading docks; many types of specialized structures on the roofs of or adjacent to buildings; effluent stacks; storage facilities; power transmission facilities and transformer farms; roads, railroads, aircraft, trucks, automobiles; security fences; and numerous other collateral features of industrial, military, and other human activity, including excavations and evidence of underground facilities. This should allow: thermal measurements to verify the non-use of a facility; visible and IR imagery to detect evidence of digging and other activities that modify the ground surface at sites of interest; monitoring of new construction sites; estimates of power line and power conversion capabilities from external characteristics; investigation of vents, roof fans, and discharge ponds associated with facilities of interest; close inspection of loading docks, storage sites and transportation vehicles; the integrity of barriers, fences , and other elements at declared secure storage sites; etc. While the current resolution's limit of Open Skies may not provide any significant enhancement over the limits achievable from space-based systems, the new data will nevertheless be valuable. In particular, despite the delay required for advance notification of an overflight, the Open Skies response time to new intelligence input may, in many cases, be shorter than is feasible from a satellite platform. Important, too, will be the open way in which the data are obtained, together with the fact that the sensors and the data will all be in the public domain. This should make it easier to seek clarification of ambiguous or suspect activities than is the case when information comes primarily from NTM. In addition, Open Skies allows simultaneous collection of visible, IR, and radar data on a given site.

2.2.2 Monitoring Under an Extended and Upgraded Treaty

The Open Skies Treaty allows for improvements in resolution and for addition of new sensors and capabilities when mutually agreed upon by the signatories. Several enhanced capabilities could be added relatively easily to aircraft being configured for open skies purposes. The simplest would be increased spatial resolution for visible and infrared sensors. As presently conceived, open skies resolution limits are based on a principle of equality among all parties to the treaty. In practice this means that the sensors cannot have resolutions greater than that of instruments commercially available to all. Unless there are other barriers at work, commercially achievable resolutions are sure to improve with time in both the visible and infrared cases. This is less likely for SARs since there are few, if any, commercial markets for such instruments; costs will remain high and technologies are unlikely to be shared equally on all sides.

The currently permitted sensor suite for open skies does not have provisions for direct air sampling. If air sampling were to become allowed, the prospects for detecting certain clandestine activities could be greatly improved. One example of particular interest involves sampling for Kr^{85}. This nuclide is produced as a by-product in about 0.3 percent of the fission reactions occurring in nuclear reactors. Krypton remains captive in the fuel rods until released in the course of reprocessing. When released, these inert atoms generally work their way into the atmosphere and eventually spread fairly uniformly around the globe. Excess concentrations can be expected, however, in the vicinity (tens to hundreds of kilometers) of operating reprocessing plants. The current atmospheric burden of Kr^{85} has arisen, predominantly, from reprocessing. The worldwide averaged atmospheric concentration of Kr^{85} with its beta decay lifetime of 10.7 years is such that a cubic meter of standard air produces about one beta decay event per second. Samples collected in the course of an overflight would be counted afterward in shielded laboratories; presumably, in the spirit of Open Skies, data and perhaps samples would be shared among the parties.

Another potential application of air sampling involves the collection of submicron particulates in the atmosphere above facilities of interest for verification. For example, one would be concerned here with particulates containing isotopes of uranium and plutonium. For particulate constituents as well as krypton, modern technology permits detection of extraordinarily small concentrations. We do not know with what concentration particulate effluents reach high altitudes, particularly the open skies minimum altitude of 30,000 ft. Particle density height profiles and lateral distributions must surely depend strongly on particle size as well as local meteorological conditions. It will be especially important to investigate more fully the way in which effluents spread laterally as well as mix vertically as a function of time. Recall that, under open skies, there is a delay of at least four days between the initial request and the actual data collection flight, including at least one day's advance specification of flight path. Suppose that a facility producing relevant effluents shuts down operations upon registration of an overflight request. We will want to know: how long does it take for the emissions to cease and, under various meteorological conditions, how long for effluents already resident near the facility to dissipate beyond detection?

Passive spectroscopy in the visible and IR, both currently disallowed under the Treaty, would be an important addition to open skies. Relative to satellite platforms, an aircraft can come much closer to the scene being targeted. For comparable resolution, it therefore achieves much greater image *intensity* at the camera focal plane. This, in turn, opens up the possibility of finer spectral resolution. It may thus become possible, for example, to detect localized vegetative stresses that signal underground chemical leakage or a high radiation environment. Similarly, it might become feasible through spectroscopy to observe and identify various chemical species released to the atmosphere in plumes. At present, the prospect for such spectroscopic interrogation of plumes appears to be very difficult. Further work is needed to determine which species, if any, are both detectable by this means and relevant to nuclear verification. The addition of LIDAR to support fluorescent spectroscopy might be useful.

2.2.3 Bilateral Open Skies

Relaxation of the sensor and other limits in open skies might become attractive to both the United States and Russia on a bilateral basis for purposes of verifying arms control agreements. The restriction to commercially available technologies could be lifted, for example, since in both countries the military sectors are well ahead of the commercial. Highly specialized instruments could therefore be built and deployed. Moreover, it might be mutually attractive to reduce the minimum altitude all the way down to, say, 2,000 feet or less, at least for certain special situations. Although it may well prove impossible or even undesirable to permit low altitude flights over all the national territory of the United States and Russia, low altitude flights over facilities that are *declared* to be closed or non-military might be more readily negotiable. For example, low overflights might be valuable in verifying that, as declared, a previously operating enrichment facility is no longer operating.

2.2.4 Research and Development Opportunities

Open Skies technology for arms control verification is in its infancy. Experience and a continuing R&D program are needed to discover the full range of possibilities.

We were briefed on the sensor development R&D program being supported in the DOE. As appropriate they are studying a broad range of technologies in order to develop the needed library of signatures for the various sensors operating under the parameters of Open Skies. What one wants to learn is how best to fuse the data from the broad variety of sensors discussed above, including high-spectral and broad aperture camera and low-light level TV, thermal imagers, and SARs.

In addition of special importance for open skies aerial overflights is the potential of LIDAR, using pulsed radar and frequency chirp, plus air sampling to add to our ability to analyze effluents from operating plants for gases such as Kr^{85} that may serve as unique signatures of plutonium separation, or for other gases indicative of chemical, biological, or nuclear material production. What we want to learn, for example, is how far away from the source, for how long after it has been operating, and at what minimum level of concentration can we identify and analyze such activities.

A strong and broad range R&D program toward this end is important in order to explore the full monitoring potential of open skies.

2.3 Cooperative Measures

Cooperative means of verification involve procedures as well as technologies. Procedures include data exchange, perimeter-portal monitoring (PPM), and on-site inspections. Relevant technologies include nearby emplaced sensors, tags and seals, and radiation monitoring, both passive and active.

2.3.1 Procedures

Cooperative procedures are described in detail in the following sections to show how they apply to different types of agreements calling for dismantlement or destruction of nuclear warheads, for a cutoff on the production of SNM, and for the storage or disposal of nuclear material. Here we only summarize their general features.

Data exchange is a necessary part of any treaty in order to establish initial conditions and provide a baseline for monitoring future progress. The exchanged data would include a declaration of all related facilities and their locations. Depending on the extent of the treaty, these could include facilities involved in production of nuclear material, facilities involved in dismantlement of warheads, facilities designated for destruction or storage of the nuclear material removed from war heads, information on the relationship of different facilities, and the traffic between them. Also if called for, there would be an accounting of all SNM and warheads, including those in development and testing. The data exchanged could also include design data (at some agreed level of detail) on certain warheads in order to be able to monitor the removal of fissionable material. In the case of old weapons, design information could be passed between the parties without fear of transfer of sensitive information; in the case of modern weapons, it might be sufficient to specify the approximate amount of plutonium and HEU in a particular type of warhead.

Perimeter-portal monitoring involves setting up inspection stations at the perimeters of relevant facilities. Inspectors and mutually agreed-upon equipment would monitor the flow of material into and out of the facility. The location of perimeter sites and the equipment employed at those sites depend on the character of the treaty. For example, if the treaty were designed only to ensure that warheads removed from treaty-limited missiles were dismantled, a perimeter site might be established around the dismantlement site (1) to verify that the warheads entering were nuclear, and (2) to verify that the appropriate amount of nuclear material was entered into secure storage. If the treaty also included a cutoff on production of weapons-grade fissile material, perimeter sites might be set up around old production facilities as well. The clear advantage of perimeter-portal monitoring is that it requires a cheating party to establish a separate, covert infrastructure if it elects to evade the agreement. If a system of tagging and perimeter-portal inspection of tags is used to monitor inventories, both the cost of covert production and the risk of detection are significantly increased.

On-site inspections at declared facilities are now a standard part of verification protocols. The sites which would be subject to inspection depend on the extent of the agreement. For example, if the treaty involved only dismantlement of warheads, a certain number of short-notice inspections would be permitted at declared dismantlement facilities, to ensure (for example) that no SNM was being covertly retained in the facility; if the treaty included destruction of warheads and storage of nuclear material, then declared destruction and storage sites would be subject to inspection as well.

A verification regime could also include provisions for inspections of sites suspected of covert production or storage. These would be short-notice inspections, and would be limited in number. Suspect sites present certain problems. They may be difficult to identify, and once they are identified nuclear material might be hard to find. In order to protect extremely sensitive installations, it would likely be necessary to grant each party limited rights to veto a particular inspection, or exclude certain areas from inspection.

Inspections increase the probability of detection of violations and increase the effort required for a cheating party to hide its covert production.

2.3.2 Technologies

Nearby emplaced sensors would rely on the same technologies used widely in the civilian industrial and home security sector of society. Their operations and communications must be, in addition, tamper proof and spoof proof. They should be reliable, durable and long lasting, and able to signal any effort to compromise or negate their effectiveness. We have nothing to add to their well-known features. In the following our discussion, which draws heavily from the 1989 JASON Report[9], is focussed on tags and seals and on passive and active radiation monitoring.

A. *Tags and seals.* "Tagging" is the process of marking an item (e.g.,

[9]JSR-89-100A, op. cit.

a missile, a warhead, the SNM removed from a dismantled weapon, or the container for any of these) so that it can be identified at some later time. A tag to be placed on the items of one side would be developed and manufactured by the other. The tags must be tamper-proof, non-reproducible, and environmentally stable. It must be possible to check the tags and describe results without transferring sensitive technology.

A number of tagging schemes have been developed over the past few years. They include, among other techniques, reflective particle tags, or "glitter paint," composed of small flakes embedded in a plastic matrix; electronic tags relying on cryptographic methods; fluorescent fingerprints that rely on specific ratios of different spectral lines; DNA signatures; and other means relying on electronic, acoustic, magnetic, or optical (holographic) scanning. A more complete description of different types of tags and seals is given in the 1989 JASON Report,[10] relevant portions of which are reproduced in Appendix A. These demonstrate that technologies exist to make each tag unique (i.e., to "finger print" each warhead, if that is desired), and to develop tags that can be checked by inspectors on-site, or tags that can be interrogated remotely. It should be noted that if a tag is designed to include a radio beacon or to be interrogated by satellite, a given level of verification can be achieved with far fewer on-site inspections. A tag like this which could be used to remotely track a warhead is a concern for mobile missiles in the field, by revealing their location and thereby allowing them to be targeted, but should not be a sensitive issue for warheads which have been removed from the field and are being dismantled. Various tagging scenarios are described in the following sections for different treaty provisions.

Note that some tags can also be used as seals. Any attempt to open

[10] JSR-89-100A, op. cit.

a sealed container would break the seal, and indicate that the contents had been tampered with. Seals can be used, for example, to preclude opening a container holding the nuclear material removed from a dismantled warhead. Though this would not prevent a cheating party from opening the container and re-using the fabricated nuclear material, subsequent examination of the seal would indicate that a violation had occurred.

B. *Detection of nuclear material.* The equipment designed to detect nuclear material would be incorporated as part of both PPM and on-site inspections. In a treaty involving dismantlement of nuclear warheads, it is necessary (1) to be able to verify the presence of nuclear material (e.g., in those warheads marked for dismantlement), and (2) to be able to verify the absence of nuclear material (e.g., in facilities or portions of facilities where there should be none). There are several technically feasible approaches to the detection of nuclear material.[11] Radiation can be monitored actively or passively. Passive monitoring involves measuring the neutrons or radiation emitted naturally by either the uranium or plutonium in the weapon. Active monitoring involves first exposing the object being examined to radiation, then measuring its response. Both methods have their advantages and disadvantages. It is interesting to note that in verification of weapon dismantlement, the party whose weapon is being examined wants the nuclear material to be detected, so covert shielding (at least at the dismantlement and destruction sites) should not be an issue in the specifications of this monitoring equipment. However, that same party likely will not want the details of the weapon design revealed; thus a monitoring scheme which does not image the warhead may be required. These considerations, as well as cost, sensitivity of technology, and safety of the monitoring equipment will

[11] JSR-89-100A, op. cit.

enter into the selection of a monitoring technology.

Passive methods to detect the presence of plutonium rely on the fact that its isotopes emit both neutrons and gamma rays. Although a detector could be designed to search for either, the gamma rays are relatively low energy, and therefore suffer significant attenuation as they travel through the warhead. The best method for detecting plutonium in a warhead is to look for neutrons emitted by the isotope Pu^{240}. The fissile isotope of plutonium is Pu^{239}, but Pu^{240} is invariably present as well. This isotope spontaneously fissions (with a half-life of 1.3 10^{11} years), and in the process, emits neutrons with a characteristic energy of 1 MeV. From a typical primary, $\sim 10^6$ neutrons per sec emerge. These neutrons are thermalized and attenuated as they travel through the warhead, but about 10% make it out. It has been estimated[12] that a warhead containing 4 kg of Pu^{239} contaminated by 6% of Pu^{240}, could reliably be detected with a detector 1 m from the warhead in only 1 second. Although it is possible to reduce the signal by reducing the fraction of Pu^{240}, it is quite difficult to get this fraction below a few percent. It would also be possible to eliminate this signature by using only HEU in the fission stage of the warhead, but this carries a significant penalty in the yield-to-weight ratio of the weapon. The vast bulk of current warheads are believed to be designed with Pu primaries containing Pu^{240}.

The principal advantage of this technique is that the neutrons do not provide a clear image of the warhead because they undergo multiple scatterings on their way out of it. The details of the warhead design are not revealed. A disadvantage, however, is that these emerging neutrons can be shielded relatively easily. These considerations suggest that this technique

[12]S. Fetter, V. A. Frolov, M. Miller, R. Mozley, O. F. Prilutskii, S. N. Rodionov, and R. Z. Sagdeev, "Detecting Nuclear Warheads," (*Science and Global Security*, No. 1, 1989).

could be very useful in examining warheads or containers at sites where nuclear material is supposed to be found (i.e., where there is no incentive to shield it; for example, to verify that warheads coming in for dismantlement are indeed nuclear). Passive neutron detection alone would not, however, be suitable for suspect site inspections, where it would be rather easy to shield small amounts from detection.

The presence of uranium can be detected passively by measuring high-energy gamma rays emitted by the isotope U^{238}. Although U^{235}emits no high-energy gamma rays (those least affected by shielding), U^{238} emits $\sim$1 MeV gamma rays at the rate of about 7.5 per gram-second. Depleted uranium (almost all U^{238}) would emit gammas at about this rate, while HEU would be expected to emit about .5 gammas per gram-second with $\sim$1 MeV energy. Depleted uranium, as well as HEU, may be used in nuclear warheads. The flux of gamma rays emerging from a warhead obviously depends on the amounts of HEU and depleted uranium. When a simple model of a nuclear warhead[13] is used to estimate this flux, the result is about 100 gamma rays per second. This level is easily detected. The main advantages of this form of detection are that (1) the counting rate is fairly high, and (2) it is difficult to shield these hard gamma rays.

One disadvantage is that U^{238} is used for other applications where high Z material is desirable; it is therefore possible that this method could result in some false positives (from U^{238} used in something other than nuclear weapons) if this method were used at suspect sites. Also, it should be noted that it is in principle possible to suppress the gamma-ray signal by using another material (e.g., tungsten) instead of U^{238} in the portion of the weapon where high-density material is required.

[13] S. Fetter, et al., op. cit.

It is considerably more difficult to shield these hard gamma rays emitted by U^{238} than to shield the neutrons emitted by Pu^{240}. One attractive possibility is to use a combination of passive monitoring techniques: detect gamma rays (from U^{238}) and neutrons (from Pu^{240}). Most modern weapons contain both elements, and it is quite difficult to shield both.

Active methods are superior to passive methods in that they are more difficult to deceive. However, they are generally more complex (and more costly), and there may be safety concerns associated with the active source. We discuss two possible active methods: radiography and induced photofission.[14] Radiography requires a source of high-energy gamma rays. The object being inspected is placed between the gamma-ray source and a gamma-ray detector. The object is illuminated from the side, scanned, and the detector on the other side records a radiographic image.

The gamma rays are attenuated as they pass through the object; the degree to which they are attenuated depends on the type and quantity of material they pass through. The high Z material (uranium and plutonium) in nuclear warheads results in significant attenuation. Although radiography does not specifically reveal whether the material is uranium or plutonium, it can unambiguously demonstrate the presence or absence of high Z material. This makes it particularly attractive for monitoring non-nuclear materials to verify that no nuclear material is present.

Transmission radiography has sufficient resolution that if it is used to examine nuclear warheads, it may reveal sensitive design information. For this reason, it may be desirable to use it only to inspect objects which should

[14]For more details see the 1989 JASON Report (op. cit.) and *Reversing the Arms Race*, edited by F. von Hippel and R. Sagdeev (Gordon and Breach, 1990).

contain no nuclear material, and use some other method to inspect warheads. It is possible, however, to limit the spatial resolution by deliberately defocusing the radiography.

Induced photofission is an active method which could be used to detect nuclear material directly. Fission can be induced by illuminating uranium or plutonium with high-energy gamma rays; the photofission cross section is largely due to the giant dipole resonance, and has a threshold around 5 MeV. (For example, the photofission cross section for U^{238} has a peak of 125 millibarns at 14 MeV with a width of 8.8 MeV.) The fissioning material then emits gamma rays,[15] which emerge at a high rate for minutes after the illuminating pulse. Detection of these delayed gammas is an indication that fission occurred, and hence that nuclear material was present. The gamma rays used to stimulate photofission could be bremsstrahlung radiation from an electron linear accelerator similar to the kind agreed to in verification provisions of the INF treaty. It is also possible to combine scanning radiography with photofission if the illuminating gamma rays are at energies above the threshold for photofission.

In the case of nuclear warhead dismantlement and destruction, there are two distinctly different conditions under which one party might employ equipment to detect nuclear material. The first is to verify that nuclear material is present, for example, by observing warheads as they come into a dismantlement site. In this case, the other party wants the nuclear material to be detected (in fact, cheating scenarios might involve trying to pass off conventional warheads as nuclear). The second is to verify that nuclear material is not present, for example in a challenge inspection of a suspect

[15]For a typical operating condition as described in the JASON Report (op. cit.)$\sim 10^7$ gammas/sec. emerge one minute after the radiating pulse.

site. In this case, the other party might be trying to hide evidence of covert production, and would want to avoid detection of nuclear material. The requirements on equipment in these two cases may be somewhat different.

Finally, it should be noted that the ability to detect nuclear material depends critically on how close one can get to the warhead. Remote detection of nuclear material is not considered feasible at suspect sites. Successful detection depends critically on the nuclear materials used in the warhead, and on the cooperation of the other party—very modest shielding efforts could easily disguise the presence of nuclear material from either a passive or active detector.

C. *Detection of radio nuclides activated in non-nuclear parts of a weapon.* As noted earlier, the Pu in a primary typically emits $\sim 10^6$neutrons per sec mainly from spontaneous fission of Pu^{240}. The neutron flux and spectrum at any given point inside the warhead depend on geometry, moderation, and shielding, but can be expected to be significant. Appreciable neutron flux will impinge on other nearby non-nuclear parts of the weapon system too, for instance structural and aeroshell parts, switches, nuts and bolts, and the high explosive. While the flux is much lower than that inside an operating reactor, numerous neutron activation products will appear at levels that can be sensed later by low-level counting techniques.

Interesting activation products are formed by neutron-induced reactions on abundant, stable isotopes in the non-nuclear part of the weapon. These products either must be absent naturally, or must occur naturally only at extremely low levels, so that their appearance would be a sure sign of past neutron exposure. In particular, activation products must always themselves be radioactive with a half-life much less than the age of the Earth in order to be interesting. Table 2.1 provides a start at a relevant catalog.

Activation products can be detected by low-level counting techniques, if their half-lives are short enough, or by accelerator mass spectroscopy for any value of their half-lives. The sensitivity of such techniques is illustrated by well-known dating methods for naturally occurring C^{14}. In pre-atmospheric-test natural organic carbon, the abundance of C^{14} is about 10^{-12} compared to C^{12}. Low-level counting can measure C^{14} at least down to 10^{-14} compared to C^{12}, while accelerator mass spectroscopy can get down at least a further factor of 10 to 10^{-15}.

Table 2.1

Isotope	Production	$\sigma_{Production}$	Half-life	Decay
Fe^{55}	$Fe^{54}+n$	2.9 barn	2.6 yr	e^- capture
Fe^{59}	$Fe^{58}+n$	1.1 barn	45 day	β^-
Co^{60}	$Co^{59}+n$	19 barn	5 yr	γ
Ni^{59}	$Ni^{58}+n$	4.4 barn	10^5 yr	e^- capture
Ni^{63}	$Ni^{62}+n$	15 barn	92 yr	β^-
P^{32}	$P^{31}+n$	0.19 barn	14 day	β^-
S^{35}	$S^{34}+n$	0.27 barn	88 day	β^-
Cl^{36}	$Cl^{35}+n$	43 barn	$3\cdot10^5$ yr	β^-
Ca^{41}	$Ca^{40}+n$	0.23 barn	$8\cdot10^4$ yr	e^- capture
Ca^{45}	$Ca^{44}+n$	0.7 barn	165 day	β^-
Be^{10}	Be^9+n	0.009 barn	$3\cdot10^6$ yr	β^-
rC^{14}	$N^{14}(n,p)$	1.8 barn	5700 yr	β^-

Some interesting neutron activation products. The cross section $\sigma_{Production}$ is for incident slow neutrons, although the actual neutron spectrum would have to be taken into account in a realistic calculation.

The Center for Accelerator Mass Spectroscopy at LLNL is a center of expertise in DOE for the latter method. The accelerator system at this center can in principle be tuned to count any isotope whatever, independent of half-life, as long as the background abundance of the isotope is low enough. However, to create the capability to count a particular isotope requires a modest amount of development work, and so not all isotopes can currently be counted. In practice the limiting factor usually is contamination of the sample, and sample preparation requires great care to achieve the best sensitivity. A typical example is C^{14} as mentioned above. Another typical example is Cl^{36}, created by neutron activation on the abundant stable isotope Cl^{35}. Here, sensitivities down to 10^{-16} relative to the natural isotopes $Cl^{35} + Cl^{37}$ have been demonstrated in sample sizes of 1 mg.[16]

Measurement of one or more activation products may be a useful technique in support of an agreement to dismantle warheads. It presents the potential for establishing a protocol to exchange agreed non-critical, non-nuclear components of a warhead being dismantled — such as a piece of the aeroshell, a specific set of nuts and bolts, and a chunk of the high explosive — and confirming that these had been exposed to a total neutron fluence consistent with the age of the weapon. A particular attraction of this technique, if it can be demonstrated in practice to sufficient accuracy and reproducability, is that it avoids any risk of revealing any sensitive, restricted data about actual bomb design.

Measurement of several activation products can potentially furnish a wealth of further information about the history of the part, including both the age of the weapon and the date of dismantlement. When several nuclides with a range of half-lives are available, each nuclide furnishes an estimate of the total neutron fluence over a single half-life, derated by decay since dismantlement. Comparison of these estimates allows one to back out the

[16]Further information is available in the May/June 1991 issue of *Energy & Technology Review* from LLNL.

actual date of dismantlement, as well as the total neutron fluence over the half-life of the longest lived nuclide. If a long-life nuclide is among those measured, the total age of the weapon follows too. Comparison of several activation products may also furnish information about the neutron spectrum, when combined with detailed modeling. Activation over the life of a weapon is not large. At a neutron flux of 10^3 per cm^2 per sec and a lifetime of 30 years, the total neutron fluence is 10^{12} per cm^2. For a 1 barn activation cross section, the proportion of target atoms converted will be 10^{-12}, much larger than the background abundance ($\leq 10^{-17}$) in inorganic carbon, but comparable to the natural abundance of C^{14} inorganic carbon. A 1 barn cross section is typical for thermal neutrons; in an unmoderated fission spectrum the cross section may be more like 10 millbarns, so that a careful assessment of the neutron spectrum and degree of moderation will be required in order to predict activation levels. This shows both that total production of neutron activation products will be readily and accurately measurable in favorable circumstances, and that competition from naturally occurring isotopes may be a major concern. For instance, high explosive in the primary contains large amounts of nitrogen, and will by Table 2.1 give rise to C^{14}. But high explosives also contain comparably large amounts of carbon, and naturally occurring C^{14} seems likely to confuse the issue, if the carbon content comes from organic rather than inorganic (i.e., petrochemical) sources.

This is a promising technique for confirming that real and not counterfeit bombs are being dismantled in accord with an agreement to do so. (It is akin to the "nuclear archeology" proposed by S. Fetter for estimating the Pu^{239} inventory from analysis of radio nuclides produced in reactor shielding blocks and structure elements (see Section 3.2).) It deserves serious study — and a team assembled for such purposes should include geologists, astrophysicists, and archeologists who are familiar with dating techniques in addition to weapons designers and engineers, radiation physicists, and material scientists. (Experts in art authentication could also be helpful.)

Speculating further, there are several other signals that may indicate whether material purported to come from dismantled real bombs has been subject to the appropriate fluence of neutrons and gammas. They include evidence of low levels of radiation damage that, on the atomic and molecular level, can take the form of lattice dislocations and chemical changes. There also may be low levels of contamination in the non-nuclear parts of dismantled weapon by nuclear materials, though such evidence (detectable with high sensitivity by inducing fissions with neutrons or gammas) would be sensitive to quality control during manufacture and may prove worthless.

In addition, small amounts of tritium (T) might be found absorbed in metal components; the natural abundance of it is very low and it can be detected by accelerator mass spectroscopy as well as low-level counting. He^3, the decay product of T, might also be present, and since helium is the most leak-prone of all gases, it may well escape the tritium reservoir in an otherwise tight system. In all these cases, the contamination level may vary substantially from weapon to weapon, and an occasional weapon may show much higher levels.

Spoofing is of course a major concern here. However a combination of forensic measures, of which neutron activation analysis is likely to be the most telling, will make spoofing very difficult, perhaps impossible.

Whether any of these schemes proves practical can be determined only by much further study. Their primary motivation would be to provide a means to increase confidence that the "item" being disassembled is a true nuclear bomb — and to do so without revealing any features of the bomb design itself.

3 INITIAL CONDITIONS

Once a given number of warheads or a given amount of SNM has been dismantled or destroyed under the terms of an agreement, it will be important to know what remains in the inventory. Evidently then, an important component of any program of monitoring reductions in the nuclear arsenals is knowledge of initial numbers for nuclear warheads, by type, as well as initial inventories of *Pu* and HEU.

3.1 Total Number of Warheads

The number of warheads in the current Russian inventory is frequently quoted[17] to be in the range between 27,000 and 33,000. This is deduced in part from force deployments observed by NTM. In addition , estimates of how many warheads could have been built are made on the basis of physical observations together with indirect inferences of how much SNM has been produced. Some of these numbers have been referred to by the Russians in various forms, both government and private, in connection with the START and INF treaties and other arms discussions.

NTM alone are incapable of giving more precise numbers. The same may be said of aerial surveillance as now permitted by the Open Skies Treaty. All source information, including Russian declarations in particular, is essential to provide better assessments.

[17]There exist more critical analyses of the inventory of Russian nuclear warheads and of HEU and *Pu* in the FSU. They in no way affect this report, and therefore, to avoid classification we rely on rough numbers here and in the following.

The inventory of nuclear warheads is divided into five categories:

1. Deployed warheads on the strategic missile forces
2. Non-deployed warheads for the strategic bomber force, that are in the war reserve and are included in the totals agreed to at START and in the June 17th Washington Accord but have been taken off alert status
3. Tactical warheads that will be retained in the war reserve, including the nuclear-armed SLCMs, but are being stored in domestic custody
4. Retired warheads slated for eventual disposal
5. Undeclared, covert warheads

Procedures and standards for verifying the total warhead inventory in categories 1 and 2 above have been established in START as signed and awaiting ratification. They are based on mutual declarations, NTM, and an agreed number of challenge inspections and on-site visits to bases of the nuclear missile and bomber forces.[18] Applications, or further tightening, of these procedures will be worked out in the implementing discussions for the recent Washington Accords. This applies primarily to verifying the necessary

[18]The following are two examples of the important inspection procedures included in START. There will be fifteen inspections a year to update data — at any identified aircraft, submarine, or ballistic missile base or deployment area for mobile ICBMs — to allow each side to verify compliance with limits on numbers and physical properties.

Ten additional inspections a year will allow investigators to verify that the number of warheads deployed on a missile does not exceed the negotiated limit. These inspections will be done on short notice: Within nine hours of the time the inspectors arrive in the country, they are to be transported to the base they select. Upon arrival, they will designate the missile to be inspected, which must remain buttoned up until they can look at it — and the inspection must begin within eight hours. These "challenge" inspections add confidence that the provisions on warhead numbers and on downloading will be obeyed. They also guard against uploading warheads and swapping old types of missiles for new ones.

increase in downloading of warheads to meet the newly agreed limits on SLBM warheads and restrictions to single-warhead ICBMs.

Verification of the size of the inventory of category 3 warheads is thus far a matter of declarations. In particular the United States has indicated that its planned tactical nuclear force will number some 1600 warheads and that the number of nuclear-armed Tomahawk sea-launched cruise missiles will be limited to a maximum of 880, with force sizes and five-year plans to be disclosed annually. Beyond such unilateral declarations, NTM and Open Skies can add a small measure of confidence by activity monitoring.

There remains the problem of determining the total number of warheads in categories 4 and 5 to complete the initial inventory count. NTM and Open Skies aerial surveillance alone would most likely be of very limited use either in establishing these numbers or in detecting a slow "leakage" or diversion of weapons for other purposes. A would-be diverter would have to be concerned that a sizable and sudden removal of hundreds of such weapons might be picked up by NTM unless very carefully concealed by taking advantage of weather and good signal discipline. In general, to determine and maintain count of the inventory in categories 4 and 5 an appropriately stated cooperative verification regime is required.

For declared warheads in category 4 this regime might start by putting tags, appropriately designed and sealed to be tamper proof, on each warhead and instituting PPM around their storage depots. [19] Two approaches would provide confidence that real and not fake warheads were included in the de-

[19] A brief description of these procedures is given in Section 2. See the 1989 JASON Report JSR-89-100A for more detailed discussion of tags and seals, and PPM procedures. The problem here is easier since it is no longer important to maintain secrecy as to the location of these items as it was for the deployed forces studied in that earlier report.

clared inventory. One approach would be to check the serial numbers on the warheads with the log books recording the activities at the final assembly plants that would be identified and made available. (This would also help confirm that none of the weapons came out of undeclared sites and would add to our confidence in establishing the full size of the Russian production complex for verifying limits on bans that may be agreed to on further weapons production.) A second approach would rely on challenge inspections (or spot samplings) to check that the warheads included in category 4 are geniune and not counterfeit. For this we might rely on radiography, with appropriate limits on spatial and spectral resolution to protect against disclosure of design information while at the same time confirming the presence of SNM.[20] Alternatively as described in Section 2, we might analyze non-critical components – such as airframe, bolts, or the high explosive – for the presence of radionuclides produced by their proximity to the Pu and U in a bomb primary. Repeated spot samplings rapidly increase confidence in detecting violations in accord with the formula

$$S = ln(1 - C)/ln(1 - F) \quad , \qquad (3-1)$$

where S is the number of spot samplings, $F = n/N$ is the ratio of the number of false objects, n, to the total inventory N, and C is the confidence that the declared population is correct to within a fraction $F = n/N$. For a small ratio F we can write

$$C = 1 - e^{-Sn/N} \quad . \qquad (3-2)$$

Figure 3.1 shows how C increases with increased samplings. For example $C > 50$ percent for $S > 0.69N/n$, or it takes 10 samples to achieve a 50 percent confidence in catching a $F = 0.07$ level of cheating.

[20]See Section 2 and JSR-89-100A, op. cit.

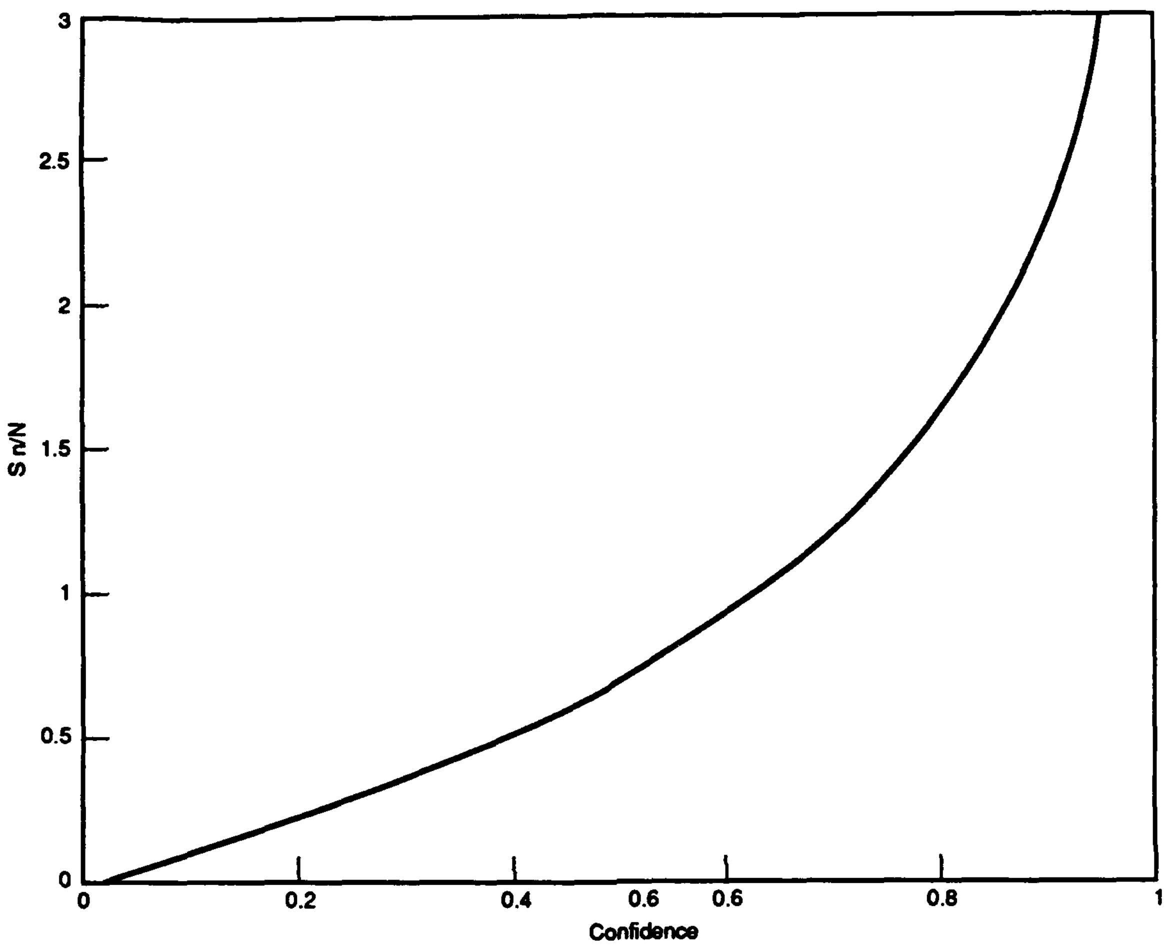


Figure 3.1

The fact that retired warheads in category 4 are presumably marked for dismantling and/or destruction in the not-too-distant future, and assuming that the United States and Russia continue on our present path of cooperative arms reductions, presents an additional strong deterrence to cheating and including fake warheads in this category. At that future time, it will presumably be necessary to verify the extraction of SNM from the dismantled warheads, so there had better be an appropriate amount present to start with.

Pursuing spot samplings to build confidence (3–1) will take time — perhaps a few years. However, the present situation is not urgent[21] in the bilateral security context of United State versus Russia; there is no prospect of a large new Russian nuclear threat to the United States during this period. If not detected over the long run, and if accompanied by the re-building or retention of a sizable force of extra launchers or delivery systems, such a threat could grow gradually, however, if we lack adequate verification procedures such as described.

Turning to category 5 of undeclared warheads, detecting these will be to some degree a matter of chance, such as a report from a defector or from cooperating communities of scientists involved in the overall process of weapons reductions. Perhaps the most important element here, and in ferreting out covert efforts to evade agreements, is the new transparency that results from the cooperation between U.S.-Russian military and nuclear establishments. We should also encourage whistleblowers with appropriate rewards and ensure that agreements are fully publicized. Furthermore, the

[21]With regard to concerns about the diversion of weapons and weapons components to other countries, however, the factor of speed in establishing SNM inventories and control is very important.

matching of records from the known assembly sites with serial numbers of the weapons tagged in category 4 may reveal inconsistencies. Beyond this it will be a matter of following up leads to inspect suspect sites in search of clandestine warheads. In particular visual inspection or merely the passive radiological detection of fission neutrons from Pu^{240} or ~1 MeV gamma rays from U^{238} will be clear evidence of an active source to be probed further for possible evasions.

Finally we note that with tags/seals of the type discussed in JASON Report JSR-89-100A, and in Section 2.3 of this report, supplemented by spot samplings it is possible to further enhance confidence in maintaining inventory control over weapons in categories 1, 2, and 3, if desired.

One can never count on finding clandestine warheads. Some uncertainty will remain in the inventory and so it is necessary to agree to an answer to the question, "How much uncertainty matters?" While the warhead inventory is still very high (in the multi-thousand range), even a thousand hidden Russian warheads would appear to be non-threatening. Later on in the dismantling process, if it goes far enough, this may be too high. With the current announced goal of 3,000-3,500 strategic warheads each, Presidents Bush and Yeltsin accepted, in effect, in the June 17, 1992 Washington Accords a difference of 500 warheads would not significantly upset the strategic balance. For lower limits, the tolerable differences will presumably decrease further.

An uncertainty of 500 warheads translates into an uncertainty of about 2–3 tons of plutonium or 10 tons of HEU. The Russian inventory of Pu and HEU is not well- enough known to exclude the possibility of several thousand undeclared Pu or HEU warheads.

3.2 Total Plutonium Inventory

Possible[22] approaches to estimating the total amount of Pu^{239} produced by the FSU and available now for Russia's nuclear weapons include measuring the total quantity of Kr^{85} that is released into the atmosphere during reprocessing. Kr^{85} is chemically inert, becomes well-mixed and circulates widely in the upper atmosphere, decaying with a lifetime of 10.7 years. Aside from nuclear weapons tests which contributed roughly 3.5 percent to the estimated Kr^{85} in the atmosphere, about 99 percent of the Kr^{85} released from the United States, Western Europe, and Japan results from Pu reprocessing. Very little escapes directly by leakage from reactor fuel rods. By subtracting the known (i.e., calculated) production of Kr^{85} by the rest of world from the measured total in the atmosphere and including the finite lifetime corrections it is possible to infer the total Kr^{85} production by the former Soviet Union, and to calculate there from the total amount of Pu produced. Such estimates are frequently quoted in the unclassified journals as adding up to 145 tonnes of which 120 tonnes is attributed to the military program and 25 tonnes to the civilian sector. This is somewhat larger than the approximately 100 tonnes quoted for the U.S. military inventory. A 20 percent, or 25 tonne, uncertainty is fairly large in its military significance, corresponding to primary fuel for as many as 5,000 warheads.

An additional uncertainty results from the unknown quantity of unreprocessed Pu^{239} in the reactor rods themselves. Although inconvenient as the material for a fission primary, reactor grade plutonium can be used for

[22]See "Quantities of Fissile Materials in US and Soviet Nuclear Weapons Arsenals" by von Hippel, Albright, and Levi (Princeton U./*CEES Report No. 168*; July 1986) for the numbers quoted in this paragraph.

Table 3.1

	Weapons-Grade Pu	Reactor-Grade Pu
Percentage of Pu^{239} 1	93.5	58
Percentage of Pu^{240}	6	24
Critical Mass of a Bare .1in Sphere (kg)	11	13

(For pure Pu^{240}, the critical mass is 40 kg.)

Due to spontaneous fission, principally from Pu^{240}, a fission bomb built with reactor-grade Pu presents thermal control problems and requires a fast implosion to avoid pre-initiation. Relevant numbers are:

neutrons (N/sec/gram)	3	10
heat generation (W/kg)	100	500

The critical mass for reactor grade PuO_2 at crystal density (theoretical) is 35 kg. If made into Mixed Oxide (MOX) (i.e., $PuO_2 + U^{238}O_2$), the critical mass is $\geq$ 350 kg for 30 percent Pu content.

nuclear weapons, as illustrated in Table 3.1 if weapons-grade plutonium is unavailable.[23]

Cooperative on-site inspection can improve the estimates of Pu^{239} inventory. This would require visiting declared facilities and performing a number of steps labelled "nuclear archeology" by S. Fetter[24] who has described the physical/chemical basis for such a procedure. The basic idea would be to review the operating record of the production reactors through the years.

[23]This possibility was discussed in some detail by Robert W. Selden in a November 1976 briefing prepared for representatives from nuclear power programs in several countries and from the IAEA. Some relevant numbers are summarized in Table 3.1, taken from Seldens' briefing charts ["Reactor Plutonium and Nuclear Explosives," Lawrence Livermore Laboratory].

[24]S. Fetter, "Nuclear Archeology: Verifying Declarations of Fissile-material Production" (January 29, 1992) submitted for publication to *Science and Global Security*.

Falsification of log books that record many years of operation may be detectable by analysis of the paper stock and ink. Independently by knowing a reactor's design, one can calculate and measure concentrations of long-lived and distinct radionuclides such as Ni^{59} and Ni^{63}, with half-lives of 75 kilo-years and 100 years, respectively, in shielding blocks or structure elements at a number of locations in the reactor. This can given an independent estimate of Pu production, or at least an upper limit if part of the operation was devoted to tritium production from Li^6 fuel. The accuracy of such results is estimated[9] at close to 10 percent.

In the last analysis, the best information on the size of the Pu inventory will come from Russian declarations and data exchange, including operating records of production reactors.

3.3 HEU Inventory

Current published estimates of the total amount of Russian HEU[10] generally lie between 500 and 900 tonnes. This translates into a very large uncertainty in the number of warheads that may be designed and built with primaries made of HEU.

The minimum estimates (from 1972) are obtained by assuming knowledge of the amount of HEU used for non-weapons purposes (such as Naval reactors), the minimum available Separated Work Units (SWUs) as a function of time for enriching uranium, the maximum amount of natural uranium enriched, and the likely assay (.2 to .6 percent of U^{235} remaining) of the

[9] S. Fetter, op. cit.
[10] HEU is defined as > 20 percent U^{235}.

tails.[11] There are large uncertainties because we do not know accurately the actual tails assay, the actual SWUs used, the fraction of operating time of the separation plants, or their efficiency.

Many of the same comments apply here as in the Pu inventory case; NTM alone are of limited use. Although there is no Kr^{85} release as for Pu production, the older facilities developed for enriching U^{235} are identified. They are generally large and have distinct signatures (see Section 6) and are well identified by NTM. However, NTM alone cannot give an accurate measure of their output.

An agreement that mandates mutual declarations of the total inventories plus inspections of separation plants and accumulated tailings would make an important contribution to an effort to reduce some of the uncertainties in HEU inventories. An agreed on-site inspection process will be required to remove suspicions triggered by Open Skies, covert, or accidental discoveries.

A method for estimating the amount of HEU produced at a given facility can, in principle, be based on measuring the amount of U^{234} in the tails. Knowing the origin of the natural uranium used in the separation, as well as the separation procedure in terms of the product streams, one can derive a correlation between the percentage of U^{235} in the output of the separation process and of U^{234}. This is illustrated in Table 3.2 calculated under specified assumptions by S. Fetter[12] which shows the amount of U^{234} left in the tails, for different levels of U^{235} in the tails, as a function of the enrichment achieved for the U^{235} output.

[11] More recently the Russians have offered to sell, and the United States now proposes to purchase about 500 tonnes of Russian HEU.

[12] op. cit

Table 3.2

	Amount of U^{234} (ppm by weight) in tails	
percent of enrichment	.2 percent of U^{235} in tails	.3 percent of U^{235} in tails
3	7.19	13.8
10	6.66	13.0
40	6.45	12.7
90	6.405	12.63
98	6.402	12.62

There are obvious uncertainties in these calculations, stemming from the fact that the plant may have been operating at varying levels of enrichment at different times. Moreover the percentage of U^{234} occurring in natural uranium is sensitive to its geologic origin (land or ocean source). For example, the amount of U^{234} changes by about 10 percent between enrichment levels of 3 percent and 90 percent for the U^{235} output. However, there is also an $\sim$ 10 percent variability of U^{234}, which occurs at roughly 5.5 $\times 10^{-3}$ percent in natural U, depending on its geologic origin.[13] Nevertheless, assaying the tails is a method of verifying that plant production records, to which we may also be given access, are accurate.

Stocks of uranium tails are large by volume and weight and are an active source of $\sim$ 1 MeV gammas from U^{238} decay. Typically they are stored in tanks of solid UF_6. The total storage volume would be about $\sim$ 10^6 cu ft to contain 300 tonnes of U^{235} at 0.3 percent concentration in the tails. These features help when it comes to searching for undeclared storage sites. However, even if the tail assays only give approximate values for the degree of enrichment for the HEU product this will still be important to know because it is much easier to enrich uranium to weapons-grade starting from slightly enriched uranium. This is illustrated in Figure 3.2, which

[13]S. Fetter, op. cit.

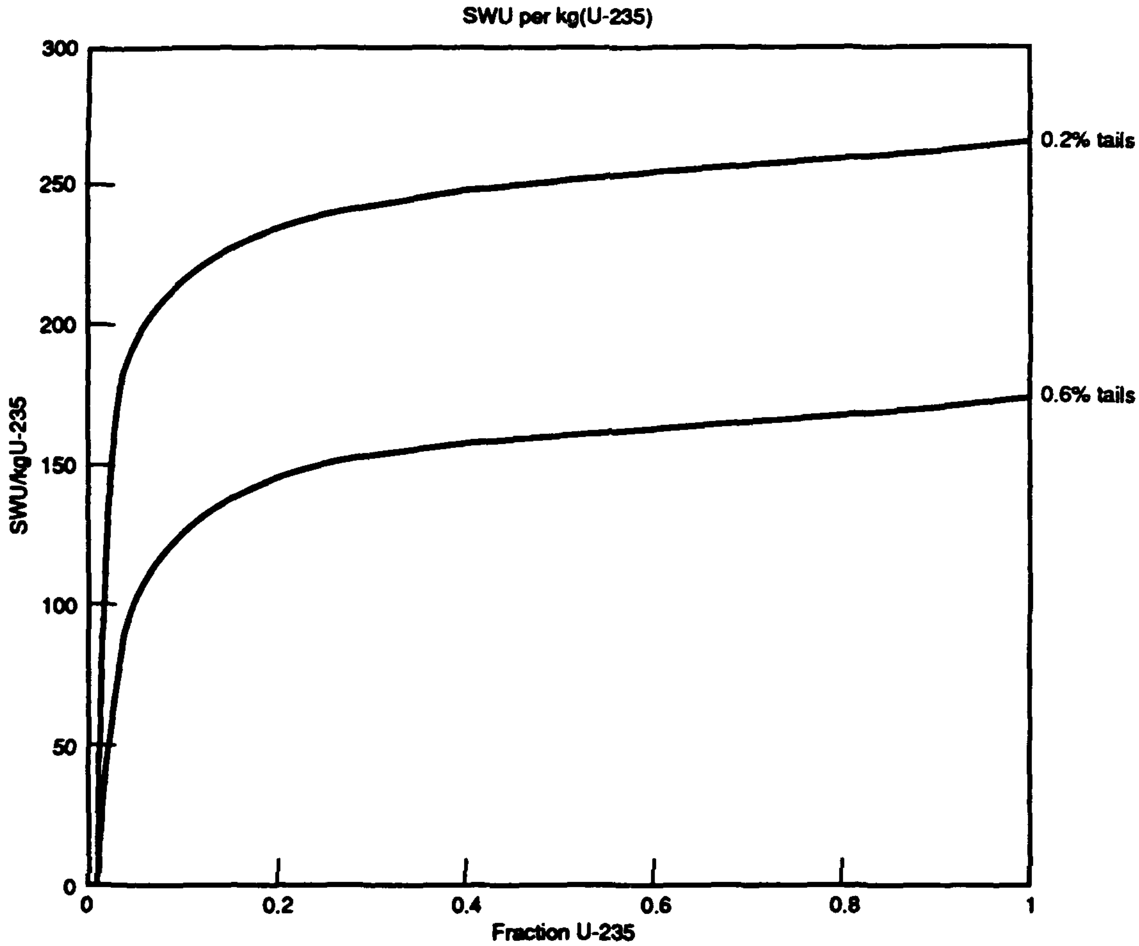

SWU per kg(U-235)
300
250
200
150
100
50
0
SWU/kgU-235
0.2% tails
0.6% tails
0
0.2
0.4
0.6
0.8
1
Fraction U-235

Figure 3.2

shows that the number of SWUs required to produce a kg of weapons-grade uranium (93 percent U^{235}) is already reduced by more than a factor of 2, relative to natural uranium if one starts with 3 percent U^{235}, and by a factor of 5 starting with 10 percent U^{235}.

4 DISASSEMBLY AND DESTRUCTION

4.1 The Dismantlement Building

The heart of any system for dismantlement of nuclear weapons is the place where dismantlement is done. We call this place a "building," although it will probably be a collection of buildings resembling the Pantex facility, or the several Russian equivalents where dismantlement of weapons is now happening. The essential feature of this building is that it is declared by its owner to be a place for dismantling weapons. The details of what is done inside the building are known only to the owner. Verifiers are allowed to look inside the building only at times when it is declared to be inactive. When it is active, verifiers may look only at packages going in and packages coming out. "Verifiers" here may be locally based inspectors, locally based sensors, or NTM sensors viewing remotely.

The first question to be settled in the design of a dismantlement program is whether the building should be a new structure or whether the existing factory buildings could be used. A new structure could be designed to make verification more reliable, for example by eliminating the possibility of hidden vaults where weapons or weapon components could be concealed, or of hidden access tunnels. On the other hand, construction of a new building would be expensive and would delay the dismantlement process substantially. Here we have an example of a recurrent problem. A choice has to be made between speed of disarmament and reliability of verification. This same choice arises at many points in the dismantlement process. There is great value to speed, to take maximum advantage of the present windows of opportunity while they last. This should be taken fully into account in balancing speed with reliability of verification. Based on political judgment, not on technical facts, we admit to a general preference for speed in making choices. We try to present the alternatives impartially, pointing out the advantages and disadvantages of each.

In the case of the choice between new and existing buildings for dismantlement, there are other advantages besides speed favoring the use of existing buildings. Since the Russians have several nuclear weapons factories, a building at one of the sites could be dedicated 100 percent to dismantlement. The most important channel of information for verifying dismantlement is to have inside knowledge of the day-to-day operation of the Russian weapons-handling bureaucracy. We need to know how the system actually works, who gives the orders, and who carries them out. Such knowledge can be acquired at various levels, from Boris Yeltsin downward. One place where it can be acquired most effectively, simply as a result of everyday contact, is at the main nuclear-weapon factories, if we have technical people living and working on the sites. For this reason, we should prefer to have inspectors with legal access to the main weapon production sites rather than to an isolated dismantlement facility. At the production sites, we would have many opportunities to see how things are actually done rather than how they are supposed to be done. The closer we are to the old Khruschev-era weapon centers, the better will be our chances to apply reality checks to official Russian declarations of stockpiles and production history.

4.2 The Dismantlement Process

The flow of weapons to be dismantled can be conceptually divided into three phases, exclusive of the dismantlement itself:

A. The movement of weapons from wherever they are to the dismantlement building entrance.

B. The passage through the building to the exit where weapon components appear in separately packaged or batch-packaged containers.

C. The movement of component packages from the dismantlement building exit to final disposal, storage, or destruction.

We describe a technical verification system for each of these three phases in turn. For each phase, we offer four alternative levels of verification ranging from 1 to 4. Here level 1 has the highest technical reliability and level 4 the lowest. We consider that level 4 is adequate to meet U.S. requirements for monitoring the process when supplemented by other non-technical channels of information. But to say that level 4 is adequate is a political and not a technical judgment. Therefore, we present also the higher level alternatives 1, 2, and 3.

In making the choice between higher and lower levels of verification, it is important to remember that higher levels are likely to be associated with more frequent false alarms. Failure of a verification system may happen in two ways. Like a medical test, the system may have false-negative failures and false-positive failures. A false-negative failure occurs when a real violation of an agreement is undetected. A false-positive failure is a false alarm, when the system declares a violation that never happened. In the world of international politics, as in medical diagnosis, a false-positive failure may be more damaging than a false-negative. In both contexts, the choice of the sensitivity threshold of the system is a delicate one, requiring political as well as technical judgment. A more sensitive verification system is not necessarily better. If a more sensitive system gives frequent false alarms, it may easily do more harm than good. The choice between levels 1, 2, 3, and 4 must be made after due consideration of the risk of false alarms and of the damage that false alarms may do to the public acceptance of disarmament.

We have set our level 4, the level we describe as "adequate," so that, at the very least, we know that weapons have been removed from delivery systems and brought to a known site. At level 4 we also know, again at the very least, that special nuclear materials have been removed from the active stockpile or the strategic reserve. Implicit in these statements is the assumption that whatever methods are used to determine quantities of special nuclear materials entering and leaving the dismantlement and disposal sites can distinguish between SNM from weapons and from other sources, perhaps with a lower enrichment.

The most crucial single step in the verification of dismantlement occurs at the beginning, when a weapon is first declared to be a weapon and officially entered into the system. The weapon is then supposed to be put into a canister which is appropriately tagged and sealed in the presence of an inspector. How does the inspector make sure that the object in the canister is a weapon? The inspector must at least be allowed to monitor nuclear radiations from the canister with some passive or active detection system. But any detection system can be defeated by the owner of the canister, given sufficient time and sufficient access to nuclear materials. The owner could, in principle, stuff the canister with a fake source of radiation simulating the responses of a real bomb. The purpose of the verification system is to make such a subterfuge unlikely. Here again, speed is more important than technical sophistication. The shorter the time before the weapons are declared and tagged, the more difficult it would be for the owner of the weapon to organize the manufacture and substitution of counterfeits. If the declaration and tagging can be done quickly enough, any large-scale substitution becomes practically impossible.

We now describe briefly the three stages, A, B, and C, of dismantlement with the four levels, 1, 2, 3, and 4, of verification that might be applied at each stage.

A. A tagged and sealed weapon is followed to the dismantlement and destruction (DandD) site by NTM (and/or GPS if the tag includes a radio beacon) or by a more cooperative means. Weapons and everything else must enter and exit the DandD site by a portal at which everything and everyone going in and out can be appropriately monitored. For example, people must go in and out through metal, neutron and gamma-ray detectors, and everything else must be tested for Pu and U by x-ray and/or neutron irradiation and appropriate detectors. Weapons would be monitored as follows:

1. (Best) A neutron source would be used to obtain the mass of SNM to a specific accuracy (e.g., 5 percent). Pu^{239} and U^{235} are separately logged for each weapon. A suitably defocused x-ray source radiographs the SNM in the weapon to get a rough idea of the shape for use at the time of destruction.

2. (Better) As in 1, but only neutron monitoring and testing with a neutron source are allowed.

3. (Good) Testing with a neutron source, to get the mass of SNM only, is allowed. (We still need the specific accuracy, but neutron irradiation is done in such a way as to limit the information other than SNM mass that can be obtained. Perhaps passive monitoring of neutrons and certain gamma-ray lines would be adequate here.)

4. (Adequate) Many tagged and sealed warheads (e.g., 10) of different design pass through the portal together and have their SNM monitored in aggregate. However, gamma-ray spectra can be obtained to the level required to determine the amounts of U^{235} and Pu^{239} separately to a specific accuracy. (Must avoid mutual shielding.) [See Section 4.3 for a specific example.]

B. The dismantlement building should be a single-purpose building to avoid confusing "traffic" in and out.

1. (Best) The building should be new (so we can watch it being built, at least with NTM) and have no basements. We would be able to "sweep" it for SNM with appropriate sources and detectors before DandD activities begin. We also are permitted re-sweeps for SNM from time to time to avoid accumulated allowed error (see A.1 above) in hiding diverted materials. (A disadvantage here is the time to build a new building).

2. (Better) The building already exists, but we get to sweep it thoroughly for SNM, including all basements. We are also allowed to check for basements and tunnels not shown to us (e.g., by seismic mapping or

any other reasonable technique). Periodic re-sweeps for diverted SNM are permitted.

3. (Good) As in B.2 above except that we are not allowed to check for concealed basements. (In this case, we could insist on them using a building that we saw being built using NTM, so that we have good reason to believe that there are no basements that we were not shown and allowed to sweep for SNM.)

4. (Adequate, especially in conjunction with A1-3 and C1-3) The building is not new, and our rights to sweep it in advance of DandD activities are limited. That is, we cannot be sure that there is no stockpile of SNM in the building in advance.

C. Dismantlement takes place in the building in B out of our sight. However, the final actions must be in our sight, as follows:

1. (Best) Pu^{239} and U^{235} come out in separate packages with the tag from the original weapon still with them. We determine the mass of each of them by the same method as A.1. The rest of the weapon pieces come out in barrels (crushed or not, as they see fit). High explosives are removed from the building and burned in our sight. Of course care in handling hazardous materials such as beryllium is required. The packaging for the SNM is designed to retain it when crushed, and "destruction" is deemed to have taken place when the two SNM containers are hydraulically flattened to a size (or pressure) that we deem will render them beyond reuse without starting over. Even better would be our being able to confirm this by another radiograph. The SNM would then be disposed of as allowed by other agreements (e.g.,

sale to the United States, France, or Japan). With appropriate choice of shipping method, and perhaps with tags and seals on the shipping containers, disposal can be monitored by NTM (and/or GPS).

2. (Better) Same as C.1 above except with SNM testing as in A.2 instead of A.1.

3. (Good enough) Same as C.1. except with SNM testing as in A.3. Since we can no longer be sure that the SNM that comes out of the dismantlement part of the building to be destroyed is actually in weaponized form, we would prefer this to be in conjunction with B.1 or B.2 (i.e., with evidence that there was no SNM stockpile in the building to draw down, so that whole weapons or undamaged pits and secondaries could be stored inside).

4. (Adequate, especially in conjunction with B.1 or B.2) Bulk SNM comes out, with the total over a specified time (1 or 2 months) balancing the amount that goes in.

5. (Also adequate) Same as C.1 or C.2 except that pits (or the primary if a weapon does not have a separable pit) go into "bonded storage" instead of being destroyed (e.g., while waiting to decide whether to dispose of Pu mixed with high -level radiation waste or to sell it) because crushing is deemed too hazardous. The "bonded storage" should be such that it can be monitored using NTM or by the observers at the DandD site.

There are a multitude of variations on the above possibilities. It seems clear that NTM can perform only a limited number of functions in the context of DandD of nuclear weapons. Still, these functions could be very important to getting an agreement signed, since they could reduce the required level of cooperation in several important ways (e.g., B.3).

4.3 Tagged Warhead Batches: An Example of Verifying Dismantlement Without Revealing Design

For the purposes of a dismantlement treaty, warheads can be grouped into batches that allow verification while preserving secrets of warhead design. For example, the Russians can decide to assemble the following (notional) group of warheads into a batch:

Warhead Type	Number of Warheads
W1	1
W2	2
W3	1
W4	2
W5	1

The warheads need not all be located at one place; they could even be left in their respective delivery vehicles until the time comes for dismantlement. The makeup of the batches is up to the country that owns the warheads. They can mix and match however they choose; they might have 17 different kinds of batches, of which the above example is only one.

Every batch will have a type that indicates its makeup (e.g., all batches of type A will consist of a set of seven warheads in the list above; batches of type B will have a different makeup). To simplify verification, they will reveal that a batch of the type given above (call it batch type B-11) contains, in total, 200 kg of 92 percent HEU and 50 kg of *Pu*. The individual breakdowns (i.e., how much HEU is in a W1) will not be disclosed, so that limited intelligence information can be deduced. All weapons will be divided into such batches.

Every batch, in addition to its type, will be uniquely identified with a serial number. For example, there may be 314 batches of type A, 271 of type B, and 577 of type C. A serial number C122 will indicate that this warhead is in the 122nd batch of type C.

For inspection, we will choose a class and a number, e.g., A137, and the Russians will be required to produce the seven warheads in that batch 137. A location for dismantlement of these warheads will be swept by a U.S. team prior to the arrival of the warheads to make certain that there is no SNM on the site. When the seven warheads arrive, they pass through the portal into the dismantlement area, and the U.S. verifies the identity of the warheads through their tags. The warheads are dismantled, and the SNM removed into such a form that it can be inspected by the U.S. to determine that the *total* amount of SNM is equal to that specified by the treaty. The remaining material of the warheads is likewise reduced to a state where it can be examined for the presence of SNM. This can be done in such a way that special metals and plastics used in the design will not be revealed to the other side; for example, special plastics can be broken into small pieces and put in small containers which have thick enough walls to hide their chemical composition, but too thin to hide the characteristic radiation of SNM. The inspection of such boxes would be done jointly, with complete openness, to assure that special techniques that could reveal secret design information will not be used.

After the dismantlement, the location where the work was done will again be swept for SNM to show that none was left behind. The site will be open to both sides except when the actual dismantlement is underway. This assures that no material can be hidden at the facility.

Note that the prior disclosure of the amount of SNM in the weapon batch is not strictly necessary, since after the first cluster is dismantled the number will be known. However, revealing such information means that the variety of batches can be increased, and it is not necessary to examine two batches in order to verify that dismantlement is taking place. As more dismantlements are conducted, the probability that the adversary has cheated in its declaration of SNM will decrease.

4.4 The Role of NTM

In the scheme for verification of weapon dismantlement that we have described, NTM appear to play only a minor role. In fact NTM play a major role, but their major role is not displayed in the public verification protocols. Every verification system has two parts, one private and one public. The private system is designed to provide information; the public system is designed to provide legal proof of violations if they occur. The private system needs to be wide-ranging and technically sophisticated; the public system needs to be sharply focussed and simple. In the case of weapon dismantlement, the public system is necessarily focussed on the tracking of small packages passing through declared channels, and the tools of verification must be local on-site inspection rather than NTM. The private system is mainly concerned with seeking evidence of large-scale clandestine activities in undeclared locations, and for this purpose the primary tools are NTM. Hidden in the background, but giving essential support to the public verification system, we have the NTM hunting for undeclared nuclear operations, security fences and excavations, or unguarded communications. NTM are particularly effective in revealing fresh traces of human activities between one observation and the next.

At present and for some time to come, Russia will be in a state of political turmoil. The most dangerous violations of a dismantlement agreement are likely to result from hard-line factions in the military/nuclear establishment, setting up private empires in territories where they have the upper hand, and, perhaps, making sales of warheads or SNM to other countries. Where such empires exist, security barriers and military movements should be visible to NTM. Effective NTM coverage of remote areas therefore provides an essential adjunct, supplementing the public part of the verification system.

In the public verification system, we have frequently to make a choice between outreach and simplicity. For example, we have the problem of verifying that warheads are genuine warheads and not fakes. We may test the genuineness of warheads, either by statistical sampling or by simply testing all those that pass through a checkpoint on the way to dismantlement. The idea of statistical sampling follows. If N warheads are declared to be of a certain type, the inspecting authority chooses a smaller number S of them for dismantlement and tests those only. The S warheads are chosen at random. If a fraction F of the warheads are fakes, then at least one fake will be detected with probability [see Equation 3-2],

$$C = 1 - \exp(-FS).$$

This formula applies, whether or not we know the signature of a genuine warhead *a priori*. If we do not know the signature of a genuine warhead, we still can detect the presence of one or more fakes because they have signatures different from the majority.

The sampling method allows us to test with some degree of confidence the genuineness of the entire declared weapons stockpile, whereas the simple checkpoint method tests with greater confidence the genuineness of those that enter the dismantlement process. The choice between the two methods must be a political one. If we desire a method that reveals violations simply and clearly, the checkpoint test is better. If we desire a method that covers the entire stockpile but may be less clear cut, the sampling test is better. Similar considerations apply to every aspect of the verification system. High-technology methods involving computers and encryption of data will increase the technical accuracy of verification but will decrease its public credibility. Fortunately, in the private part of the verification system where NTM are most useful, public credibility is not essential.

In the end, political considerations will usually outweigh technical considerations. For example, we now have two golden opportunities to make rapid progress with weapon dismantlement without any need for technical verification. One opportunity is the Russian offer to sell weapons-grade uranium in large quantities for hard currency. It would be easy for us, in consultation with other countries, to buy a large fraction of the Russian stockpile of HEU and convert it to LEU for use in commercial reactors. The primary motivation should not be commercial profit. The dismantlement of a large fraction of the Russian weapons potential is well worth the price of the uranium, even if the value of the uranium as fuel is low because of a current surplus. The second golden opportunity that is now open to us is to conclude dismantlement agreements quickly with the non-Russian republics. The non-Russian republics are a good place to begin dismantlement, and the practical experience of dismantling weapons there would be helpful in tackling the more complicated problems that will arise in Russia.

5 SNM CUTOFF

How might we increase our confidence that the FSU has truly terminated its production of SNM within the constraint that verification measures be acceptable to both the United States and the FSU?

It is important first to set the scale of meaningful production. Since the FSU has hundreds of metric tons of SNM (most of which will not be in warheads at currently projected stockpile levels), only facilities capable of producing at least a few metric tons per year will be significant. Of course, the threshold of interest for other nuclear powers in a multilateral treaty would be lower, and it drops to a few kg for potential proliferators.

For a quantitative benchmark, we consider the task of producing fissile material for 100 warheads per year: a nominal 400 kg of Pu and 2,000 kg of 90% HEU. With a natural U feed and a 0.2 percent tails assay, the HEU would require about 450,000 kg-SWU per year. However, if the feed is 20 percent HEU (the highest enrichment defined as LEU by the IAEA) and the tail assay is raised to 5 percent, then only an incremental 20,000 kg-SWU per year (one-twentieth as much) is required. Thus the cost of enrichment to weapons-grade uranium would be greatly reduced when compared with starting from natural uranium.

For Pu production, operation of reactors with a high power output is required. For example light water reactors operating at a 70 percent duty cycle will yield approximately 400 kg of Pu per year from 500 tonnes of U^{238} fuel[30] with a total electric output of 2.3 GWe.

[30]The exact value depends on the degree of burn-up.

The production of such amounts of Pu or HEU can (but need not) imply physically large facilities. An important first step for a monitoring regime would be to have each country declare to the other all their facilities capable of U enrichment, Pu production, or fuel reprocessing. These could then be placed under the standard IAEA safeguards designed to prevent production of SNM. (The efficacy of these safeguards in the face of a determined effort to cheat is an important issue that we discuss separately.) Although both the United States and the FSU are signatories to the IAEA treaty and have some facilities that have been, in principle, subject to these safeguards, the IAEA safeguards have never been applied to them in practice for lack of funding. It is estimated that application of safeguards to U.S. and FSU facilities would cost upward of $50M per year, more than doubling the IAEA budget for inspection activities.

More problematic are the undeclared facilities. Here, the first step must be the detection of suspicious sites. NTM clearly have a role to play here, although they need not do the job alone. Under an open skies inspection regime, suspicions raised by NTM capabilities that we might not wish to divulge to the FSU could be followed up by more detailed and overt overflights. Note that the mere identification of a site as an undeclared U enrichment or Pu production facility, even if it is not producing HEU or weapons-grade Pu, would already be a serious breach of confidence, as *all* such facilities are supposed to have been declared.

The signatures of reactors, reprocessing plants, and enrichment plants and their visibility by NTM have been much discussed elsewhere. Briefly, reactors have cooling ponds, cooling towers, and refueling activities around them (the latter particularly so if weapons-grade Pu is being produced). Reprocessing plants have fuel cooling ponds and emit Kr^{85}, which is produced in 0.3 percent of the fissions of U^{235}. Diffusion plants on a scale to be significant require considerable floor space and power. The nominal 20,000 kg-SWU/yr plant discussed above would consume 6 MW of electrical power.

Unfortunately, both centrifuge and laser isotope separation methods seem to be much less amenable to remote detection. A 20,000 kg-SWU per yr centrifuge plant would fit easily within an ordinary factory footprint and consume only 600 kW of electrical power; power consumption for the laser isotope separation methods would be about a factor of three smaller. There are no known remotely observable signatures for either separation method, barring an accidental release.

The next step would be to confirm any such suspicion by more overt and intrusive methods. At one end of the spectrum, the challenger could have the right to deploy sensors around the site that would detect signatures of SNM production. These might include the Kr^{85} characteristic of fuel reprocessing, small U particles with anomalous isotopic ratios, the temperatures and flow rates in cooling facilities, the electrical power flows into enrichment plants, etc. We expect that such measures would likely be acceptable to both countries.

At the more intrusive end are challenge inspections, which would necessarily involve entry into buildings. Modern microanalytical techniques can easily detect the small particles that are inevitably present in an SNM facility, so that a violation could be detected with high confidence, even with very limited access.

One might worry that such challenge inspections could be abused to obtain sensitive materials information from non-nuclear facilities. For example, the B-2 factory in Palmdale might be challenged in an effort to learn about the radar absorbing materials used. Such abuse could be prevented by allotting each side a yearly quota of challenges and by having the analyses performed by a third party using only agreed-upon methods.

Another aspect of cutoff is the commitment not to manufacture new nuclear weapons, except as may be agreed for safety upgrades. It would make a mockery of an era in which 90 percent of the nuclear weapons were being destroyed if nuclear weapons could also be manufactured without control to replace any desired number of those destroyed. Any allowed new nuclear weapons would be appropriately tagged and registered.

As long as nuclear weapons are legitimately retained by Russia and the United States, a manufacturing facility will also be needed. Verification would require that the facility be declared, that it submit to monitoring, and that it obey the clean desk edict. It should be subject to inspection when no fissile material is present to verify that none is accumulating in the form of weapons stockpiled there. Any manufacturing or assembly facility must be unique and separate from disassembly facilities.

6 STORAGE AND DISPOSAL

6.1 Intermediate Storage

It should be noted that if retirement of weapons proceeds along the broad schedule agreed to by Presidents Bush and Yeltsin, storage of either complete weapons or special nuclear materials withdrawn from those weapons is the *only* means of management for at least a decade. The disposal options discussed below in 6.2 are either non-existent today and would involve substantial R&D and decision-making cycles, or, if they do exist, do not have the capacity to cope with the volumes envisaged.

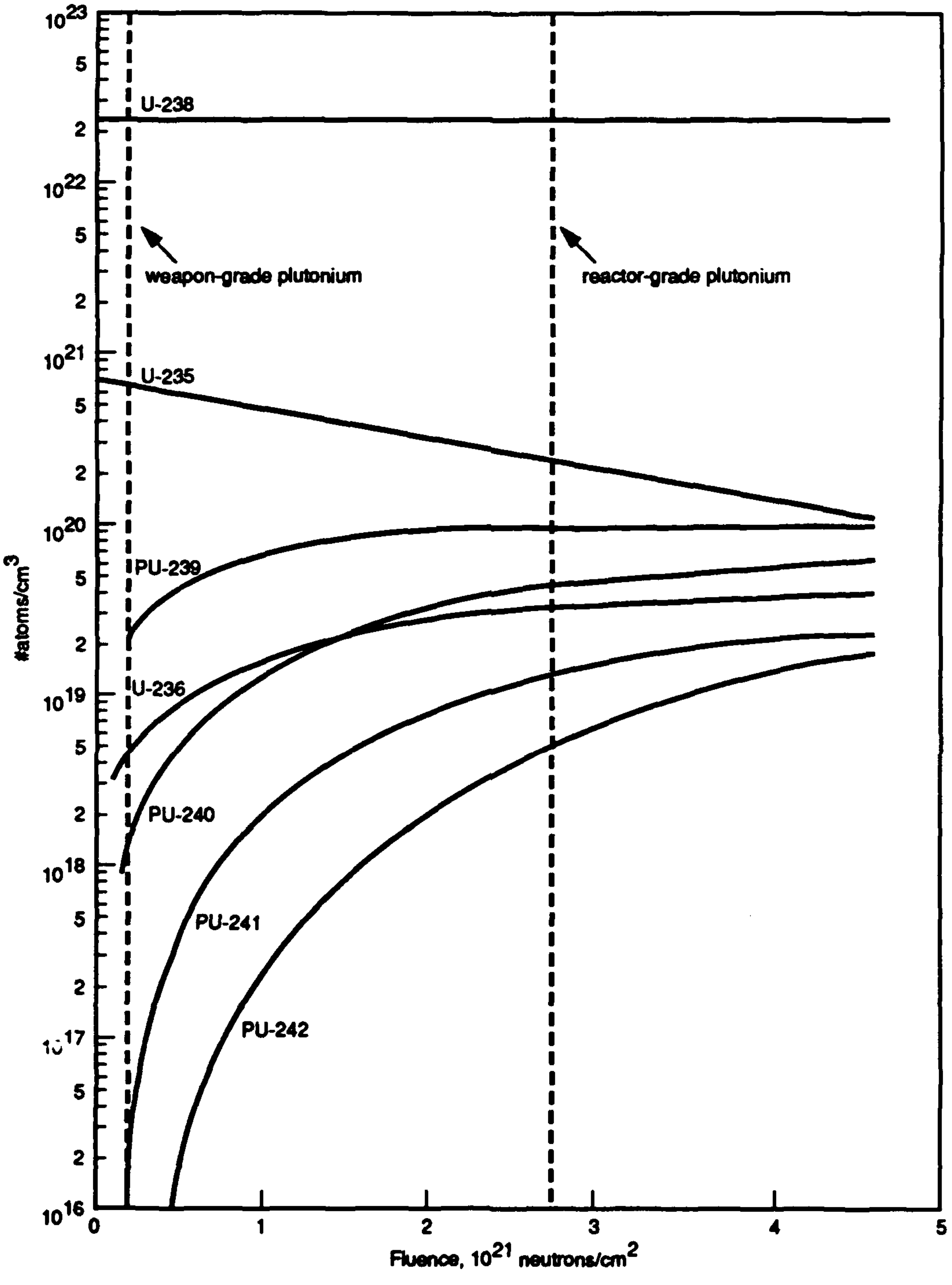
In considering verification of storage of plutonium from weapons some review of civilian inventories is useful. Currently there exist about 650 tons of civil reactor-grade plutonium[31] compared to the 250 tons or so of military inventories. Most of the civil plutonium exists in the form of discharged, non-reprocessed fuel but about 120 tons have been separated. Of the separated amount about 50 tons have already been reused in the civilian fuel cycle, leaving an estimated stockpile of civilian separated, but not reused, plutonium of around 70 tons. This is more than one-quarter of the total military stockpiles and is comparable to the amounts of plutonium which might be retired from military stockpiles over the next 4–5 years. Worldwide civilian reprocessing capacity, once plants under construction in the United Kingdom, France, and Japan are completed, will reach 32 tons per year.

[31] W. Walker, D. Albright, F. Berkhout, Oxford University Press, to be published Autumn 1992.

The isotopic composition of the plutonium resulting from civilian or military fuel cycles depends on the total neutron fluence (flux times time) to which the uranium fuel elements in the reactor yielding the plutonium have been exposed. Figure 6.1 illustrates the situation. It is conventional to divide plutonium into weapons-grade and reactor-grade material, as shown in Table 3.1, but we are dealing with a continuum. Although the spontaneous fission rate of Pu^{240} complicates weapons design, it is possible to design a usable weapon containing substantial fractions of Pu^{240}. Thus even heavily irradiated civilian plutonium constitutes a diversion risk.

That part of the civilian plutonium which is produced by signatories of the NPT who are non-nuclear weapons states is under IAEA surveillance; a small fraction — perhaps 2% — of the civil plutonium has been reprocessed by suspected proliferants like India who are not officially nuclear weapon states. At this time, the nuclear weapons states have no obligation to submit to IAEA safeguarding.

Thus the principal issues to be addressed under the general heading of verification of safeguarded plutonium are: 1) how is the retired military plutonium to be integrated into the already existing safeguarding structure that is applied to separated plutonium from the civilian cycle?; and 2) how is the overall safeguarding regime to be managed? Our bias is to recommend that both the civilian nuclear fuel cycles of the nuclear weapons states under the NPT and the retired military stockpiles be subject to IAEA safeguards. This would be revitalization of the "International Plutonium Storage" proposal by the IAEA.



U-238
weapon-grade plutonium
reactor-grade plutonium
U-235
PU-239
U-236
PU-240
PU-241
PU-242
#atoms/cm3
Fluence, 10^21 neutrons/cm^2

Figure 6.1

A separate issue is whether it is appropriate for IAEA to carry such expanded responsibilities or whether other existing international institutions should be utilized or new international institutions be created. We will not deal with this question here.

Storage of HEU is a simpler issue in reference to civilian nuclear power, since HEU is used only in small quantities in civilian nuclear power and is not a product of that cycle. HEU is used in U.S. naval reactors, and at a much lower enrichment in Russian naval power units. At the same time HEU from weapons would be of clear economic value (although disruptive to the market) to civilian nuclear power.

For nuclear weapons that are stored intact, the retirement process may be reversed on short notice. Moreover should safeguarding fail, that is, should there be some diversion of stored inventory, this could be a considerably more dangerous event than if the HEU and plutonium were stored separately. Thus the United States has chosen to remove and store the pits, and assurance has been given that Russia is doing likewise. At this time, assurance that this separation is taking place is based on public declaration and not on verification. After initial complaints, Ukraine has now publicly stated that they are satisfied that separation is actually taking place; however, that satisfaction is apparently based on direct assurances, not verification.

The separated pits can be stored in the same form as withdrawn from weapons. However, this places a double security burden on their safeguarding: their shapes reveal sensitive information and at the same time the physical inventory must be controlled. Alternately, one can convert the pits into ingots or even further convert plutonium into chemical components, either solid or in solution.

The United States has chosen to store withdrawn primary pits containing plutonium without further modification, at least temporarily. This is preferable from environmental considerations since no processing of the plutonium is required.

Storage of plutonium is in the form of sealed material canisters so that handling does not involve contact with plutonium. From the verification point of view, this means that there is no assurance that traces of plutonium will be associated with storage operations. The possible physical signatures from plutonium cannisters are the relatively weak gamma-ray emissions and neutron fluxes from spontaneous fission. Both of these can be readily shielded; if the cannisters are stored in thick-walled bunkers, no external signatures are observable. Neither satellite observation nor aircraft overflight could identify bunkers as being dedicated to plutonium storage if they were not declared.

As a result of the above, it is unavoidable that verification of withdrawal of plutonium from weapons into safeguarded storage and the maintenance of that storage is a matter of inventory control rather than verification using external observables. This by its nature must be cooperative.

Inventory control of *Pu* and HEU would begin with tagging and sealing of weapons starting at the point of their removal from delivery systems or from the stockpiles as described in Section 4. The accounting for the weapons would be done on a unit and discrete basis, just as one accounts for pictures in a museum and other articles of value. For SNM entering storage, accounting at the outset will take place in the same fashion. It will enter custody in individual storage containers, particularly if the fissile material is in such a form that criticality is a consideration. The *Pu* will probably remain in discrete form, because of the intense health hazard for Pu that is not sealed in a container. On the other hand, uranium, particularly at low or medium enrichment, is less reactive chemically and not nearly as toxic or as much of a radialogical hazard. The verification of material in storage follows the same principles discussed in the previous sections. A verification system must prevent slow erosion and leakage, and, to do so, must not require exposing and adding up all of the material in the storage facility. It must be possible to have a spot check, which means that the stock must be broken down for accounting and verification purposes, and the amounts either available in the clear or in a secure registration procedure, if there were some reason to keep the details either from the other side or from the inspecting personnel.

There is a totally different aspect of storage, and that is the protection of the material against massive threat, invasion, terrorism, and the like. This is not an accounting and verification problem but one that requires design of facilities, guard forces, international military commitments, etc. To discuss these matters would go far beyond our charter.

A cooperative measure could be pre-notification if SNM are to be moved out of or into storage, combined with a prohibition on underground transfer. Above-ground transfer could be verified to a fair extent by NTM or overflight, provided trucks exhibiting externally distinguishable observables or radiating identification signals are used; such use, in turn, would require verification by tagging at the point of loading. Of course any such observables might make such truck convoys easier targets for terrorists to identify and appropriate custodial security is called for.

6.2 Long-range Management

Following intermediate storage there exist numerous options for longer-range management. This is largely a political and an economic problem rather than a verification one.

For HEU, which poses no direct environmental hazards and is of economic value as fuel, the most straightforward procedure is to dilute it either with natural uranium or depleted uranium "tails" to an appropriate isotopic mixture. To assume maximum flexibility for future reactor use and to minimize up-front costs, initial dilution to perhaps 20% is adequate to prevent the usefulness of the material for nuclear weapons.[32] Diluting to 20% "wastes" only about 10% of the total SWUs per unit weight of U^{235} which have been spent in producing the weapons-grade material. This de-enriched material is of economic value as a reactor fuel, although the magnitude of that value and the timing of its use in reactors is subject to the uranium market situation and the expectancies for expansion of nuclear power. Since de-enrichment is essentially a reversal of the original enrichment process the safeguards and accounting methods of the IAEA would be applicable here also and no additional verification measures are required.

At this time there is no U.S. national policy on the option of choice for long-range plutonium management. Most attention has been focussed on the reactor disposal options which preserve the principal fuel value of the

[32]A nitric acid dissolution process was briefed to us and seems to offer an economical means for diluting the U^{235}, and with minimal environmental impact and hazardous materials handling requirements. The steps in this process are nitric acid dissolution of the HEU metal followed by mixing with natural uranyl UNH and finally denitrating to UO_3 and storing.

plutonium. This option cannot be justified on strictly economic terms. Only about 10% of the cost of nuclear electricity derives from fuel and with present expectations for the nuclear power industry fuel supplies are assured for a large part of the next century. In addition the reactor use of weapons plutonium requires large capital investment. Thus using weapons plutonium as a reactor fuel has to be justified largely by national security and arms control objectives. Disposal options for plutonium as a fuel for power production are subject to the future of nuclear power in general, and to the particular choices which are apt to be made among power reactors in the future.[33]

We looked briefly at a number of possibilities for *Pu* management or disposal of various degrees of irretrievability. They include:

1. Fabricating the plutonium into MOX fuel rods and use of these fuel rods in light water reactors.

2. Using the plutonium in once-through fast neutron reactors or in breeder reactors.

3. Mixing it with nuclear waste (spent fuel) or other contaminants, and then glassifying and clading it for geological disposal deep underground.

4. Using an accelerator beam to transmute the plutonium.

5. Using several other methods of *Pu* disposal that are technically viable but may be unacceptable for safety, environmental, political, or economic reasons. They include:

[33]The current status of the technical and institutional options for the future of nuclear power was studied in a report by a panel of the National Research Council: "Nuclear Power, Technical and Institutional Options for the Future." (National Academy Press, Wash. D.C., June 1992.

- Detonation underground of retired nuclear weapons or primaries individually;
- Introduction of separate retired nuclear weapons and/or pits withdrawn from nuclear weapons into an underground cavity followed by detonation of a nuclear weapon in that cavity;
- Launch of the plutonium into an escape orbit or into an orbit impacting the sun;
- Disposition in appropriate ocean bottom mud;
- Dilution of plutonium in the ocean.

The first two options still lead to remaining inventories of plutonium, albeit in forms already in existence in civilian inventories. We here list only summary descriptions of these options for plutonium with remarks in respect to the ease of verification and safeguard.

Fabrication of plutonium into MOX fuel rods and use of these fuel rods in light water reactors. The technology for fabricating MOX fuel rods is well established and the operating characteristics of MOX-fired reactors has been well established. Note that 20 tons of MOX fuel contains 1 ton of plutonium. Existing plants are in Belgium (35 tons of MOX per year) and a new plant in Germany capable of operating at 120 tons per year has not as yet received authorization to operate. There are partially completed plants in Russia. The Belgian plant is the most successful, having produced about 150 tons of MOX. The problem is one of capacity of MOX fuel-rod fabrication, not of total LWR fuel demand. The existing capacity just mentioned is fully committed for civilian use and amounts to only a burn-up rate of perhaps 35 tons of plutonium per year. Thus the MOX route to weapons plutonium disposal requires considerable capital investment and heavy (and observable) construction activity.

A MOX fabrication plant and the power-producing reactor would presumably operate under established IAEA safeguards that assure that no *Pu* leaves the plant without full accounting of its destination and use.

Use of the plutonium in fast reactors using a once-through fuel cycle. The fast reactor route to plutonium disposal, if adopted, is apt to be in the distant future since worldwide capacity corresponds to only 7 tons of plutonium per year and there are varying degrees of trouble associated with all existing plants. Fast reactors are more "capital intensive" than light water reactors. An attraction for this route is the option of adopting a once-through fuel cycle, or breeding reactor-grade plutonium, and thereby extending the fuel resource. This latter makes the fast reactor route politically unattractive from the point of weapons plutonium disposal. The object is to diminish the supply of plutonium, not to increase it! One option is repeated recycling at a breeding ratio much less than unity. This can, in principle, lead to a very large reduction factor but involves a great deal of handling. Again, verification issues are not a major component affecting the choice of this route.

Irretrievable storage underground (a) after mixing with spent fuel and/or (b) after addition of other plutonium isotopes or other contaminants. Deep geological storage has been analyzed repeatedly in the past in connection with nuclear reactor waste. Several geologically and apparently environmentally safe solutions have been identified but none has as yet achieved public acceptance. Even if it is assumed that such acceptance will sooner or later be secured for waste from nuclear reactors, it is not a foregone conclusion that such acceptance can be secured for nuclear materials from weapons. Verification that nuclear weapons, their pits, or SNM are actually introduced into the disposal site appears to be straightforward by methods indicated above, but some continued safeguarding appears to be essential since "mining" of the underground depository cannot be excluded. The attractiveness of such mining can be greatly impaired by mixing the plutonium with highly radioactive contaminants such as spent reactor fuel or other highly radioactive nucleids. It has also been suggested that the attractiveness of such mining can be greatly reduced by adding plutonium isotopes (e.g., Pu^{238}) which would make the material highly radioactive, or Pu^{240}, which makes the material less suitable for weapons. This latter path would involve costly efforts in producing adequate quantities of such isotopic additives.

Transmutation of the plutonium in an accelerator beam. As a sideline of studies examining the use of proton accelerators to destroy actinides in reactor waste streams, it has been suggested that such an accelerator might be used to destroy plutonium. The process is to have a proton beam generate spallation neutrons in a heavy element target, and have those neutrons fission the plutonium. A rough numerical calculation, assuming 50 percent efficiency from power line to beam of an accelerator, indicates that 1 gigawatt year of electric power feeding the accelerator would be required to destroy one-half to one tonne of plutonium. If the source of electricity were nuclear, one could rightfully ask why one would not directly burn the plutonium in a reactor rather than using this method. An answer is that this method can in principle lead to complete burn-up, but it is clearly highly inefficient and one still has to deal with the waste streams from the reactors generating the electric power. In principle energy efficiency could be increased by having the plutonium target configured as a subcritical assembly, thereby increasing the neutron multiplication.[34] This would indeed decrease the demand on accelerator power, but in that case the criticism "why not proceed directly via direct reactor burn-up" would have even more validity. This is potentially interesting as a cooperative procedure with the Russians.

In the following, we comment on five schemes that make the *Pu* difficult, if not impossible, to retrieve but which present other more serious problems of public acceptability for various reasons.

Detonation of retired nuclear weapons or primaries individually. While this is feasible, in principle, it would require literally thousands of underground detonations of weapons or their primaries. Costs would be high, and it is unlikely that it would be politically acceptable. Verification should be fairly straightforward, consisting of tagging and identification of the device to be detonated, and utilization of seismic or other sensors in place near the detonation site.

Introduction of separate retired nuclear weapons or/and pits withdrawn from nuclear weapons into an underground cavity followed by detonation of a nuclear weapon in that cavity. This method has recently been strongly advocated by spokesmen for one of the Russian weapons laboratories, Arzamas-16. In essence it constitutes a means for diluting the plutonium in the weapons to be disposed of by embedding the plutonium in fused rock, generated by the nuclear explosion. The dilution factor can be estimated as follows: Per kiloton of yield, a nuclear weapon would vaporize about 60 tonnes (hard rock) to 80 tonnes (tuff or aluvium), and would melt about one order of magnitude more. Thus if 250 nuclear weapons or pits containing perhaps

[34] A candidate design by Los Alamos National Laboratory includes actinide waste with the *Pu* in the target assembly and can generate net power.

one tonne of plutonium are placed in the same cavity, then the plutonium would be diluted to 10^{-3} in glassified form with the vaporized rock by a 20 kt detonation. Such a dilution would make retrieval by mining difficult, although not impossible.[35] Needless to say, this method raises many as yet unanswered questions, such as questions of unintended subsequent nuclear detonations or other criticality events, safety against future environmental releases, etc. Moreover, although the method could be relatively quick and cheap, its political acceptability is doubtful. Nevertheless the method deserves further detailed examination. Verification to assure that the weapons, pits or designated quantities of SNM, which are to be introduced into the cavity are in fact so emplaced, is relatively straightforward following our earlier discussion. However, because of the possibility of future mining some continuous safeguarding on the surface is required. This could possibly be achieved by pre-emplaced sensors which could be interrogated remotely to assure that the surface has not been disturbed.

Launch of the plutonium into escape orbit or into orbit impacting the sun. This method has been advocated periodically in the past. Its obvious problems are very high cost and risk of a launch-pad accident or of one shortly after launch. For both of these reasons, it has not gained wide support, and public and political acceptability are dubious. Verification that the devices to be disposed of are indeed introduced into the payload of the space vehicle should be straightforward by the methods discussed earlier.

Disposition in appropriate ocean bottom mud or subduction zones. Studies are in progress (Woods Hole) which lead to optimistic assertions that plutonium could be introduced into ocean bottom mud and that subsequent

[35] It should be noted that gold is mined profitably from ore containing a concentration of one ounce of gold per ton, or slightly less than half of a 10^{-4} dilution factor.

release would be extremely unlikely. We have no independent views on these conclusions and suggest that public acceptance of this means of disposal may be exceedingly difficult. The disposal site would need to be monitored, in view of the increasing facility of remote and potentially covert ocean bottom retrieval technology.

Dilution of plutonium in the ocean. It has been suggested that the plutonium be introduced into the ocean and diluted to an extent sufficient to ensure that the residual concentration would be well below acceptable tolerances. If uniformly diluted in the 10^{21} liters of ocean water, one hundred tons of Pu^{239} would lead to a concentration of 10^{-13} grams per liter, which should be compared with the concentration of 1.5×10^{-8} grams per liter considered acceptable in waste water discharge. Note that if the plutonium were diluted uniformly, its radioactive decay rate would be 100 times lower than that of the natural uranium content of sea water. The problem is, therefore, how to assure uniform dilution on a reasonable time scale and how to prevent selective concentrations which might enter the biosphere. A possible solution to this problem using long outfall pipes extending off the continental shelf is analyzed in a preliminary way in Appendix B. The results are sufficiently interesting to deserve further technical study. From the viewpoint of public acceptability, it should be noted that introducing 100 tons of Pu^{239} into the ocean would constitute more than an order of magnitude increase beyond the current concentration resulting from nuclear tests.

7 CONCLUSIONS AND RECOMMENDATIONS

We present our conclusions and recommendations in terms of the technical capabilities for monitoring agreements to dismantle or destroy nuclear weapons and/or to store and dispose of SNM. We also offer several concluding observations of a more political nature.

1.) NTM alone are inadequate for verification of warhead dismantlement and material production. However, they are important as part of a larger verification system including cooperative procedures for monitoring activities and changes. They can raise suspicions and trigger the application of Open Skies and other more detailed inspections, overt and cooperative or covert, of suspect sites and activities. They are very valuable for monitoring the shut-down of declared facilities and for providing early indications of large construction.

This conclusion agrees with that of the Robinson Report, which identified the limited value of NTM for detecting and monitoring warhead dismantlement and materials production signatures and for detecting clandestine activities by the Russian weapons complex. We emphasize however that, working together with cooperative procedures, NTM can give the United States a greatly strengthened ability to monitor indicators of the production of special nuclear materials, the transport of weapons, and the construction of new facilities. We also note that, while a determined and highly disciplined evader could undertake clandestine production of weapons or special nuclear materials without being detected by NTM, real-world lapses of discipline are most likely to leave traces of any sizable activity that NTM could detect. This is especially true of activities in Russia in its presently unsettled conditions and with extensive disillusionment and emigration of former functionaries.

Looking ahead, improved NTM capabilities for monitoring activities and detecting changes are making important progress at the R&D level.

For visible imagery at ground resolutions of one to two meters, headway is possible in two directions: distributed remote sensing by constellations of small satellites in LEOs that provide for rapid and frequent revisit, and a single large aperture satellite with a sparse optical aperture (i.e., a largely unfilled aperture) that incoherently superposes successive images taken from different azimuths in a geo or near-geo orbit.

For multi-spectral imagery covering the visible through near-infrared band, there is progress in the commercial sector in probing simultaneously several spectral intervals in order to view and interpret accurately small temperature changes that reflect activity — viz warm cooling ponds and towers or vegetative damage — at ground resolutions of 10 m or better. This can also be extended to thermal infra-red imagery (8–12 microns) for higher sensitivity to smaller temperature changes with less ground resolution (20–40 meters). The value of refined spectroscopy with high wave-length resolution ($\lambda/\delta\lambda \sim 10^3$) is also being explored. Infra-red of course extends the power of viewing to night-time and can defeat many forms of deception by camouflage.

For day-night and all-weather coverage, SAR imagery offers powerful capabilities, both in stand-alone operation and as a supplement to visible and multi-spectral imagery.

2.) Open Skies is a new and potentially valuable component of the verification system. We are just beginning to test and analyze its full potential. Viewing with multi-spectral sensors — visible, IR, LIDAR, and SAR — and from closer range than NTM, can help clarify ambiguities and provide useful triggers for raising challenges concerning suspected non-compliance. Open Skies is of unique value in that it can be used to provide an overt signal of suspicious activities that we may have learned of from sources and methods, perhaps covert or involving advanced and secret technological capabilities, that we do not wish to disclose.

The prospective enhancement of Open Skies to allow collection of air samples for gas and particulate analysis will increase its value in identifying clandestine activities.

3.) Cooperative verification includes a very broad range of technologies and operational procedures; altogether these can be very effective in uncovering covert activities. However, we face a tension in setting standards and requirements for monitoring activities by cooperative inspection: with more comprehensive and intrusive procedures we learn more about the other party and increase the probability of detecting a violation. At the same time, however, they may be able to learn more about us, including sensitive information, and because comprehensive procedures take time to set up, we both may lose opportunities for valuable progress during the currently open "window of opportunity."

There are several important elements to keep in mind in setting standards and requirements for detecting clandestine activities. One is the new transparency in Russia as a result of extensive emigration and contacts with present and former members of their military and nuclear establishments.

Secondly in today's world the disadvantage to Russia if we detect a violation is considerably greater than any benefit should they escape detection. And finally, successful cooperation between the two countries — on a personal, technical, and business level, as well as government-to-government — will in time, lead to higher confidence.

7.1 Recommendations

1. Continue strong R&D support for space-based sensors and systems for monitoring activities and changes.

2. Develop and support a strong R&D program for identifying and characterizing source signatures and multi-spectral optical, IR, LIDAR, SAR, and air-sampling sensors for Open Skies observations of activities.

3. Develop an effective monitoring system that integrates cooperative procedures with Open Skies and NTM without requiring unnecessary and unwanted intrusive and comprehensive procedures so that we can take full advantage of the current favorable circumstances for working with Russia to reduce the nuclear danger by dismantling/destroying warheads and ceasing production of SNM.

7.2 Conclusions and Observations

Throughout this report our primary focus has been on a bilateral U.S.-Russian context for verifying the dismantling/destroying of nuclear warheads, the cutoff on the production of SNM, and the storage and disposal of SNM. However over the past year, and since the Robinson Report was issued, the Soviet Union has ceased to exist and the former Soviet block has fragmented and developed more cooperative relations with the United States and our allies. Meanwhile, and particularly since the Gulf War, concerns about nuclear-proliferation and of other means of mass destruction have heightened.

As a result the verification communities are paying increased attention to monitoring and characterizing the proliferation threat. We note that many of the NTM techniques (both existing and future) most useful for monitoring nuclear weapons dismantlement and SNM materials controls *within* Russia would also be applicable for advances in technologies for non-proliferation monitoring. Both have room for a considerably enhanced capability.

It will also be valuable to reduce the Russian nuclear threat if we can make a deal on the basis of their recent proposals to sell sizable quantities of HEU to the industrialized west. Any such confirmation of a reduction of their weapons stockpile and inventory of SNM, coupled with our own reductions and the establishment of a strengthened international regime for maintaining controls against diversion or the development of new threats, will be of great value and should be pursued aggressively

A APPENDIX: TAGS AND SEALS*

Many types of physical tags are under development. We include a partial list below, with a short comment on each one: [36]

- Reflective particle tag (RPT), also known as "glitter paint," small flakes embedded in a plastic matrix. The most widely discussed of the tags, largely because it is inexpensive, and has received the most effort.
- Scanning electron microscope (SEM) images of tags or the surface of a treaty limited item (TLI). Present technology cannot duplicate the sub-micron structure visible in these images. Portable SEMs are under development.
- Holographic correlation; a holograph of a TLI surface is compared with the original; differences smaller than a wavelength of light can be discovered by the distortion of interference fringes.
- Subsurface ultrasonics, shows the structure of a seal in three dimensions. This method can also help assure a tag has not been removed.
- Eddy current scanning, shows voltonic structure in 3-D. Three dimensions are more difficult to duplicate than two.
- Geologic crystal acoustic microscopy; flaws in crystals cannot be duplicated with any known method. Sealing presents a problem because of the large size of the crystal; most of the crystal can be removed.
- Fluorescent fingerprint; ratios of spectral lines when illuminated under different wavelengths depend on the physical history of the tag as well

[36] Extracted from JSR-89-100A op. cit.

as the chemical makeup. The *amount* as well as the spectrum must be measured to make sure material from one tag has not been shared.

- DNA signature.
- Electronic tagging, possibly using cryptographic methods.

"Electronic tags" are physical tags based on the established technology of tamper-proof microchips. By a combination of passivating and antietch coatings, the information stored in a chip can be powered by batteries or else by induction fields only at the time of interrogation. The tag is the size of a wristwatch and can be designed for remote readout. All such verification tags for both the United States and the Soviet Union could be physically identical and made to specifications openly shared and inspected. Electronic tags can use either a cryptographic algorithm, or else a one-time pad.

A seal provides a means of ensuring that a tag remains attached to a treaty-accountable item. In most cases, the seal is simply some kind of physical glue believed to be unremovable by surreptious means. There are established sophisticated technologies for seals, utilized by the diplomatic and intelligence communities. The purpose of the seal can be either simply to attach the tag, or also to ensure that some accountable component limited by the treaty has not been altered (e.g., that a weapons compartment has not been opened). In the latter role, a seal based on current technology might be a multi-layer adhesive tape with a hologram (like those on credit cards) embedded in it, designed to tear apart if the tape is tampered with, and perhaps also with a unique fluorescent signature.

For electronic tags, fiber-optic technologies might be utilized to make seals that are more highly tamper resistant. The underlying idea is to have a loop of fiber optics with both ends terminated on a tamper-proof, powered, microchip. The chip sends coded interrogation pulses, one every few microseconds, through the loop of fiber. If the fiber is ever broken (even for a fraction of a millisecond), the chip permanently erases itself and powers off.

B APPENDIX : PLUTONIUM DISPOSAL IN THE OCEAN

The reduction in nuclear weapons has led to the problem of disposing of a quantity of order 100 tons of Pu^{239}. We consider disposal in the ocean.

If uniformly diluted through the roughly 10^{21} liters of ocean water, 100 tons of Pu^{239} would have a concentration of 10^{-13} g/ℓ. This may be compared to the concentration of 1.5×10^{-8} g per ℓ considered acceptable in waste-water discharge [*Plutonium Handbook*, p. 583]. The natural concentration of U^{238} in seawater of 3 μg/ℓ produces more than 100 times the radioactivity of uniformly distributed Pu^{239}, even though the uranium has a half-life about 200,000 times longer. It is clear that at a dilution of 10^{-13} g per ℓ re-extraction of Pu^{239} would be uneconomical (to obtain 1 kg would require extraction from $10^{16}\ell$ of seawater, roughly equal to the volume of rain which falls on the United States in a year), so ocean disposal may safely be considered permanent and irreversible. However, the kinetics of plutonium scavenging are a nontrival problem in chemical oceanography which is worthy of investigation.

The plutonium may be introduced as a soluble compound into the deep ocean water by an outfall pipe extending off a continental shelf to the abyssal slope. It would then be mixed throughout an ocean basin on a time scale of roughly 1,000 years.

The magnitude of the pumping facilities required depends on the degree of dilution required at the outfall. The standard of 1.5×10^{-8} g per ℓ for water discharged to fresh water sources cannot reasonably be achieved within the outfall pipe, but will be achieved in a turbulent mixing zone at its end. For discussion, we consider the disposal of 100 tons of Pu^{239} in 10 years at a flow of $10^5 \ell$ per sec. This flow is roughly comparable to the water supply to the Los Angeles or New York metropolitan areas, and requires a $r_o = 2.5$ m pipe carrying water at $v_o = 5$ m/sec. The cost of the plutonium disposal system would be much less, because the length of pipe is less, and it can be laid on the seabed rather than being tunneled through the land. The power required to pump this flow to an outfall 150 km offshore is 500 MW (taking a friction factor of 0.012, appropriate to a smooth-walled pipe), and varies as the 2.5 power of the assumed velocity or the -5 power of the assumed pipe radius; pumping power may be traded off against the capital cost of larger pipes. To avoid excessive pressures at the pumping station (about 700 psi for this example), several booster pumps along the pipe would be required. These boosters would have to be submerged. Pumping and piping requirements are reduced if the discharge of more concentrated plutonium solutions is permitted. The required power P $\propto \dot{m}^{2.5}/r_o^5$, so that a tenfold reduction of the flow rate (implying a tenfold increase in Pu concentration) and a reduction of r_o to 1 m reduces the power requirement to a modest 150 MW.

It may be desirable that the plutonium-containing water be nearly neutrally buoyant at the depth and location of outfall, in order that it not form a plume rising to the surface (where biological concentration is possible) or a stable sublayer on the bottom. A rough estimate shows that for our flow parameters, a 2 cm steel pipe wall is a good heat exchanger. Surface water may be taken from the coast; the pumped water relaxes to the ambient temperature with an e-folding length of about 10 km.

Small differences in buoyancy (such as those resulting from excess surface salinity or incomplete thermal relaxation) may be adjusted by the addition of salt or fresh water; for example a 1° temperature excess (at 4°C) may be compensated by an increase in salinity of 1 part in 10^4, or 10 kg per sec of salt (1000 tons per day), while a 1° deficit may be compensated by the addition of 0.3% fresh water (300 ℓ per sec). It may be that such fine density control is not required, as a modest residual buoyancy may lead to (desirable) vertical mixing.

At a flow rate of 10^5 ℓ per sec the Pu^{239} concentration would be 3μg per liter, about 200 times that permitted in fresh water discharged to waterways. It is therefore necessary to consider a final stage of dilution. We consider three possible mechanisms: a momentum-driven free jet, a buoyancy-driven free plume, and deliberate mechanical mixings.

1. We first consider the momentum-driven jet, taking our canonical flow rate of 10^5 ℓ per sec at 5 m per sec (the single governing parameter is the jet momentum).

Once the water leaves the outflow pipe, it entrains clean ocean water and forms a turbulent jet, initially of canonical shape and half-angle ≈ 0.1 radian. The radius of this jet is roughly $r \approx 0.1L$, where L is the distance from the outfall, its velocity $v \approx v_o r_o / r$, and the entrained mass flux varies as r/r_o. The plutonium concentration varies as r^{-1}. By the time the jet is 100 m in radius (about 1 km from the outfall), the plutonium concentration has fallen to roughly 8×10^{-8} g per ℓ. This fluid takes between one and two hours to reach that point. The entrainment of ambient water implies that the plutonium is now contained in water whose buoyancy is essentially ambient at the discharge point.

The typical deep-ocean Brunt-Väisälä period is 2 hours, so further spreading of a neutrally buoyant jet is only horizontal, unless the waste is discharged into neutrally buoyant Arctic or Antarctic water. Such a horizontal wedge-shaped (100 m thick) jet will gradually entrain further seawater, with velocity and plutonium concentration now decreasing $\approx r^{-1/2}$. The desired value of 1.5×10^{-8} g per ℓ would be reached about 25 km from the outfall. Ultimately, turbulent internal motion would provide further dilution by vertical mixing as well as horizontal shear.

2. An alternative method of mixing the plutonium in the ocean is to introduce it at negligible velocity dissolved in a fluid with a large buoyancy excess or deficit (for example, fresh water at the bottom or concentrated brine high above the bottom). If we ignore the effects of any momentum it carries, an elementary analysis shows that a buoyancy-driven plume will rise to a height (or fall to a depth) *from the release point*

$$z = \left(\frac{gS_o}{\rho\theta^2 w_{BV}^3}\right)^{1/4},$$

where S_o is the magnitude of the source of buoyancy (difference in equivalent density $\Delta\rho$ multiplied by volume flux $\dot{V}$), θ is the half-angle of the canonical buoyancy plume, g the acceleration of gravity, and w_{BV} the Brunt-Väisälä angular frequency. The dilution factor of introduced material is

$$F = \left(\frac{g\Delta\rho}{\rho}\right)^{3/4} w_{BV}^{-5/4}\theta^{1/2}\dot{V}^{-1/4}.$$

Substituting numerical values $\dot{V} = 10^4 \ell per$sec, $w_{BV} = 10^{-3}$ sec^{-1} (appropriate to the deep ocean), $\Delta\rho = 0.3$ g per cm^3 (corresponding to saturated brine), and $\theta = 0.1$ radian, yields $z = 1,300$ m and $F = 2300$. These values provide sufficient dilution to reduce the pipe concentration of 30μg per ℓ to the allowed fresh-water discharge concentration of 1.5×10^{-8} g per ℓ

at the bottom of the (negatively buoyant) discharge plume. The required fluid flux in the pipe is one tenth that assumed in the neutrally buoyant jet mechanism, reducing the pumping and piping costs by a large factor. The required quantity of salt is, however, 3 tons per sec (100,000,000 tons per year), which may be unacceptably expensive (it is for this reason that we took $\dot{V}$ ten times smaller than in the discussion of the momentum-driven jet). Use of multiple discharges with smaller $\dot{V}$ leads to greater dilution factors, but the improvement obtained is slow (only the 4th root of $\dot{V}$). Similarly, use of larger volumes of less saline brine permits a 4th root reduction in the required quantity of salt.

3. In the third approach, a comparatively concentrated plutonium solution is pumped to the discharge point, where it is mixed with ambient ocean water by a giant turbine. The volume pumped through the long pipe may be 10^4 ℓ per sec, as in (2) above, or less, depending on the acceptable Pu concentration in the pipe, so that pipe and pumping costs are much smaller than in (1). At the discharge point, the more concentrated solution is fed through a large number of distributed orifices into a turbulent mixing chamber, through which a giant turbine drives a flow of 2×10^7 ℓ per sec, sufficient to reduce the concentration to the required 1.5×10^{-8} g/l. As a numerical example, a 100 MW turbine is sufficient to drive this fluid flow to a speed of 3 m/sec, at which the required turbine radius is 45 m. This requires a rather formidable structure; the net force on the water is about 14,000,000 lb, and bending moments on the blades exceed 10^9 ft-lb. The turbine blades could have the stiffness required to avoid gross deflection if they were hollow structures several meters thick. The engineering problems of design and fabrication are not insoluble, but the cost is not known. It should be noted that the turbine will not re-ingest most of its exhaust, because the intake and output flow fluids

are very different; the latter is a directed jet, while the former is roughly an isotropic area half-space (as is familiar from an ordinary window fan).

In each method of mixing, the fluid ultimately enters the ocean gyres, whose flow fluid assists the mixing. Numerical calculation is necessary for quantitative results, but it is apparent that the required dilution may be achieved earlier and more easily than we have estimated from the ocean at rest.

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Mr Ralph W Alewine, I I I
Director
DARPA/NMRO
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Arlington, VA 22203-1714

Mr Robert T Andrews
Department of Energy Field Offices
University of California
Lawrence Livermore National Lab
P O Box 808/L-389
Livermore, CA 94550

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DARPA/NMRO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Dr H Lee Buchanan, I I I
Director
DARPA/DSO
3701 North Fairfax Drive
Arlington, VA 22203-1714

Dr Curtis G Callan, Jr
Physics Department
PO Box 708
Princeton University
Princeton, NJ 08544

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Deputy Assistant Secretary for Weapons
Complex Reconfiguration
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Washington, DC 20520

Mr Theodore E Divine
Department of Energy Field Offices
Idaho National Engineering Lab/EG&G
P O Box 1625, MS 3411
Idaho Falls, ID 83415-3411

Dr Nancy Dowdy
USACDA
320 21st Street NW
Washington, DC 20451

Professor Freeman J Dyson
Institute for Advanced Study
Olden Lane
Princeton, NJ 08540

Dr Douglas M Eardley
618 Miramonte Drive
Santa Barbara, CA 93109

Radm Wilford G Ellis
Deputy Assistant Secretary for
Military Applications
DP-20 (4C-024/FORS)
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Mr John N Entzminger
Chief Advance Technology
DARPA/DIRO
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Capt Kirk Evans
Director Undersea Warfare
Space & Naval Warfare Sys Cmd
Code PD-80
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FM-15
University of Washington
Seattle, WA 98195

Adm (R) Thomas Fox
Department of Energy Field Offices
Pacific Northwest Laboratory
MS P7-35
P O Box 999
Richland, WA 99352

Col Mike Fry
Arms Control CW/SNF Advisor
National Security Council
Washington, DC

Dr James Fuller
Department of Energy Field Offices
Pacific Northwest Laboratory
MS P7-35
P O Box 999
Richland, WA 99352

Dr Richard L Garwin
IBM TJ Watson Research Center
PO Box 218
Route 134 and Taconic State Parkway
Yorktown Heights, NY 10598

Brig Gen John Gordon
Chairman Arms Control Policy
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National Security Council
Washington, DC

Mr Bradley Gordon
Assistant Director Bureau of Non-Proliferation Policy /ACDA
320 21st Street NW
Washington, DC 20451

Dr S William Gouse
Sr Vice President and General Manager
The MITRE Corporation
Mail Stop Z605
7525 Colshire Drive
McLean, VA 22102

Mr Douglas R Graham
Deputy Assistant Secretary for Strategic
Defense, Space & Verification Policy
Office of the Secretary of Defense
The Pentagon
Washington, DC 21311

Mr William R Grundemann
Arms Control & Non-Proliferation Div
Intelligence Community
The Pentagon
Washington, DC 20505

Mr Stephen J Hadley
Assistant Secretary for International
Security Policy
Office of the Secretary of Defense
The Pentagon
Washington, DC 21311

Dr David A Hammer
109 Orchard Place
Ithaca, NY 14850

Mr Stephen Read Hammer, Jr
Deputy Director/ACDA
320 21st Street NW
Washington, DC 20451

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Mr Thomas H Handel
Office of Naval Intelligence
The Pentagon, Room 5D660
Washington, DC 20350-2000

Dr William Happer
Director
Science and Technology Advisor
ER-1 (7B-058/FORS)
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Maj G Hard
Director of Space and SDI Programs
Code SAF/AQS
The Pentagon
Washington, DC 20330-1000

Dr Robert G Henderson
Director
JASON Program Office
The MITRE Corporation
7525 Colshire Drive
Mailstop Z561
McLean, VA 22102

Mr James Hirsch
Deputy Director for Science & Technology
Intelligence Community
Washington, DC 20505

Ms Sally K Horn
Director Verification Policy
Office of the Secretary of Defense
The Pentagon
Washington, DC 21311

Dr Barry Horowitz
President and Chief Executive Officer
The MITRE Corporation
202 Burlington Road
Bedford, MA 01730-1420

Dr William E Howard I I I [2]
Director
Space and Strategic Technology Office
Assistant Secretary of the Army
The Pentagon, Room 3E474
Washington, DC 20310-0103

Admiral Jonathan T Howe
Chairman Deputies Committee
National Security Council
Washington, DC

Dr Gerald J Iafrate
US Army Research Office
PO Box 12211
4330 South Miami Boulevard
Research Triangle Pk, NC 27709-2211

Dr Joseph P Indusi
Department of Energy Field Offices
Brookhaven National Laboratory
Building 197C
Upton, NY 11973

J A S O N Library [5]
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Mail Stop W002
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McLean, VA 22102

Dr George Jordy [25]
Director for Program Analysis
US Department of Energy
ER30 OER
Washington, DC 20585

Dr O' Dean P Judd
Los Alamos National Lab
Mail Stop A-110
Los Alamos, NM 87545

DISTRIBUTION LIST

Dr Bobby R Junker
Office of Naval Research
Code 412
800 North Quincy Street
Arlington, VA 22217

Mr William Kahn
Director Theater Nuclear Forces Policy
Office of the Secretary of Defense
The Pentagon
Washington, DC 21311

Mr Arnold L Kanter
Under Secretary of State for
Political Affairs
2201 C Street, NW
Washington, DC 20520

Dr Steven E Koonin
Kellogg Radiation Laboratory
106-38
California Institute of Technology
Pasadena, CA 91125

Mr Max A Koontz
Director Systems and Technology Div
AN-10.1 (GA-045/FORS)
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Col Harold Kowalski
Nuclear Risk Reduction Center
State Department
2201 C Street, NW
Washington, DC 20520

Col Hard Kowalski
Science, Technology & Proliferation Div
2201 C Street, NW
Washington, DC 20520

Lt Gen Edward Leland
Director Strategic Plans and Policy
The Joint Staff
The Pentagon
Washington, DC 20305

Lt Gen Edward Leland
Director, Strategic Plans and Policy
The Joint Staff
The Pentagon
Washington, DC 20305

Dr Nate Lewis
5259 Gould Avenue
La Canada, CA 91011

Mr Allen Locke
Science, Technology & Proliferation Div
State Department
2201 C Street, NW
Washington, DC 20520

Mr Frank A Loturco
Deputy Director for Counterintelligence
On-site Inspection Agency
P O Box 17498
Washington, DC 20041-0498

Mr Doug Maceachin
Special Assistant for Arms Control
Intelligence Community
Washington, DC 20505

Mr Robert Madden [2]
Department of Defense
National Security Agency
Attn: R-9 (Mr. Madden)
Ft George G Meade, MD 20755-6000

Dr Arthur F Manfredi Jr [10]
OSWR
Central Intelligence Agency
Washington, DC 20505

DISTRIBUTION LIST

Ms Michelle Markoff
Office of Senior Advisor and Policy
Planning Group/ACDA
320 21st Street NW
Washington, DC 20451

Mr Joe Martin
Director
OUSD(A)/TWP/NW&M
The Pentagon, Room 3D1048
Washington, DC 20301

Mr James J Mattice
Deputy Assistant Secretary
SAF/AQ
The Pentagon, Room 4D-977
Washington, DC 20330-1000

Dr Claire Max
617 Grizzly Peak Boulevard
Berkeley, CA 94708

Mr Scott Mc Kenney
Department of Energy Field Offices
Martin-Marietta Energy Systems, Inc
P O Box 2003
MS P7-35
Oak Ridge, TN 37831

Mr Franklin C Miller
Deputy Assistant Secretary for Nuclear
Forces and Arms Control Policy
Office of the Secretary of Defense
The Pentagon
Washington, DC 21311

Mr Lee P Minichiello
Deputy Director for Strategic Arms
Control and Compliance
Office of the Secretary of Defense
The Pentagon
Washington, DC 21311

Mr Douglas P Mulholland
Assistant Secretary for Intelligence
and Research
State Department
2201 C Street, NW
Washington, DC 20520

Dr Richard A Muller
2831 Garber Street
Berkeley, CA 94705

Mr. Ronald D Murphy
Director
DARPA/ASTO
3701 North Fairfax Drive
Arlington, VA 22203

Dr Julian C Nall
Institute for Defense Analyses
1801 North Beauregard Street
Alexandria, VA 22311

Mr Larry C Napper
Office of Independent States and
Commonwealth Affairs
State Department
2201 C Street, NW
Washington, DC 20520

Mr David Nickels
Office of Arms Control Policy
for Implementation
State Department
2201 C Street, NW
Washington, DC 20520

Mr Michael F O' Connell
On-Site Monitoring Group Leader
AN-10.1 (GA-045/FORS)
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

DISTRIBUTION LIST

Mrs Hazel Rollins O' Leary
Secretary of Energy
S-1 (7A-257/FORS)
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dr Gordon C Oehler
Central Intelligence Agency
Washington, DC 20505

Dr Wolfgang K Panofsky
Stanford Linear Accelerator Center
Bin #76
P O Box 4349
Stanford, CA 94309

Dr Peter G Pappas
Chief Scientist
US Army Strategic Defense Command
PO Box 15280
Arlington, VA 22215-0280

Maj Gen Robert W Parker
Director OSIA
P O Box 17498
Washington, DC 20041-0498

Dr Ari Patrinos
Director
Environmental Sciences Division
ER74/GTN
US Department of Energy
Washington, DC 20585

Dr Bruce Pierce
USD(A)D S
The Pentagon, Room 3D136
Washington, DC 20301-3090

Mr Hugo Pomrehn
Under Secretary of Energy
S-3 (7A-219/FORS)
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Mr Daniel Poneman
Arms Control Non-Proliferation Adviso
National Security Council
Washington, DC

Dr William H Press
Harvard College Observatory
60 Garden Street
Cambridge, MA 02138

Mr John Rausch [2]
Division Head 06 Department
NAVOPINTCEN
4301 Suitland Road
Washington, DC 20390

Records Resource
The MITRE Corporation
Mail Stop W115
7525 Colshire Drive
McLean, VA 22102

Dr Sally K Ride
UCSD
California Space Institute
9500 Gilman Drive
La Jolla, CA 92093-0221

Brig Gen Ted E Rinebarger
Assistant Deputy Director of
International Negotiations
The Joint Staff
The Pentagon
Washington, DC 20305

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Mr John M Rooney
Director Office of Export Control
& International Safeguards
AN-30 (GA-045/FORS)
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dr Marshall N Rosenbluth
Physics Department
Mayer Hall/B-019
University of California/San Diego
La Jolla, CA 92093

Dr Malvin A Ruderman
29 Washington Square West
New York, NY 10027

Mr Alan Ryall
Deputy Director Nuclear Monitoring
Research Office
Defense Advanced Research Project
3701 North Fairfax Drive
Arlington, VA 22203-1714

Dr Fred E Saalfeld
Director
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Mr Mark B Schneider
Principal Director
Office of the Secretary of Defense
The Pentagon
Washington, DC 21311

Dr John Schuster
Technical Director of Submarine
& SSBN Security Program
Department of the Navy OP-02T
The Pentagon, Room 4D534
Washington, DC 20450-2000

Dr Barbara Seiders [2]
Chief of Research
Office of Chief Science Advisor
ACDA
320 21st Street NW
Washington, DC 20451

Mr Thomas A Sellers
Department of Energy Field Offices
Sandia National Laboratories
P O Box 5800
Albuquerque, NM 87185

Dr Philip A Selwyn [2]
Director
Office of Naval Technology
Room 907
800 North Quincy Street
Arlington, VA 22217-5000

Mr Richard Sokolsky
Office of Strategic & Theatre Policy
State Department
2201 C Street, NW
Washington, DC 20520

Ms Linda G Stuntz
Deputy Secretary of Energy
S-2 (7B-252/FORS)
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dr Jeremiah D Sullivan
604 Burkwood Court, East
Urbana, IL 61801

Superintendent
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Monterey, CA 93943

DISTRIBUTION LIST

Mr James P Timbie
Senior Advisor to Deputy Secretary of State
State Department
2201 C Street, NW
Washington, DC 20520

Dr Armando Travelli
Argonne National Laboratory
Department of Energy Field Offices
9700 South Cass Avenue
Argonne, IL 60439-4822

Dr Sam B Treiman
69 McCosh Circle
Princeton, NJ 08540

Dr James M Turner
Associate Director for Weapons Safety
DP-20.1 (A-386/GTN)
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585

Dr George W Ullrich [3]
Deputy Director
Defense Nuclear Agency
6801 Telegraph Road
Alexandria, VA 22310

Ms Michelle Van Cleave
Asst Dr/National Security Affairs Office
Science and Technology Policy
New Executive Office Building
17th and Pennsylvania Avenue
Washington, DC 20506

Mr Vann Van Diepen
Office of Weapons Proliferation Policy
State Department
2201 C Street, NW
Washington, DC 20520

Mr Richard Vitali
Director of Corporate Laboratory
US Army Laboratory Command
2800 Powder Mill Road
Adelphi, MD 20783-1145

Dr Steven Weinberg
Physics Department - Theory Group
Robert Lee Moore Hall - Room 5208
The University of Texas at Austin
Austin, TX 78712-1081

Dr Edward C Whitman
Deputy Asst Secretary of the Navy
C3I Electronic Warfare & Space
Department of the Navy
The Pentagon, Room 4D745
Washington, DC 20350-5000

Rear Admiral H D Wisely
Director for Operations
Defense Nuclear Agency
Washington, DC 20305

Mr Paul D Wolfowitz
Under Secretary of Defense for Policy
Office of the Secretary of Defense
The Pentagon
Washington, DC 21311

Mr Roy Woodruff
Department of Energy Field Offices
Los Alamos National Laboratory
P O Box 1663
Los Alamos, NM 87545

Mr Donald J Yockey
U/Secretary of Defense For Acquisition
The Pentagon, Room 3E9333
Washington, DC 20301-3000

DISTRIBUTION LIST

Dr Herbert F York
IGCC (D-018)
University of California/San Diego
La Jolla, CA 92093

Dr Fredrik Zachariasen
California Institute of Technology
452-48
1201 East California Street
Pasadena, CA 91125

Dr Linda Zall
Central Intelligence Agency
Washington, DC 20505

Mr Charles A Zraket
Trustee
The MITRE Corporation
Mail Stop A130
202 Burlington Road
Bedford, MA 01730