How To Dismantle an Atomic Bomb

On Overview of the Global Zero Nuclear Warhead Verification Project

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Background

Nuclear Weapons After the Cold War
and the Challenge of Verifying Nuclear Disarmament
“While the new START treaty is an important step forward, it is just one step on a longer journey. As I said last year in Prague, this treaty will set the stage for further cuts. And going forward, we hope to pursue discussions with Russia on reducing both our strategic and tactical weapons, including non-deployed weapons.”

U.S. President Obama, upon signing the New START Treaty, April 2010
Thousands of Nuclear Weapons Are No Longer Deployed and Currently In Storage

W87/Mk-21 Reentry Vehicles in storage, Warren Air Force Base, Cheyenne, Wyoming

Photo courtesy of Paul Shambroom, www.paulshambroom.com
What Are We Worried About?
(The Challenges of Nuclear Disarmament Verification)
Example (U.S. Nuclear Arsenal, 2013)

- 1,650 Deployed strategic warheads (as declared under New Start, March 2013)
- 2,150 Total deployed warheads (estimated)
- 4,650 Total stockpile, including reserve (declared, 5,113 as of September 2009)
- 7,700 Total stockpile, including reserve and retired (but intact) warheads (estimated)

Example
Notional Cheating Scenarios

Tampering with declared treaty accountable items (under a disarmament regime with verified warhead dismantlement)
What About the Secret Nuclear Weapons Stockpile Stashed Away on that Remote Island?
Notional Cheating Scenarios

Tampering with declared treaty accountable items (under a disarmament regime with verified warhead dismantlement)

Keeping undeclared warheads
“Hawaii Option”
Main Cheating Scenarios and Associated Verification Challenges

1. **Party offers hoax or tampered devices instead of authentic treaty accountable items (TAI) so that real warheads, warhead components, or fissile material can be “diverted” to a secret stockpile of nuclear weapons**

   ➔ Verifying the dismantlement of nuclear warheads

2. **Party provides incomplete baseline declarations so that some treaty accountable items (e.g. warheads) are never part of the verification regime**

   ➔ Verifying the completeness of declarations

3. **Party has undeclared fissile material production capacities, which are used to supply material for new weapons, e.g. to replace dismantled TAI**

   ➔ Verifying the non-production of new fissile material for weapons
   
   (Same challenge for NPT and FMCT)
Verified Warhead Dismantlement
(Previous Efforts)
Nuclear Warheads Have Unique Signatures
(but most of them are sensitive and cannot be revealed)

Gamma radiation spectrum from a Soviet warhead measured in 1989

Steve Fetter, Thomas B. Cochran, Lee Grodzins, Harvey L. Lynch and Martin S. Zucker
Inspection Systems for Nuclear Warhead Verification Have Been Under Development Since the 1990s

**Attribute Approach**
Confirming selected characteristics of an object in classified form (for example, the presence/mass of plutonium)

**Template Approach**
Comparing the radiation signature from the inspected item with a reference item ("golden warhead") of the same type

**Information Barrier**
Technologies and procedures that prevent the release of sensitive nuclear information (needed for both approaches)

Edited by David Spears, 2001
Warhead Dismantlement Verification

Some Precedents Exist and Future Work Can Build on Them

Inspection System developed as part of the 1996–2002 Trilateral Initiative during a demonstration at Sarov
*Source: Tom Shea*

Visual contact with a mockup nuclear weapon during a UK-Norway Initiative Dismantlement Exercise
*Source: UK Norway Initiative, David Keir*
“After all these years, no one has yet demonstrated either an attribute or template type system using a classified test object in such a way that specialists from the inspecting country can then thoroughly examine and proof the measurement equipment.”

James Fuller, October 2012
Global Zero Verification Project
Princeton/PPPL Verification Project

GENERAL APPROACH

- Use 14.1-MeV neutron source ($10^8$ n/s) available at PPPL
- Use unclassified test objects that do not contain fissile materials (tungsten, lead, depleted uranium, ...)
- Template approach without information barrier
- Validate conceptual approach with simulated data

Project currently funded by Global Zero (www.globalzero.org) and U.S. Department of State and previously supported by PPPL Proposal Development Funds
What We Don’t Use
(and Don’t Need for Our Proof-of-concept)

Mockup of a MK-12 Reentry Vehicle with a W62 warhead
(Note: the final W62 was dismantled in August 2010, www.energy.gov/articles/dismantling-history-final-w62-warhead)
What We Use Instead

“British Test Object”

Experimental Setup

- Neutron source
- Neutron collimator (polyethylene)
- British Test Object in container
- Detector array (367 bubble detectors)
How Do We Prevent Sensitive Information from Being Detected?

(Basic Inspection Protocol)
We Use a Zero-Knowledge Protocol

7,779,194,804,244,557

is not a prime number

23,985,737 x 324,325,861 = 7,779,194,804,244,557

Can one prove that a number is not a prime without revealing its factors?
“Number of Marbles in a Cup”

Alice has two small cups each containing the same number of marbles. She wants to prove to Bob that both cups contain the same number of marbles without revealing to him what this number is.
“Number of Marbles in a Cup”

1. Alice claims that the two cups contain the same number of marbles

   She then also offers two buckets of marbles

   Presumably, these buckets also contain an identical number of marbles

2. Bob can choose into which bucket which cup is poured
   (L,L) and (R,R) or (L,R) and (R,L)

3. Bob is now allowed to count the marbles in each bucket and should find the same number in both

   50% confidence after 1st game
   75% confidence after 2nd game
   99% confidence after 7th game
Bubble Detectors May Offer A Way To Implement this Protocol
(and Avoid Electronics on the Detector Side)

Detectors with different neutron-energy thresholds are available
(no cutoff, 500 keV, 1 MeV, 10 MeV)
Inspection Protocol
(simplified)

1. Template ("Golden warhead") selected at deployment site
   Warheads offered for inspection/dismantlement (presumably already in storage)

2. Template and test items are placed in sealed containers
   All items are brought to a dedicated dismantlement facility
Proposed “Hardware Implementation” of a Zero-Knowledge Protocol for Warhead Verification

After every measurement, each bubble detector has “exactly” the same number ($N_{\text{MAX}}$) of bubbles.

Since the host knows the “secret” (i.e., the design of the warhead), she can individually preload pairs of detectors for every orientation/direction so that they will be “topped up” to $N_{\text{MAX}}$ during the measurement.

<table>
<thead>
<tr>
<th>Before measurement</th>
<th>After measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₁ B₁</td>
<td>A₁ B₁</td>
</tr>
<tr>
<td>A₂ B₂</td>
<td>A₂ B₂</td>
</tr>
<tr>
<td>A₃ B₃</td>
<td>A₃ B₃</td>
</tr>
<tr>
<td>A₄ B₄</td>
<td>A₄ B₄</td>
</tr>
</tbody>
</table>

Preload is unknown to inspector, i.e., bubble detectors are “wrapped in black tape”

For every position, inspector chooses, which detector (Aᵢ, Bᵢ) to use on golden warhead or on test item

(so that it becomes impossible for the host to conceal a spoof by unequally initializing the detectors)
### Inspection Protocol (simplified)

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Template</strong>&lt;br&gt;(&quot;Golden warhead&quot;) selected at deployment site&lt;br&gt;Warheads offered for inspection/dismantlement (presumably already in storage)</td>
</tr>
<tr>
<td>2</td>
<td><strong>Template and test items</strong>&lt;br&gt;are placed in sealed containers&lt;br&gt;All items are brought to a dedicated dismantlement facility</td>
</tr>
<tr>
<td>3</td>
<td><strong>Inspector announces</strong>&lt;br&gt;which detector positions she wants to measure&lt;br&gt;Host prepares pairs of preloaded bubble detectors</td>
</tr>
<tr>
<td>4</td>
<td><strong>Inspection</strong>&lt;br&gt;is carried out (template vs test item)&lt;br&gt;Inspector should find the number $N_{\text{max}}$ in all measurements</td>
</tr>
</tbody>
</table>
Valid versus Suspect/Invalid Item

Simulated data (MCNP5) for $N_{\text{MAX}} = 1000$ bubbles per detector

Radiograph (never measured)  Valid Item  Another valid item

- Small deviations from $N_{\text{MAX}}$
- Significant deviations from $N_{\text{MAX}}$ (2.0, 2.5, 3.0 sigma)
Valid versus Suspect/Invalid Item

Simulated data (MCNP5) for $N_{\text{MAX}} = 1000$ bubbles per detector

- Radiograph (never measured)
- Valid Item
- Invalid Item

- Diversion Scenario A
  (tungsten rings replaced by lead rings)

Small deviations from $N_{\text{MAX}}$

Significant deviations from $N_{\text{MAX}}$ (2.0, 2.5, 3.0 sigma)
Statistical Noise of Measurement $= (N_{MAX})^{0.5}$

(No information in signal or its noise)
Localized Diversions

and the “Battleship Game Approach”
Localized Tungsten Diversion

36-degree segment of outer tungsten ring (543 grams, 7% of total tungsten)
Diversion Scenario B

Simulated data (MCNP5) for $N_{\text{MAX}} = 1000$ bubbles per detector

BTO in Orientation 1 (unknown to inspector)
Bubble detectors are sensitive to neutron energies above 1 MeV

- Measurement 1
- Measurement 2
- Measurement 3

- Small deviations from $N_{\text{MAX}}$
- Significant deviations from $N_{\text{MAX}}$ (2.0, 2.5, 3.0 sigma)
Diversion Scenario B

Simulated data (MCNP5) for $N_{\text{MAX}} = 1000$ bubbles per detector

BTO in Orientation 2 (unknown to inspector)
Bubble detectors are sensitive to neutron energies above 1 MeV

- Measurement 1
- Measurement 2
- Measurement 3

![Graphs showing bubble detection patterns](image)

- Small deviations from $N_{\text{MAX}}$
- Significant deviations from $N_{\text{MAX}}$ (2.0, 2.5, 3.0 sigma)
Scoring Function

Detector counts $X_1 \ldots X_n$ are independent Poisson variables with expectation $N_{\text{max}}$ (approximated in the following as normal variables)

Define $\ell$-pixel “windows” with standard normal variables $Y_j$

(k windows can be tested across the detector bank)

$$Y_j = \left( \sum_{i=1}^{\ell} (X_i - N_{\text{max}}) \right) / \sqrt{\ell N_{\text{max}}}$$

$$S = \max_j |Y_j|$$

Test is positive (“diversion detected”) if score $S > T$

$T$ is computed such that a valid item fails the test with probability $p = 0.05$

$T$ depends on the number of windows; e.g. for $k = 295$, $T = 3.76$
Results

Based on 10,000 simulations using results from MCNP5 calculations
Bubble detectors are sensitive to neutron energies above 1 MeV

<table>
<thead>
<tr>
<th>Match</th>
<th>Success Rate (Score)</th>
<th>“295-pixel” (1 draw)</th>
<th>“7-pixel” (295 draws)</th>
<th>“1-pixel” (295 draws)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation 1</td>
<td>95% (0.82 ± 0.62)</td>
<td>95% (3.03 ± 0.40)</td>
<td>95% (3.08 ± 0.36)</td>
<td></td>
</tr>
<tr>
<td>Scenario A</td>
<td>&gt; 99.9% (11.32 ± 1.00)</td>
<td>&gt; 99.9% (7.69 ± 0.62)</td>
<td>&gt; 99.9% (5.96 ± 0.52)</td>
<td></td>
</tr>
<tr>
<td>Orientation 1</td>
<td>61.0% (2.23 ± 0.98)</td>
<td>&gt; 99.9% (12.84 ± 1.06)</td>
<td>&gt; 99.9% (10.57 ± 1.03)</td>
<td></td>
</tr>
<tr>
<td>Scenario B</td>
<td>24.3% (1.38 ± 0.87)</td>
<td>99.6% (6.35 ± 0.96)</td>
<td>97.1% (5.28 ± 0.91)</td>
<td></td>
</tr>
<tr>
<td>Orientation 2</td>
<td>10.5% (0.98 ± 0.72)</td>
<td>13.0% (3.21 ± 0.50)</td>
<td>7.0% (3.16 ± 0.40)</td>
<td></td>
</tr>
<tr>
<td>Scenario B</td>
<td>10.5% (0.98 ± 0.72)</td>
<td>13.0% (3.21 ± 0.50)</td>
<td>7.0% (3.16 ± 0.40)</td>
<td></td>
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A. Glaser, Zero-Knowledge Nuclear Warhead Verification, Massachusetts Institute of Technology, 2013
What’s Next?
Way Forward

**THIS PROJECT**

Provide proof-of-concept experimentally

Zero-knowledge protocols appear as an important new approach to nuclear warhead verification

**DISARMAMENT VERIFICATION IN GENERAL**

Concepts and technologies need to be developed now in order to be available for the next round of arms-control negotiations
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