Nonproliferation Challenges – S&T Solutions

Monitoring Centrifuges and Blend Down

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Simple Steps to Proliferation

• Obtain nuclear material
  – Purchase or steal materials
  – Enrich uranium
  – Extract plutonium from spent nuclear fuel

• Build the weapon
  – Designs out there
  – Engineering problem – not new science

• Deliver the weapon
  – Missile
  – Mini-van?
## Dual Nature of the Nuclear Threat

<table>
<thead>
<tr>
<th></th>
<th>National</th>
<th>Sub-National</th>
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<tbody>
<tr>
<td><strong>Who seeks nukes?</strong></td>
<td>“Rogue” states</td>
<td>Sophisticated terrorists</td>
</tr>
<tr>
<td><strong>Why?</strong></td>
<td>Deterrence, prestige, scientific momentum</td>
<td>Catastrophic use against civilians</td>
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<tr>
<td><strong>What kind of weapon?</strong></td>
<td>Ballistic-missile delivered warhead</td>
<td>Covertly-delivered improvised nuclear device</td>
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<td><strong>How many?</strong></td>
<td>Dozens to hundreds</td>
<td>Handful or fewer</td>
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<tr>
<td><strong>How obtain?</strong></td>
<td>National program, perhaps clandestine</td>
<td>Theft of weapon or fissile material (likely HEU)</td>
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<td><strong>Technical needs?</strong></td>
<td>Nuclear fuel cycle; weapons &amp; delivery systems design, testing &amp; manufacturing</td>
<td>Rudimentary nuclear materials processing &amp; handling, simple gun-type design</td>
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<tr>
<td><strong>Sources of technology?</strong></td>
<td>Black market, weapons states, legitimate purchase</td>
<td>Black market, insiders, open literature</td>
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<tr>
<td><strong>Most sought-after input?</strong></td>
<td>Reliable, miniaturized warhead design</td>
<td>100+ kg of HEU (enough for gun-type bomb)</td>
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“No nuclear material…no nuclear terrorism”--- Former Sen. Sam Nunn
Technology Development in Support of Nonproliferation Objectives

Example 1 – Monitoring Centrifuge Enrichment
- Overview of Uranium Enrichment
- International Atomic Energy Agency (IAEA)
- Enrichment Safeguards - Concerns
- Technology Development

Example 2 – Monitoring HEU Blend Down
- HEU Purchase Agreement
- HEU Transparency Program
- Technology Application
Uranium – A Quick Primer

• Uranium found in nature is called natural or normal uranium

• Its isotopic composition is:
  0.0054% U-234 (92 protons, 142 neutrons)
  0.72% U-235 (92 protons, 143 neutrons)
  ~99.3% U-238 (92 protons, 146 neutrons)

• Concentration of the U-235 isotope above its natural value is called - uranium enrichment

• LEU – Low Enriched Uranium defined as <20% U-235

• HEU – High Enriched Uranium defined as >20% U-235

• Light water reactors (LWRs): ~ 3-5%,   Weapons: > 90%
Uranium Processing

- Uranium ore is mined, similar to iron, and the pure uranium is extracted
- It is reacted with hydrofluoric acid to create the gas uranium hexafluoride
- The enrichment and/or blend down is done on the uranium hexafluoride gas
- Calcium is added to the gas which reacts with the fluoride to form a salt and uranium metal is extracted
- Using this metal one can fuel a reactor or bomb
Overview of Uranium Enrichment

• 1940s-1950s: uranium enrichment was pursued on industrial scale for military motives

• Gaseous diffusion plants in U.S., Russia, England, France, and China

K-25 Gaseous Diffusion Plant, Oak Ridge, TN
Overview of Uranium Enrichment (Cont)

- 1960s-1980s: Focus shifted to peaceful uses
- Gas centrifuge programs emerged in U.S., Russia, England, Germany, Netherlands, and Japan
Overview of Uranium Enrichment (Cont)

Each centrifuge only enriches a tiny fraction of a percent.
In order to maximize throughput and minimize feedstock waste, centrifuges are arranged in both in series and in parallel in clusters called cascades.

Large facilities with complicated piping.
Examples of Gas Centrifuge Cascades
Typical Operations at a UF$_6$-based Enrichment Plant

UF$_6$ Feed stock

Product and tails (depleted)
Introduction to International Atomic Energy Agency (IAEA) Safeguards

• Provides international assurances on voluntary declarations made by members through various treaties

• Established in 1957

• 159 member states

• 178 States with safeguards agreements

• ~2,474 professional and support staff from ~100 countries

• 2012 inspection statistics:
  – Applies safeguards to ~600 facilities and LOFs
  – Applies safeguards to ~172,000 SQs of material
  – ~2000 inspections
  – ~124M Euro (~$150M) budget + 7.6M Euro extra-budgetary
IAEA Safeguards Objectives

• Timely detection of the diversion of UF₆
• Timely detection of the misuse of the facility to produce undeclared product (at declared enrichment levels) from undeclared feed
• Timely detection of the misuse of the facility to produce UF₆ at higher than declared enrichment level – in particular, HEU

Issues

• Many aspects of cascade design and operation are classified or proprietary
• IAEA budgetary constraints
• Necessity to minimize impact on operations
Indicators Associated with Potential HEU Production

- Reduced throughput
- Portable feed and withdrawal equipment/stations in cascade area
- Extra UF$_6$ cylinders in cascade area
- Valve settings
- Piping reconfigurations (e.g., inter-cascade piping, feed/withdrawal points)
- Radiation signatures indicating HEU
- Ratios of minor isotopes
“Traditional” IAEA Safeguards Measures on Enrichment Plants – pre 1990

“evolving roles of inspectors”

- Nuclear material accountancy
- Containment and surveillance (C/S)
- On-site inspection
Initial Cascade Area Inspection Activities – 1990s

- Visual observation
- Radiation monitoring and NDA measurements
- Sampling
- Application and verification of seals
Additional Cascade Area Inspection Techniques – late 90s, early 00s

- Environmental sampling
- Continuous on-line enrichment monitors
- Portable neutron uranium hold-up counter
Sampling of Surface Soil

Swipe Sampling from Vegetation

High Volume Water Sampling with a Special Filter
Cotton Swipe

Swipe sampling the surfaces of equipment inside a facility
The Typical ES Sample

Standard sample: **Swipe samples**
- are easy to collect and transport
- can be used to detect a variety of nuclear signatures.

**Standard swipe kit**

**Sampling kit for hot cells**
IAEA Network of Analytical Labs for Environmental Sampling

- SAL + 14 Laboratories worldwide
- Provide complementary analytical capability
- Samples sent anonymously to Laboratories
- Two lab confirmation of results
- NWAL expansion expected in the future

Looking for undeclared activities, undeclared facilities, unusual material species, etc.
Some Safeguards Measures Being Investigated Currently

• Continuous, unattended UF$_6$ verification
  – Cylinder tracking
  – Process scale monitoring
  – Enrichment monitoring
  – Accountancy scale monitoring

• Portable analytical instruments

• New design information verification (DIV) tools
Cylinder Tracking

Enhanced tools for inventorying of UF₆ cylinders

For example, RFID tags for continuous inventory
Continuous monitoring of process load cells in feed and withdrawal areas
Design Information Verification (DIV) Instrumentation

- 3 dimensional – DIV systems to identify changes in piping
- Gamma and neutron imaging to identify changes in material flows, both quantity and enrichment
Technology Development Continues

- Each technology introduced provides greater and greater assurances that there isn’t diversion of the materials, unauthorized use of the facility, and no additional enrichment occurring
- Inspector time-on-site is optimized
- Impact on operations minimized

Technology development continues to address IAEA safeguards concerns – more automated, continuous monitoring allows inspectors to become investigators
Example 2 – Monitoring Blend Down of HEU

- HEU Purchase Agreement
- HEU Transparency Program
- Technology Application
HEU Purchase Agreement

• United States and the Russian Federation signed an agreement allowing the United States to purchase highly enriched uranium (HEU) removed from Russia’s dismantled nuclear weapons and blended into low enriched uranium (LEU).
  – Over a period of 20 years, starting 1993
  – 500 tons of HEU (1.1 million pounds)

• This LEU was then sold to U.S. fuel fabricators via USEC and was made into reactor fuel to supply U.S. commercial power reactors
Megatons to Megawatts: Turning Warheads Into Electricity
U.S.-Russian Contract between USEC and TENEX (for MINATOM)
$12 Billion*, 20 years

1. SOVIET ERA NUCLEAR WEAPONS
2. HIGHLY ENRICHED URANIUM TOTAL: 500 METRIC TONS
3. DILUTED TO LOW ENRICHED URANIUM TOTAL: ABOUT 15,000 METRIC TONS
4. SHIPPED TO U.S.A.
5. $ $$ $ PAYMENT
6. TO BECOME FUEL FOR COMMERCIAL NUCLEAR POWER PLANTS

RUSSIA

TOTAL ENERGY EQUIVALENTS

15,000 METRIC TONS OF LEU
THE ENERGY IN 15,000 METRIC TONS OF LOW ENRICHED URANIUM WOULD LIGHT THE UNITED STATES FOR ABOUT TWO YEARS

This much low enriched uranium is equal to the energy in...

Natural Gas
Natural Gas
TOTAL: 60 TRILLION CUBIC FEET OF NATURAL GAS

Coal
TOTAL: 3 BILLION TONS OF COAL

6 TRILLION KILOWATT HOURS

OIL
TOTAL: 10 BILLION BARRELS OF OIL
10,000 SUPERTANKERS

* $8 billion for SWU purchases; $4 billion of natural uranium transferred for Russian disposition

USEC INC. G200-N 10/98
DOE/NNSA HEU Transparency Program

• The HEU Transparency Program was established within the Department of Energy to provide assurance that the HEU being purchased is from dismantled weapons and that the same HEU is converted, processed, and blended to LEU.
The goal is to provide confidence that:

**Objective One**  
500 MT is from Russian weapons-usable material.

**Objective Two**  
This same HEU is converted to an oxide.

**Objective Three**  
This same HEU is downblended to LEU.

- Tactical nuclear device
- Russian facility glove box where HEU metal is burned and converted into oxide
- Russian facility glove box where HEU metal is burned and converted into oxide
DOE/NNSA HEU Transparency Program

• The program implements extensive access and monitoring rights during 24 annual monitoring visits to four Russian HEU processing facilities. At these facilities, a cadre of nearly 100 U.S. experts measure and observe HEU processing firsthand, analyze Russian HEU-to-LEU processing forms, perform enrichment measurements.

• The Blend Down Monitoring System (BDMS) was developed to provide better assurances that Objective 3 goals were met. The BDMS was a joint project between ORNL and LANL.
The BDMS in Transparency Monitoring

- The BDMS provides a significantly increased confidence that HEU is blended into reactor-grade LEU:
  - The BDMS permits monitoring of flows of fissile material through the blending point, allowing the U.S. to verify flow rate information from plant documents.
  - The BDMS permits monitoring of enrichments, allowing the U.S. to verify the enrichment assay of UF6 in the HEU line (~90%), LEU Blend Stock Line (~1.5%) and the LEU Product Line (3-5%).
  - The BDMS traces the flow of HEU from the HEU supply piping, through the blending tee, and out the product leg as down-blended reactor-grade LEU, verifying the down-blending of HEU into reactor grade LEU Product.
• The BDMS actually consists of two parts: the enrichment monitor (LANL) and the flow monitor (ORNL)

• BDMS equipment is installed on each leg of the blending tee

• The BDMS equipment monitors the flow rate and enrichment of the UF₆ flowing through each leg
The Basics of BDMS Operation

**Enrichment Monitor**

- **The Enrichment Monitor** measures the enrichment assay (\( \%^{235}\text{U} \)) of the UF6 flowing in a pipe through gamma spectroscopy. Two measurements are made:
  
  - The transmission of 122kev gamma-ray from a Cobalt-57 source through the UF6 flow, giving an indication of the total quantity of Uranium present, and
  
  - The presence of 186 kev gamma-ray, giving an indication of the quantity of \( ^{235}\text{U} \) present in the UF6 flow.

- Taking a ratio of these two values gives a measure of the enrichment of the UF6 flowing through the pipe.
The Basics of BDMS Operation

Flow Monitor

- The Flow Monitor uses a modulated neutron source to introduce a small number of fissions in the flow of UF6 through the pipe. Once again, two separate measurements are required:
  - The time delay for the fission fragments to reach a downstream gamma detector, and
  - The magnitude of the gamma generated by the $^{235}\text{U}$, which gives an indication of the fissile density in the pipe

- These two measurements are used to calculate a fissile mass flow rate in grams of $^{235}\text{U}$ per second flowing through the pipe.
Implementation Challenge

• Combine two technologies from two separate labs into a single operational system

• Software developed to control hardware and acquire data

• System tested in lab, in a field test at US enrichment plant, then deployed in a harsh industrial environment 1000s of miles away

• System collected data for 8 years, was updated and collected for another 7 years

• Unique solution to a very challenging and difficult problem!
Technique has added benefit of traceability through the blending tee

- Activation of gas in HEU stream
- Detection in HEU stream
- Can also be detected in P-LEU stream!
- Confirms that material in the product stream came from High Enriched Uranium stream!
- Confirms material traceability
HEU Purchase Agreement &
Transparency Program

• A tremendous nonproliferation success!
• 500 Metric tons of HEU blended down, roughly 20,000 weapons worth of HEU eliminated.
• 50% of fuel in U.S. power reactor fleet derived from Russian weapons, about 10% of all the electricity generated in the U.S.!

“The HEU Purchase Agreement has reached yet another important milestone on the path towards blending down and eliminating 500 metric tons of Russian weapons HEU. The HEU Program has been one of the most successful nonproliferation and material disposition programs in U.S. history and is a success we share with our Russian partners”

.....Anne Harrington, NNSA Deputy Administrator for Defense Nuclear Nonproliferation
Final Thought

The application of technology can be a force multiplier, detecting, verifying, measuring, etc., providing additional assurances necessary for effective nonproliferation measures.