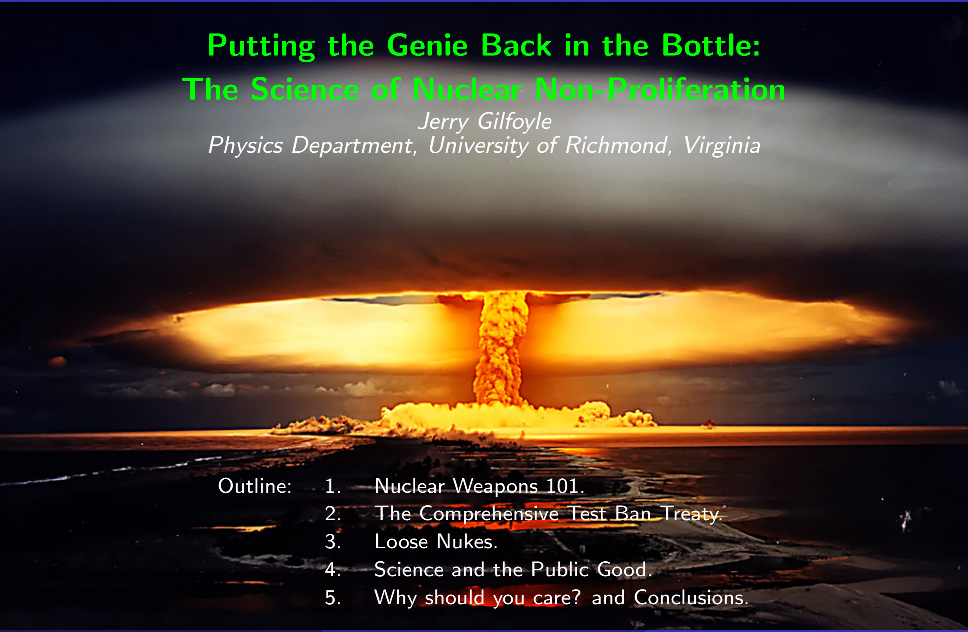

Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation

Jerry Gilfoyle
Physics Department, University of Richmond, Virginia

Outline:
1. Nuclear Weapons 101.
2. The Comprehensive Test Ban Treaty.
3. Loose Nukes.
4. Science and the Public Good.
5. Why should you care? and Conclusions.

Some Bits of History

- US develops and uses nuclear weapons on Japan at the end of World War II (1945). Other countries follow; current count is nine.

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- Collapse of the Soviet Union
  - Many components of the Soviet nuclear arsenal left behind in the former Soviet Union (FSU).
  - Collapse of Russian ruble in 1998 leaves even Russian arsenal with limited funds for maintenance and security of nuclear materials.

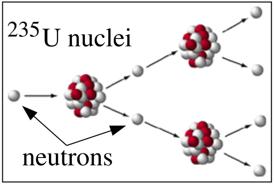
Nuclear Weapons 101 - Radiation

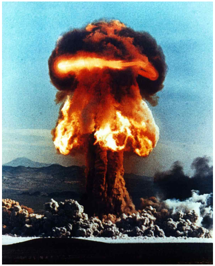
- Emission or release of energy from atomic nuclei in the form of sub-atomic particles like photons, electrons, or other atomic nuclei.
- Ionizes atoms in material it passes through and disrupts the material.
- Natural background radiation accounts for about 80% of exposure.
- Wide range of uses: sterilize food, medical supplies, smoke detectors, cure industrial materials.
- Types
  - γ - high-energy photons; greatest penetrating power (requires several cm of aluminum to shield).
  - β - electrons and positrons; medium penetrating power (a few mm of aluminum).
  - α - $^{4}\mathrm{He}$ nuclei with little penetrating power (not relevant here).

Nuclear Weapons 101 - Fissile Materials

- Fissile materials (^{235}U, ^{239}Pu) release enormous energies.
- As nucleus splits, it emits $\approx$ 2 neutrons plus energy (≈ 180 MeV).
- If density is high, a 'chain reaction' will cause other fissions in a self-propagating process.

A Chain Reaction

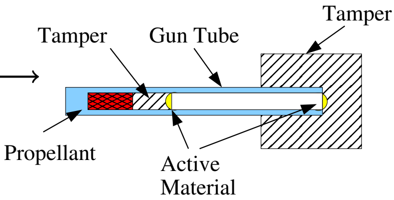




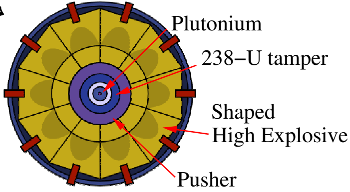
- Only about 8 kg of plutonium or 25 kg of highly-enriched uranium (HEU) is needed is needed to produce a weapon.
- Low-enriched material can be used in reactors.

Nuclear Weapons 101 - Design

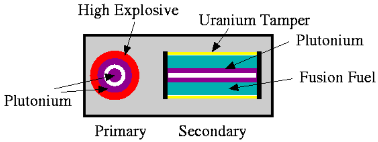
- Uranium, gun-type weapon - High explosive fires highly-enriched uranium slug down the gun tube and into the uranium target. The density increases enough to sustain the chain reaction.

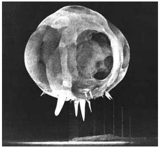


- Plutonium implosion device - High explosive crushes the plutonium primary to a density where fission can occur.



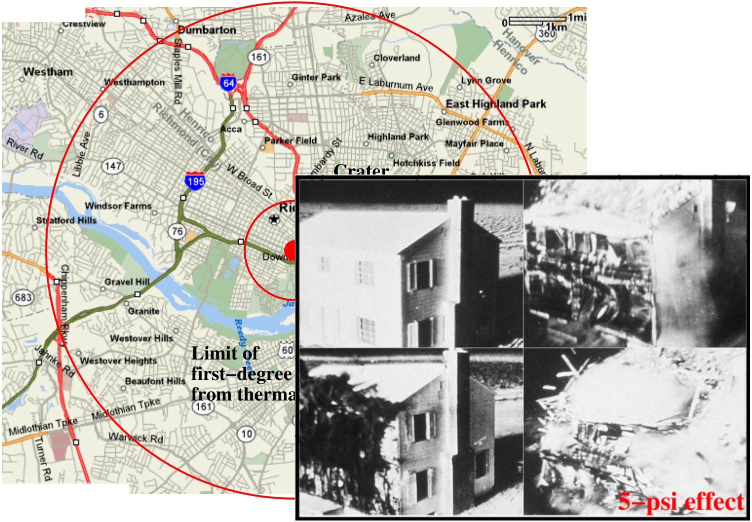
- Two-stage, thermonuclear weapon - Fission weapon crushes secondary containing deuterium and tritium gas and/or a fissile 'spark plug'.





Nuclear fireball 1 *ms* after detonation (Tumbler Snapper); it is about 20 m across.

Nuclear Weapons 101 - Effects


Crestview
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Hanover
Henrico
Westham
Westhampton
Staples Mill Rd
161
64
Cloverland
Ginter Park
E Laburnum Ave
Lynn Grove
East Highland Park
Glenwood Farms
6
Richmond (City)
Henrico
Acca
Parker Field
Highland Park
Mayfair Place
River Rd
Libbie Ave
147
W Broad St
Hotchkiss Field
Crater
195
Windsor Farms
Stratford Hills
76
Gravel Hill
683
Chippenham Pkwy
Granite
Westover Hills
Westover Heights
Jahnke Rd
Beaufont Hills
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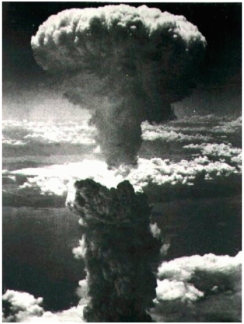
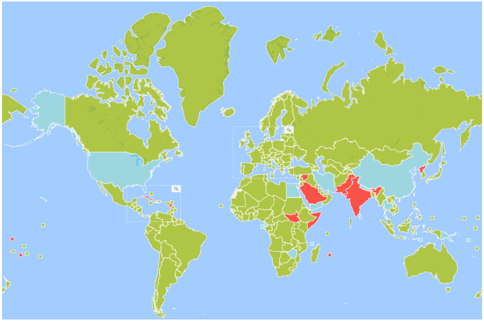
first–degree
from therma
60
Midlothian Tpke
Warwick Rd
10
Turner Rd
5–psi effect

The Comprehensive Test Ban Treaty (CTBT)

- The CTBT bans all nuclear explosions to limit the proliferation of nuclear weapons.
- A network of seismological, hydroacoustic, infrasound, and radionuclide sensors will monitor compliance.
- On-site inspection to check compliance.
- The US has signed the CTBT (1996), but has not ratified it.

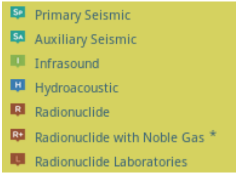


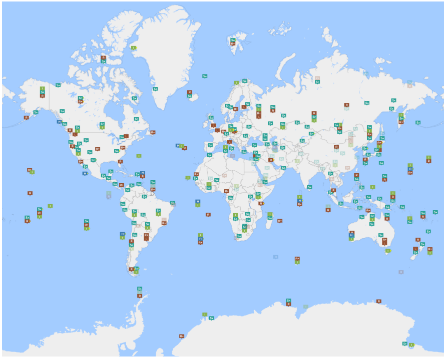


Green - ratified
Blue - signed
Red - outside treaty

The CTBT Verification Regime

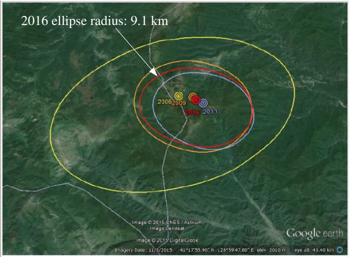
- The International Monitoring System (IMS), consists of 337 facilities that constantly monitor for signs of nuclear explosions. Over 70% are already collecting data.
- Detection technologies:
  - Seismic: 50 primary and 120 auxiliary seismic stations monitor shock waves.
  - Hydroacoustic: 11 hydrophone stations ‘listen’ for sound waves in the oceans.
  - Infrasound: 60 stations on the surface can detect ultra-low frequency sound waves (inaudible to the human ear) that are emitted by large explosions.
  - Radionuclide: 80 stations measure radioactive particles in the atmosphere, 40 also pick up noble gases.
- On-site-Inspection: If IMS data show a nuclear test has ocurred, a Member State can request an on-site-inspection subject to a vote .





Testing the Testers

- North Korean tests a nuclear bomb on October 9, 2006.
  - Over 20 CTBTO seismic stations detect the blast.
  - Radionuclides detected two weeks and 4700 miles away (!) in the Yukon.
  - Yield: 0.7 - 2.0 kt.
- They do it again on May 25, 2009
  - 61 CTBTO seismic stations detect blast.
  - No radionuclides are found!!?? Epic fail?
  - Yield: 2 - 5.4 kt
- February 12, 2013 Test
  - 94 CTBTO seismic and two infrasound stations detect the blast.
  - Radionuclides found again!
  - Yield: 6 - 16 kt



REB event locations for 2006, 2009, 2013
Analyst reviewed event location for 2016

- January 6, 2016 Test
  - 77 seismic stations detect blast.
  - Yield: 7 - 10 kt
  - No radionuclides detected.
- September 9, 2016 Test
  - Over 100 seismic stations detect blast.
  - Yield: 20-30 kt
  - No radionuclides detected.

What is Happening?

- Geologists detect the shaking induced by the blast and pinpoint the site of the explosion - first sign of a test. And then estimate the yield (**geology**).
- A few special nuclei made in the blast (xenon) are chemically inert and find their way through a kilometer of rock to reach the atmosphere.
- Calculations of the weather enables meteorologists to predict the spread of the plume from the blast (**meteorology, physics, computer science**).
- Air monitoring stations process huge amounts of air to capture the xenon atoms (**chemistry**).
- Nuclear physics detectors make the final identification of the decay of the xenon nuclei (**nuclear physics**).
- Now comes the response (**political science**).

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International response is driven by the scientific results - scientists have to get it right!

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- Nucl … decay of the xenon nuclei (**nuclear physics**).
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> The American Geophysical Union and the Seismological Society of America have stated the IMS will detect all explosions down to 1 kiloton (and much less in some areas) and within a radius of 35 km (October, 2009).

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Why Should You Care?

- ... clandestine nuclear tests could not be verified (by the IMS). ... even when Pyongyang declared that it would conduct a nuclear-weapons test and announced where and when it would occur, this monitoring system failed to collect necessary radioactive gases and particulates to prove that a test had occurred.

Senator Jon Kyl - R, Arizona: *Why We Need to Test Nuclear Weapons*, Wall Street Journal, October 20, 2009.

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- The worst-case scenario under a no-CTBT regime poses far bigger threats to U.S. security - sophisticated nuclear weapons in the hands of many more adversaries - than the worst-case scenario of clandestine testing in a CTBT regime, within the constraints posed by the monitoring system.

  National Academy of Sciences (NAS), *Technical Issues Related to the Comprehensive Nuclear-Test-Ban Treaty*, Washington, D.C., National Academy Press, 2002, pp. 10.

Why Should You Care?

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(Original Signature of Member)

115TH CONGRESS
1ST SESSION

H. R. _____

To restrict funding for the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, and for other purposes.

IN THE HOUSE OF REPRESENTATIVES

Mr. WILSON of South Carolina introduced the following bill; which was referred to the Committee on ________________

A BILL

To restrict funding for the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, and for other purposes.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. RESTRICTION ON FUNDING FOR THE PREPARATORY COMMISSION FOR THE COMPREHENSIVE NUCLEAR-TEST-BAN TREATY ORGANIZATION.

(a) STATEMENT OF POLICY.—Congress declares that United Nations Security Council Resolution 2310 (Sep-

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January 31, 2017 (12:44 p.m.)

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tember 23, 2016) does not obligate the United States nor does it impose an obligation on the United States to refrain from actions that would run counter to the object and purpose of the Comprehensive Nuclear-Test-Ban Treaty.

(b) RESTRICTION ON FUNDING.—

(1) IN GENERAL.—No United States funds may be made available to the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization.

(2) EXCEPTION.—The restriction under paragraph (1) shall not apply with respect to the availability of United States funds for the Comprehensive Nuclear-Test-Ban Treaty Organization's International Monitoring System.

Sponsored by Joseph Wilson of South Carolina, February 7, 2017

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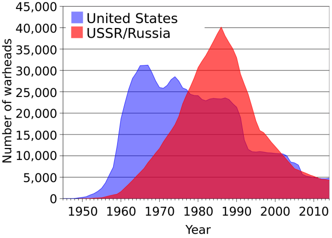
January 31, 2017 (12:44 p.m.)

The Soviet/Russian and US Nuclear Arsenals

- By the end of the Cold War the US and USSR had nuclear arsenals containing about 64,000 warheads on various delivery vehicles.
- US and Soviet military stockpiles contained about 1600 tons of highly-enriched uranium (HEU) and about 200 tons of plutonium.



- An unforeseen consequence of the end of the Cold War was the disposition of nuclear weapons materials.

Loose Nukes?

Fissile Material Security in Russia Declines in the 1990's

- The economic situation in Russia left few funds for maintaining the security of now-unused nuclear materials.
- Reports by the National Research Council in 1994, 1997 and 1999 revealed the extent of the decline of security.

Building at the Kurchatov Institute housing HEU with no motion sensors, detectors, or portal monitors.

- In the 1990's there have been numerous instances of smugglers apprehended with nuclear materials.
- In late 1998 the Russian FSB (successor to the KGB) reports stopping an attempt to steal 18.5 kg of weapons-usable material (HEU?).

Why Should You Care?

- The US and most other nations have a long-standing policy of nuclear nonproliferation.
- A nuclear blast would have horrific consequences; loss of life, property, and security.
- Even acquisition of a nuclear weapon by an adversary could have a devastating influence on US security and non-proliferation.
- **One of the highest hurdles to obtaining a nuclear weapon is acquiring enough weapons-grade fissile material to produce a bomb**. Iraq spent \$5-\$10 billion in the 1980's to produce a few grams of plutonium.
- Smuggling fissile material is a 'short-cut' to acquiring nuclear weapons; it lowers the acquisition hurdle.
- Prevention (*i.e.*, security) is critical especially against an 'insider' threat.

What Can an Opponent Do?

- What can a terrorist organization do?
  - Acquiring the necessary technology to enrich uranium or plutonium is beyond the capabilities of most terrorists.
  - Stealing the necessary fissile material is NOT!
  - A gun-type, uranium weapon of low yield is still a difficult endeavor, but could be done.
  - There are other alternatives for terrorists like a 'dirty bomb'.
  - The likeliest terrorist weapons are still guns and bombs.
- All of the above can be negated if one of the current nuclear powers gives one away. This is unlikely.
- There is continued smuggling activity for nuclear materials.
- The ITBD includes three incidents involving HEU and three involving plutonium during the period 1992-2015.

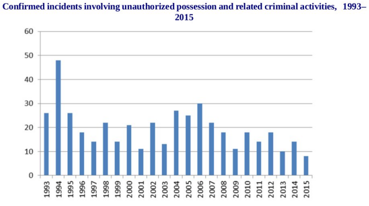


Figure 1 Incidents reported to the ITDB involving unauthorized possession and related criminal activities, 1993–2015.

IAEA Incident and Trafficking Database (2016 Fact Sheet)

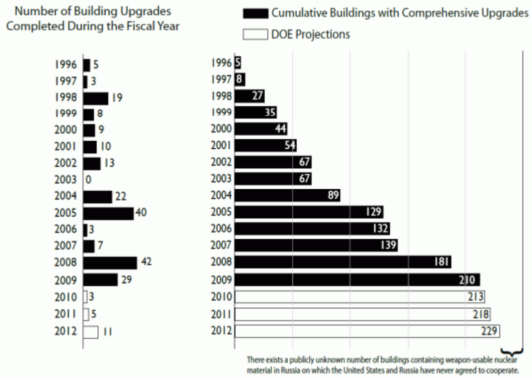
The US Response

- In 1991 the US Congress passes the Nunn-Lugar Act. The US pays to improve security of fissile materials and to dismantle the Russian nuclear complex (cooperative threat reduction).
  - The US spent about $700 million a year to reduce this threat.
  - The Fissile Material Storage Facility (FMSF) securely stores plutonium and uranium from dismantled weapons.
  - HEU Purchase Agreement downblended about 500 metric tons of HEU to reactor fuel (not usable in a nuclear weapon) for $20 billion.

Fissile Material Storage Facility at Mayak financed by the US Cooperative Threat Reduction program.

- Most of these cooperative programs ended by December, 2014 due to the conflict over Russian actions in the Ukraine.

How Loose are the Nukes?



Country	Year
Iraq	1992
Colombia	1996
Spain	1997
Denmark	1998
Georgia	1998
Philippines	1999
Thailand	1999
Slovenia	1999
Brazil	1999
Sweden	2002
Greece	2005
South Korea	2007
Latvia	2008
Bulgaria	2008
Portugal	2008
Romania	2009
Libya	2009
Taiwan	2009
Turkey	2010

Countries that have eliminated all weapons-usable fissile material.

Reproduced from M. Bunn, *Securing the Bomb 2010*, Harvard University and the Nuclear Threat Initiative, April 2010).

How Loose are the Nukes?

Number of Building Upgrades Completed During the Fiscal Year

Cumulative Buildings with Comprehensive Upgrades

DOE Projections

1996 5

1996 5

Country	Year
Iraq	1992
Colombia	1996

Action Taken	Completed	% of 2017 Goal	Action Taken	Completed	% of 2017 Goal
Warheads Deactivated	7616	82.2%	SLBM Launchers Eliminated	492	80.4%
ICBMs Destroyed	914	87.8%	Nuclear Air-to-Surface Missiles Destroyed	906	100%
ICBM Silos Eliminated	498	76.4%	Bombers Eliminated	155	100%
ICBM Mobile Launchers Destroyed	197	54.9%	Nuclear Test Tunnels/Holes Sealed	194	100%
Nuclear Weapons-Carrying Submarines Destroyed	33	84.6%	Nuclear Weapons Transport Train Shipments	611	73.7%
Submarine-Launched Ballistic Missiles (SLBMs) Destroyed	695	95.3%	Nuclear Weapons Storage Facility Upgrades	24	100%
Cooperative Biological Engagement Laboratories Secured	47	57.3%	Declared CW Agent Destroyed (Metric Tons)	4018.6	73.4%

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The Nukes are Looser. - NTI Threat Index 2016

The Nuclear Threat Initiative (NTI) is a nonpartisan, nonprofit organization that works to prevent catastrophic attacks and accidents with weapons of mass destruction and disruption. Its threat index ranks the nuclear security practices of 176 countries.

OVERALL SCORE

Rank / 24		Score / 100	Change since 2014	Change since 2012
1	Australia	93	0	+3
2	Switzerland	91	+2	+4
3	Canada	87	+2	+8
4	Poland	84	+3	+7
=5	Belgium	83	+3	+13
=5	Germany	83	+1	+6
=5	Norway	83	+2	+5
=8	Belarus	81	0	+7
=8	France	81	+1	+3
10	United States	80	+3	+2

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Since early 2010, a dozen countries have eliminated weapons-usable nuclear materials from their territories, dozens more have strengthened their nuclear security practices and policies...

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However, the global threat environment has worsened...

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Without a comprehensive and effective global system in place, states approaches to nuclear security continue to vary widely, thereby creating dangerous weak links that terrorists could exploit as they seek the easiest path to weapons-usable nuclear materials.

Conclusions

- Do we live in a safer world than during the Cold War? Yes, sort of.
    - The threat of nuclear Armageddon has receded with the lowering of tensions between Russia and the US.
- Has the threat of a nuclear conflict increased? Yes, sort of.
    - While the threat of a large-scale nuclear war between Russia and the US is smaller, the proliferation of nuclear weapons technology has increased the risk of nuclear weapons being used.
- What can be done? Lots, but it will take time, money (Opps! There goes my tax cut!) and leadership from the US (CTBT, NPT, ABM, BWC, CTR).
- What can I do?
    - Learn! Cut through the hype.
    - Vote! Write to Congress.
    - The US and other countries are in desperate need of technical expertise.

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4. Production of trained scientists, engineers, technicians. .... all from basic science research.
   About 200 doctoral theses from JLab.

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In Paris in 1783 Benjamin Franklin watched with amazement one of the first hot-air balloon flights. The following exchange was said to occur.

Questioner to Franklin: Sir, what's the use of flying in the air?

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Questioner to Franklin:	Sir, what's the use of flying in the air?
Ben Franklin's answer:	Sir, what's the use of a newborn baby?

-

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Additional Slides

Assessing Risk

What should you stay awake worrying about at night?

Deaths in 2014*	Cause
2,626,418	All causes
614,348	Heart disease
33,736	Vehicle accidents
55,227	Influenza/Pneumonia
42,826	Suicide

Deaths in 2014*	Cause
11,019	Homicide
42,032	Poisoning
31,959	Falling
3,406	Drowning
2,701	Fire

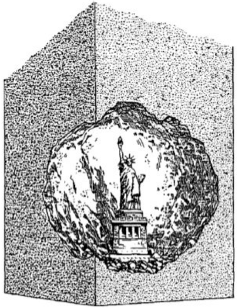
*National Vital Statistics Reports, **65**, no. 4, June 30, 2016.

Can an Opponent Cheat on the CTBT?

- U.S. and Russian experiments have demonstrated that seismic signals can be muffled, or decoupled, for a nuclear explosion detonated in a large underground cavity.
- Such technical scenarios are credible only for yields of at most a few kilotons.
- Other scenarios require mine-masking, multiple explosions, hide-in-an-earthquake.
- The IMS is expected to detect all seismic events of about magnitude 4 or larger corresponds to an explosive yield of approximately 1 kiloton (the explosive yield of 1,000 tons of TNT).

What can be learned from low-yield, surreptitious blasts?

Can it extrapolated to full-up tests?

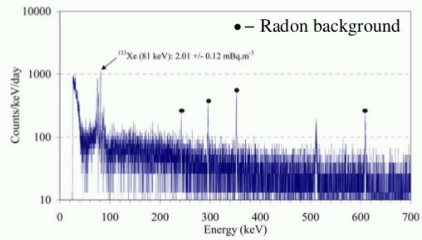


Demonstration of size of cavity needed to decouple a 5 kT blast.

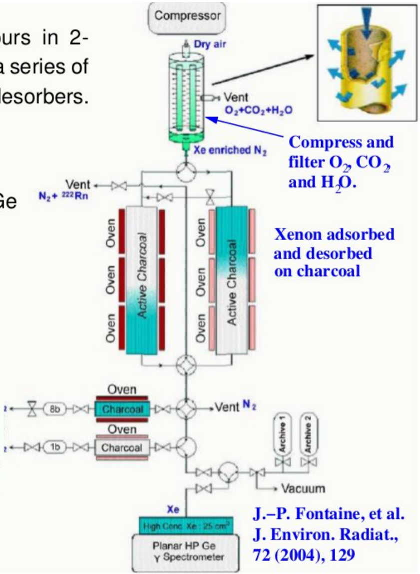
US Congress, Office of Technological Assessment, *Verification of Nuclear Testing Treaties*, OTA-ISC-361, (Washington, DC; US Government Printing Office; May, 1988).

- Atmospheric gas is collected for 24 hours in 2-hour cycles and xenon extracted through a series of permeation membranes and absorbers/desorbers. Can detect $^{133}\mathrm{Xe}$ at $1.5 \times 10^{-4}\ Bq/m^3$.

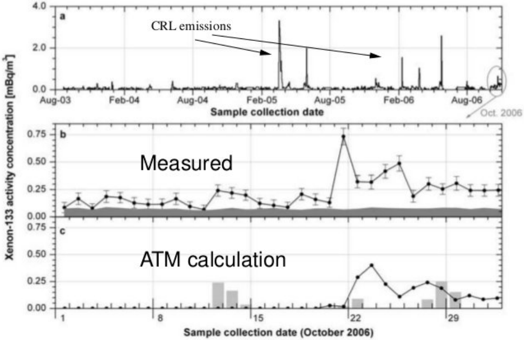
- Finding it! Detection with high-purity Ge crystals for high-resolution γ detection.

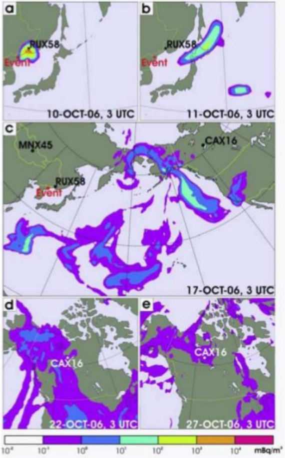


- direct detection of all four radioxenons
- well suited to field work.
- several automated systems used by IMS.



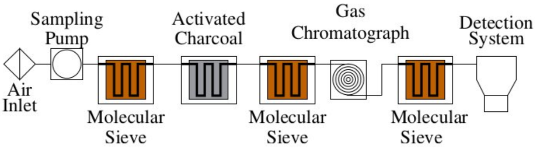
- Background studies of known sources are required to eliminate false positives.
- Atmospheric transport modeling (ATM) is done to determine the effect of known backgrounds and hypothesized nuclear explosions.
- Background, measured, and ATM prediction of $^{133}\mathrm{Xe}$ activity from Yellowknife station (γ detection).



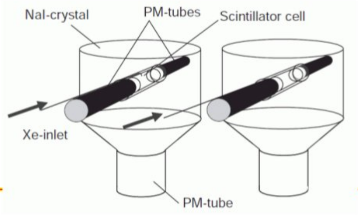


P.R.J.Saey *et al.* Geophys. Res. Lett. 34, L20802 (2007).

- Atmospheric gas is collected for many (6) hours and xenon extracted through a series of filters, absorbers, gas chromatograph, *etc*.



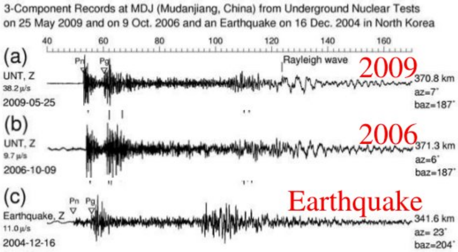
- Detection system uses $\beta - \gamma$ coincidences or high-resolution γ detection.
- For $\beta - \gamma$ method xenon is passed into the chamber of a hollow cylinder made of plastic scintillator inserted in a cylindrical hole inside a NaI crystal. Light produced by β and γ particles is detected with photomultiplier tubes and counted.



A. Ringbom *et al.* Nucl. Instr. Meth., A 508 (2003) 542.

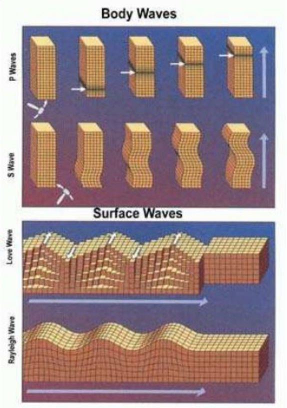
One of several automated systems used by IMS.

- The 2006 North Korea test was the smoking gun of remote detection of nuclear explosions. Everybody is happy (except maybe the North Koreans).
- On May 25, 2009 the North Koreans test again. The yield is a few kilo-tons and it's detected by 61 IMS stations.

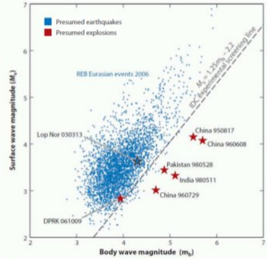


- No radioxenons are detected at any of the IMS stations!

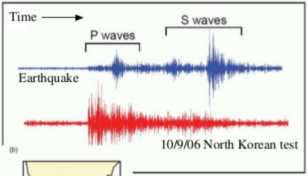
- The Problem
  - Use tremors created by underground explosions to detect treaty violations.
  - Big backgrounds! 600-700 earthquakes/day plus hundreds of mining explosions; about 25 events/day with magnitude > 4.
  - Can we identify a nuclear test among all this noise?
- Some seismology.
  - Surface waves - slow, transverse, low attenuation.
  - Body waves - fast, longitudinal (P) and transverse (S).
  - P waves emitted first.
  - Teleseismic - detected far from source; basis for National Technical Means (NTM) during Cold War.
  - Regional - detected close to epicenter; basis for CTBT IMS.



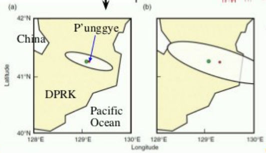
- Ratio of amplitude of surface waves to body waves is small for explosions (Annu. Rev. Earth Planet. Sci. 2009. 37:209).



- Ratio of S waves to P waves is small for explosions.



- Source depth and epicenter
  - Explosions are near the surface ...
  - ... and in the right place (*S&TR*, Mar, 2009).
- Regional data crucial.
  - Surface wave amplitudes can be small.
  - S waves blocked by liquid outer core.
  - P/S ratio altered by medium.
- Need accurate 3D maps of geology
  - Correct regional data.
  - Test source hypotheses.
- Need high-performance computing.



Locating epicenter with improved 3D models.

What is the Threat?

- Vulnerability of fissile material to insider theft.
  - The USSR relied on 'guards, guns, and gulag' for security. Morale in the defense complex was high and there was less concern about smuggling by the staff.
  - Financial and economic problems in the Russian nuclear cities during the 1990's made the staff susceptible to the temptation of nuclear smuggling.
- Are there buyers?
  - Maybe!
  - Iraq spent $5-$10 billion in the 1980's to produce a few grams of plutonium. They continue this effort.
  - Iran has been acquiring nuclear technology (some from the Russians) for many years.
  - Aum Shinrikyo and Osama bin Laden's group (two terrorist organizations) supposedly tried to obtain fissile material.

Public Policy Opportunities

If you want to get paid (jobs):

- The National Academies (NAS, NAE, NRC, IOM) hire Senior Project Assistants and Research Assistants.
- The scientific societies (AIP, APS, AGU, AGI, ACS, AAAS or AAS) hire science policy researchers.
- Other organizations like the Center for Science, Policy, and Outcomes, the Federation of American Scientists, and the Union of Concerned Scientists sometimes hire researchers.
- The General Accounting Office hires researchers.
- The Congressional Research Service (CRS) produces an annual guide of policy jobs in Washington, DC.

Science Policy and Education

- Policy-makers are in dire need of technical expertise in writing laws to evaluate national security threats, handle privacy, and regulate medical diagnostic testing.
- People are hungry for information.
- An educated electorate is essential.
- Training the populace could save lives in the event of an attack.
  - Panic will amplify the effect of an attack.
  - Panic is greatly diminished when people receive training.