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

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Outline:

1. Some Bits of History.
2. Nuclear Weapons 101.
3. The Comprehensive Test Ban Treaty.
4. Testing The Test Ban Treaty.
5. Why should you care? and Conclusions.

Some Bits of History

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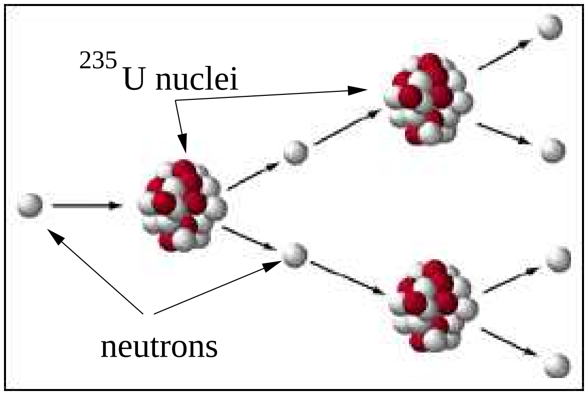
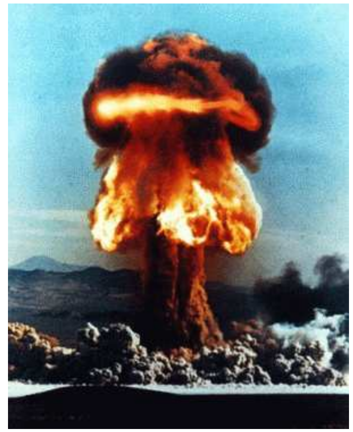
- US Nonproliferation activities
  - Signatory to the NPT.
  - Nunn-Lugar threat reduction.
  - The Comprehensive Test Ban Treaty NOT ratified by the US Senate in 2000. President Obama will try again.

Nuclear Weapons 101 - Fission and Fusion

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

A Chain Reaction

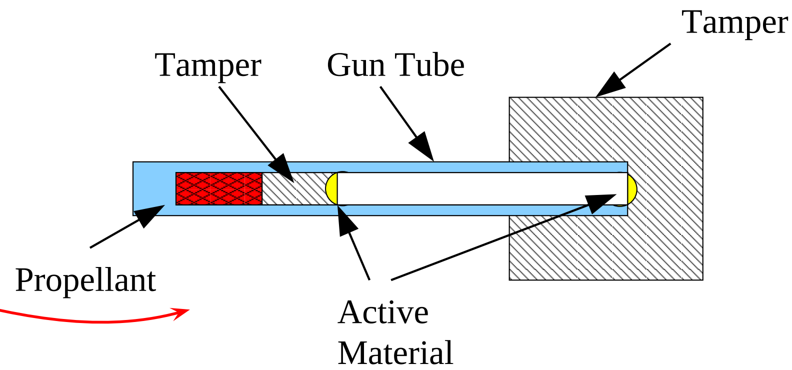


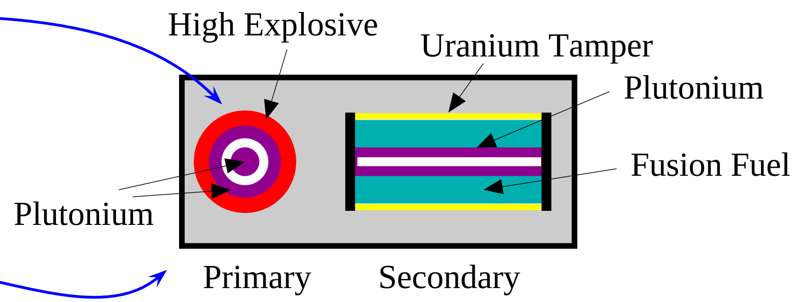


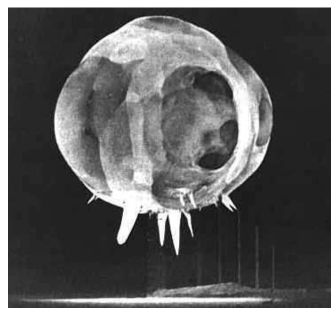
- As a fission bomb explodes deuterium and tritium can fuse releasing neutrons and even more energy; $^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV}$.
- Only about 8 kg of plutonium or 25 kg of highly-enriched uranium (HEU) is needed is needed to produce a weapon.

Nuclear Weapons 101 - Basic Weapons Designs

- 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'.
- Uranium and plutonium in the secondary burn and increase the temperature so fusion starts. The fusion energy further raises the temperature more fission fuel burns.



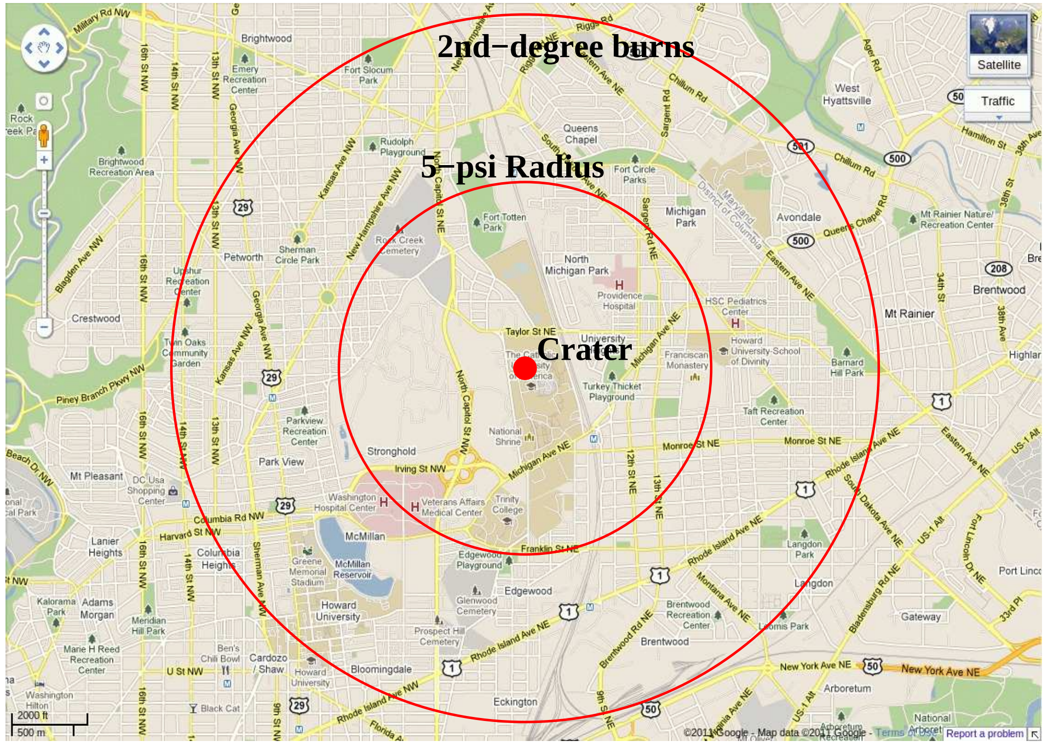




Nuclear fireball $1\ ms$ after detonation (Tumbler Snapper). The fireball is about 20 m across.

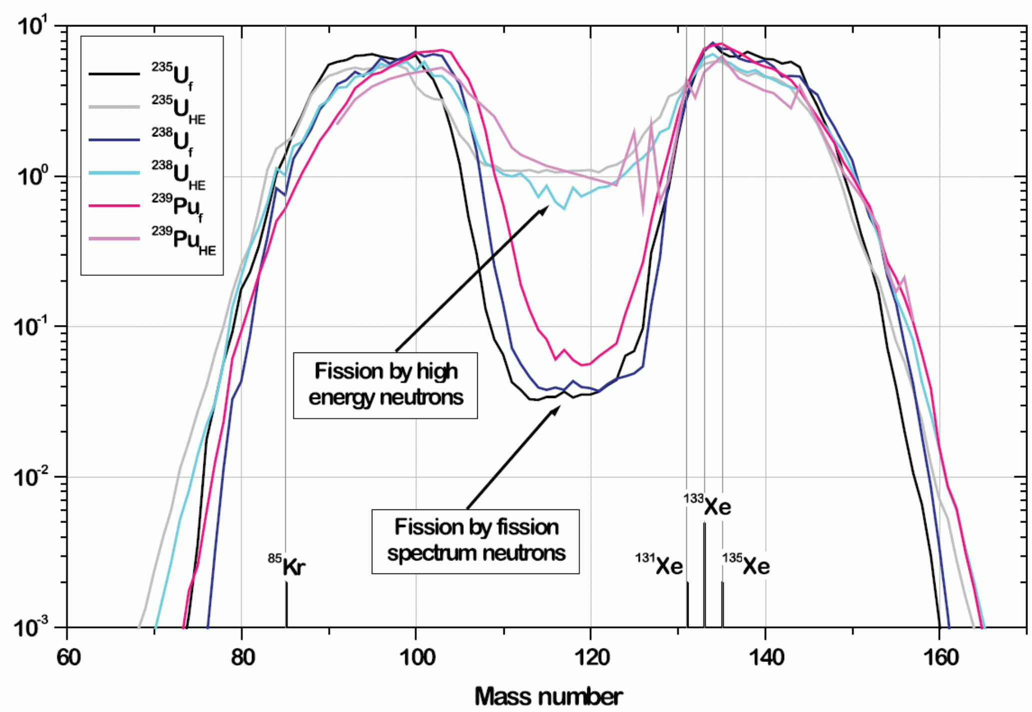
Nuclear Weapons 101 - Effects

- Energy released in the form of light, heat and blast.
- Blast $\approx$40-50% of total energy.
- Thermal radiation $\approx$30-50% of total energy.
- Ionizing radiation $\approx$5% of total energy.
- Residual radiation $\approx$5-10% of total energy.
- Figure shows effect of a 15 kiloton bomb (about the size of the Hiroshima bomb) exploded over Hannan Hall at Catholic University, Washington, DC.



Nuclear Weapons 101 - Nuclear Forensics

- Nuclear explosions leave behind a mixture of atomic nuclei that can reveal the fissile materials used and design features.
- Figure shows the fission yield in % for 235U, 238U and 239Pu, for fission induced by fission spectrum neutrons (f) and high energy neutrons (HE) (14.7 MeV).*
- Xenon is a noble gas that is chemically inert.



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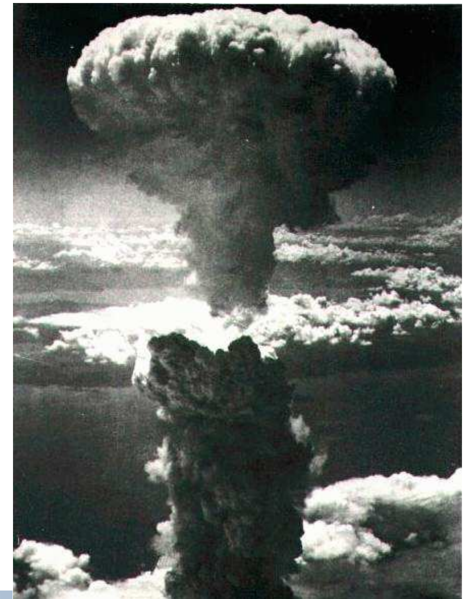
* P.R.J. Saey, ESARDA Bulletin, 36 (2007) 42.

The Comprehensive Test Ban Treaty (CTBT)

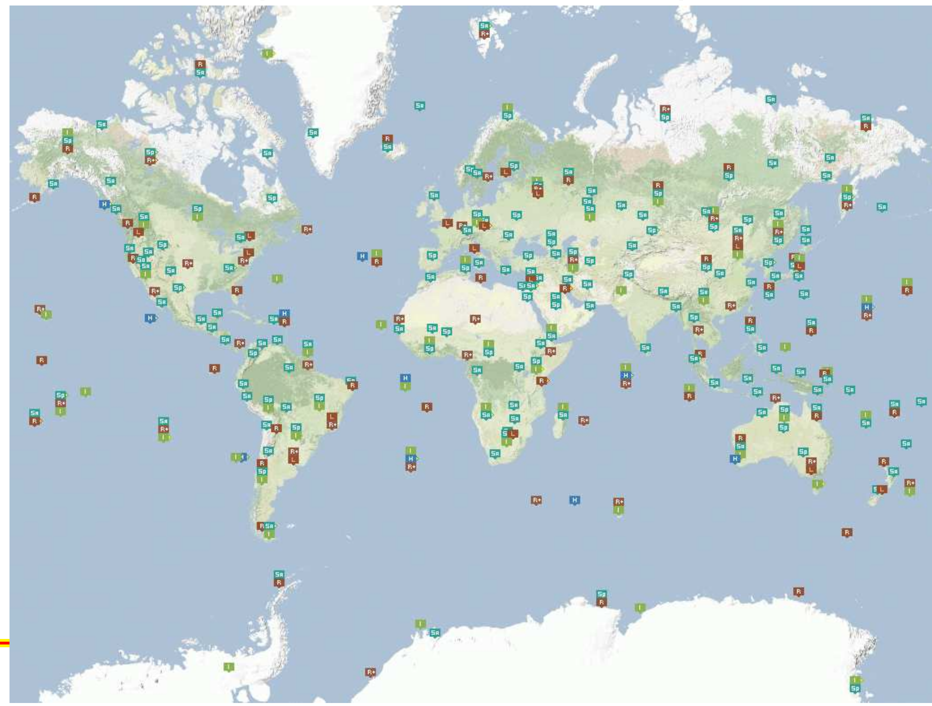
- The CTBT bans all nuclear explosions to limit the proliferation of nuclear weapons.
- A network of seismological, hydroacoustic, infrasound, and radionuclide sensors will monitor compliance.
- On-site inspection will be provided to check compliance.
- The US has signed the CTBT, but not ratified it.



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. Around 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 from the IMS show a nuclear test has ocurred, a Member State can request an on-site-inspection subject to a vote .



Testing the Test Ban Treaty

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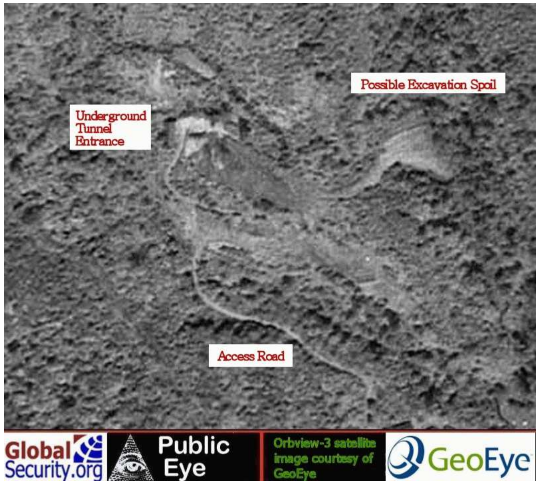

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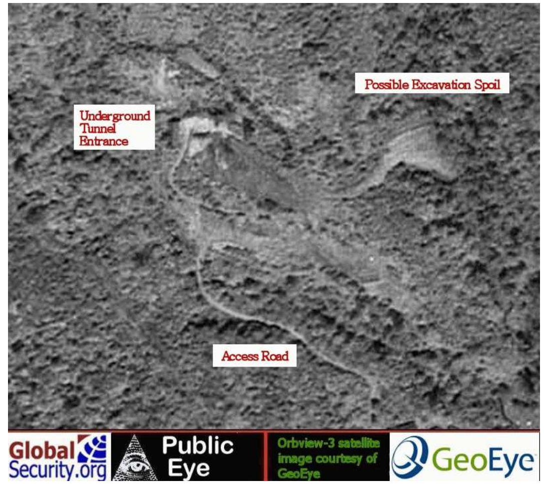

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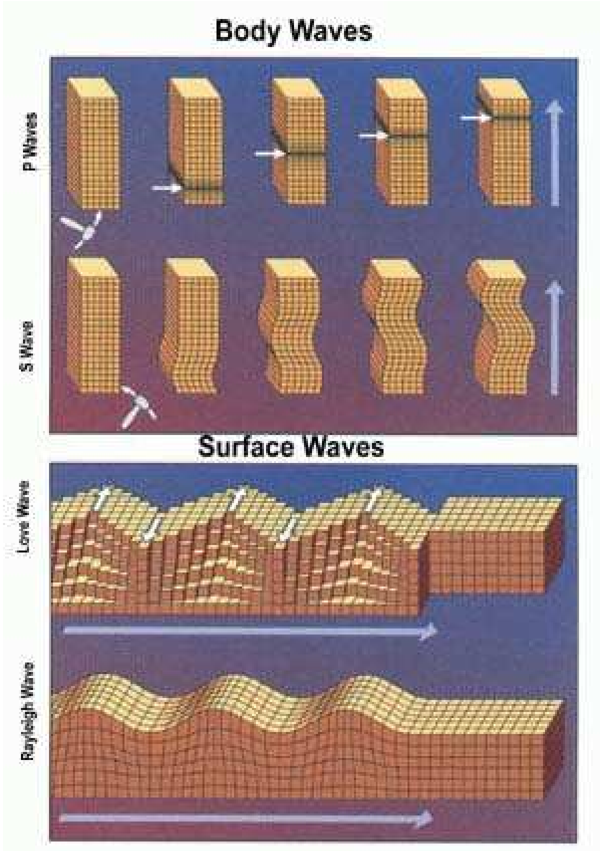
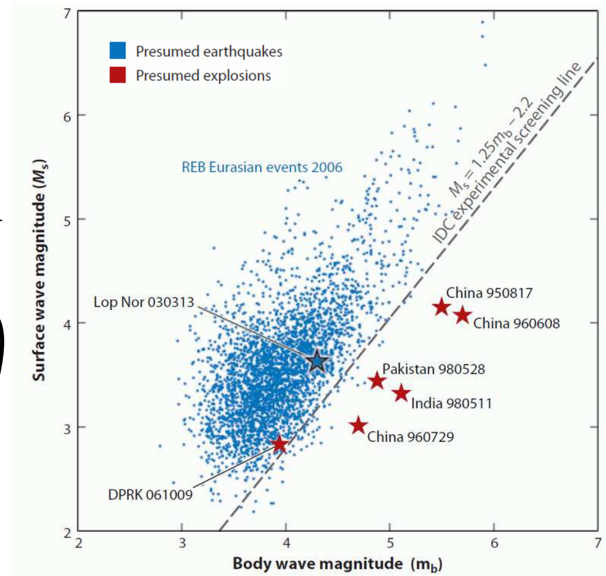
Detecting Seismic Signatures of Nuclear Tests

- 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.

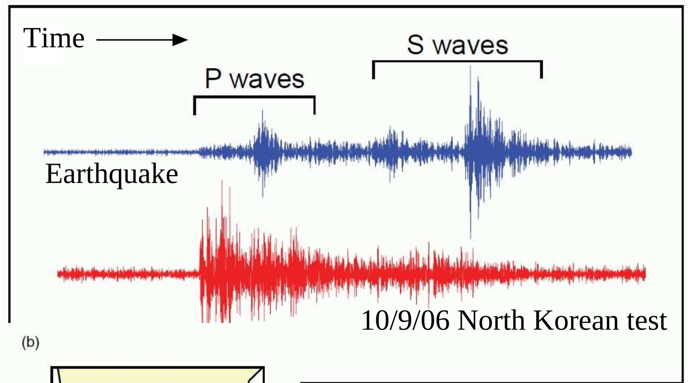


Identifying Nuclear Tests

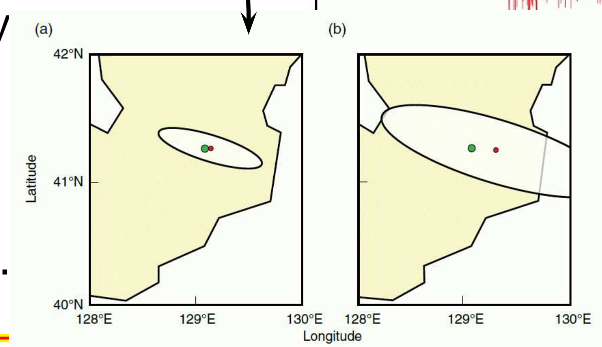
- Ratio of amplitude of surface waves to body waves is small for explosions (Annu. Rev. Earth Planet. Sci. 2009. 37:209).



- 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.

Detecting Radioxenons from Nuclear Tests

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- The xenon isotopes in the table are entirely man-made so they must come from reactors and explosions.

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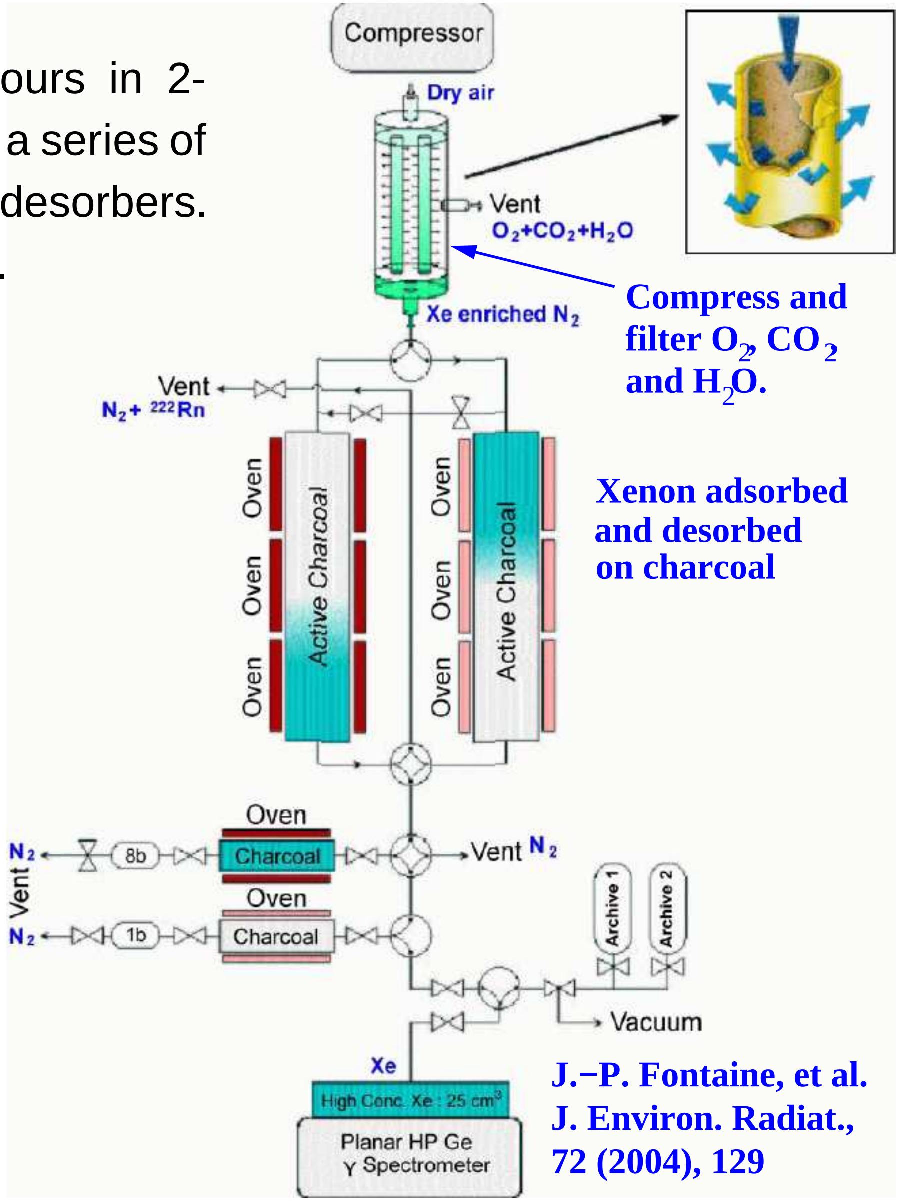
Looking for the Smoking Gun

- 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 $1.5 \times 10^{-4}\ Bq/m^3$.



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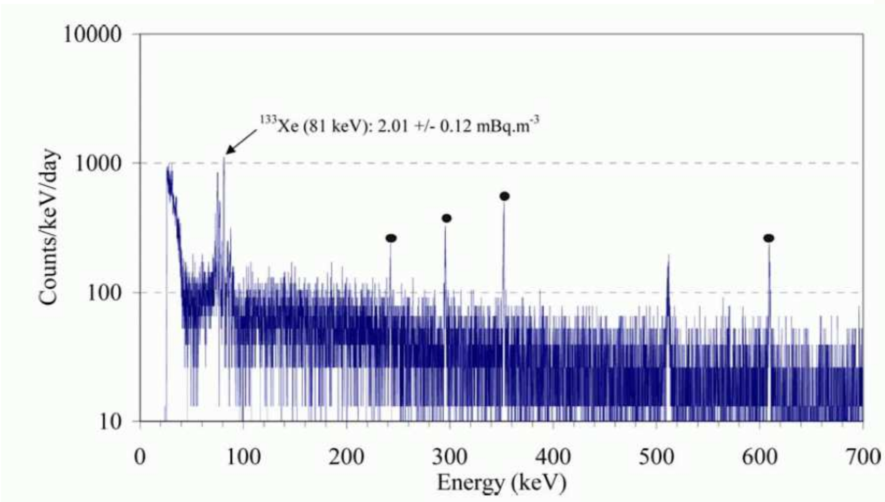
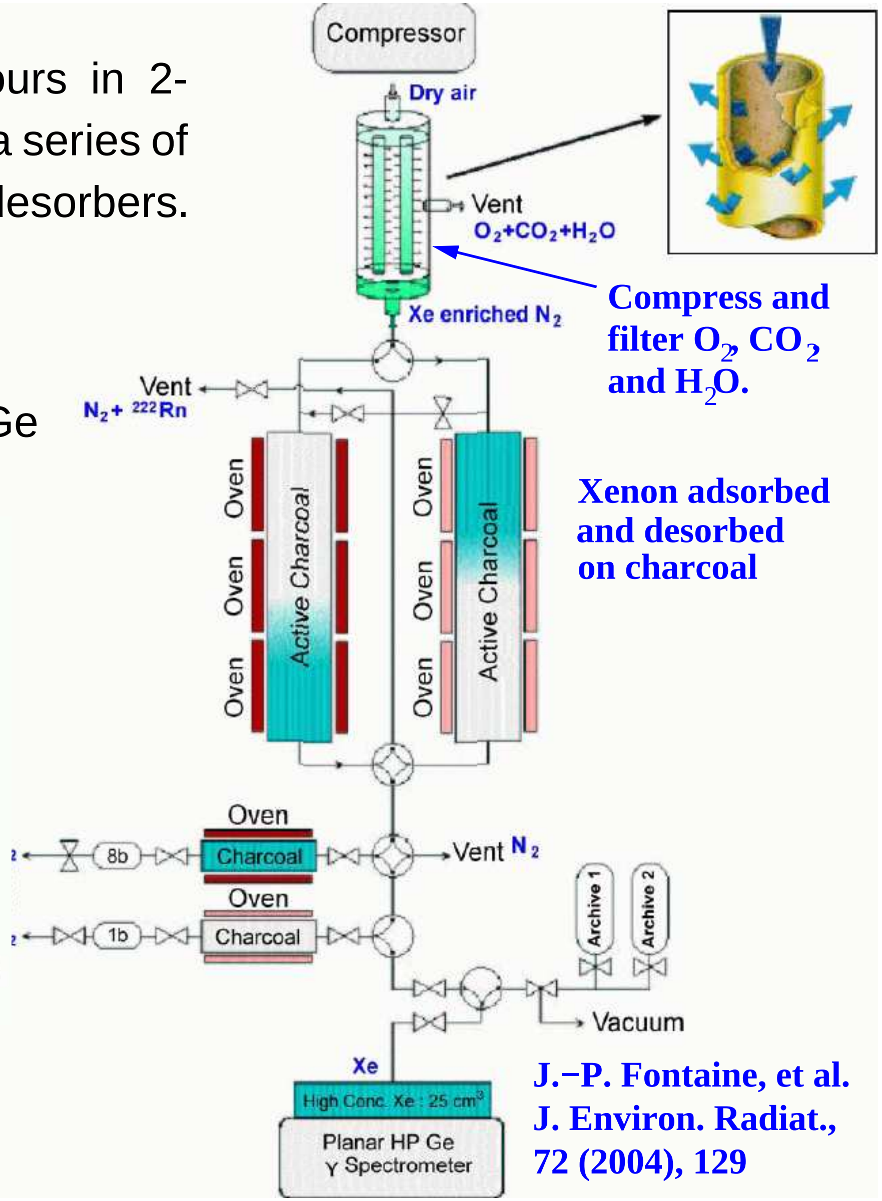
- Finding it! Detection with high-purity Ge crystals for high-resolution γ detection.



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



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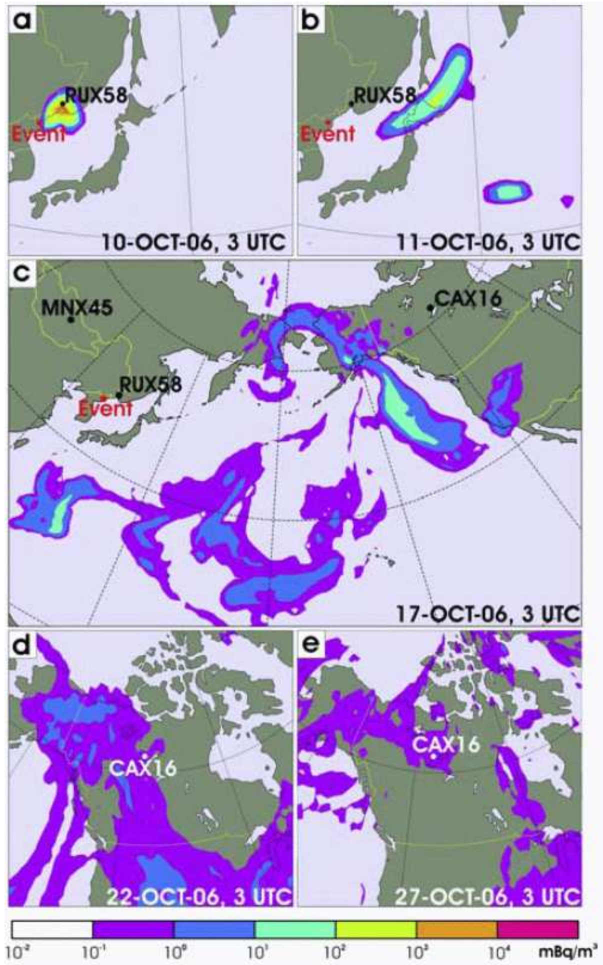

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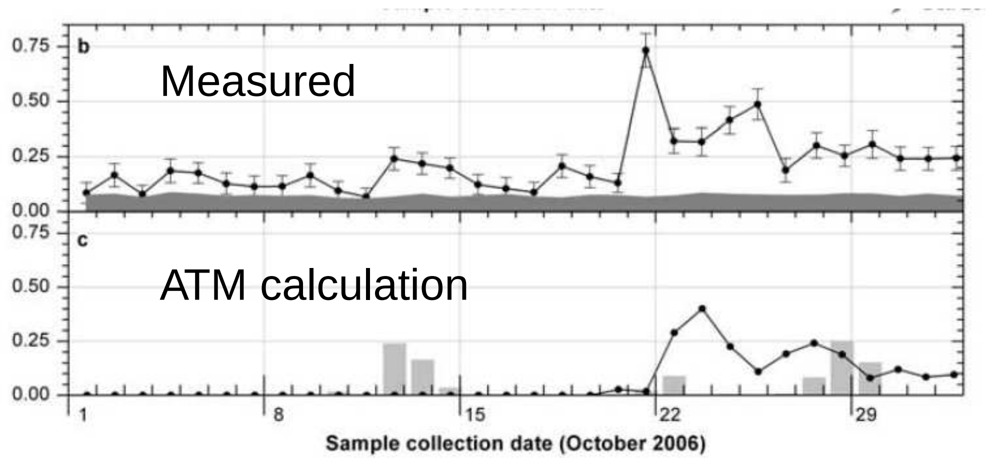

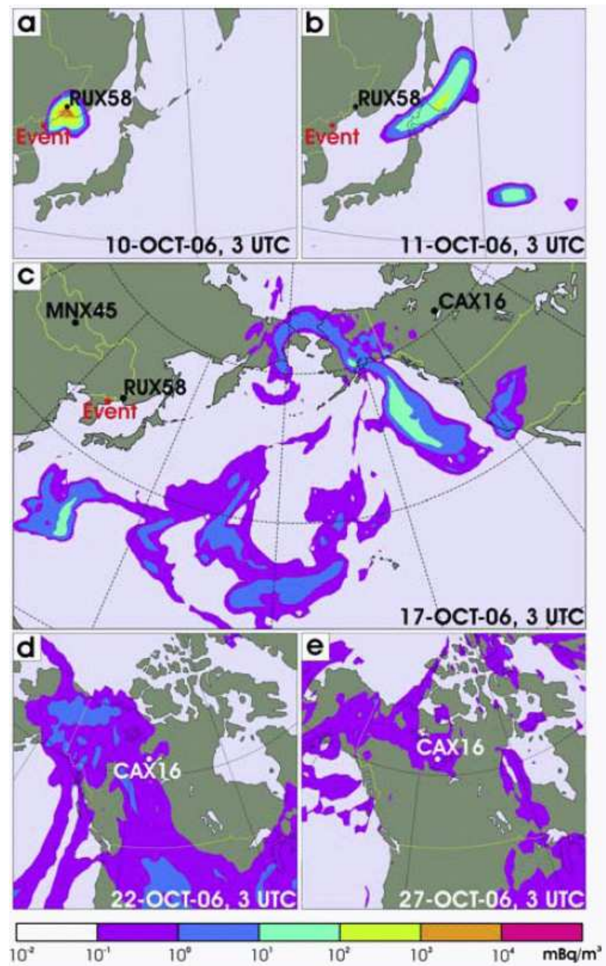

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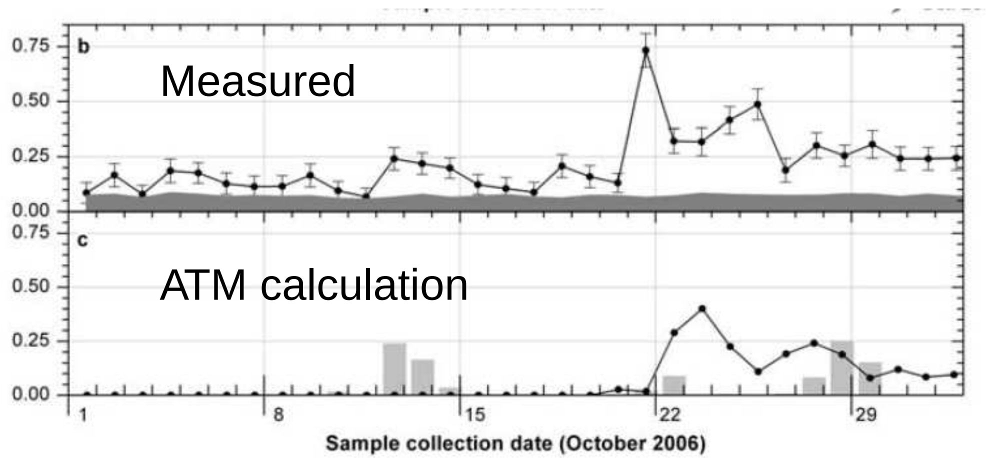

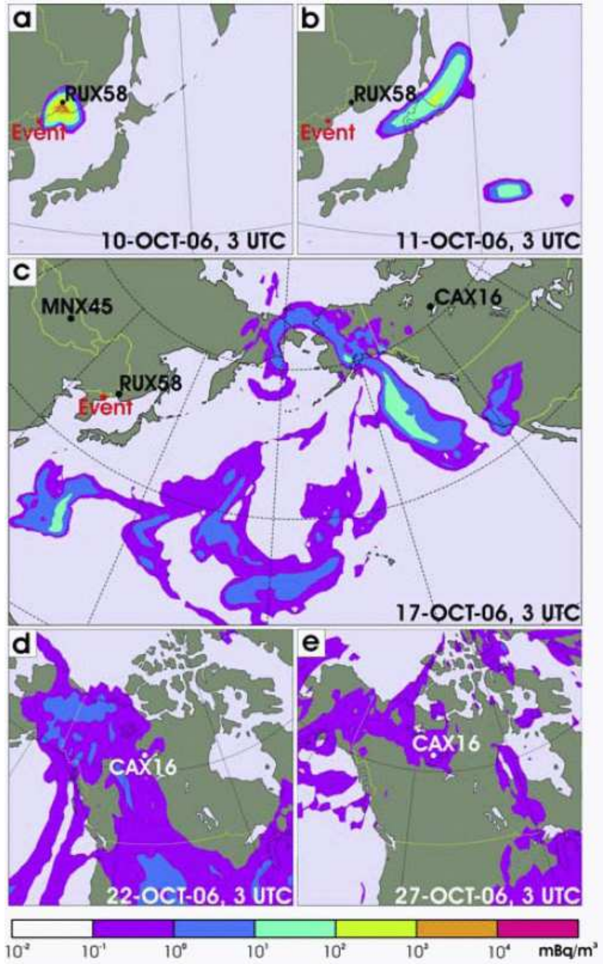

- Consistent with venting about 10% of the $^{133}\mathrm{Xe}$.

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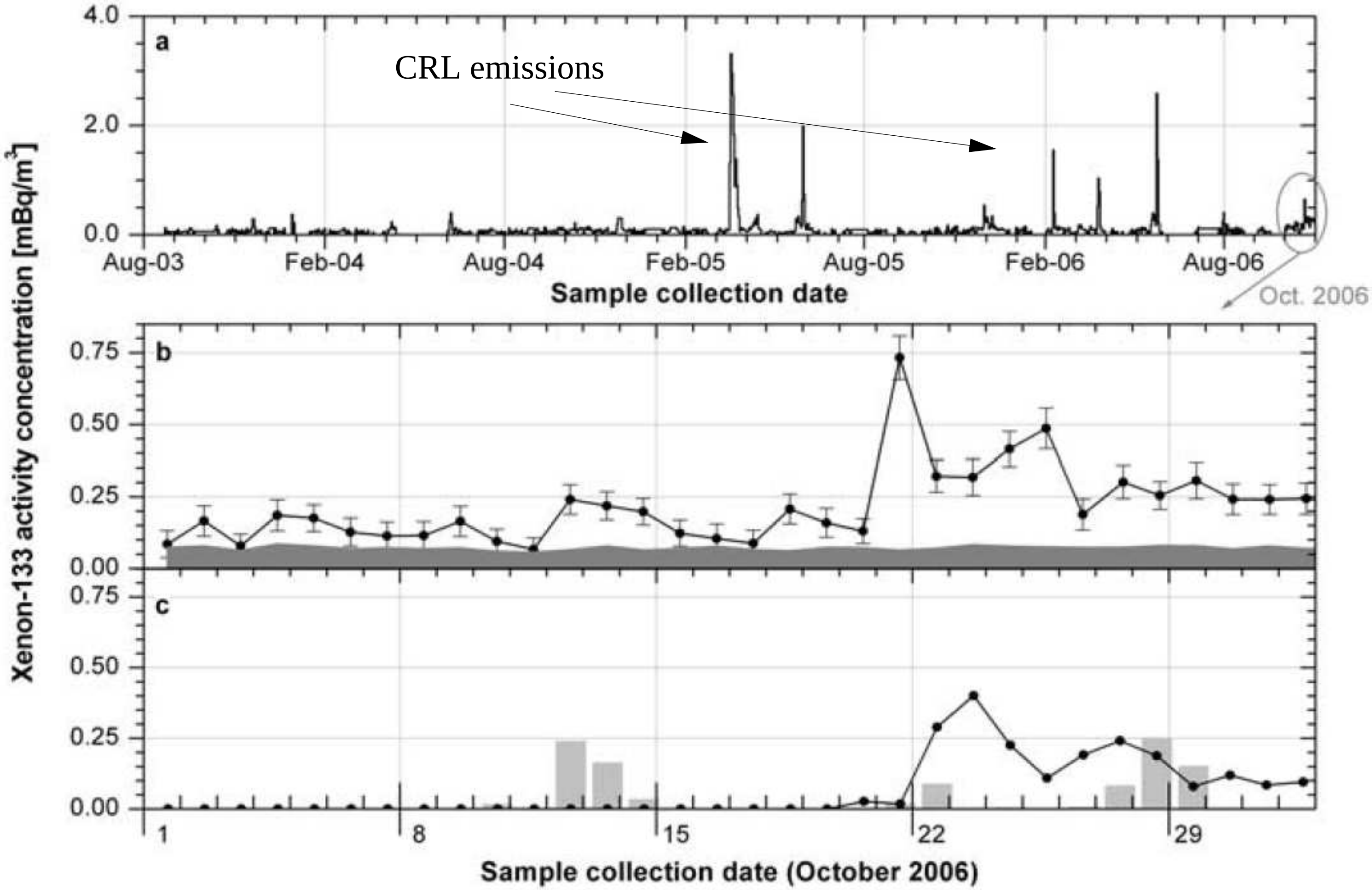
NOT Getting the Wrong Gun

- A reactor at the Chalk River Laboratory in Ontario is used to produce radiopharmaceuticals that form a background to the $^{133}\mathrm{Xe}$ measurement.
- Top panel in figure below shows the $^{133}\mathrm{Xe}$ concentration before the detection of the North Korean 2006 test (from P.R.J.Saey *et al.* Geophys. Res. Lett. 34, L20802 (2007)).



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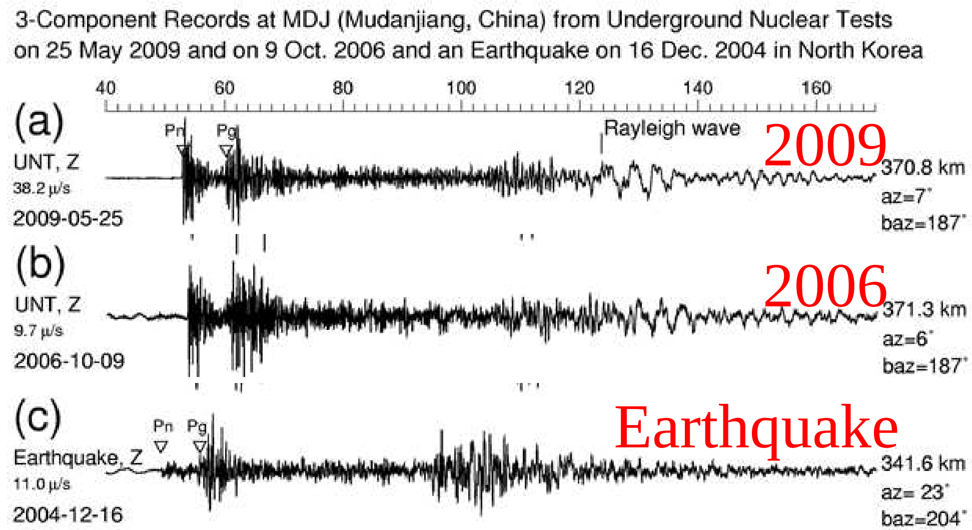

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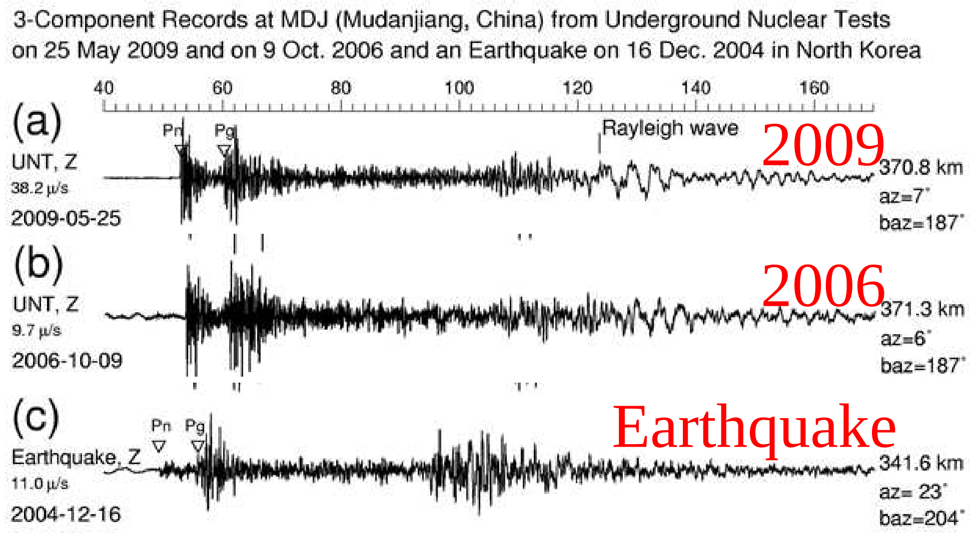

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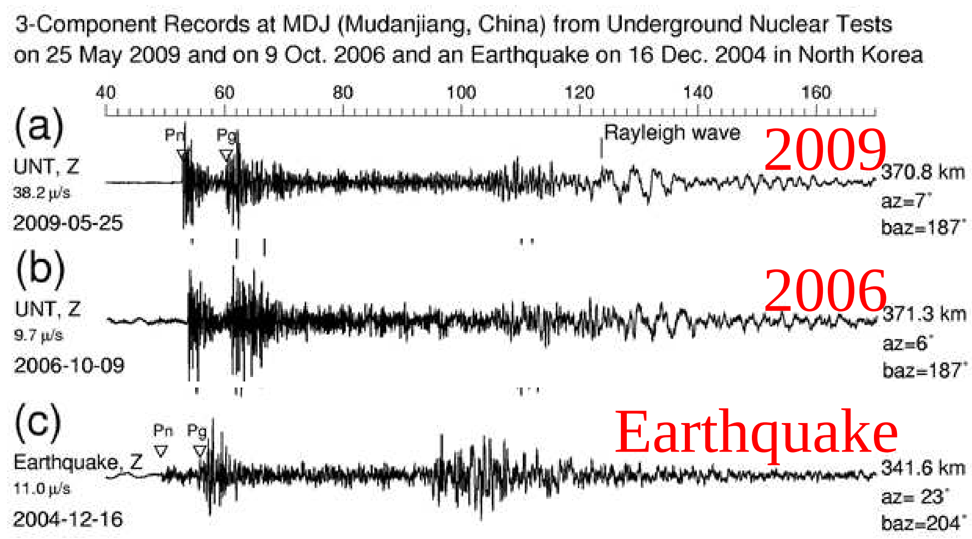

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What went wrong?

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* J. Medalia, *North Korea’s 2009 Nuclear Test: Containment, Monitoring, Implications*, Congressional Research Service, R41160, April 2, 2010.

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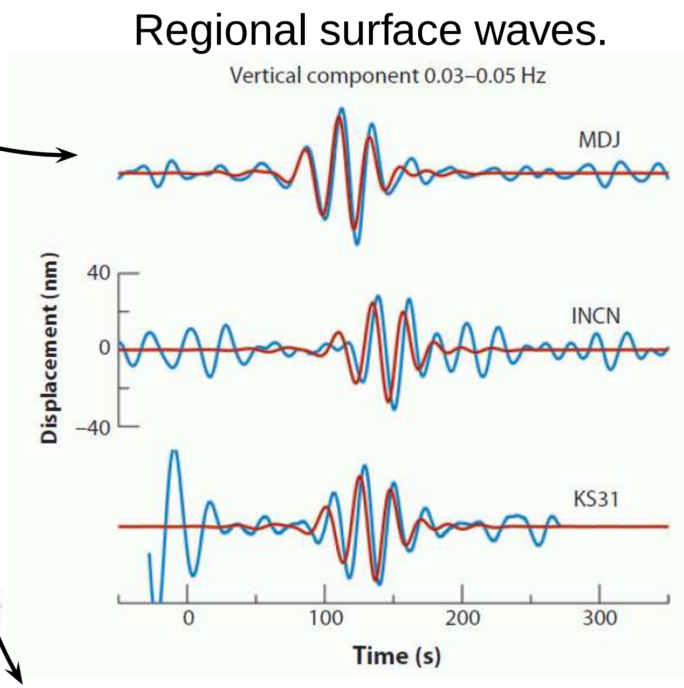
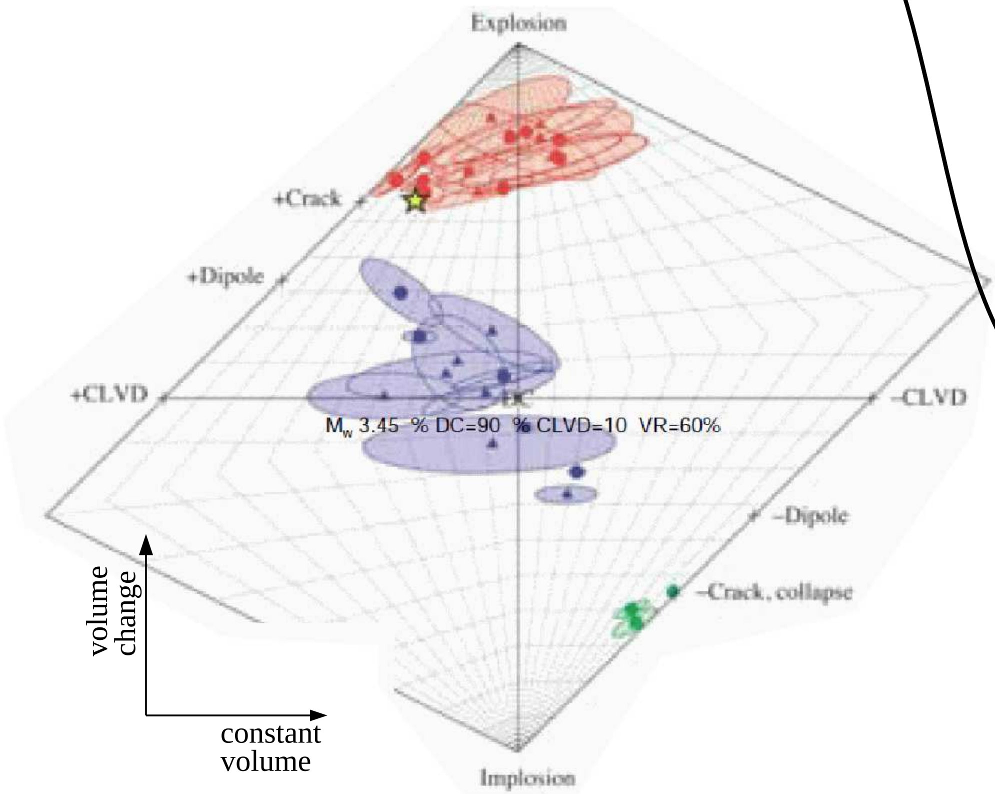
> The American Geophysical Union and the Seismological Society of America have stated the IMS will detect all explosions down to 1 kiloton (and much less in some areas) and within a radius of 35 km (October, 2009).

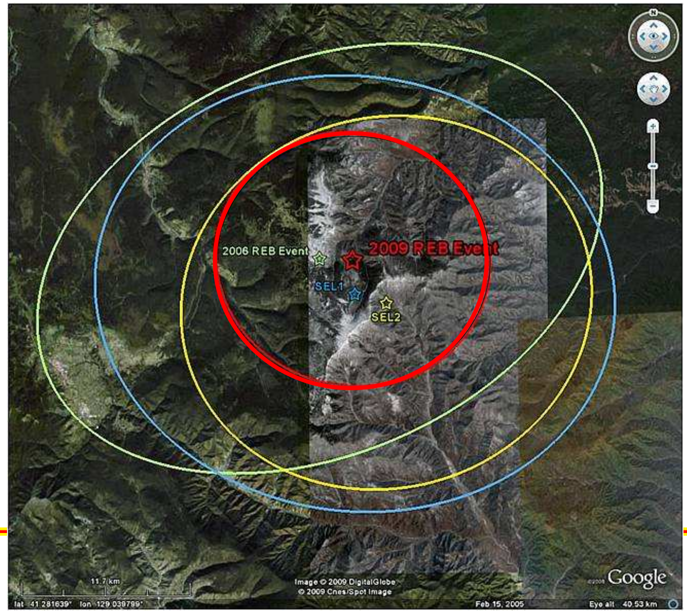
* J. Medalia, *North Korea’s 2009 Nuclear Test: Containment, Monitoring, Implications*, Congressional Research Service, R41160, April 2, 2010.

Another Test for the Test Ban

- Identifying the explosion.
- Epicenter/Location of the test.
- Moment tensor analysis.





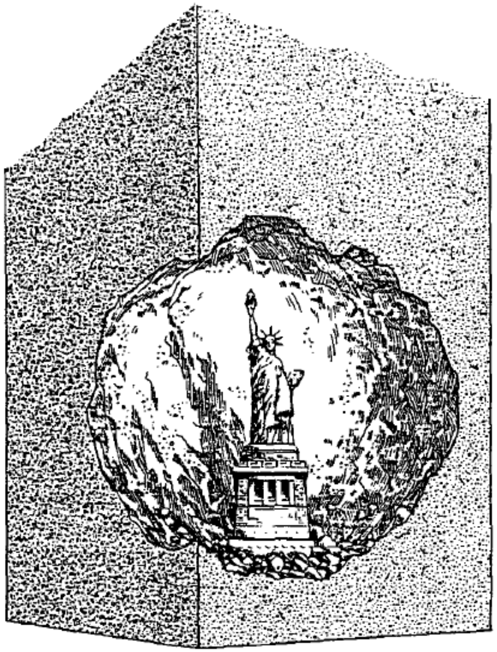


Can an Opponent Cheat on the CTBT?

- 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).

Why Should You Care?

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- ... 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.

Why Should You Care?

- The President is committed to bringing the CTBT to a vote for ratification in the Senate.
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  Senator Jon Kyl - R, Arizona: *Why We Need to Test Nuclear Weapons*, Wall Street Journal, October 20, 2009.

- 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.

Conclusions

1. Diverse, interdisciplinary technologies have demonstrated that detection and identification of nuclear explosions is possible.
2. Seismic detection will remain the primary tool of the IMS for monitoring underground nuclear explosions with additional methods like radioxenon detection supporting it.
3. The fate of the CTBT relies, in part, on the quality of the science supporting it and how well that message is transmitted to policy makers.
4. There is exciting, important physics to be done here.

Research Opportunities

- Congress recently passed the Nuclear Forensics and Attribution Act (Feb, 2010).
  - Creates the National Technical Nuclear Forensics Center within the Domestic Nuclear Detection Office (DNDO) of the Department of Homeland Security (DHS).
  - Establishes fellowships for undergraduates (summer research) and graduate students and awards for their advisors.
- Examples of DNDO research.
  - Hope College - Cathodoluminescent Signatures of Neutron Irradiation.
  - CUNY - Infrared Studies of CdMgTe as the Material of Choice for Room Temperature Gamma-Ray Detectors
  - Stanford - Improved Transparent Ceramic Fabrication Techniques for Radiological and Nuclear Detectors
- US National Labs
  - PNNL - Triple Coincidence Radioxenon Detector
  - Office of Defense Nuclear Nonproliferation (part of NNSA).

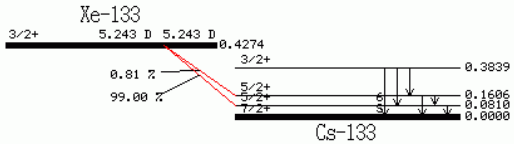
Additional Slides

Radioxenon decay chains.

^{133}Xe

133XE B- DECAY (5.243 D)

Parent state: G.S.
Half life: 5.243 D(1)
Q(gs): 427.4(24) keV
Branch ratio: 1.0



Beta ray:

Max.E(keV)	Avg.E(keV)	Intensity(rel)	Spin
346(3)	100.5(10)	99(3)	3/2+
266.8(-)	75.0(10)	0.81(9)	5/2+
43.5(-)	11.0(8)	0.0076(4)	5/2+
			3/2+

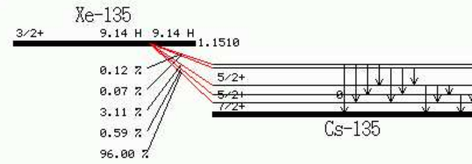
Gamma ray:

Energy(keV)	Intensity(rel)
79.623(10)	0.27(3)
80.997(3)	38.0(7)
160.613(8)	0.066(5)
223.234(12)	0.00012(2)
302.853(1)	0.0048(3)
383.851(3)	0.0024(2)

^{135}Xe

135XE B- DECAY (9.14 H)

Parent state: G.S.
Half life: 9.14 H(2)
Q(gs): 1151(10) keV
Branch ratio: 1.0



Beta ray:

Max.E(keV)	Avg.E(keV)	Intensity(rel)	Spin
910(10)	305(4)	96(4)	3/2+
743.0(-)	243(4)	0.59(3)	5/2+
550	168(4)	3.11(14)	
169.7(-)	46(3)	0.075(5)	5/2+
88.6(-)	23(3)	0.123(6)	

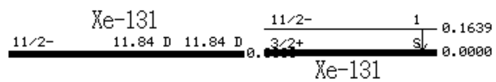
Gamma ray: for absolute intensity multiply by 0.90(3)

Energy(keV)	Intensity(rel)
158.197(18)	0.321(11)
200.19(10)	0.013(5)
249.794(15)	100
358.39(3)	0.245(9)
373.13(10)	0.017(3)
407.99(2)	0.398(13)
454.2(2)	0.0040(8)
573.32(9)	0.0053(8)
608.185(15)	3.22(10)
654.432(16)	0.050(2)
731.52(2)	0.061(3)
812.63(3)	0.078(2)
1062.41(2)	0.0045(9)

^{131m}Xe

131XE IT DECAY

Parent state: 163.930(8) keV
Half life: 11.84 D(7)
Q(gs): () keV
Branch ratio: 1.0



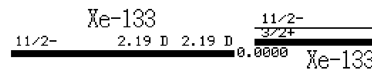
Gamma ray:

Energy(keV)	Intensity(rel)
163.930(8)	1.95(6)

^{133m}Xe

133XE IT DECAY (2.19 D)

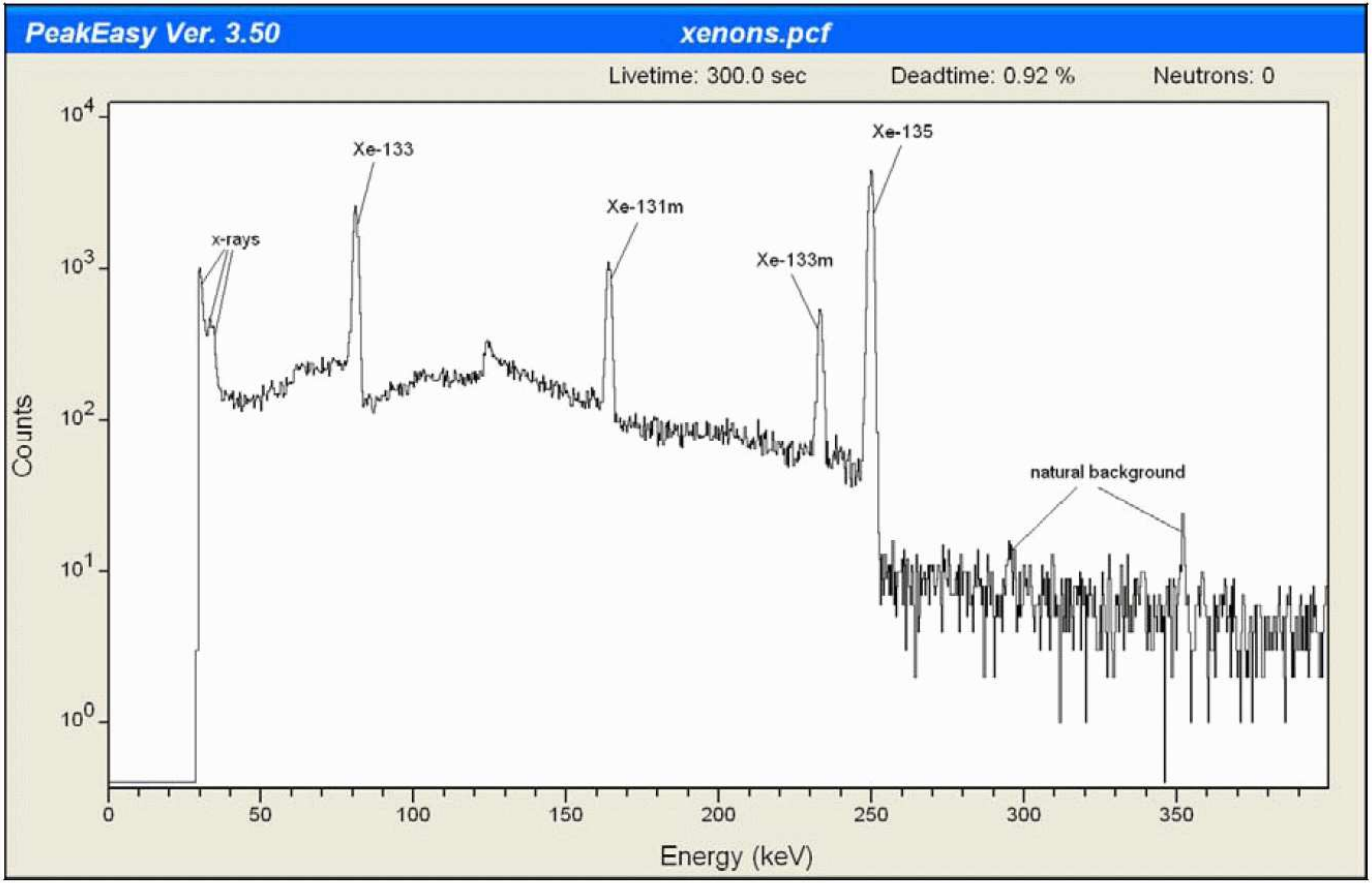
Parent state: 233.221(18) keV
Half life: 2.19 D(1)
Q(gs): () keV
Branch ratio: 1.0



Gamma ray:

Energy(keV)	Intensity(rel)
233.221(18)	10

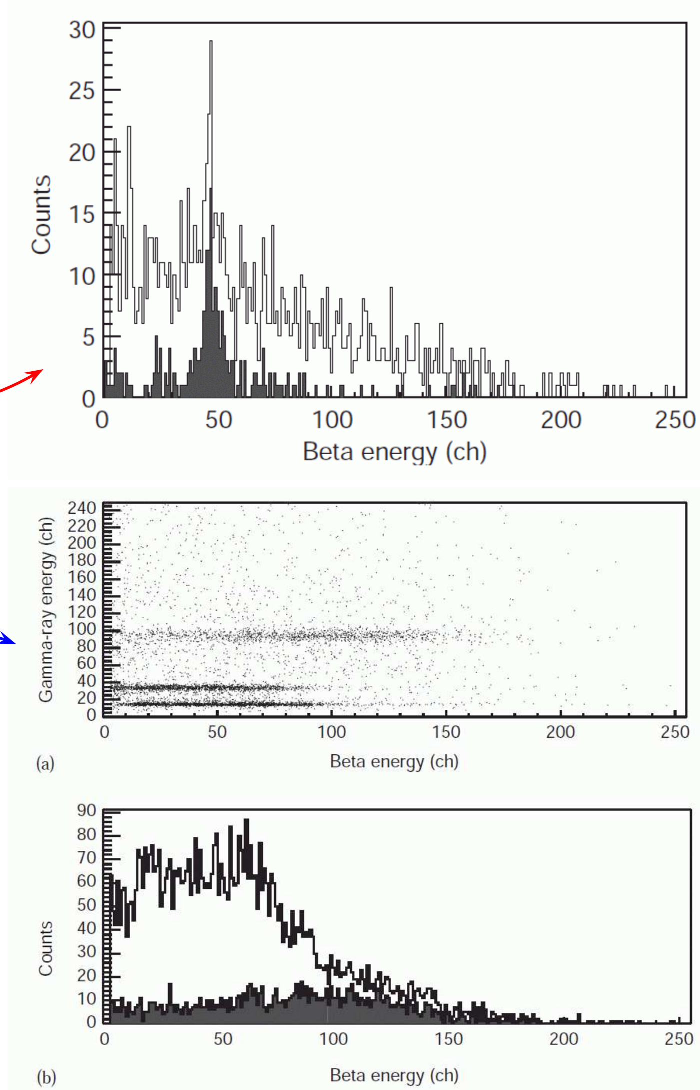
Radioxenon γ-Rays



Finding the Smoke

- Each radioxenon isotope sample emits a mixture of e's, β's and γ's from its decay chain.
- $^{131\mathrm{m}}\mathrm{Xe}$ can γ decay to its ground state ($E_\gamma = 0.164\ \mathrm{MeV}$) or internally convert emitting an electron ($E_e = 0.129\ \mathrm{MeV}$) and a coincident X-ray ($E_X = 0.030\ \mathrm{MeV}$).
- $^{135}\mathrm{Xe}$ will mostly β decay to an excited state of $^{135}\mathrm{Cs}(0.250\ \mathrm{MeV})$ which emits a γ-ray in coincidence.
- Values for the minimum detectable concentrations for the radioxenons are 1-2 $\mathrm{mBq/m^3}$.

1-2 events every 1000 seconds
per m^3 of air!



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

Assessing Risk

What should you stay awake worrying about at night?

Deaths in 2005*	Cause
2,447,910	All causes
853,188	Heart Disease
45,043	Vehicle Accidents
62,804	Influenza/Pneumonia
31,769	Suicide

Deaths in 2005*	Cause
17,694	Homicide
21,416	Poisoning
19,488	Falling
3,468	Drowning
3,144	Fire

*National Vital Statistics Reports, **56**, no. 16, June 11, 2008.

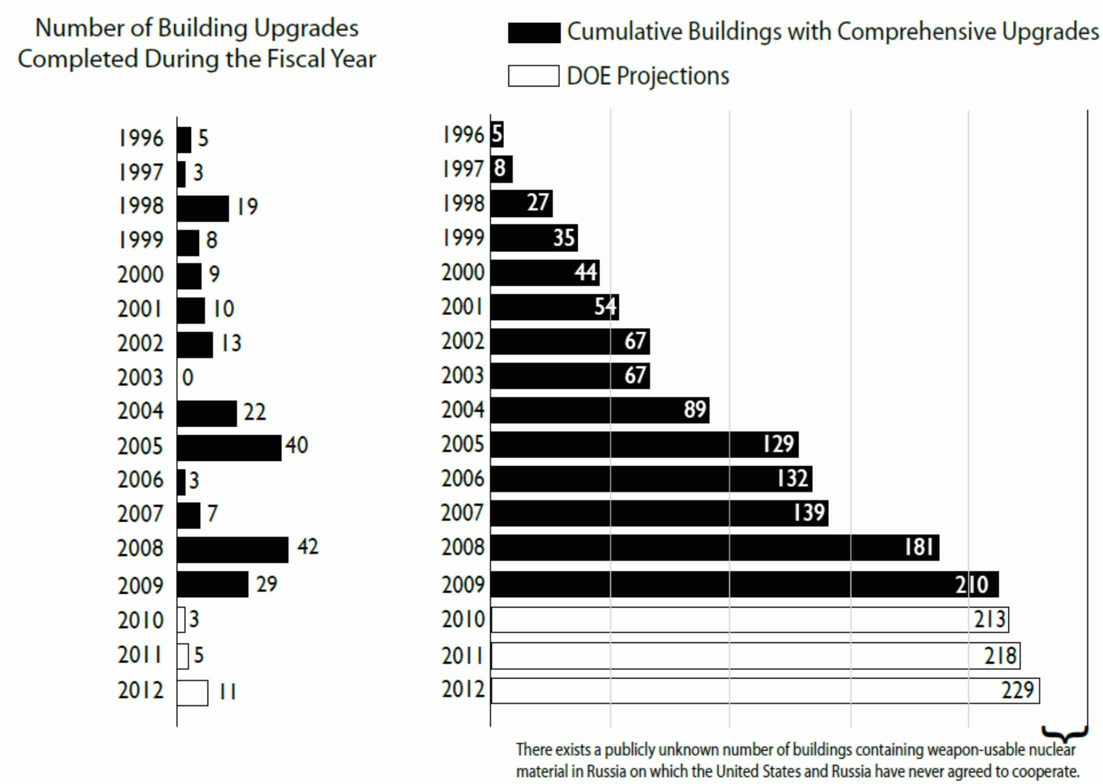
Preventive Threat Reduction

- The US spends taxpayer monies to remove and reduce weapons to increase homeland security.
- The Nunn-Lugar programs in cooperation with Russia spend $\approx$\$1B each year dismantling and securing the Russian nuclear weapons complex and destroying chemical and biological weapons.

Russian Missile Sub Dismantlement

- Operation Sapphire in 1995 removed 1300 pounds of insecure, weapons-grade uranium from Kazakhstan.
- Removal in summer 2003 of about 90 pounds of weapons-grade uranium from Vinca Institute in Serbia (with help from Ted Turner).
- Destruction of Scud missiles in Bulgaria.

How Are We Doing?



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.

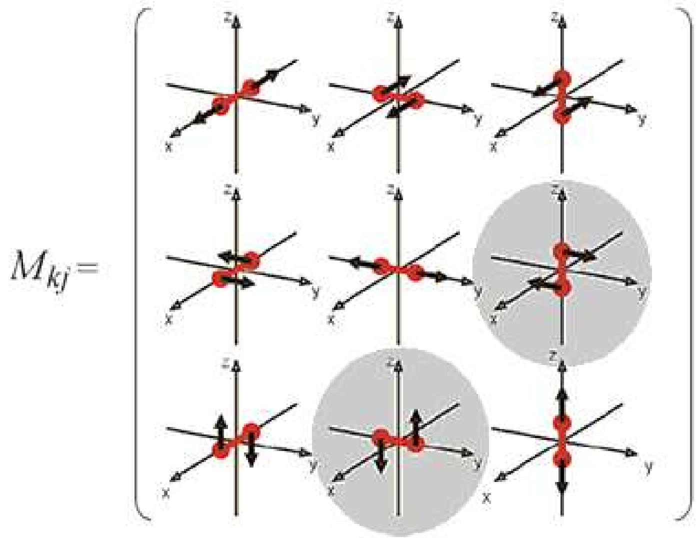
Reproduced from M. Bunn, *Securing the Bomb 2010*, Harvard University and the Nuclear Threat Initiative, April 2010).

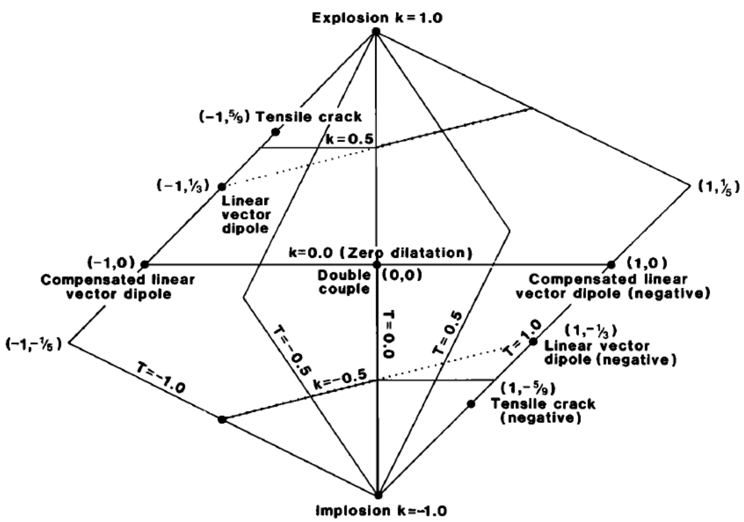
Moment Magnitude Measures Energy Released

Size	Description	Effects	Frequency
2.0-2.9	Minor	Micro earthquakes, generally not felt.	1,000 per day
3.0-3.9	Minor	Often felt, but rarely causes damage.	49,000 per year
4.0-4.9	Light	Noticeable shaking indoors. Significant damage unlikely.	6,200 per year
5.0-5.9	Moderate	Major regional damage to poorly constructed buildings; slight damage to well-designed buildings.	800 per year
6.0-6.9	Strong	Destructive over 100 mi regions	120 per year
7.0-7.9	Major	Can cause serious damage over larger areas.	18 per year
8.0-8.9	Great	Can cause serious damage in areas several hundred kilometers across.	1 per year
9.0-9.9	Great	Devastating in areas several thousand kilometers across.	1 per 20 years
10.0+	Massive	Never recorded, widespread devastation across very large areas .	Unknown

Moment Tensor Analysis

- Assume a general model for the source (*i.e.*, double-couple model for an earthquake).
- Describe the seismic waves with a multipole expansion truncated after the first terms that do not violate conservation of linear and angular momentum; get a 3×3 tensor (the moment tensor) with six independent components.
- Extract eigenfunctions (*i.e.*, the principle axes) and eigenvalues.
- Characterize source in terms of the fraction of constant volume (shear) component T and the fraction of volume change component k.
- Plot on a scale where the probability of a source in a particular range of (T, k) is proportional to the area of the plot.

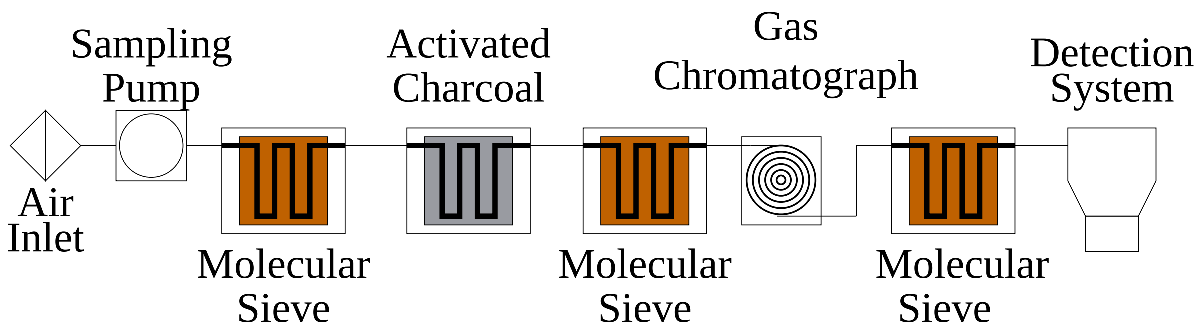




J.A.Hudson, R.G.Pearce, and R.M.Rogers, *Jour. Geophys. Res.*, 94, B1, 765 (1989).

Looking for the Smoking Gun

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



Looking for the Smoking Gun

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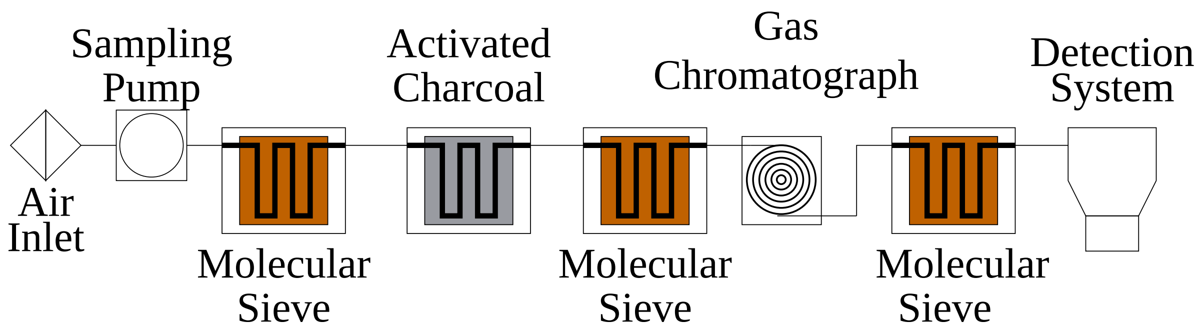
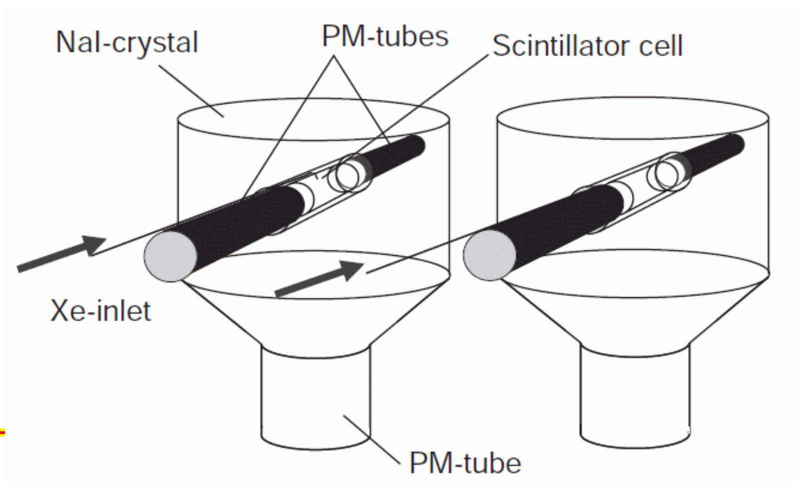


- Detection system uses $\beta - \gamma$ coincidences or high-resolution γ detection.
- For $\beta - \gamma$ method xenon is passed into the chamber of a hollow cylinder made of plastic scintillator inserted in a cylindrical hole inside a NaI crystal. Light produced by β and γ particles is detected with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



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

One of several automated systems used by IMS.

Finding the Smoke - High-Resolution γ Method

- High-purity Ge crystals can also be used for detecting γ's from radioxenon.
- Less sensitive that $\beta - \gamma$ spectrometry, but....
- Direct detection of all four radioxenons of interest can be made with high resolution.
- Robust technology well-suited to field work.
- Analysis uses standard tools.

J.-P. Fontaine *et al.*
72 (2004) 129.