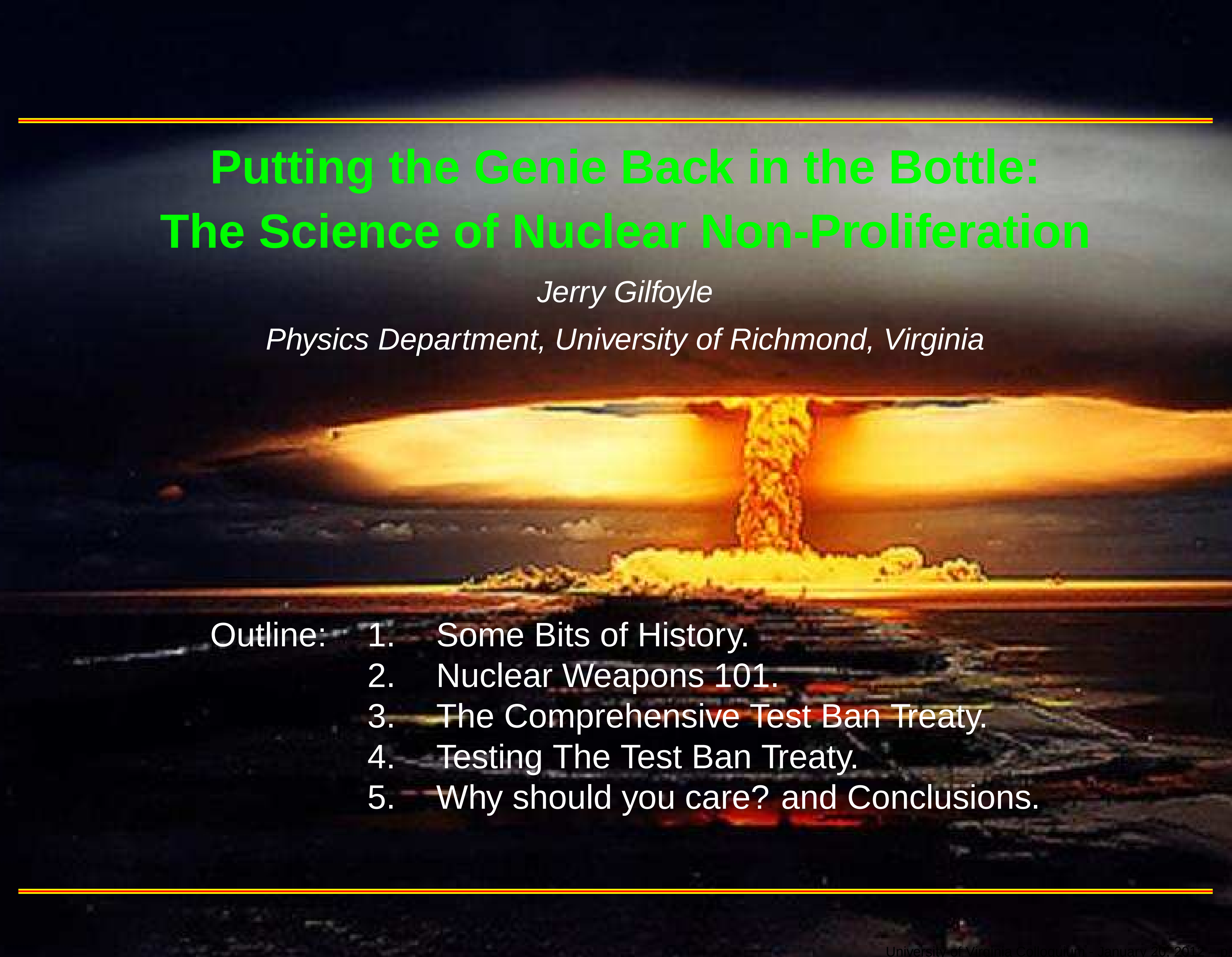

Putting the Genie Back in the Bottle: The Science of Nuclear Non-Proliferation

Jerry Gilfoyle

Physics Department, University of Richmond, Virginia

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.

Putting the Genie Back in the Bottle:

"All the News
That's Fit to Print"

The New York Times

Late Edition

New York: Today, cloudy with some light snow, high 35. **Tonight**, early snow, low 27. **Tomorrow**, becoming partly sunny, high 35. **Yesterday**, high 34, low 25. Weather map, Page D8.

VOL. CL . . No. 51,624 Copyright © 2001 The New York Times *NEW YORK, FRIDAY, JANUARY 5, 2001* $1 beyond the greater New York metropolitan area. *75 CENTS*

REPORT TO CLINTON ASKS U.S. TO RATIFY TEST-BAN TREATY

A LAST-DITCH CAMPAIGN

Retired Head of Joint Chiefs Seeks to Assuage Critics of Pact Assailed by Bush

By MICHAEL R. GORDON

A former chairman of the Joint Chiefs of Staff who conducted a comprehensive study of the nuclear test ban treaty at the request of President Clinton has concluded that the United States must ratify it in order to mount an effective campaign against the spread of nuclear weapons.

The assessment by Gen. John M. Shalikashvili, who was chairman of the Joint Chiefs from 1993 to 1997, is part of a last-ditch attempt by Mr.

Road Ban Set For One-Third Of U.S. Forests

Clinton Order Will Put Logging Off Limits

By DOUGLAS JEHL

WASHINGTON, Jan. 4 — In the biggest land conservation act in decades, President Clinton will approve an order on Friday putting nearly a third of the national forest land permanently off limits to road building and logging.

The move, covering more than 58 million acres in 39 states, is to be cast by the White House as a capstone in the president's efforts to protect public lands from development. It would effectively prohibit not only commercial logging but also oil and gas development across an area larger than the nation's current national parks. And while not specifically banned, off-road vehicle activity would probably be severely limited in the roadless areas because of

Three Who Are Losing Their Old Chairmanships . . .

Associated Press

Bud Shuster *of Pennsylvania*

Former chairman of the Transportation and Infrastructure Committee announced yesterday that he was resigning.

Associated Press

Henry J. Hyde *of Illinois*

Former chairman of the Judiciary Committee, who led the impeachment of President Clinton; new chairman of International Relations.

Reuters

Jim Leach *of Iowa*

Former chairman of Banking and Financial Services Committee; still in Congress but no longer a chairman.

. . . and Three New Chairmen of Powerful Committees

HONORING '95 VOW, HOUSE REPUBLICANS REPLACE 13 CHIEFS

FIGHT FOR COVETED POSTS

In the Evenly Divided Senate, Democrats Move Toward a Deal to Share Power

By LIZETTE ALVAREZ

WASHINGTON, Jan. 4 — Six years after promising to change the ways of Washington fundamentally, House Republicans today made good on their pledge to curtail the power of committee barons and replaced 13 of their most senior chairmen.

The newly created selection process created fierce competition among members who sought the positions, intensified party fund-raising by the members seeking to demonstrate loyalty and led to the creation

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  - Support the right to peacefully use nuclear technology

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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.

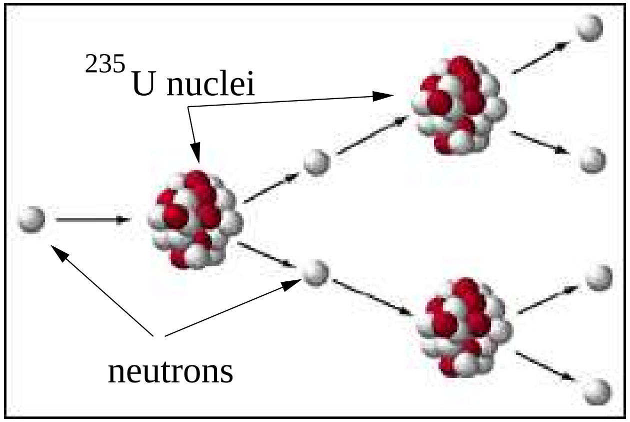
Nuclear Weapons 101 - Radiation

- 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 - 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.

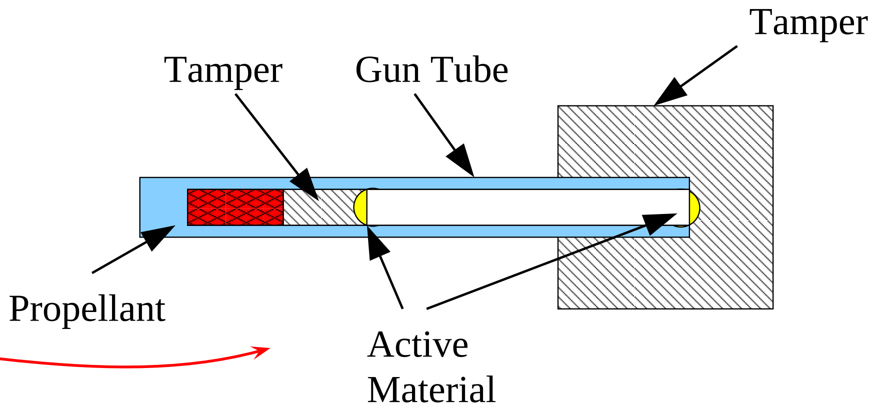
A Chain Reaction



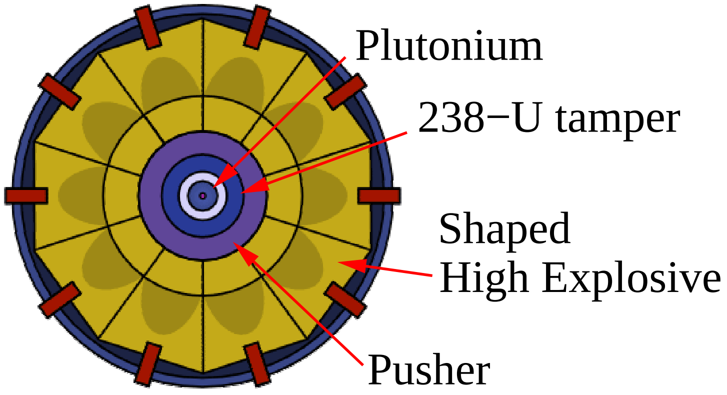
- Only about 8 kg of plutonium or 25 kg of highly-enriched uranium (HEU) is needed is needed to produce a weapon.

Nuclear Weapons 101 - Basic Weapons Designs

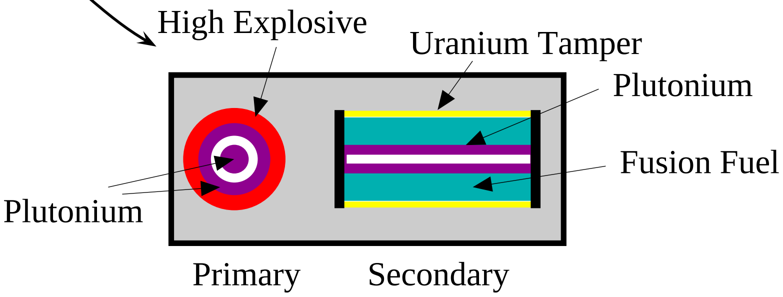
- Uranium, gun-type weapon - High explosive fires highly-enriched uranium slug down the gun tube and into the uranium target. The density increases enough to sustain the chain reaction.

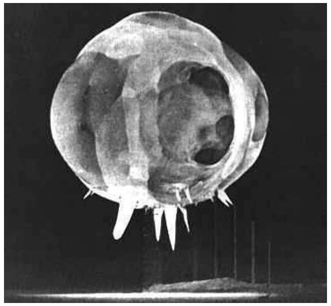


- Plutonium implosion device - High explosive crushes the plutonium primary to a density where fission can occur.



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

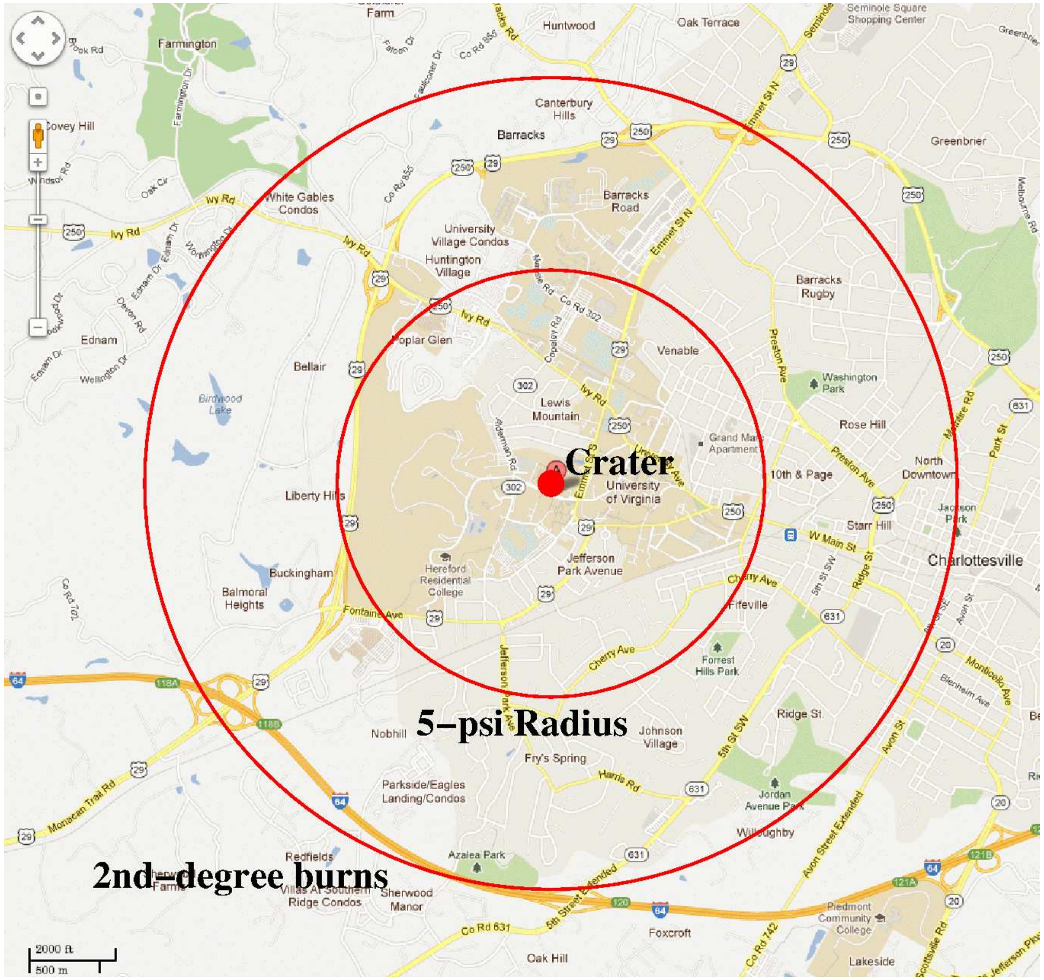




Nuclear fireball $1\ ms$ after detonation (Tumbler Snapper); it is about 20 m across.

Nuclear Weapons 101 - Effects

- Energy released in the form of light, heat and blast.
- Blast ≈40-50% of total energy.
- Thermal radiation ≈30-50% of total energy.
- Ionizing radiation ≈5% of total energy.
- Residual radiation ≈5-10% of total energy.
- Figure shows effect of a 15 kiloton bomb (about the size of the Hiroshima bomb) exploded over the Jesse Beams Laboratory.



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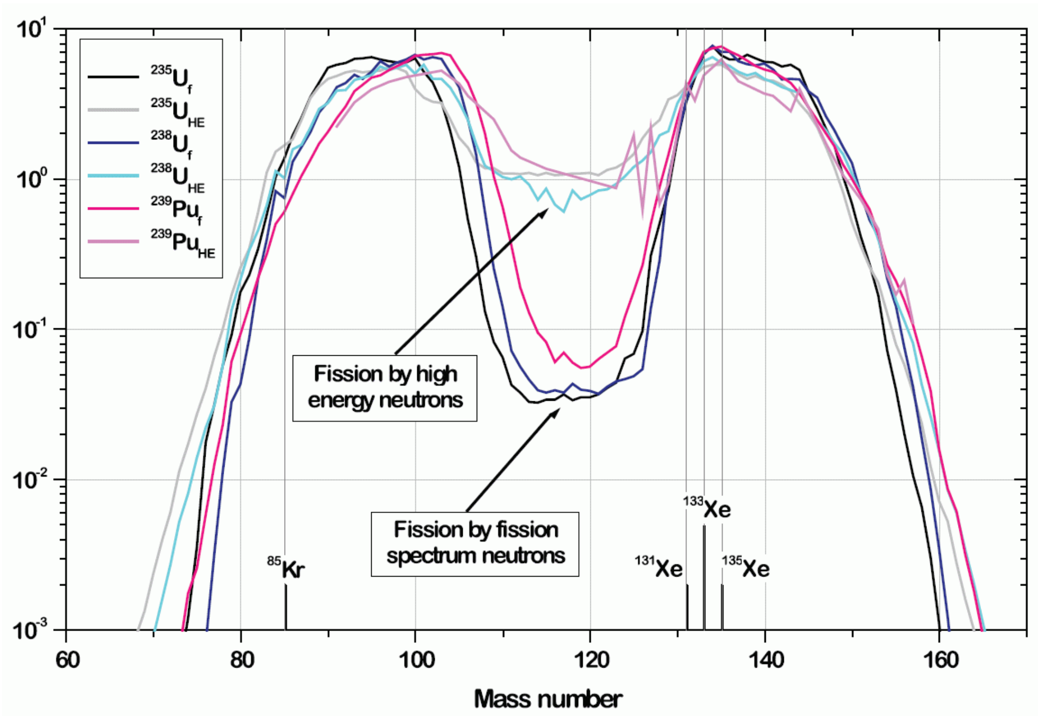
Nuclear Weapons 101 - Nuclear Forensics

- 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.



Fission by high energy neutrons

Fission by fission spectrum neutrons

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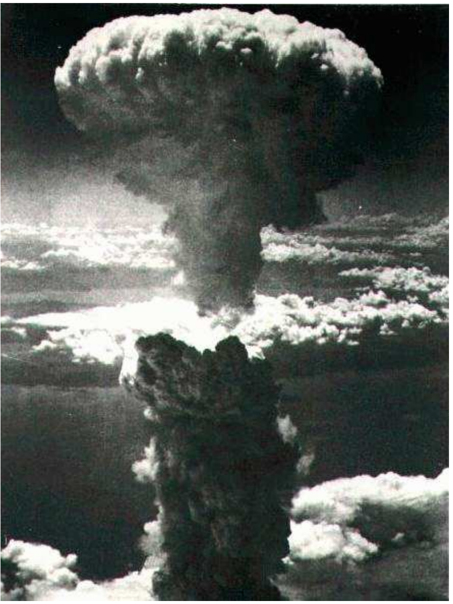
* P.R.J. Saey, ESARDA Bulletin, 36 (2007) 42.

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.



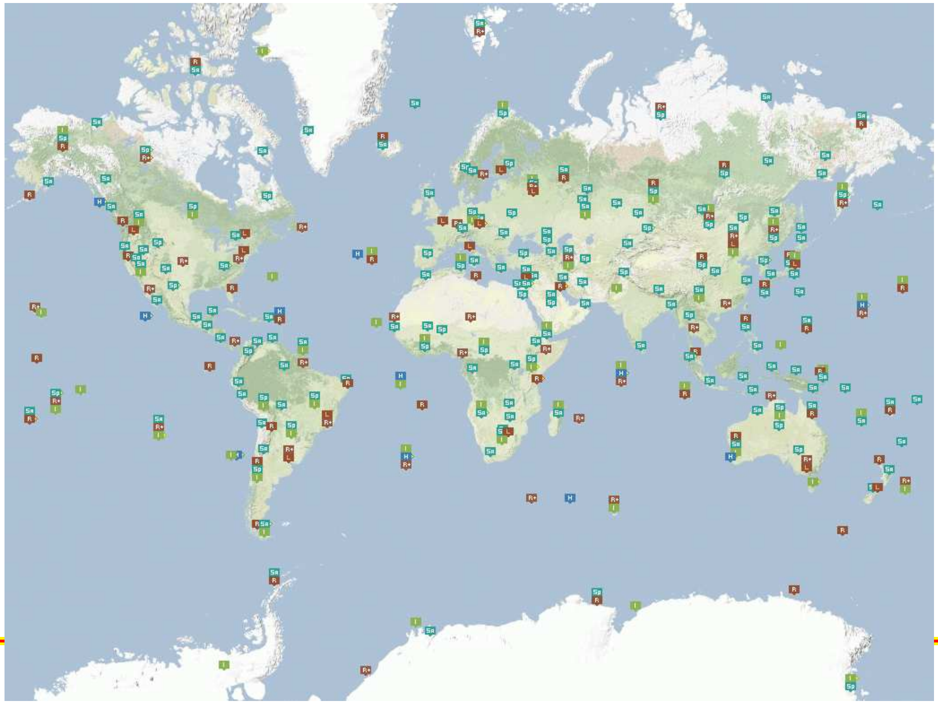
Green - ratified

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 re-quest an on-site-inspection subject to a vote .



Testing the Test Ban Treaty

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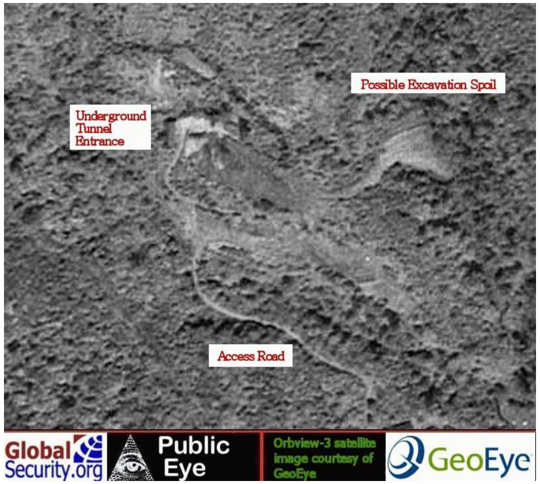

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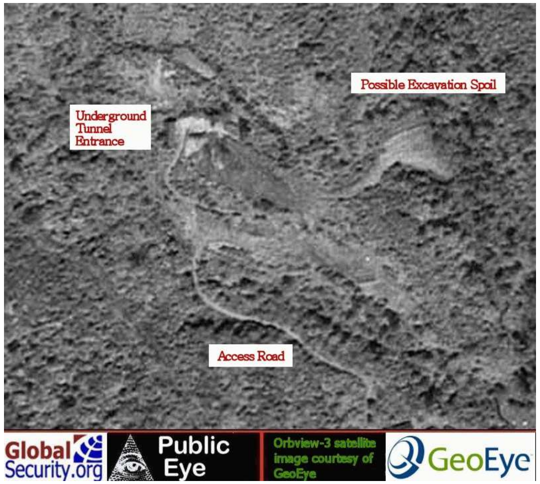

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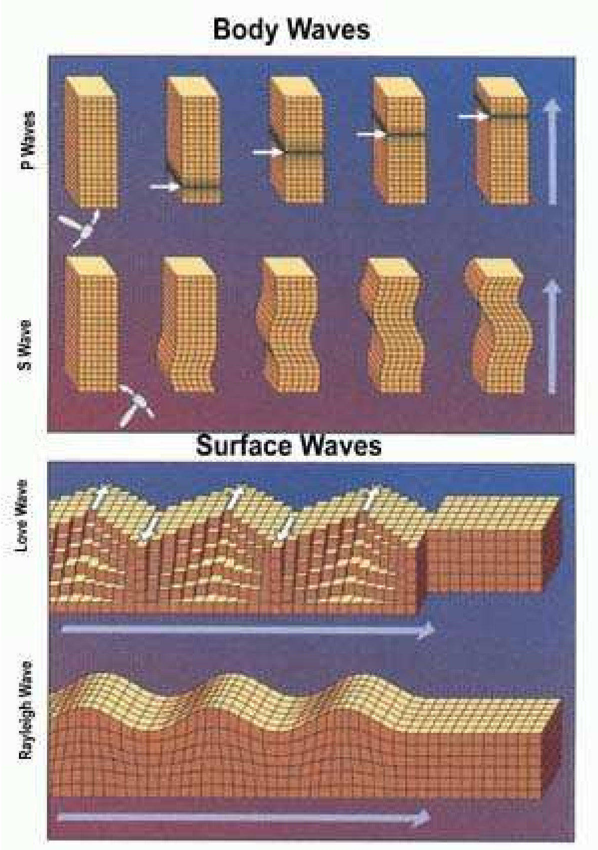
How??

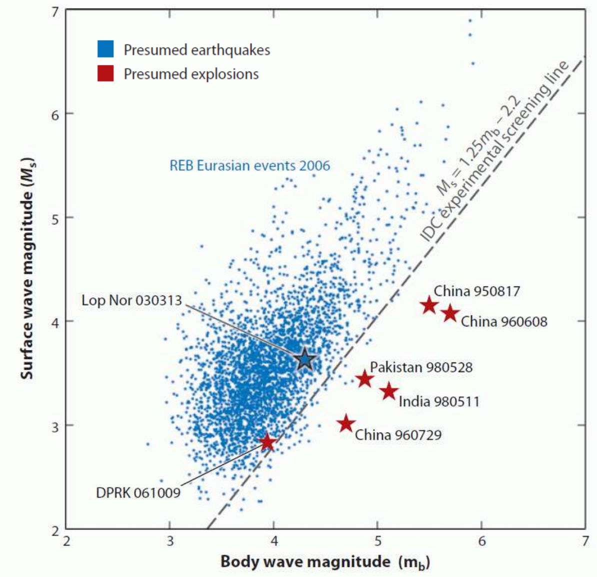
Detecting Seismic Signatures of Nuclear Tests

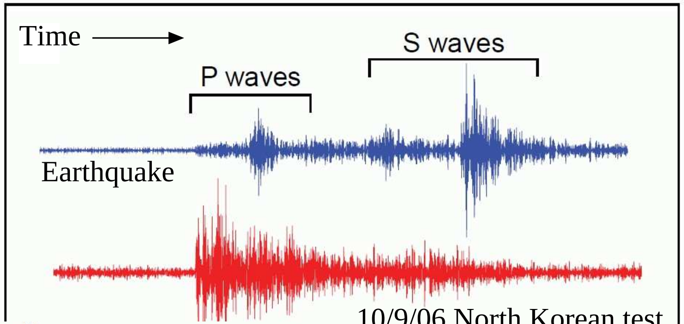
- The Problem
  - Use tremors created by underground explosions to detect treaty violations.
  - Big backgrounds! 600-700 earthquakes/day plus hundreds of mining explosions; about 25 events/day with magnitude > 4.
  - Can we identify a nuclear test among all this noise?
- Some seismology.
  - Surface 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.

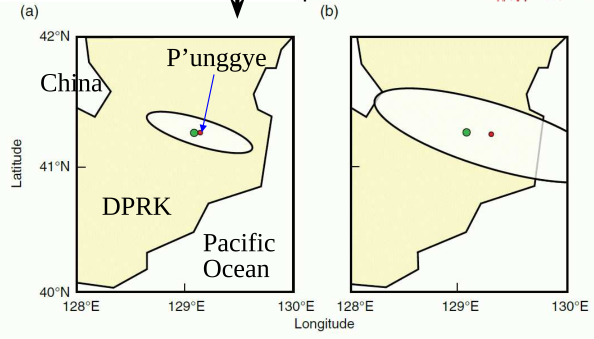


Identifying Nuclear Tests

- 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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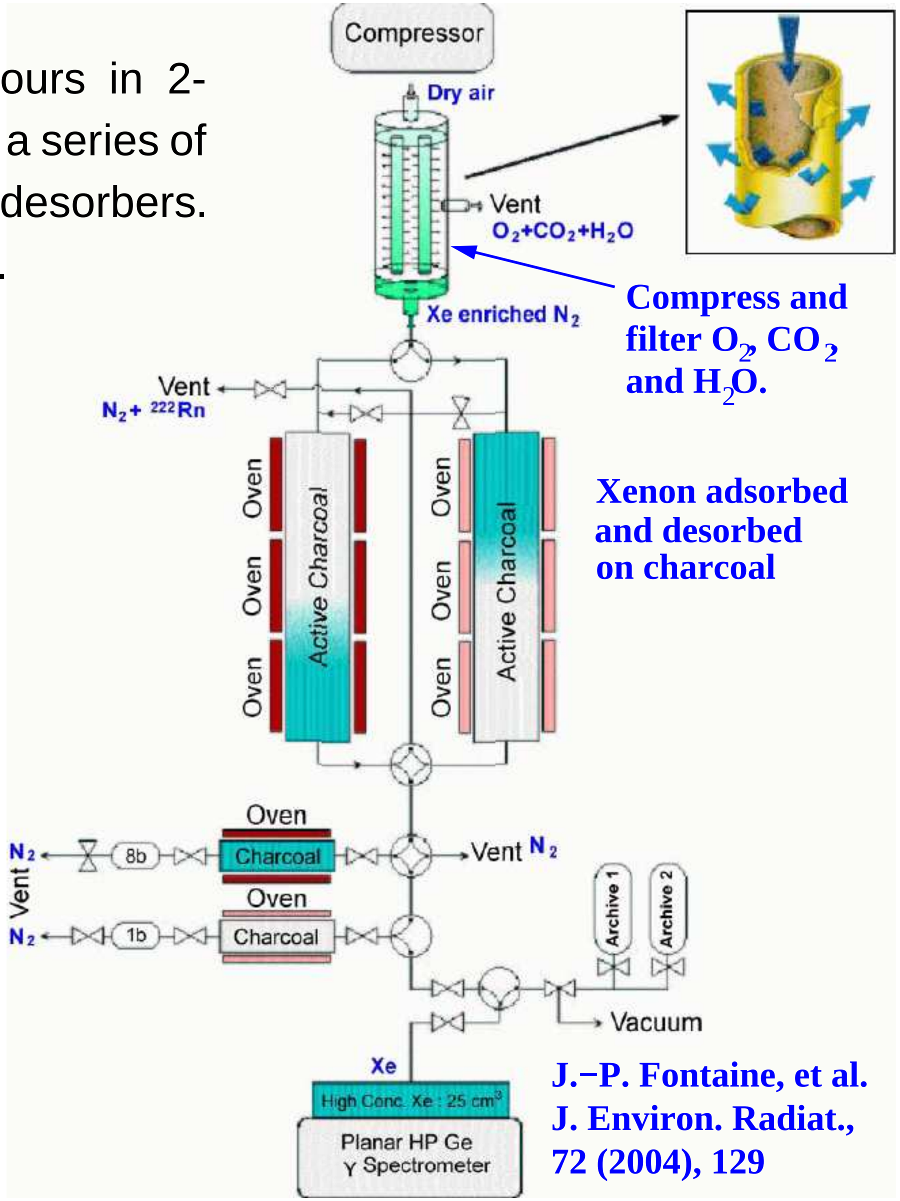
Looking for the Smoking Gun

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



Compress and filter O_2, CO_2 and H_2O.

Xenon adsorbed and desorbed on charcoal

J.−P. Fontaine, et al. J. Environ. Radiat., 72 (2004), 129

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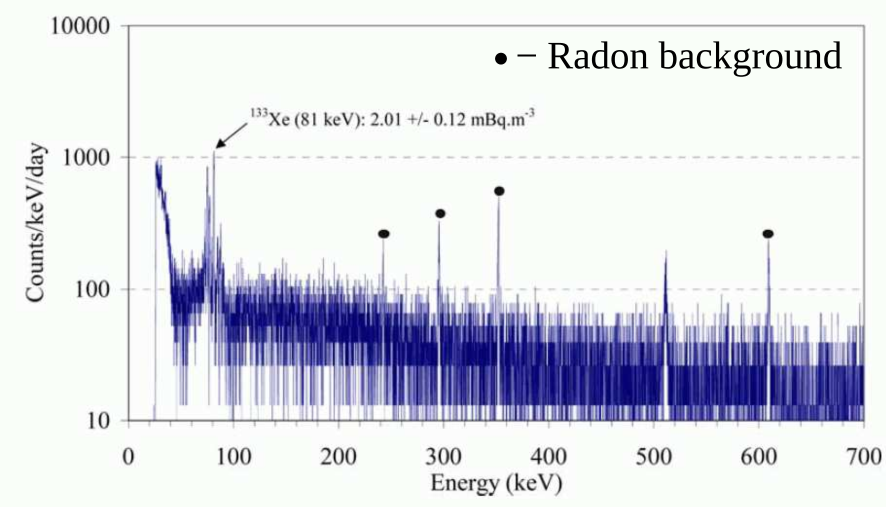
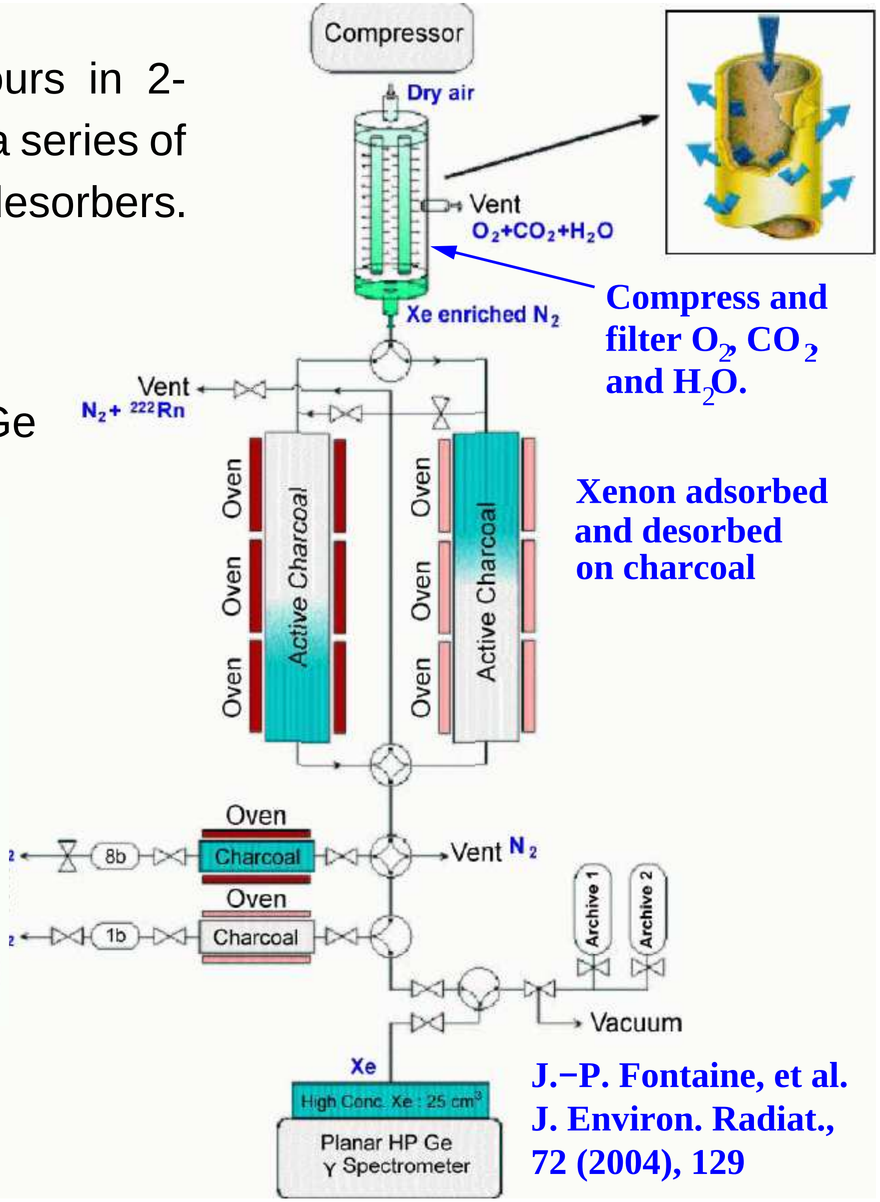
- Finding it! Detection with high-purity Ge crystals for high-resolution γ detection.



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



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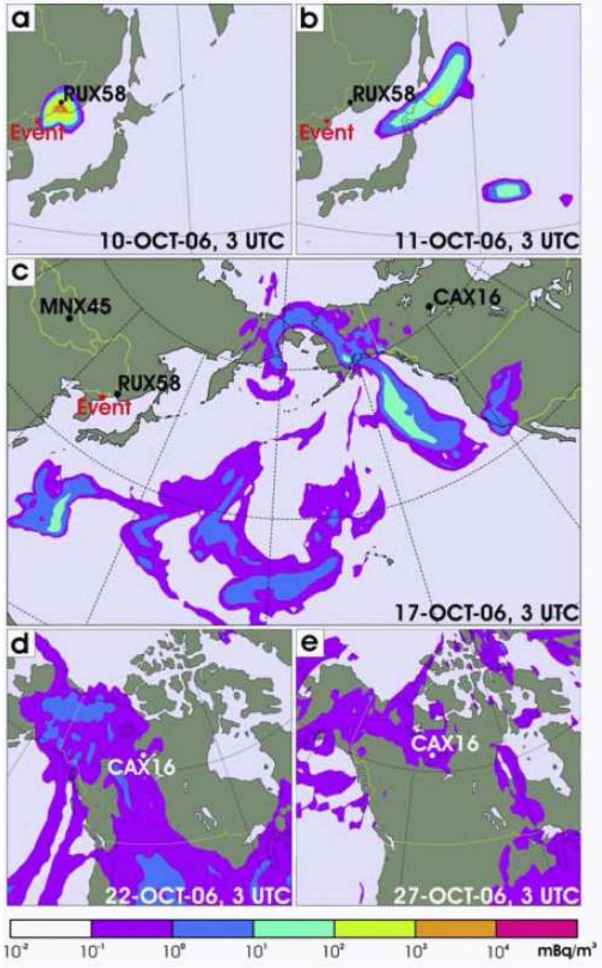

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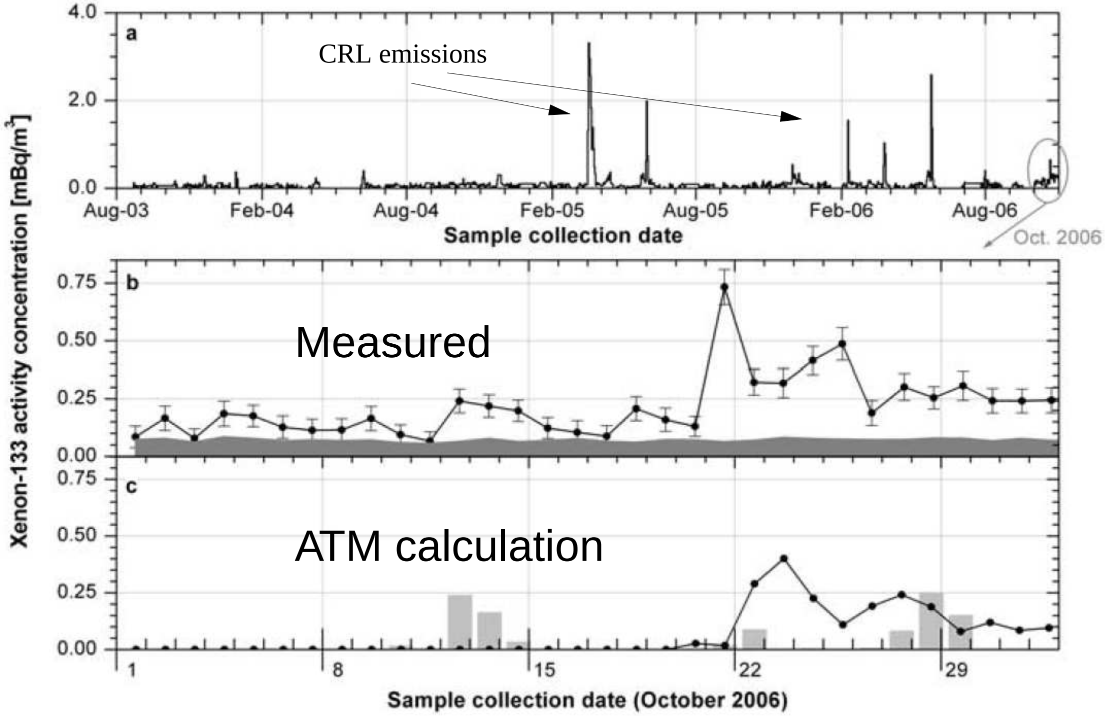
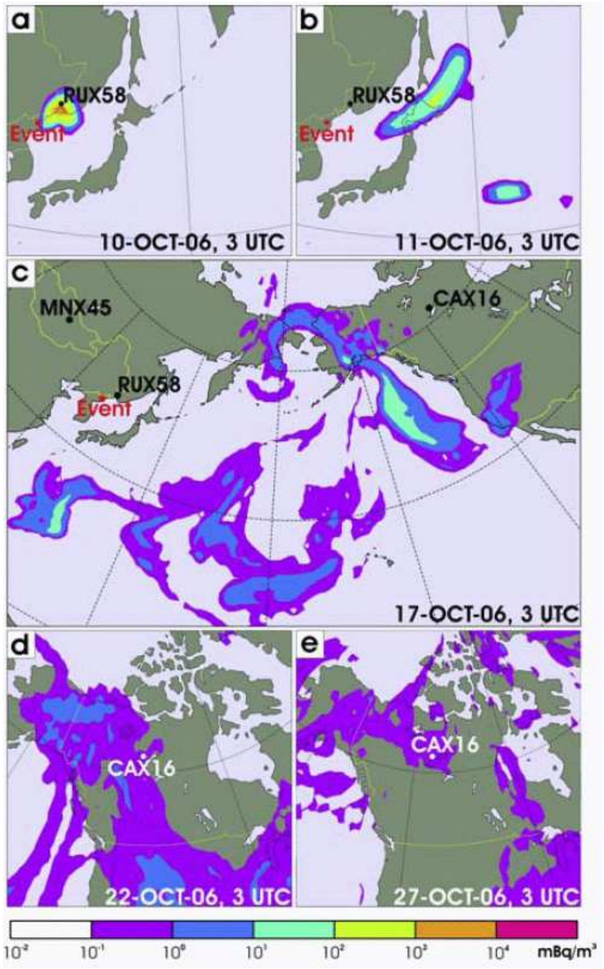
- Background, measured, and ATM prediction of $^{133}\mathrm{Xe}$ activity from Yellowknife station (γ detection).





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

Another Test for the Test Ban

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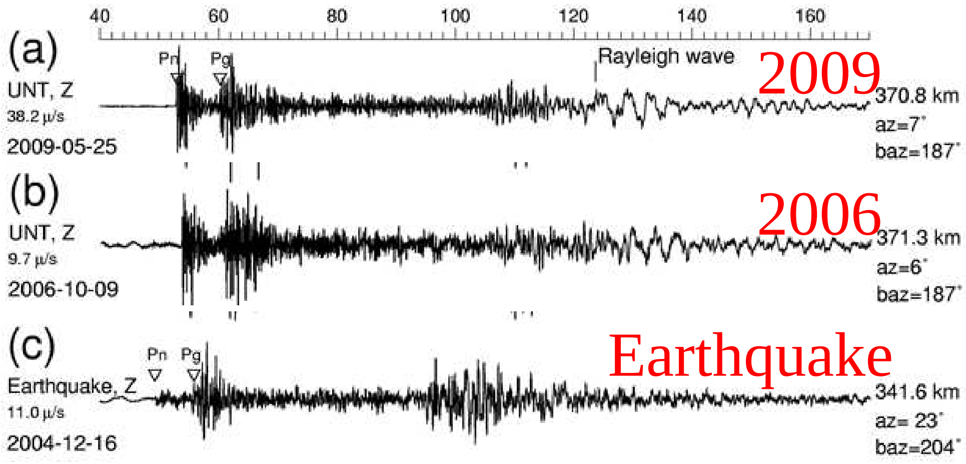

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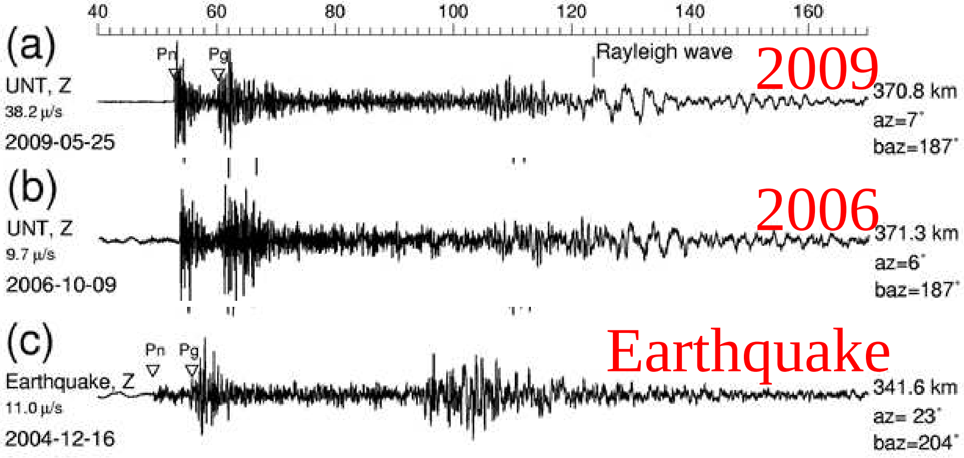

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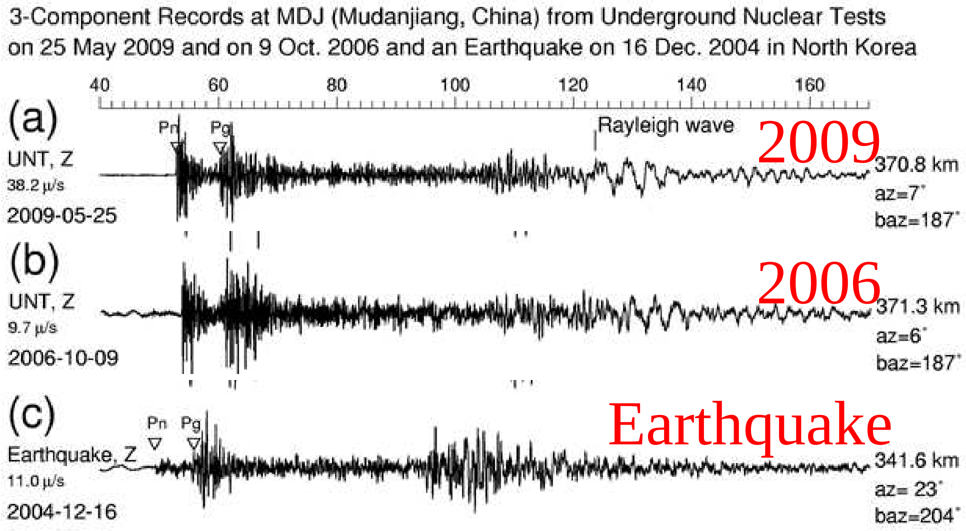
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What went wrong?

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  - Higher yield bomb could have sealed the rock from venting.
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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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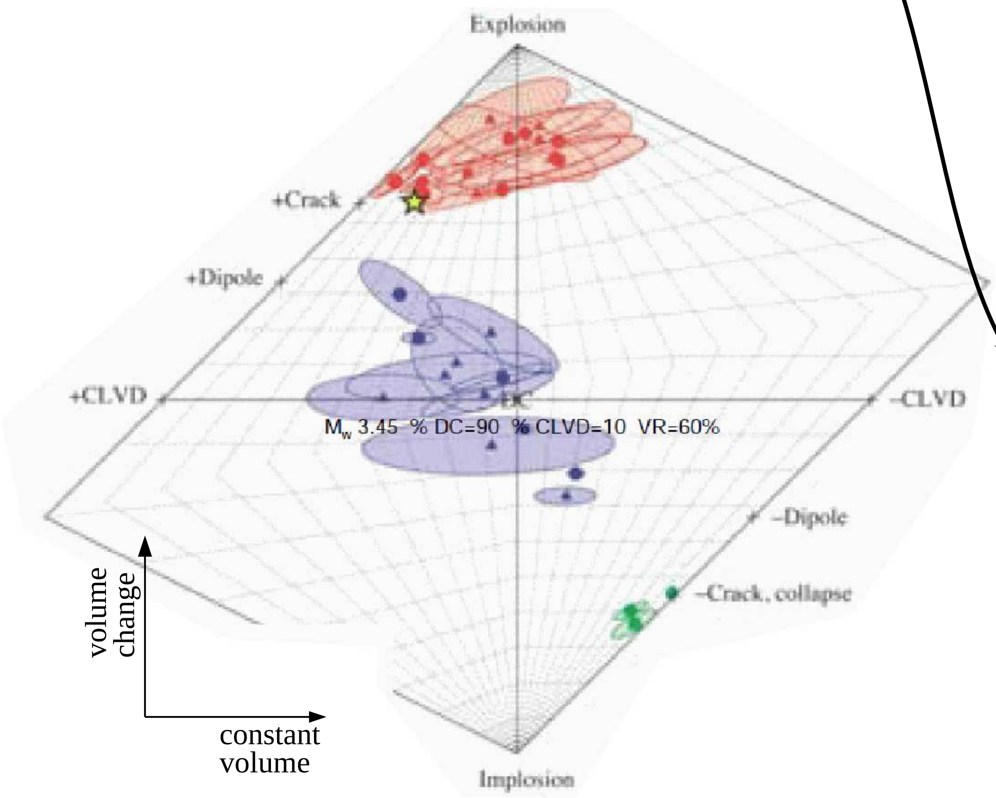
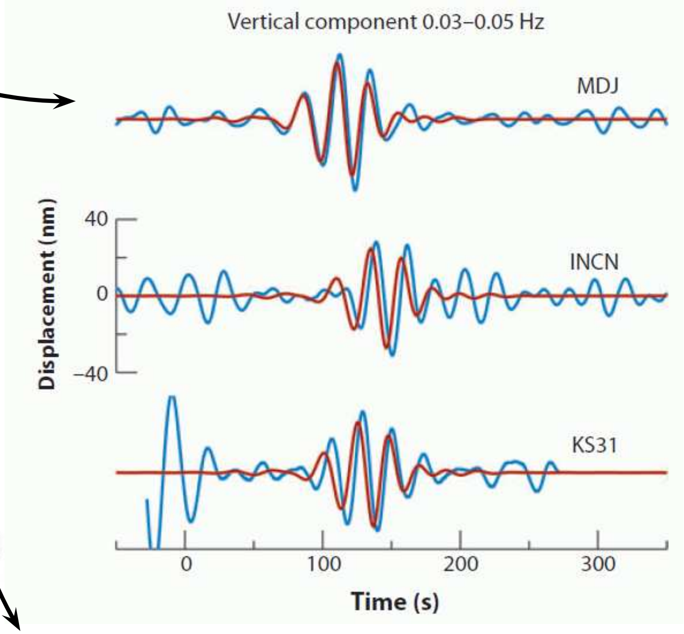
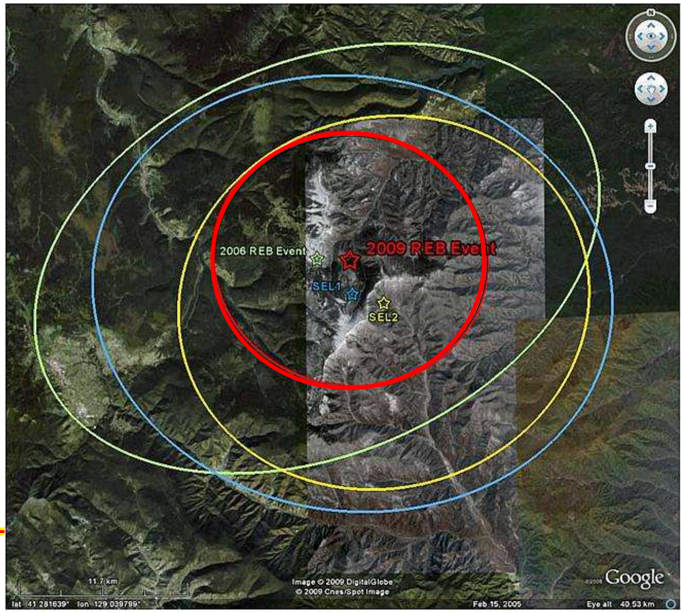
Another Test for the Test Ban

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



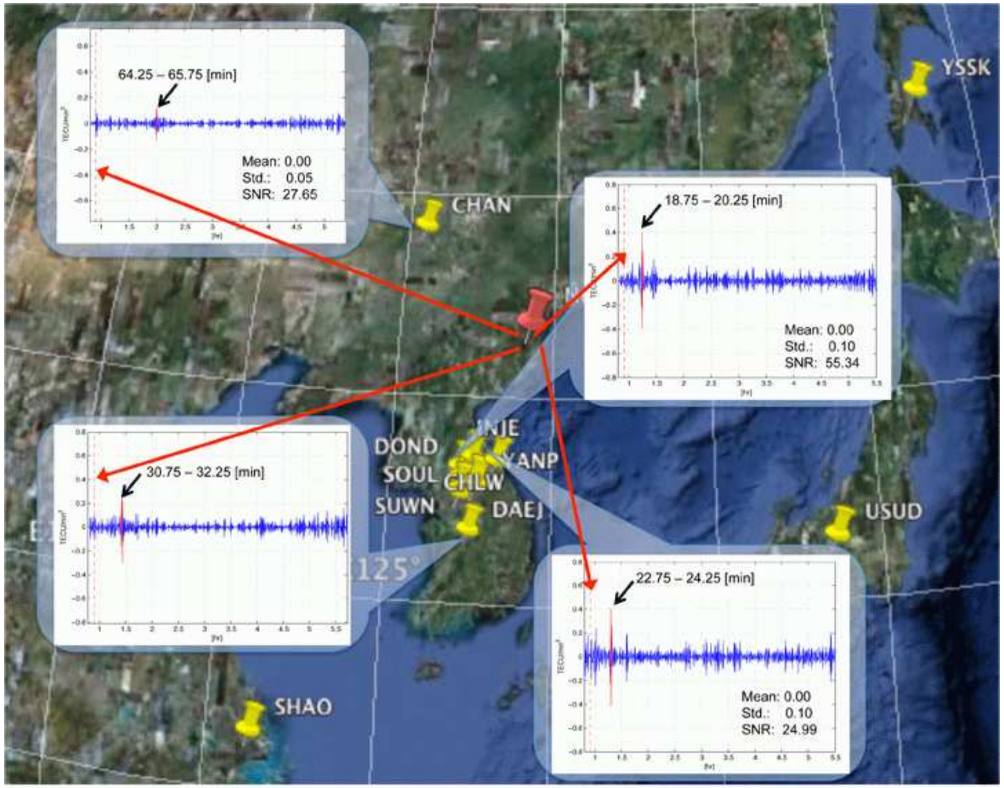
Regional surface waves.





Another Test for the Test Ban

- Underground nuclear explosions create a ‘bubble’ of disturbed air propagating outward.
- This shock wave alters the electron density in the ionosphere.
- It can be detected by the changes in the performance of the Global Positioning System (GPS).
- J. Park *et al.* discovered the signal of the 2009 North Korean test in data from 11 GPS receivers.
    - A sudden spike appeared in the electron energy density.
    - The disturbance propagated outward from P‘unggye-yok at 540 mph.
    - Source was located with 2.7 km of the seismically determined epicenter.



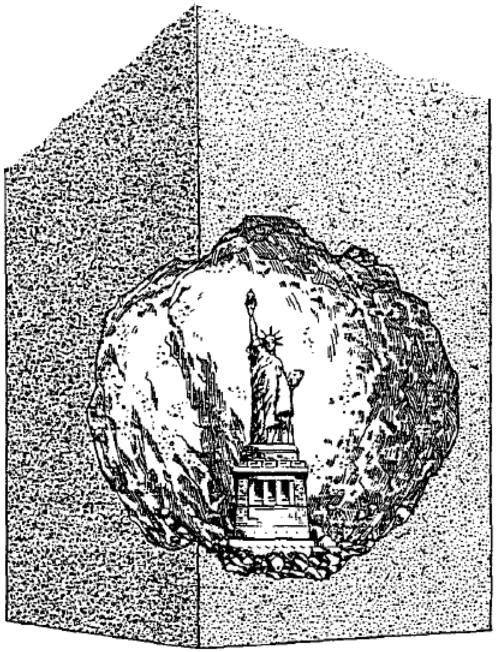
J. Park *et al.*, CTBTO S&T Conf., 8-10 June 2011.

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).

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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.

Conclusions

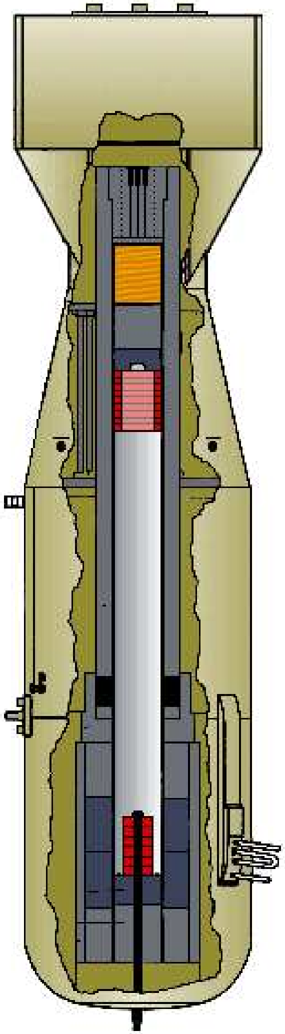
1. Diverse, interdisciplinary technologies have demonstrated that detection and identification of nuclear explosions is possible.
2. Seismic detection will remain the primary tool of the IMS for monitoring underground nuclear explosions with additional methods like radioxenon detection supporting it.
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).

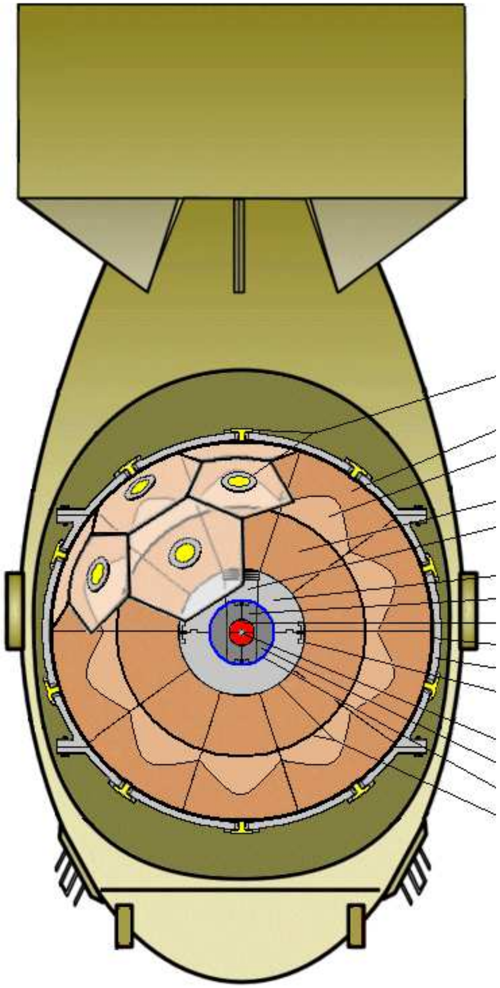
Additional Slides

Nuclear Weapons 101 - Design Types



To the left is the ‘Little Boy’ dropped on Hiroshima. The fissile material, $^{235}\mathrm{U}$ is shown in red. A cordite charge was detonated behind one of the pieces of $^{235}\mathrm{U}$ firing it into the $^{235}\mathrm{U}$ target to form a critical mass. A neutron trigger/initiator was used to start the chain reaction.

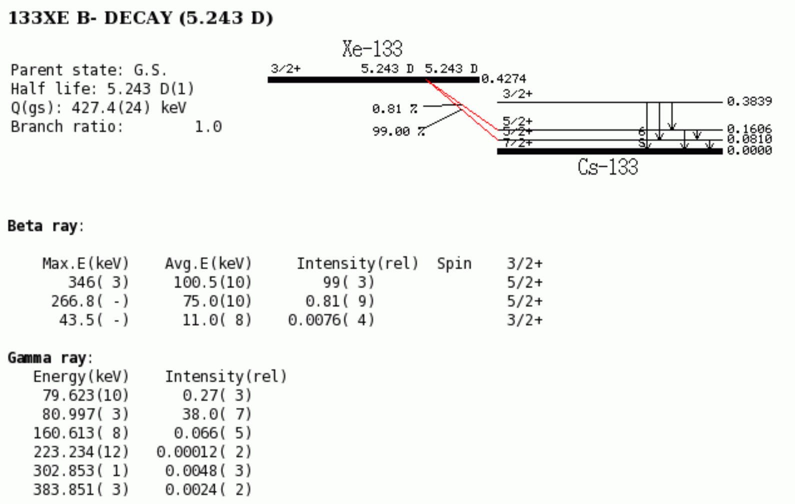
To the right is the ‘Fat Man’ bomb dropped on Nagasaki. The fissile material, $^{239}\mathrm{Pu}$ is shown in red. Shaped, explosives were detonated around the spherical pieces of $^{239}\mathrm{Pu}$ compressing it to a high density. A neutron trigger/initiator was used to start the chain reaction.



Figures from Wikipedia.

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
```

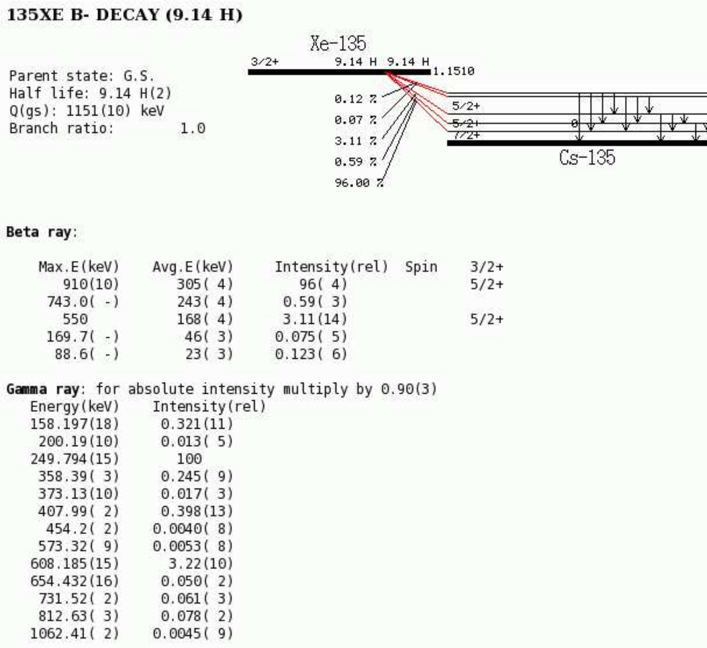
Beta ray:

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

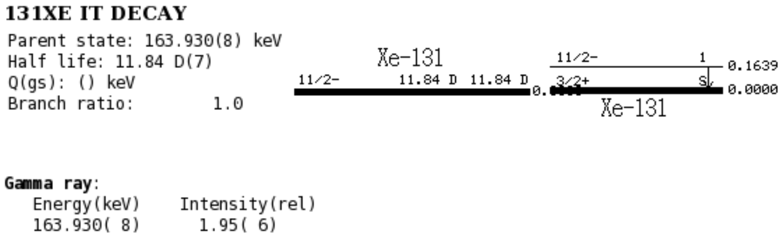
Beta ray:

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



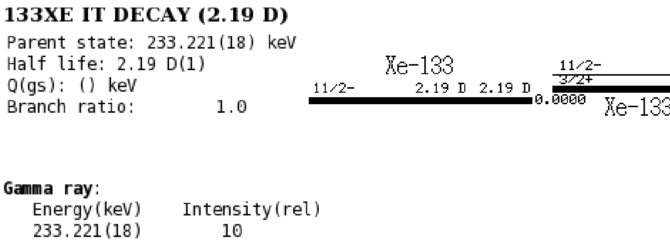
131XE IT DECAY

```
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



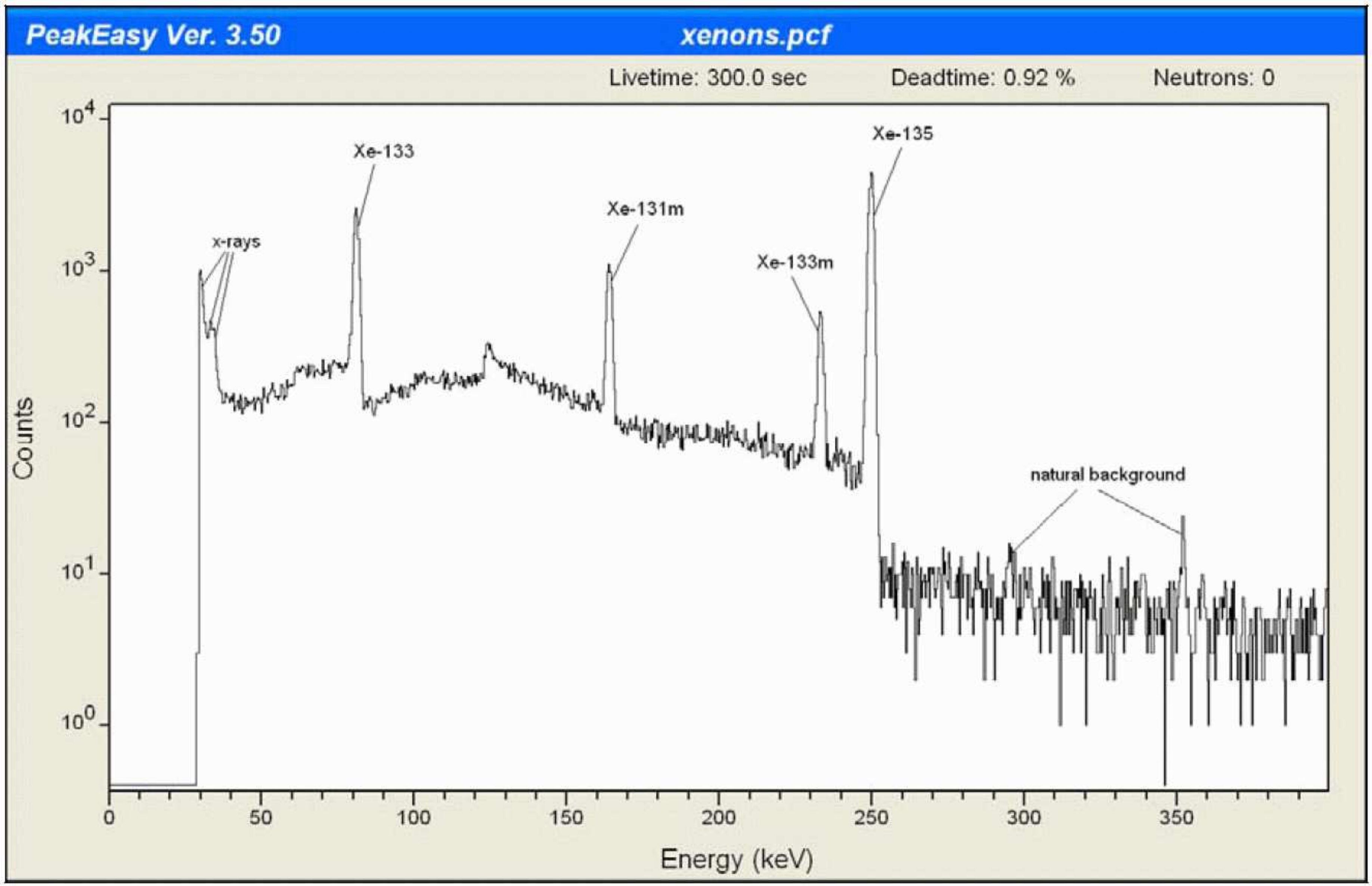
133XE IT DECAY (2.19 D)

```
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
```

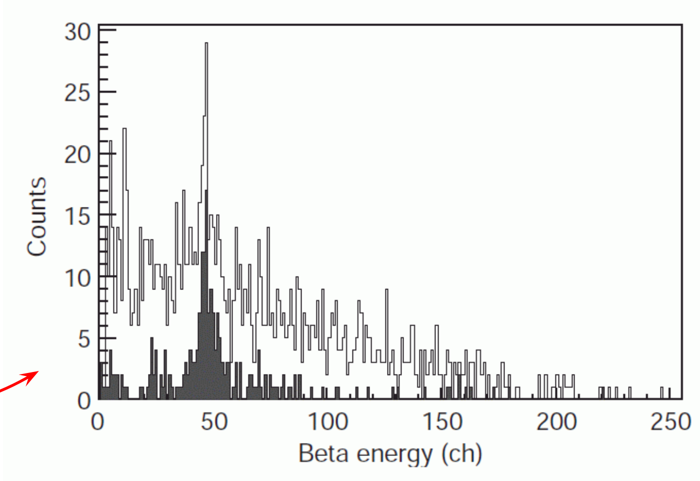
Radioxenon γ-Rays

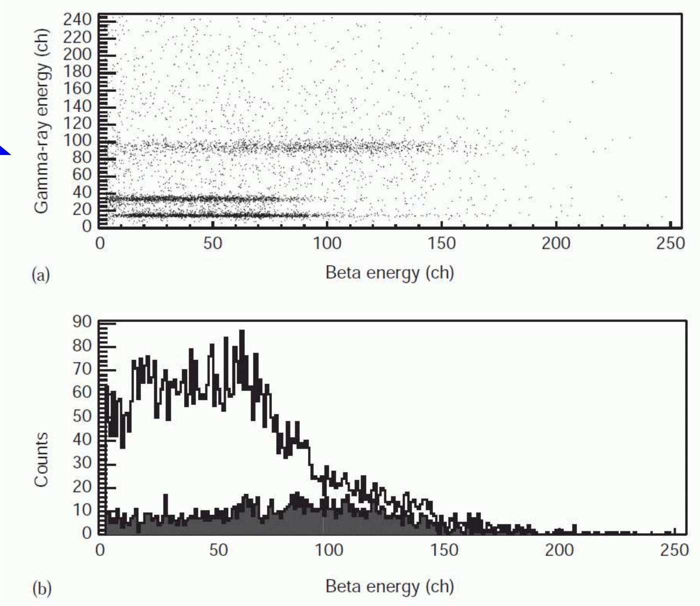


Finding the Smoke

- 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.

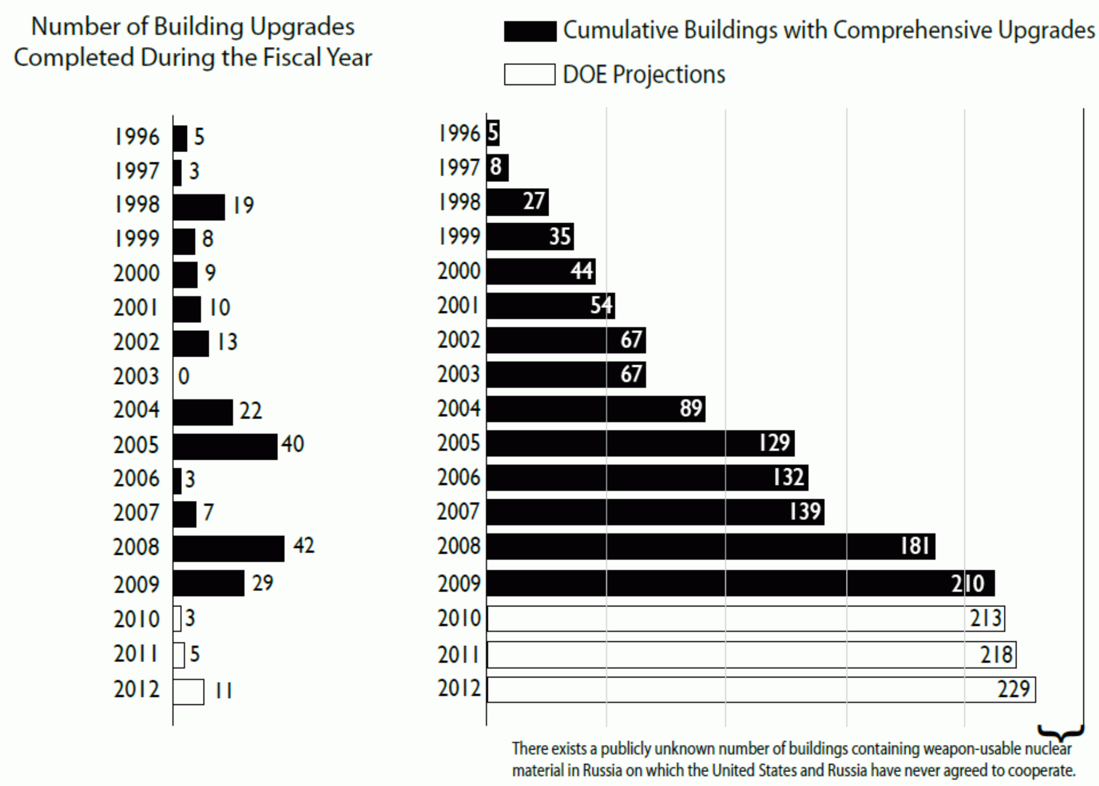
Preventive Threat Reduction

- 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?



There exists a publicly unknown number of buildings containing weapon-usable nuclear material in Russia on which the United States and Russia have never agreed to cooperate.

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.

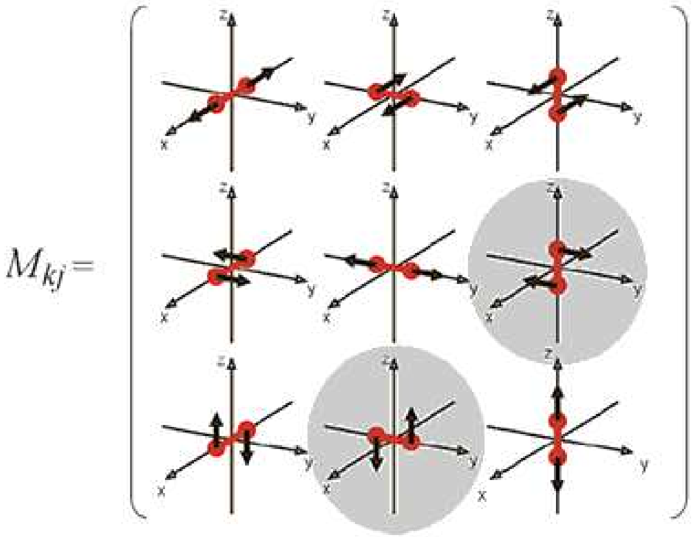
Reproduced from M. Bunn, *Securing the Bomb 2010*, Harvard University and the Nuclear Threat Initiative, April 2010).

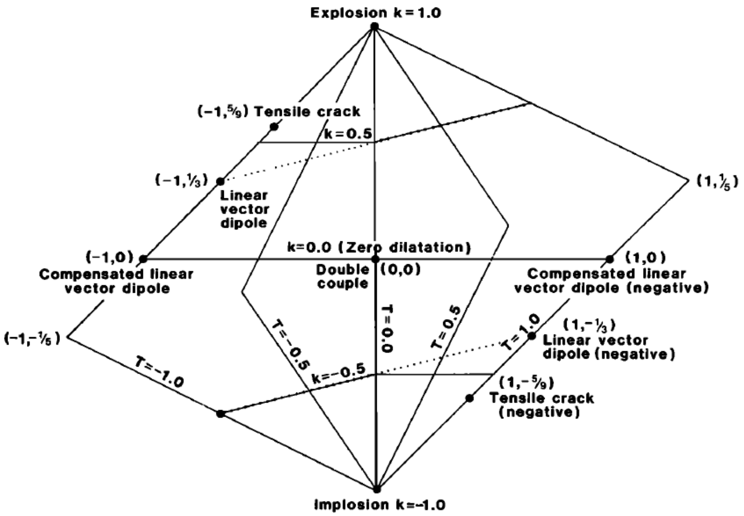
Moment Magnitude Measures Energy Released

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.

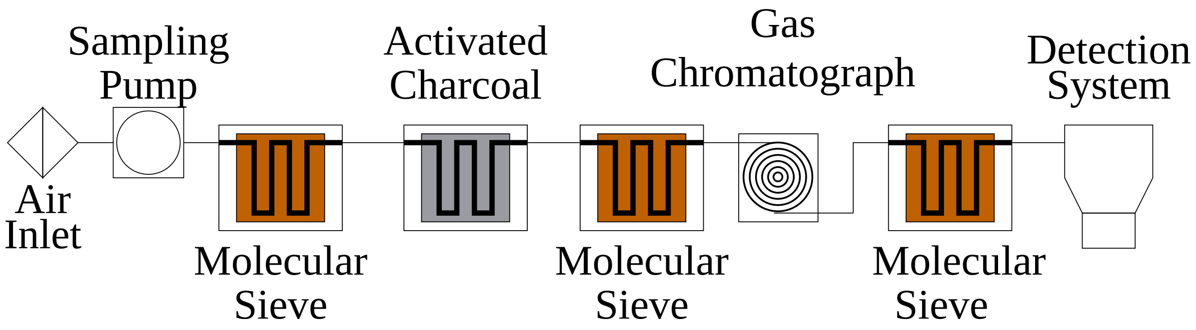

$M_{kj}=$



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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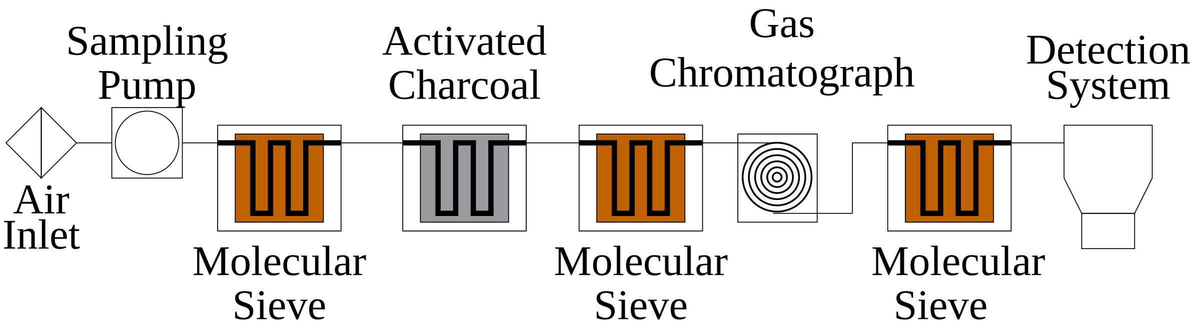
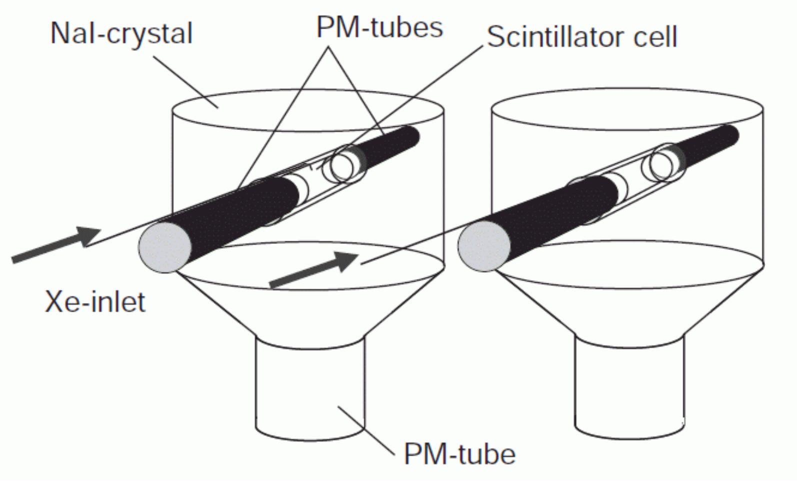


- Detection system uses $\beta - \gamma$ coincidences or high-resolution γ detection.
- For $\beta - \gamma$ method xenon is passed into the chamber of a hollow cylinder made of plastic scintillator inserted in a cylindrical hole inside a NaI crystal. Light produced by β and γ particles is detected with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