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.

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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.

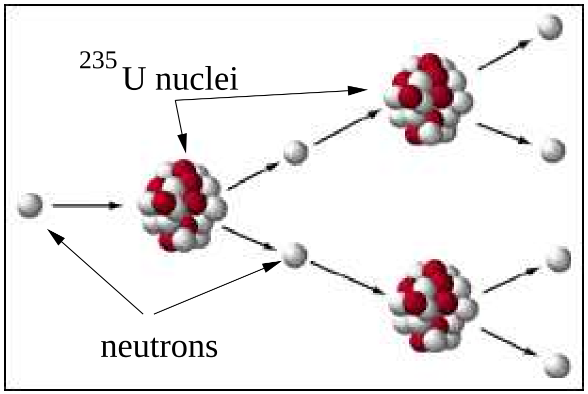
Nuclear Weapons 101 - Radiation

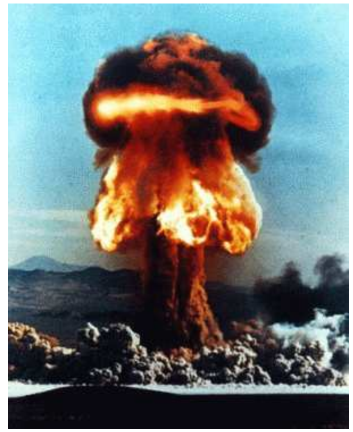
- Emission or release of energy from atomic nuclei in the form of sub-atomic particles like photons, electrons, or other atomic nuclei.
- Ionizes atoms in material it passes through and disrupts the material.
- Natural background radiation accounts for about 80% of exposure.
- Wide range of uses: sterilize food, medical supplies; 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

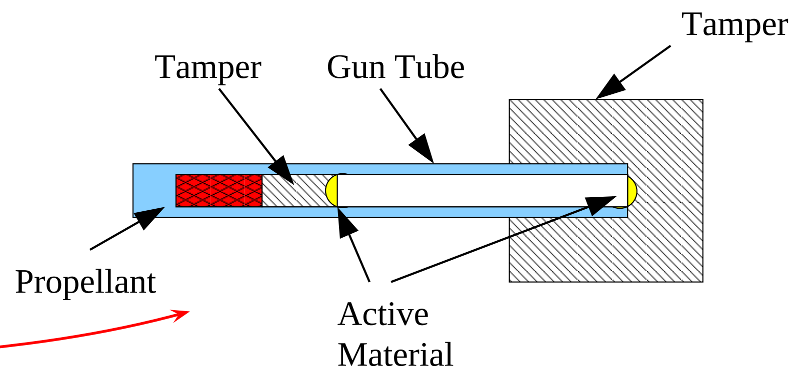




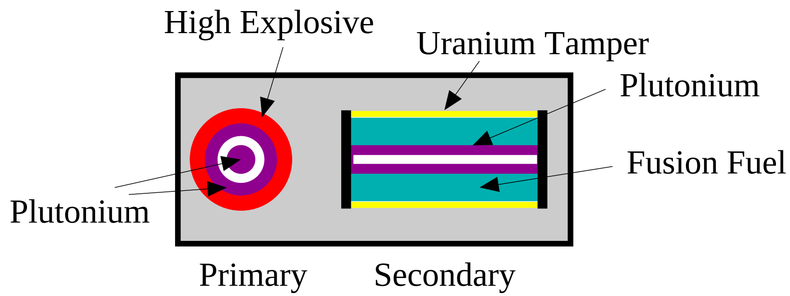
- As a fission bomb explodes deuterium and tritium can fuse releasing neutrons and even more energy; $^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \mathrm{n} + 17.6\ \mathrm{MeV}$.
- Only about 8 kg of plutonium or 25 kg of highly-enriched uranium (HEU) is needed is needed to produce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

Nuclear Weapons 101 - Basic Weapons Designs

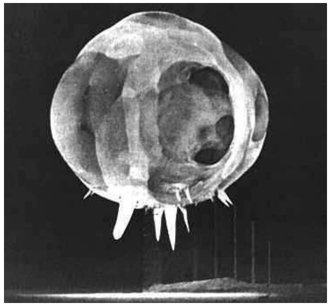
- A uranium, gun-type nuclear weapon - High explosive pushes highly-enriched uranium at high speed down the gun tube and into the other piece of active material. The density increases enough to sustain the chain reaction.



- A two-stage, thermonuclear weapon. - High explosive crushes the plutonium primary to a density where fission can occur.

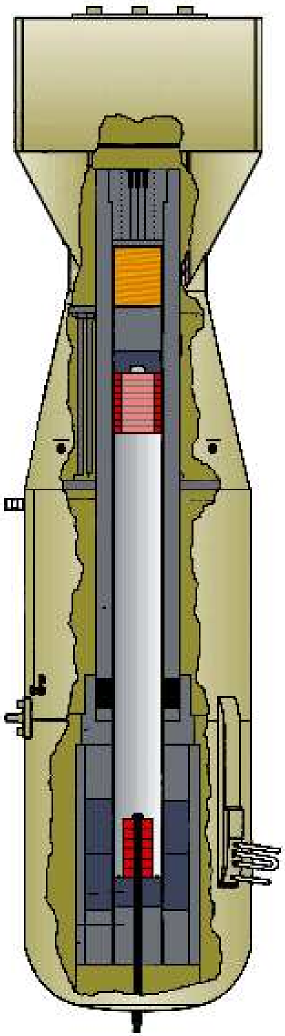


- The uranium and plutonium in the secondary burn and increase the temperature until fusion starts. The energy released by the fusion reaction raises the temperature even higher and burns more of the fission fuel.



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

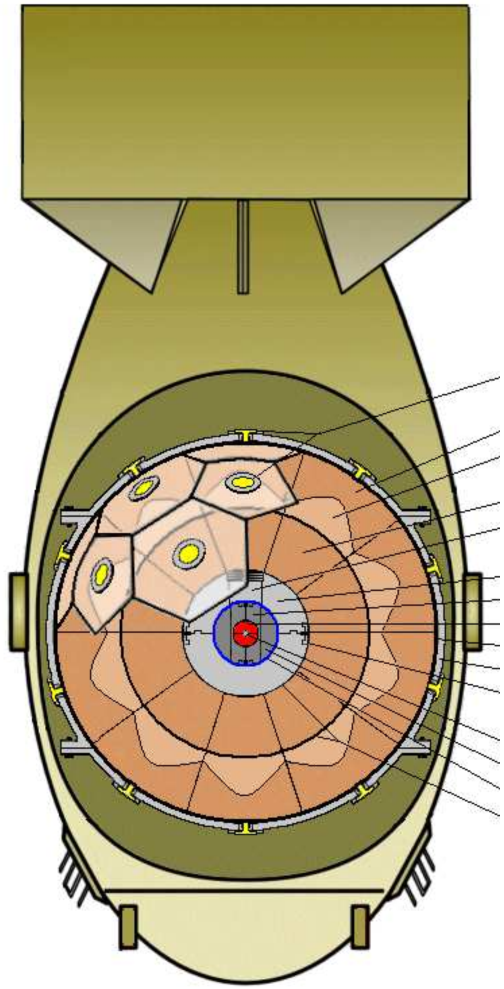
Nuclear Weapons 101 - Design Types



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.

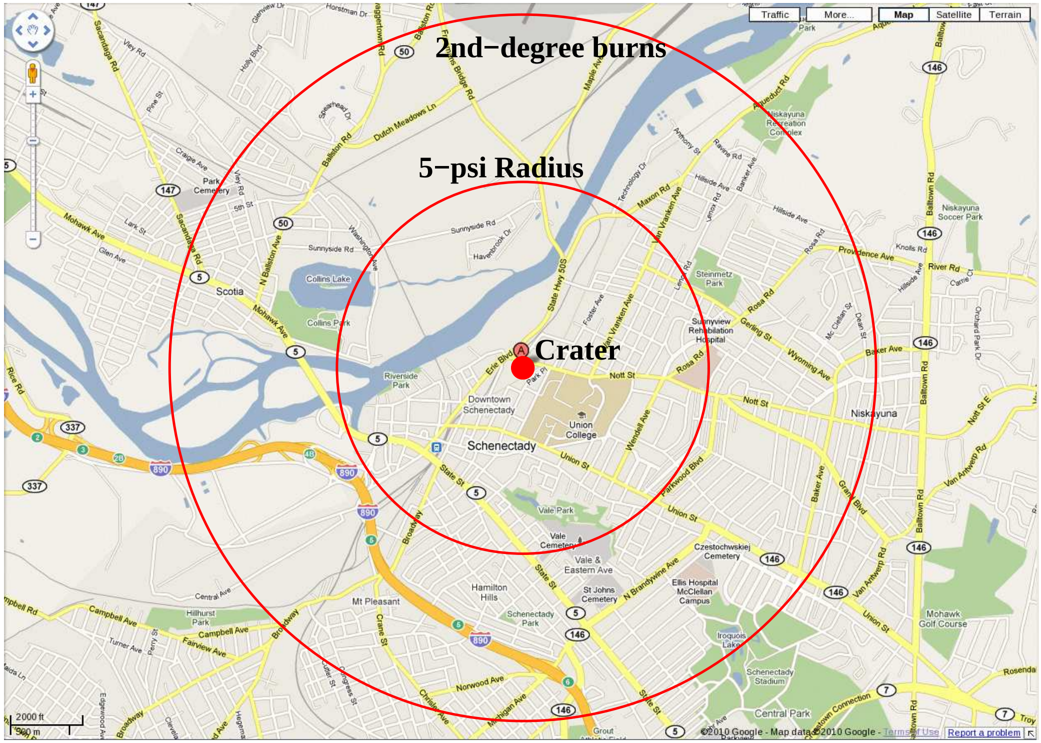
To the right is the 'Fat Man' bomb dropped on Nagasaki. The fissile material, $^{239}\mathrm{Pu}$ is shown in red. Shaped, explosives were detonated around the spherical pieces of $^{239}\mathrm{Pu}$ compressing it to a high density. A neutron trigger/initiator was used to start the chain reaction.

Figures from Wikipedia.



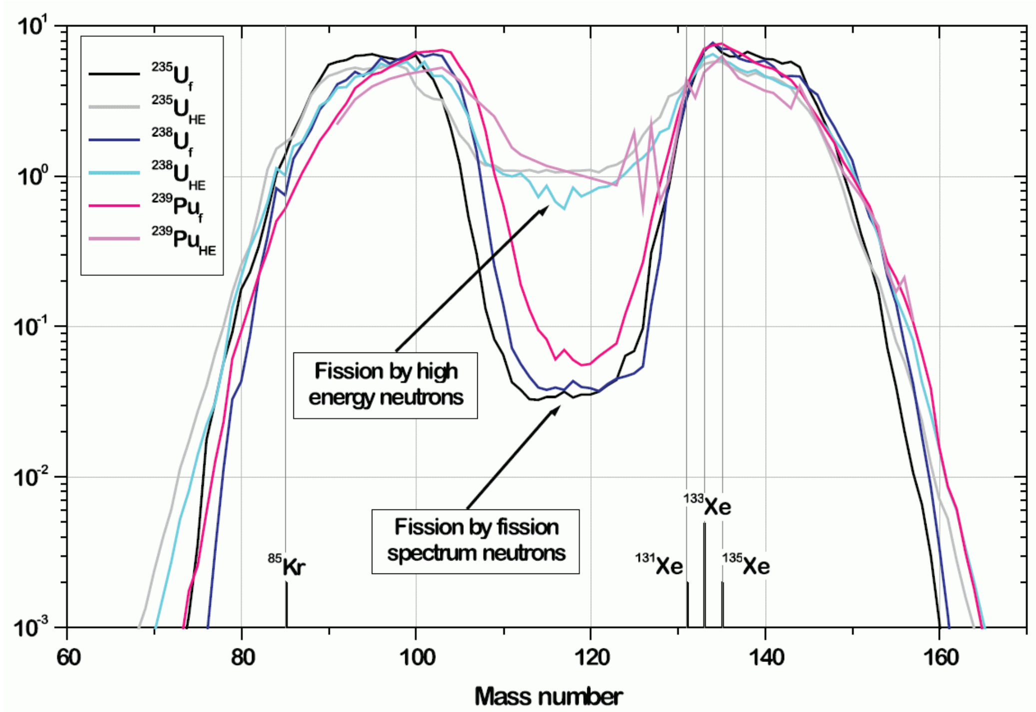
Nuclear Weapons 101 - Effects

- 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 15 kiloton bomb (about the size of the Hiroshima bomb) exploded over the College Park Hall in Schenectady, NY.



Nuclear Weapons 101 - Fingerprints Left Behind

- 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.

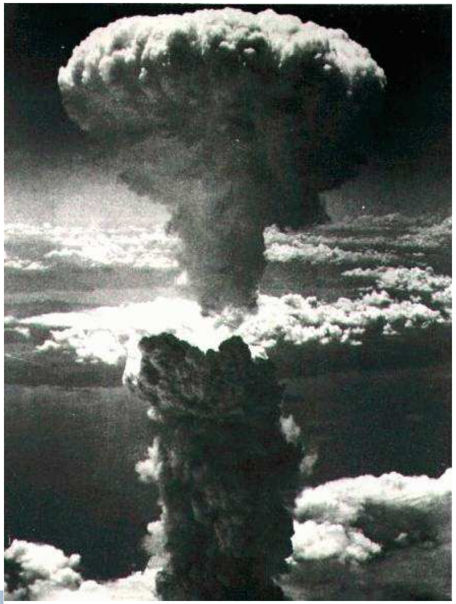


Nucleus	Radiations (energy)	Half-life
^{131m}Xe	γ (0.164 MeV)	11.9 d
^{133m}Xe	γ (0.233 MeV)	2.2 d
^{133}Xe	β (0.346 MeV), γ (0.081 MeV)	5.2 d
^{135}Xe	β (0.910 MeV), γ (0.250 MeV)	9.1 h

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

The Comprehensive Test Ban Treaty (CTBT)

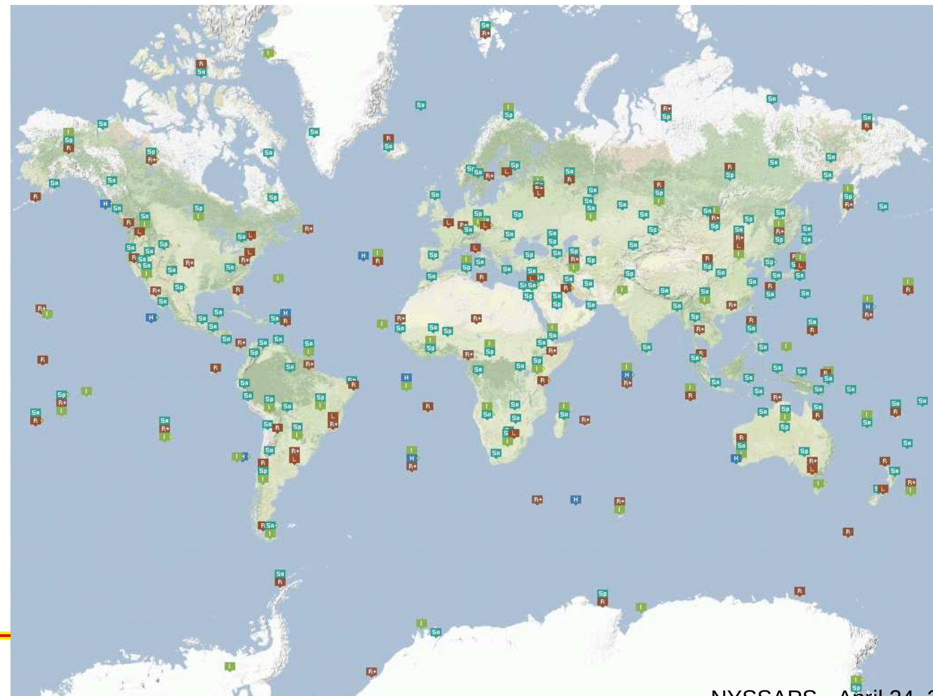
- The CTBT bans all nuclear explosions to limit the proliferation of nuclear weapons.
- A network of seismological, hydroacoustic, infra-sound, and radionuclide sensors will monitor compliance.
- On-site inspection will be provided to check compliance.
- The US has signed the CTBT, but not ratified it.



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 data from the IMS stations indicate that a nuclear test has taken place, a Member State can request an on-site-inspection.



Testing the Test Ban Treaty

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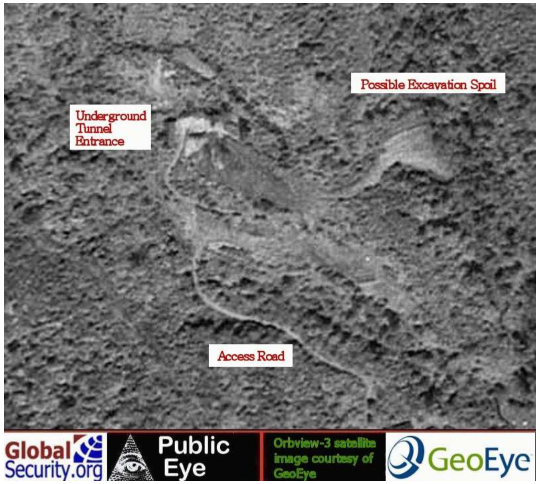

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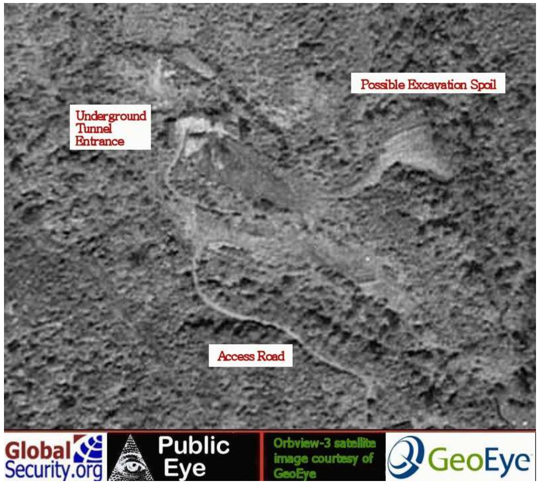

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- The xenon isotopes in the table are entirely man-made so they must come from reactors and explosions.

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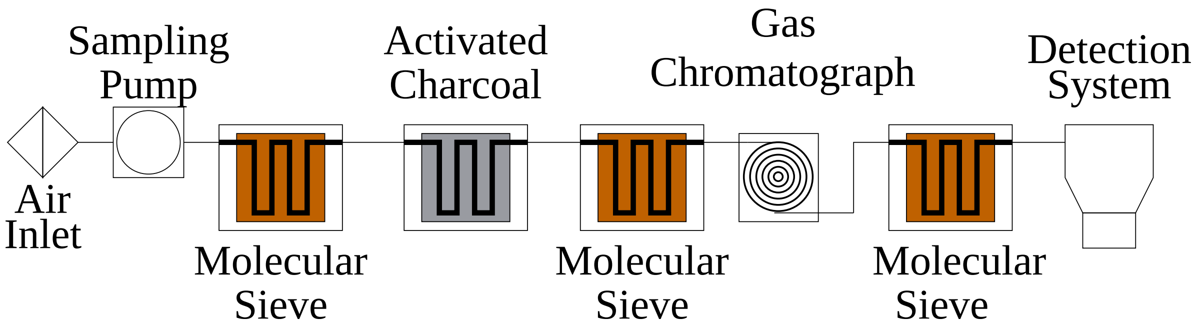
Looking for the Smoking Gun

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



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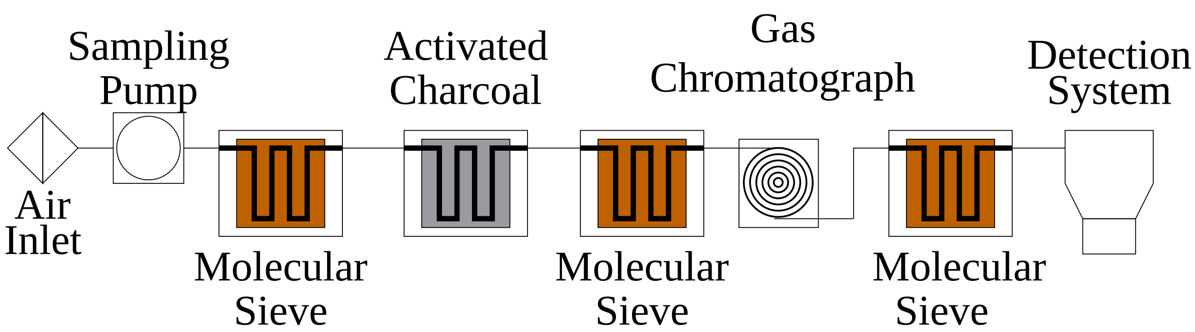
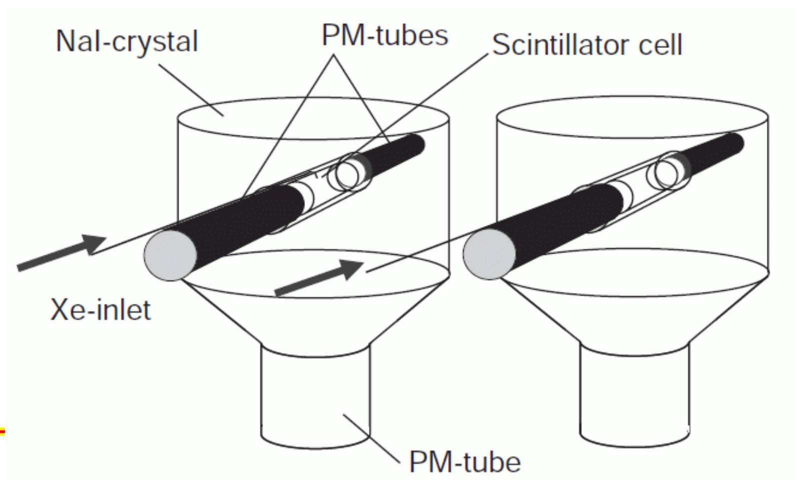


- Detection system uses $\beta - \gamma$ coincidences or high-resolution γ detection.
- For $\beta - \gamma$ method xenon is passed into the chamber of a hollow cylinder made of plastic scintillator inserted in a cylindrical hole inside a NaI crystal. Light produced by β and γ particles is detected with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



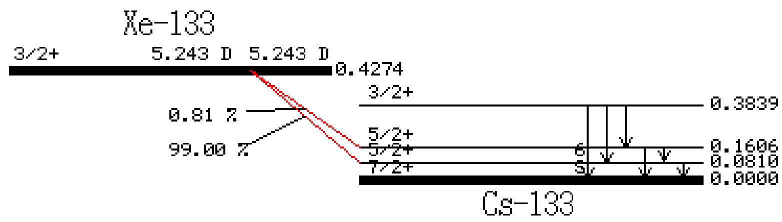
A. Ringbom *et al.* Nucl. Instr. Meth., A 508 (2003) 542.

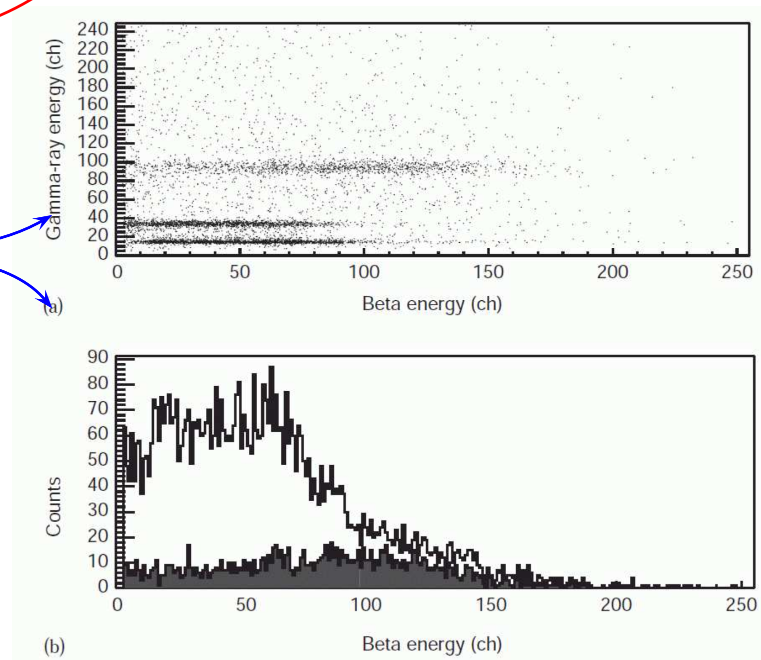
One of several automated systems used by IMS.

Finding the Smoke - $\beta - \gamma$ Method

- Each radioxenon isotope sample emits a mixture of e's, β's and γ's from its decay chain.
- $^{133}\mathrm{Xe}$ will β-decay ($n \to p + e^- + \overline{\nu}_e$ with $\mathrm{E_e} \leq 0.346\ \mathrm{MeV}$) to $^{133}\mathrm{Cs}(0.081)$ 99% of the time. This daughter $^{133}\mathrm{Cs}(0.081)$ then rapidly emits a γ-ray with energy 0.081 MeV to reach the ground state.
- Plots show $\beta - \gamma$ coincidence test results for a similar decay of $^{135}\mathrm{Xe}$: β-decay to $^{135}\mathrm{Cs}(0.250\ \mathrm{MeV})$ followed by a γ-ray.
- 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!





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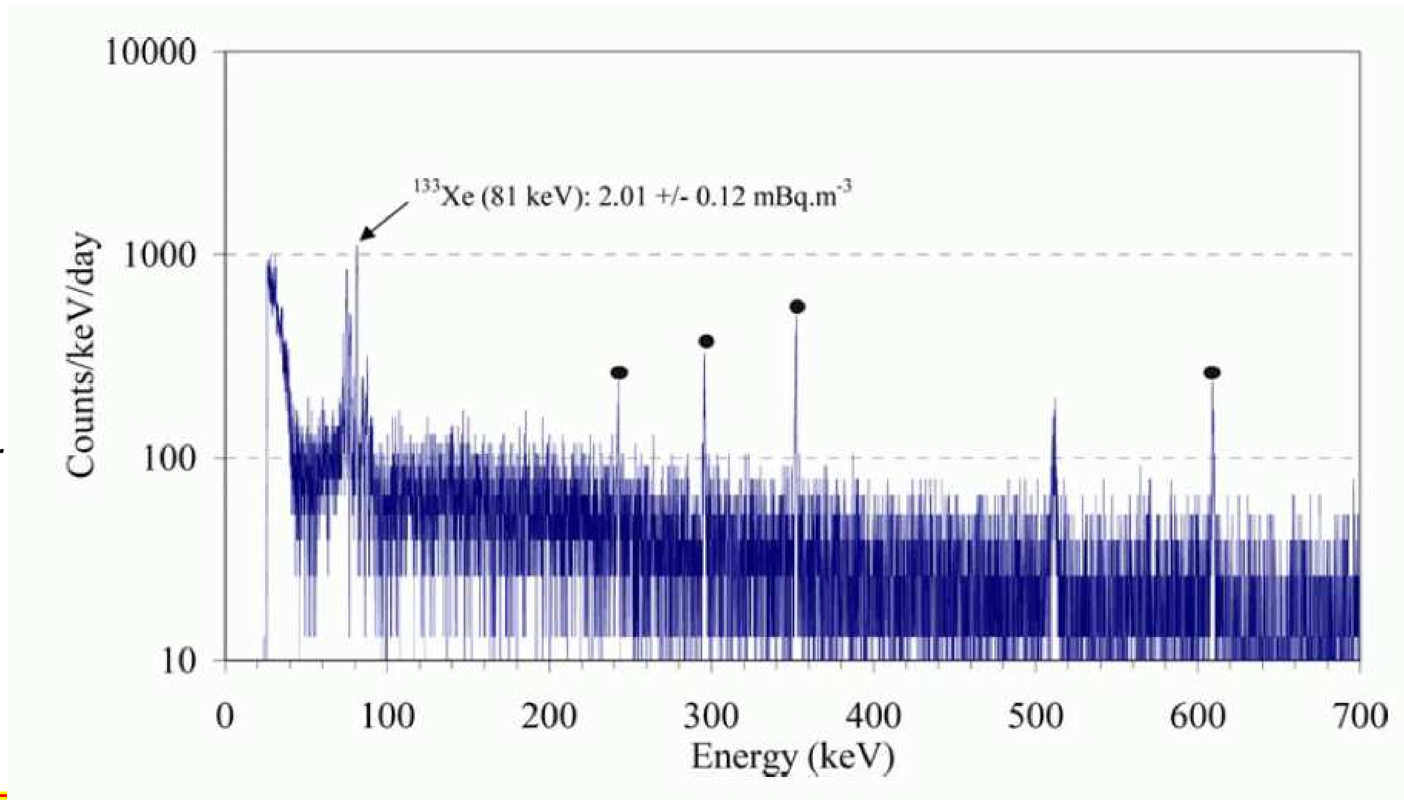
Finding the Smoke - High-Resolution γ Method

- 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.



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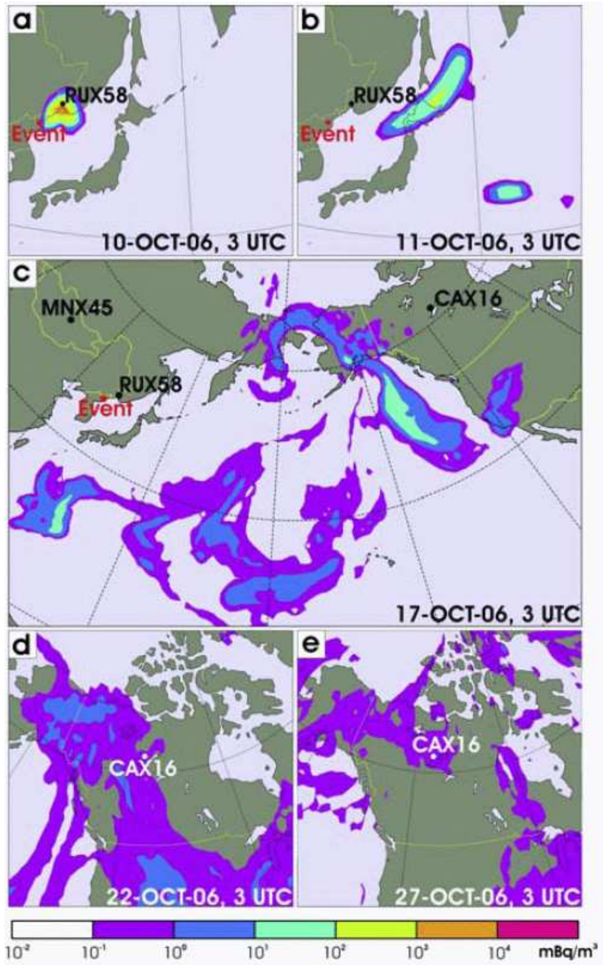

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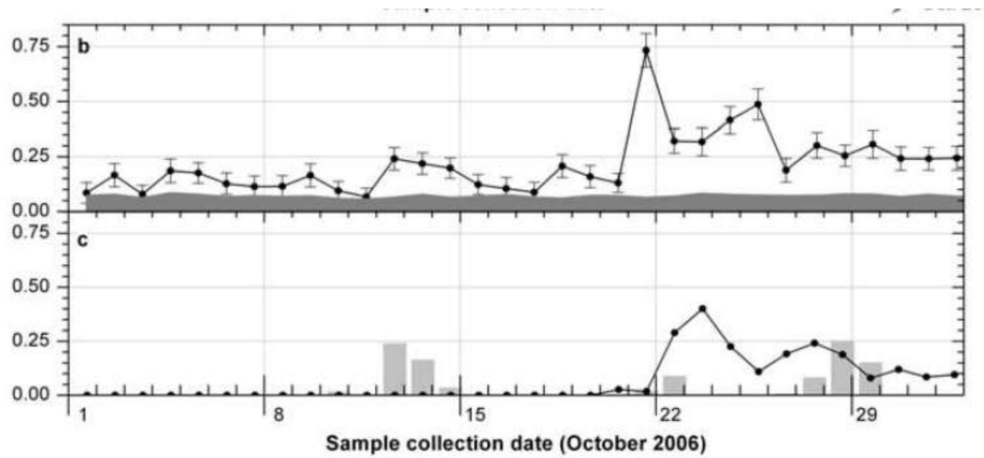

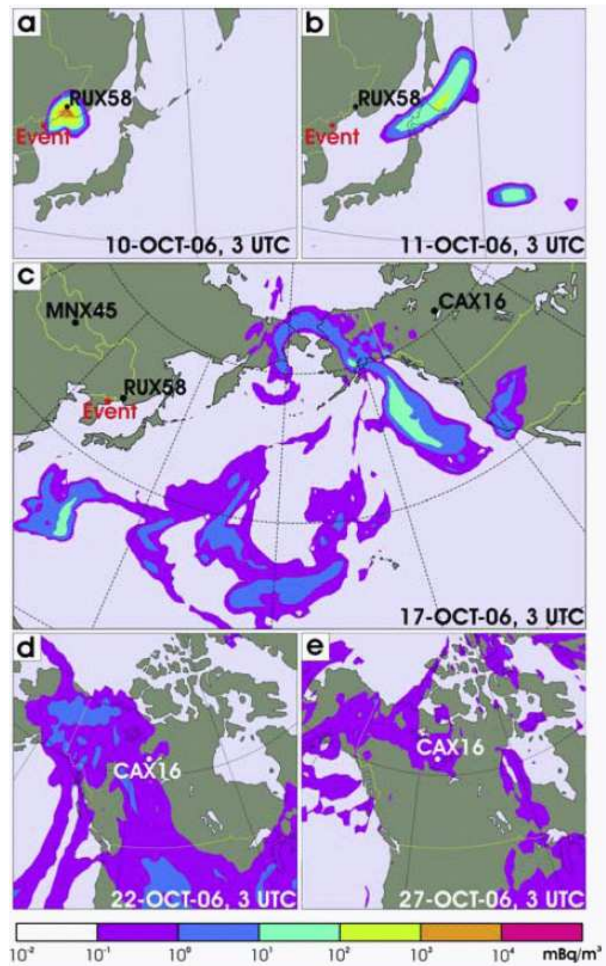

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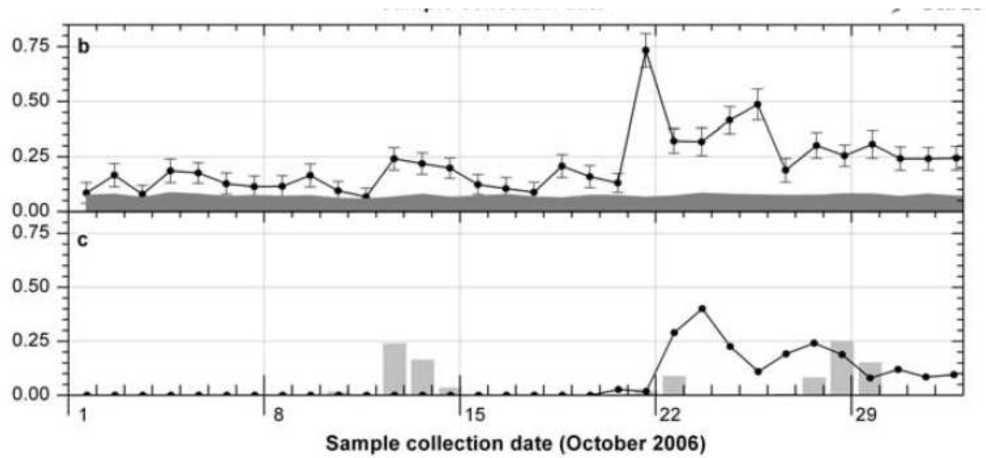
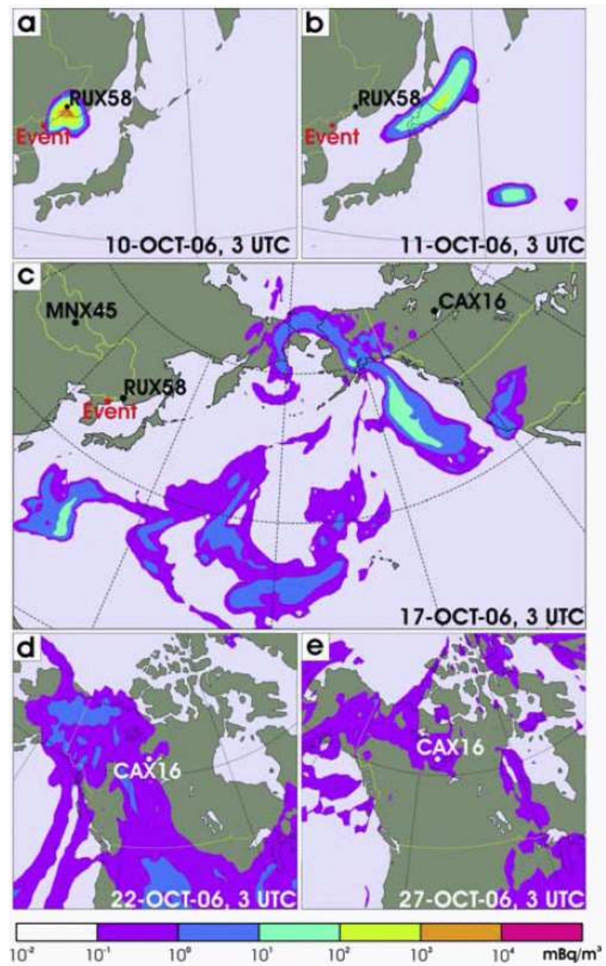


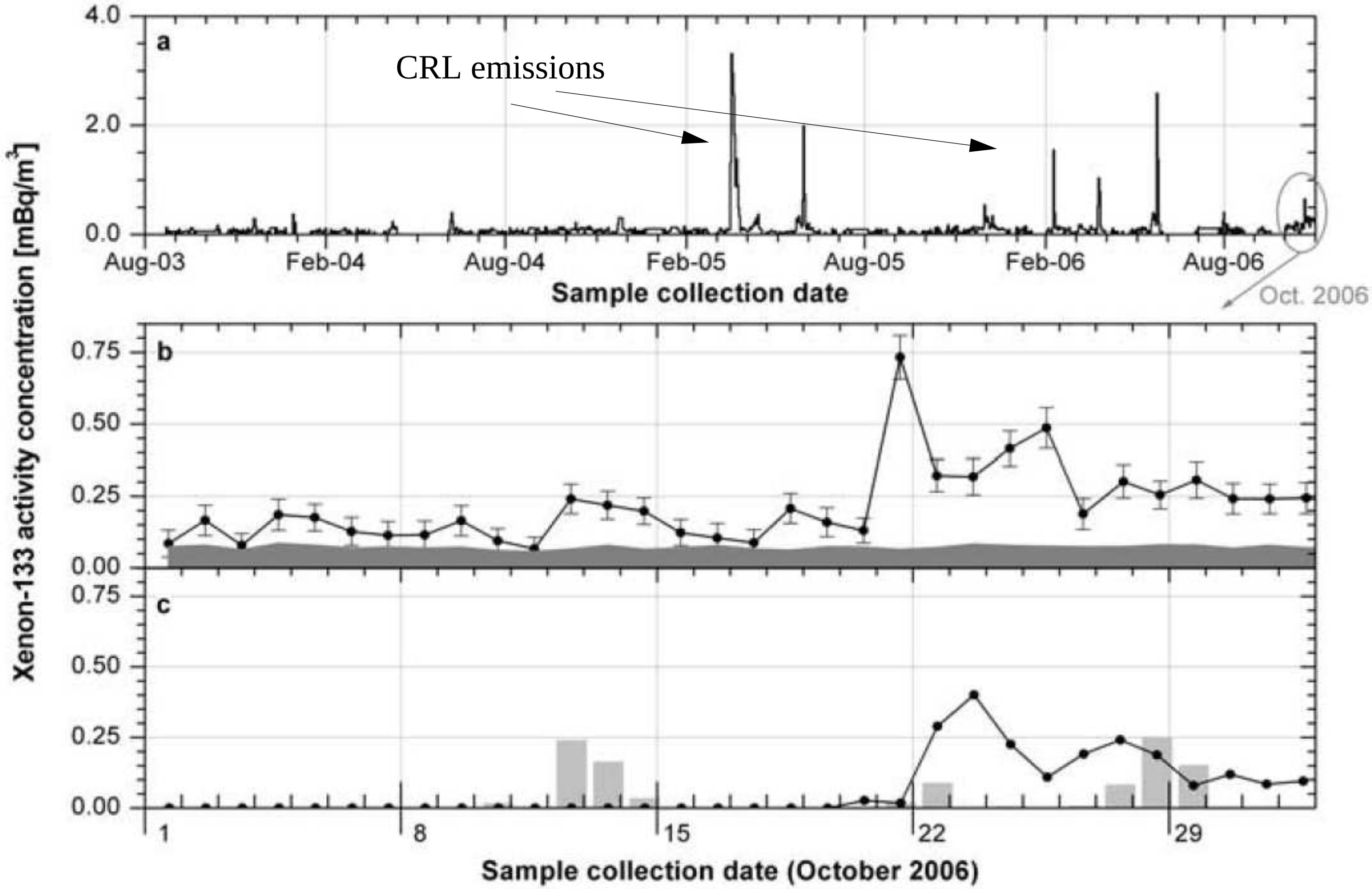


- Consistent with venting about 10% of the $^{133}\mathrm{Xe}$.

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

Getting the Right Gun - 2

- 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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What went wrong?

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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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- 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 long-range detection of nuclear explosions is possible.
2. Seismic detection will remain the primary tool of the IMS 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.

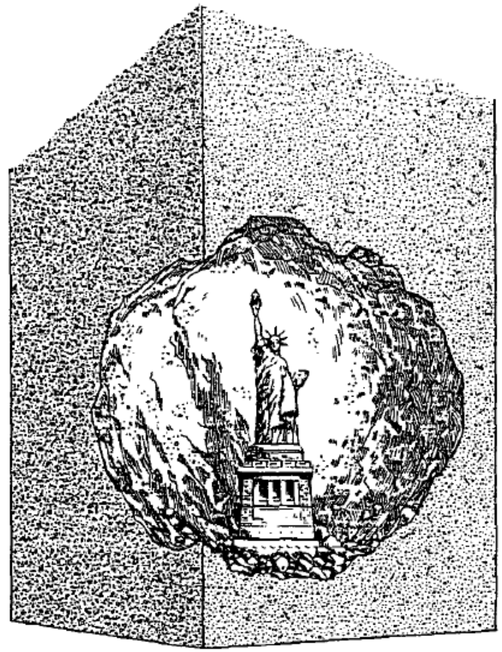
Research Opportunities

- 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

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.
- Seismic component of the International Monitoring Syster consist of 170 seismic stations.
- 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).



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

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

Can it extrapolated to full-up tests?

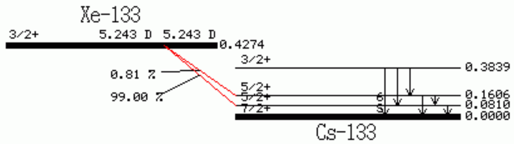
US Congress, Office of Technological Assessment, *Verification of Nuclear Testing Treaties*, OTA-ISC-361, (Washington, DC; US Government Printing Office; May, 1988).

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+

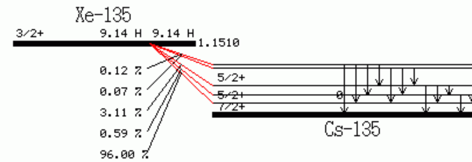
Gamma ray:

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)		

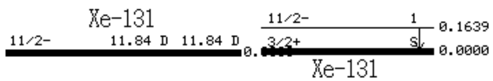
Gamma ray: for absolute intensity multiply by 0.90(3)

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



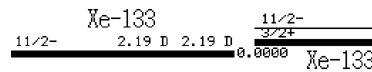
Gamma ray:

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

^{133m}Xe

133XE IT DECAY (2.19 D)

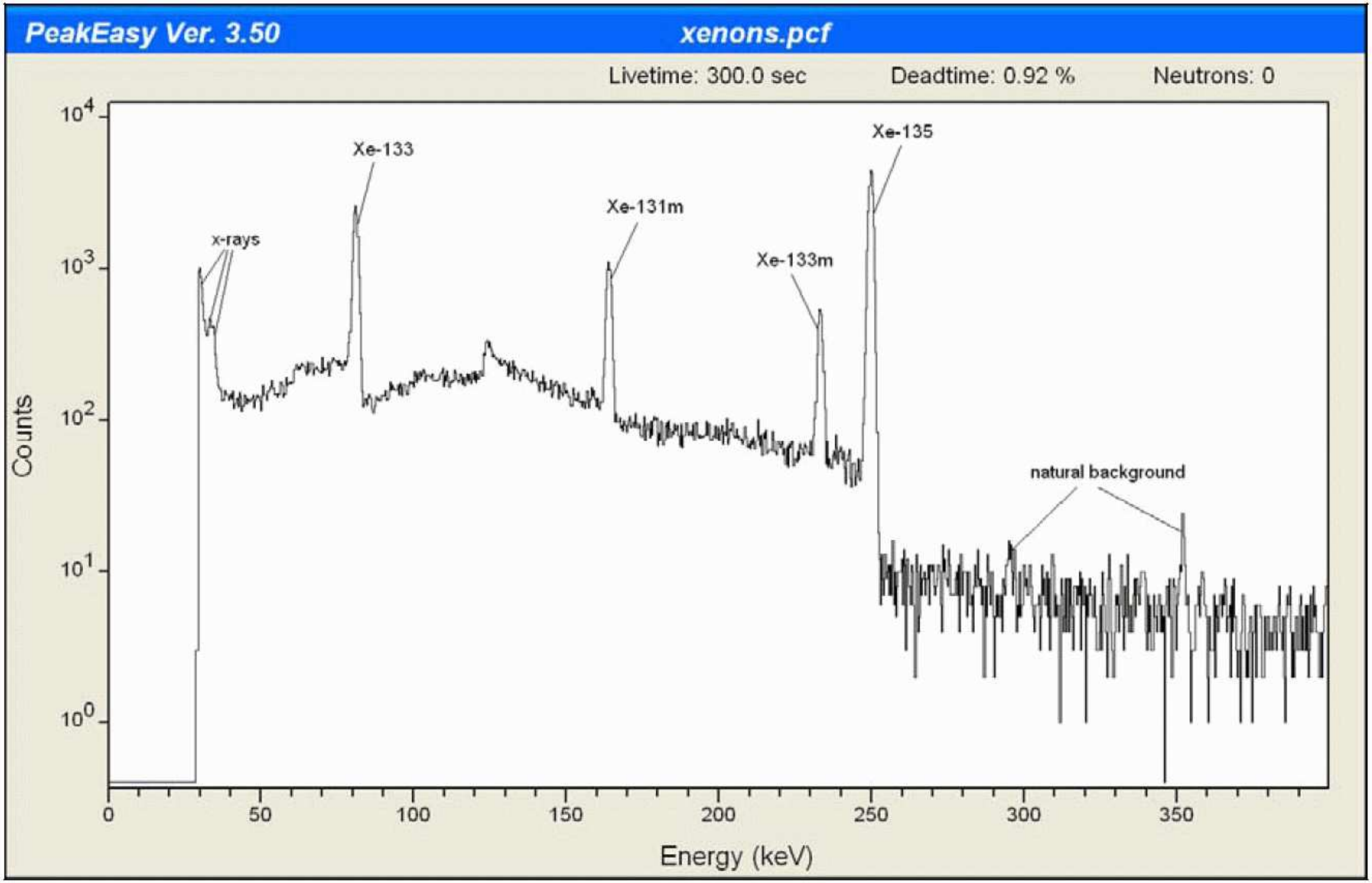
Parent state: 233.221(18) keV
Half life: 2.19 D(1)
Q(gs): () keV
Branch ratio: 1.0



Gamma ray:

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

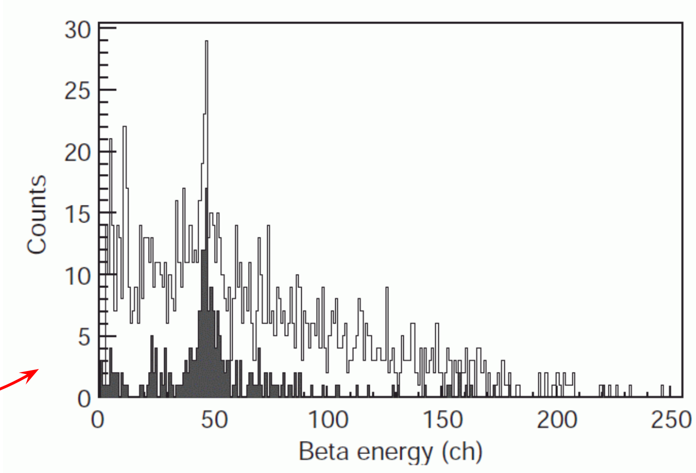
Radioxenon γ-Rays

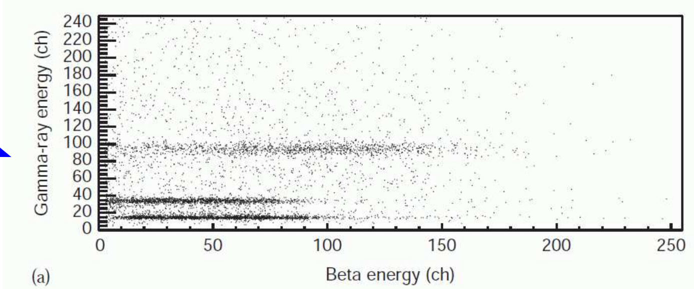


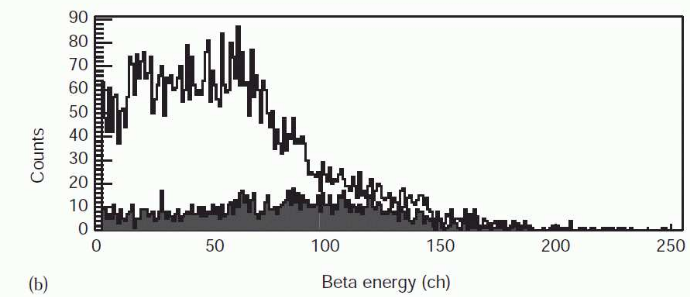
Finding the Smoke

- 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.

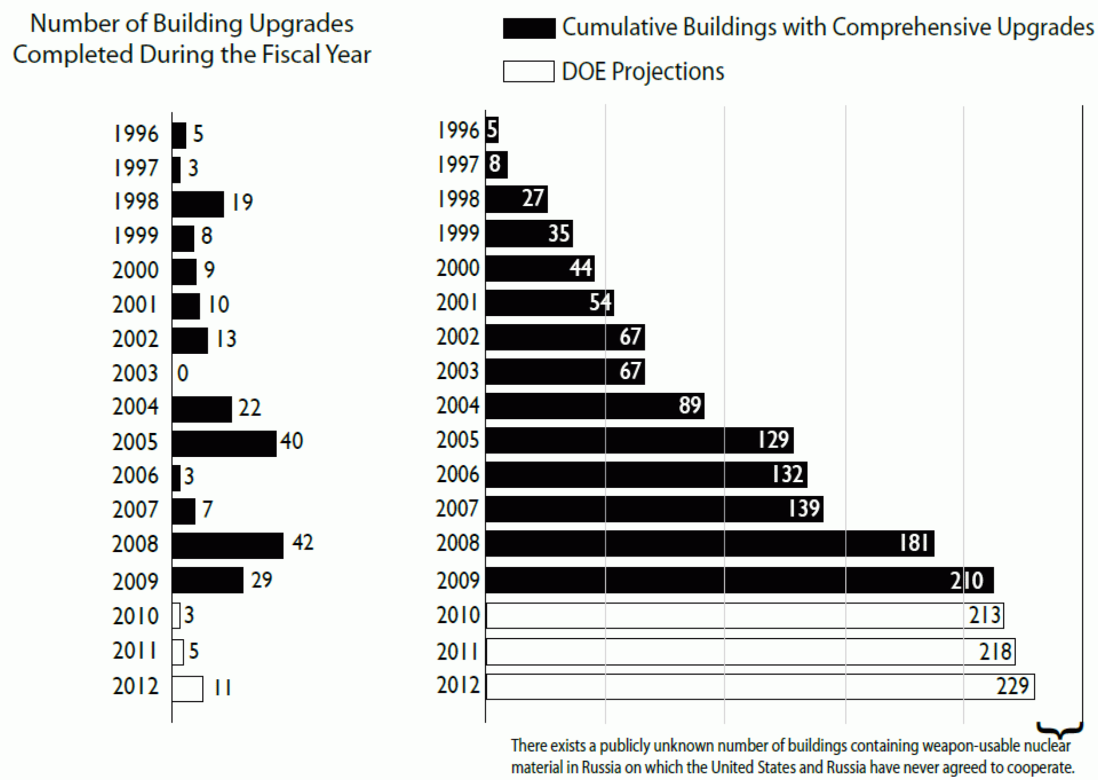
Preventive Threat Reduction

- 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?



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).