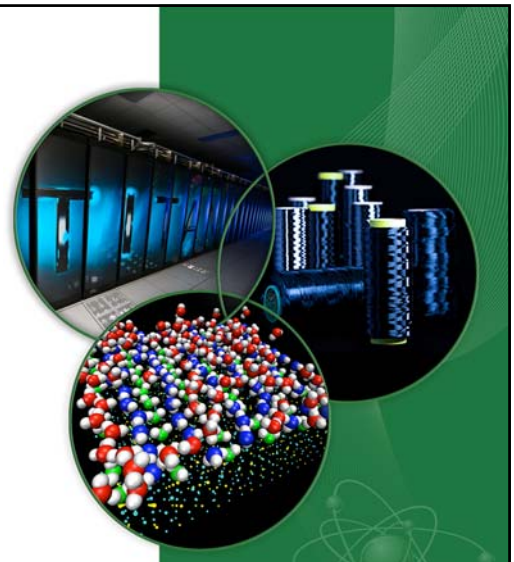
Identification of Leakage Spectra from Neutron Activation in Glass/Cherenkov Detectors



Douglas E. Peplow and Steven P. Hamilton
Reactor and Nuclear Systems Division
Oak Ridge National Laboratory

Zane W. Bell
Nuclear Security and Isotope Technology Division
Oak Ridge National Laboratory

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ORNL is managed by UT-Battelle
for the US Department of Energy

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Background

- In the event of a nuclear detonation in the US, the government needs to identify state/organization responsible.
  - Key pieces of information needed: the weapon type and yield
  - The emitted neutron spectrum can be used to help determine type
- Several systems have been developed to measure other aspects
  - Very fast systems – based on prompt signals
  - Long term systems – forensics (fallout)
- ORNL has proposed two systems based on neutron activation
  - Low-cost, can easily be implemented in many cities
  - Compare activation measurements to simulations of known spectra to determine the best match and yield

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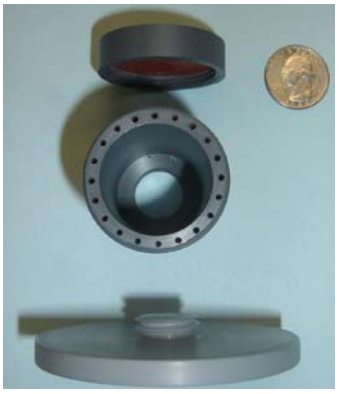
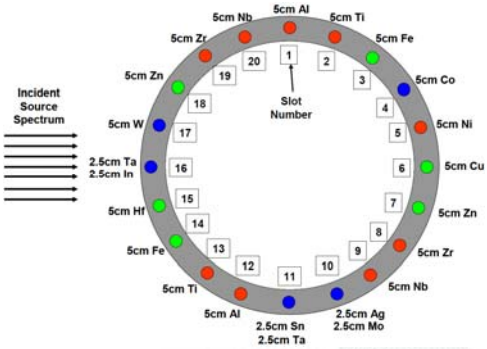
Background

- AFIDS - Activation Foil Integrated Detector System
  - Pre-placed sets of known masses of pure activation foils/wires
  - Collected within hours/days of event
  - Gamma spectroscopy measurements determine absolute activation
  - Comparison to simulated activation amounts from library of known spectra is used to determine best matching spectrum and yield.





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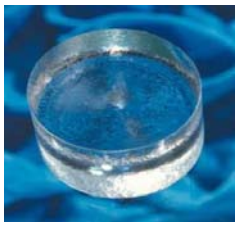
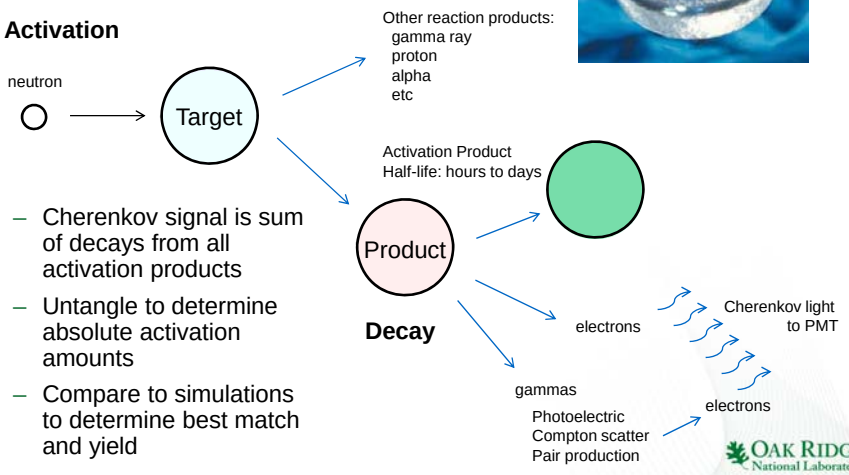
Overview

- Glass/Cherenkov Detectors
  - Glass doped with activation targets
  - Connected to PMT





  - Cherenkov signal is sum of decays from all activation products
  - Untangle to determine absolute activation amounts
  - Compare to simulations to determine best match and yield

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Activation/Decay Equations

For activation target M,

activation product N,

and reaction rate $R = \int \sigma_{M\to N}(E)\,\phi(E)\,dE$

Initial Condition $t = 0$	During Irradiation $(0 < t \le T)$	After Irradiation $(T < t)$
$M(0) = M_0$	$\frac{d}{dt}M(t) = -RM(t)$	$\frac{d}{dt}M(t) = 0$
$N(0) = 0$	$\frac{d}{dt}N(t) = +RM(t) - \lambda N(t)$	$\frac{d}{dt}N(t) = -\lambda N(t)$

Solution is:

During Irradiation $(0 < t \le T)$	After Irradiation $(T < t)$
$M(t) = M_0 e^{-Rt}$	$M(t) = M_0 e^{-RT}$
$N(t) = \frac{RM_0}{\lambda - R}\left(e^{-Rt} - e^{-\lambda t}\right)$	$N(t) = \frac{RM_0}{\lambda - R}\left(e^{-RT} - e^{-\lambda T}\right) e^{-\lambda(t-T)}$

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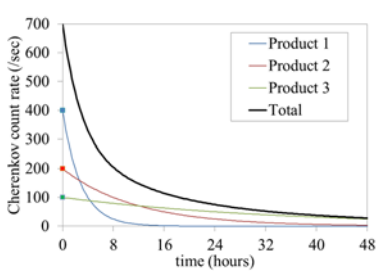
Measured Data: Cherenkov Signal

- Count rate $C(t)$ [counts/sec] is the sum of the different activation products decaying
  - t time since the irradiation
  - J number of activated products
  - x_j number of initial atoms of activation product j
  - λ_j decay constant of activation product j [/sec]
  - κ_j Cherenkov conversion constant (counts per decay of activation product j)



$$C(t) = \sum_{j}^{J} \kappa_j \lambda_j x_j e^{-\lambda_j t}$$

Measure $C(t)$, need to find $\vec{x}$.

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Untangling the Cherenkov Signal

- For time bin i, with $\Delta t_i = t_i - t_{i-1}$, the measured count rate is

$$c_i = \frac{1}{\Delta t_i}\sum_j^J \kappa_j x_j \left(1 - e^{-\lambda_j \Delta t_i}\right) e^{-\lambda_j t_{i-1}}$$

- For each activation product j, a basis function can be defined

$$f_{ij} = \frac{1}{\Delta t_i}\sum_j^J \kappa_j \left(1 - e^{-\lambda_j \Delta t_i}\right) e^{-\lambda_j t_{i-1}}$$

- so that $c_i = \sum_j^J x_j f_{ij}$

$$\begin{bmatrix} f_{11} & f_{12} & f_{13} & \cdots & f_{1J} \\ f_{21} & f_{22} & f_{23} & \cdots & f_{2J} \\ f_{31} & f_{32} & f_{33} & \cdots & f_{3J} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ f_{I1} & f_{I2} & f_{I3} & \cdots & f_{IJ} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_J \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \vdots \\ c_I \end{bmatrix}$$

need uncertainties on x_j

use QR factorization
to get
$x_j \pm \sigma_j$

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Detonation Modeling

- Library of leakage spectra for various types
- City models
- Current conditions at time of event
  - Location, altitude
  - Weather conditions
- Predict activations
  - At each detector location
  - From each source in the library
  - Denovo (ORNL)

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Spectrum Matching

- Measured activation amounts
  - $M_{dj} \pm \sigma_{dj}$ for detector d product j
- Predicted activation amounts
  - $B_{sdj} \pm u_{sdj}$ for source s, detector d, product j
- For each source, find the yield y_s that minimizes

$$\chi_s^2 = \sum_d^D \sum_j^J \frac{\left(y_s B_{sdj} - M_{dj}\right)^2}{y_s^2 u_{sdj}^2 + \sigma_{dj}^2}$$

- With those yields, rank the χ_s^2 values
  - Lowest χ_s^2 value is the best match
- Note that
  - A 'good' match has $\chi_s^2 \leq$ d.o.f.
  - There may be several with similar χ_s^2 values
  - There may be none with good χ_s^2 values

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Basic Workflow of the Glass/Cherenkov System

- Pre-event data
  - Glass materials – compositions, Cherenkov conversion constants
  - Detector info – which glasses are in which detectors, locations
  - Source library – leakage spectrum, each scaled to 1kT
  - City model (NYC) – with detector locations
  - Physics data – elemental, isotopic, neutron cross sections

Event

- Detonation modeling
  - Simulate each library source at detonation location
  - Compute expected activation amounts
- Event Analysis - as data comes in (over days)
  - Untangle count rates into measured activation amounts
  - Matching analysis – determine yields and best matching source

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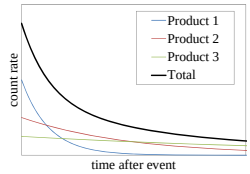
Big Picture

Doped Glass Detectors

Signal from Cherenkov Light Detector



$(t_j, C_j \pm \sigma_j)$ for j=1..J

Number of Activated Products

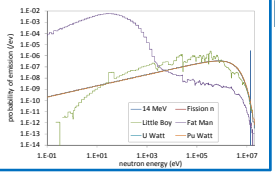
$N_i \pm \sigma_i$

After the blast event

For many products, at many locations

Simulation

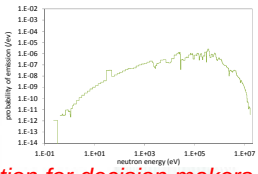
Predict the number of activation products at the detector locations for every source spectra in the library (Challenging 3-D transport problem)



Forensics

Determine the *yield* and *source type* from the library that best matches the measured values of activation

yield = 25 kT



Vital information for decision makers

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Glass Information

	Name	Initial Composition	Density (g/cm3)	Final Composition (weight fractions)			
1.	"quartz"	SiO_2	2.6	O	0.53254	Si	0.46746
2.	"PbP"	30 g $PbHPO_4$	4.7920	O P	0.19036 0.10529	Pb	0.70435
3.	"MnPbP"	30 g $Pb_2P_2O_7$ 1.8 g $MnCl_2$	4.5906	O P	0.18550 0.10260	Mn Pb	0.02552 0.68637
4.	"MgPbP"	30 g $Pb_2P_2O_7$ 3.0 g $MgCl_2$	4.7060	O Mg	0.18562 0.02499	P Pb	0.10267 0.68682
5.	"GaPbP"	36.75g $PbHPO_4$ 5.04 g Ga_2O_3	4.7043	O P	0.19850 0.09225	Ga Pb	0.09213 0.61712
6.	"AsPbP"	30 g $PbHPO_4$ 1.2 g As_2O_3	4.8300	O P	0.19243 0.10112	As Pb	0.02999 0.67646
7.	"sellaite"	MgF_2	3.148	Mg	0.39012	F	0.60988
8.	"MgNaP"	26.74 g $MgHPO_4{\cdot}3H_2O$ 10.0 g $Na_2HPO_4{\cdot}7H_2O$ 21 g $(NH_4)_2\ HPO_4$	2.5830	O Na	0.36923 0.05549	Mg P	0.16644 0.40884
9.	"InPbP"	30 g $PbHPO_4$ 4.5 g In_2O_3	5.0276	O P	0.18802 0.09119	In Pb	0.11075 0.61004
10.	"ScPbP"	45 g $Pb_2P_2O_7$ 2.5 g Sc_2O_3	4.7920	O P	0.20210 0.09719	Sc Pb	0.05053 0.65017

1. quartz

N	16	0.84050
O	19	0.87502
Mg	27	0.66727
Mg	28	0.87565
Al	28	0.87995
Al	29	0.78718
Si	31	0.60572

9. InPbP

Al	28	0.87992
Si	31	0.60573
P	32	0.53877
Ag	112	0.70474
Cd	115	0.37550
In	112	0.09695
In	114	0.49478
In	116	0.74302
Hg	205	0.00455
Tl	206	0.01213
Tl	207	0.14751
Pb	203	0.18915
Pb	209	0.13862

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Detector Locations

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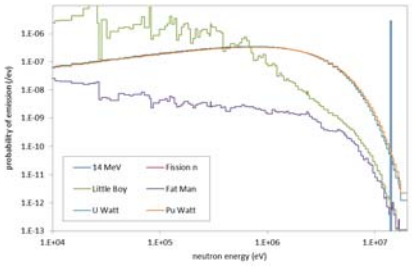
Library of Leakage Sources



Source	n/kT
LANL Source 1 - 14 MeV, N Source	
LANL Source 2 - Fission N Source	
LANL Source 3 - Little Boy, N Source	
LANL Source 4 - Fat Man, N Source	
Combo source: 20% 14 MeV, 80% Fission N	
Combo source: 40% 14 MeV, 60% Fission N	
Combo source: 60% 14 MeV, 40% Fission N	
Combo source: 80% 14 MeV, 20% Fission N	
Combo source: 20% 14 MeV, 80% Little Boy	
Combo source: 40% 14 MeV, 60% Little Boy	
Combo source: 60% 14 MeV, 40% Little Boy	
Combo source: 80% 14 MeV, 20% Little Boy	
Combo source: 20% 14 MeV, 80% Fat Man	
Combo source: 40% 14 MeV, 60% Fat Man	
Combo source: 60% 14 MeV, 40% Fat Man	
Combo source: 80% 14 MeV, 20% Fat Man	
Watt spectrum for u-235 with $E_n = 1$ MeV	
Watt spectrum for pu-239 with $E_n = 1$ MeV	

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Demonstration

- Demonstration inject data
  - With the 'true' source, compute activation amounts, with noise
  - Compute total count rate from each detector, with noise
  - Format into files that look like feeds from real detectors

Source 2: Fission-N Source

10 kT

Times Square

- Event Analysis
  - Read in 'inject' data as detector count rates
  - As data comes in (over days)
    - Untangle count rates into measured activation amounts
    - Matching analysis – determine yields and best matching source

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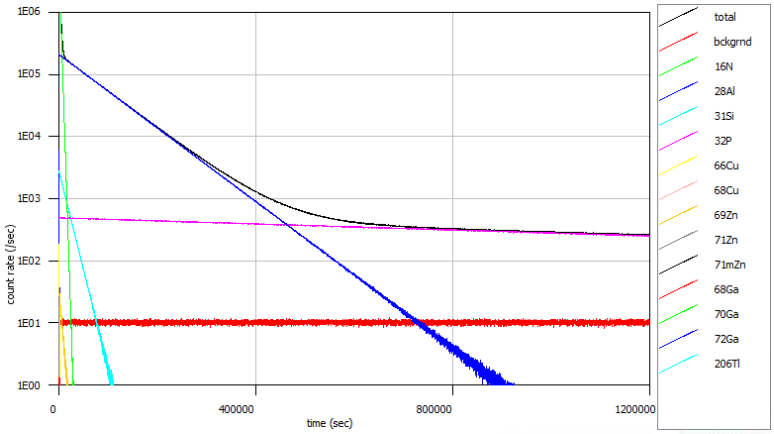
Inject Data

Source 2: Fission-N Source, 10 kT

GaPbP glass

NYC0505 – Mad. Sq. Grdn
869 m from source



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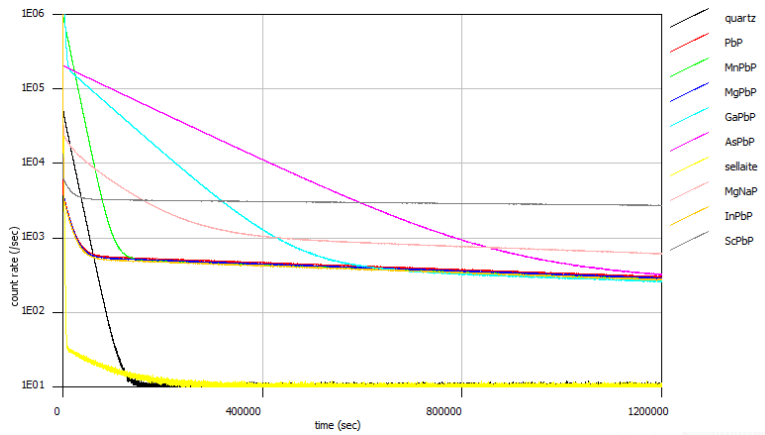
Inject Data

Source 2: Fission-N Source, 10 kT

NYC0505 – Mad. Sq. Grdn
869 m from source



34 detectors, 10 glasses each => 3502 activation amounts

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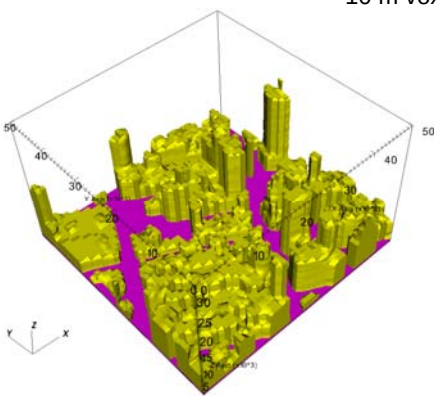
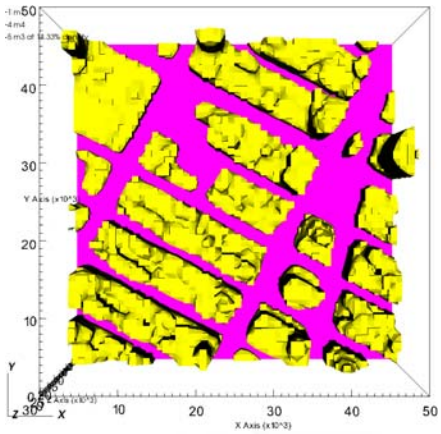
Detonation Simulations

500 m section



10 m voxels



300×300×115 over 3 km center section
P_3 Legendre expansion of scattering xsec
QR quadrature 4 pol/4 azi

350 Gbytes
~400 cpu·hours

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Analysis

- Predicted activation amounts
  - In every glass
  - At every detector location
- Untangle 'measured' count rate data
  - Predicted activation amounts
  - Determine yield and ranking

} Repeat as more 'measured' data becomes available

Product		1 Day Number	1 Day Rel. Unc.	3.5 Days Number	3.5 Days Rel. Unc.	14 Days Number	14 Days Rel. Unc.
N	16						
Al	28						
Si	31					6.377E+07	0.7904
P	32			1.605E+09	0.5104	1.604E+09	0.0071
Cu	66						
Cu	68						
Zn	69						
Zn	71						
Zn	71m						
Ga	68						
Ga	70	1.865E+10	0.0023	1.865E+10	0.0016	1.865E+10	0.0014
Ga	72	2.561E+10	0.1692	2.553E+10	0.0010	2.553E+10	0.0001
Tl	206						

NYC0505 – Mad. Sq. Grdn
869 m from source

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Analysis

- Only using NYC0505 detector location (33 activation amounts)

rank	χ^2	kT	source spectra
1	8.90E-03	10	LANL Source 2 - Fission N Source
2	1.50E+00	29	Watt spectrum for u-235 with En = 1 MeV
3	3.80E+02	28	Watt spectrum for pu-239 with En = 1 MeV
4	1.80E+03	845	LANL Source 4 - Fat Man, N Source
5	1.90E+04	111	LANL Source 3 - Little Boy, N Source
6	4.10E+04	6	Combo source: 20% 14 MeV, 80% Fission
7	5.80E+04	5	Combo source: 40% 14 MeV, 60% Fission
8	6.90E+04	4	Combo source: 60% 14 MeV, 40% Fission
9	7.30E+04	14	Combo source: 20% 14 MeV, 80% Little Boy
10	7.70E+04	4	Combo source: 80% 14 MeV, 20% Fission
11	7.90E+04	7	Combo source: 40% 14 MeV, 60% Little Boy
12	8.00E+04	15	Combo source: 20% 14 MeV, 80% Fat Man
13	8.10E+04	5	Combo source: 60% 14 MeV, 40% Little Boy
14	8.10E+04	8	Combo source: 40% 14 MeV, 60% Fat Man
15	8.20E+04	5	Combo source: 60% 14 MeV, 40% Fat Man
16	8.20E+04	4	Combo source: 80% 14 MeV, 20% Little Boy
17	8.20E+04	4	Combo source: 80% 14 MeV, 20% Fat Man
18	8.40E+04	3	LANL Source 1 - 14 MeV, N Source

31 other detectors pick Source 2 as best

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Analysis

- Using 34 detector locations together (927 activation amounts)

rank	χ^2	kT	source spectra
1	1.50E+02	10	LANL Source 2 - Fission N Source
2	2.30E+02	29	Watt spectrum for u-235 with En = 1 MeV
3	1.00E+04	28	Watt spectrum for pu-239 with En = 1 MeV
4	4.00E+05	735	LANL Source 4 - Fat Man, N Source
5	1.40E+06	6	Combo source: 20% 14 MeV, 80% Fission
6	2.10E+06	5	Combo source: 40% 14 MeV, 60% Fission
7	2.20E+06	12	Combo source: 20% 14 MeV, 80% Little Boy
8	2.50E+06	134	LANL Source 3 - Little Boy, N Source
9	2.60E+06	7	Combo source: 40% 14 MeV, 60% Little Boy
10	2.70E+06	4	Combo source: 60% 14 MeV, 40% Fission
11	3.00E+06	5	Combo source: 60% 14 MeV, 40% Little Boy
12	3.20E+06	16	Combo source: 20% 14 MeV, 80% Fat Man
13	3.30E+06	4	Combo source: 80% 14 MeV, 20% Fission
14	3.40E+06	8	Combo source: 40% 14 MeV, 60% Fat Man
15	3.50E+06	4	Combo source: 80% 14 MeV, 20% Little Boy
16	3.60E+06	6	Combo source: 60% 14 MeV, 40% Fat Man
17	3.70E+06	4	Combo source: 80% 14 MeV, 20% Fat Man
18	3.90E+06	3	LANL Source 1 - 14 MeV, N Source

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Variations

- After 1 day of 'measured' data
  - Source 2 is best match of 33 detectors individually, best global match
  - Yield is correct
- After 3.5 days of 'measured' data
  - Source 2 is best match of 33 detectors individually, best global match
  - Yield is correct
- Using only closest 16 detectors – correct match and yield
- Removing closest 1, 4, 9 detectors – correct match and yield
- Different 'true' source spectrum (source 10, "Combo source: 40% 14 MeV, 60% Little Boy") – correct match and yield
  - Second best match had χ_s^2 that was 28 times that of best match

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Summary

- Analysis of Cherenkov signals to find matching source works well
  - Untangling activation amounts uses robust algorithm that also computes uncertainties
  - Uncertainties of glass composition can be taken into account in matching
  - The χ_s^2 value indicates quality of the best match
    - May be more than one good match
    - May be no good matches – true source not in the library
- Any system that 'identifies' the source type relies on a comparison
  - Measurement of a physical property does not identify the serial number
    - Experts determine what sources share that property
  - The glass/Cherenkov system and the AFIDS foil-based system incorporate the comparison into the algorithm, making it automatic
- This work was sponsored by DTRA (Defense Threat Reduction Agency)

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Questions?

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