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Associated-Particle Sealed-Tube Neutron Generators and Hodoscopes for NDA Applications[1]

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Abstract

With radioisotope sources, gamma-ray transmission hodoscopes can inspect canisters and railcars to monitor rocket motors, can detect nuclear warheads by their characteristic strong gamma-ray absorption, or can count nuclear warheads inside a missile by low-resolution tomography. Intrinsic gamma-ray radiation from warheads can also be detected in a passive mode. Neutron hodoscopes can use neutron transmission, intrinsic neutron emission, or reactions stimulated by a neutron source, in treaty verification roles. Gamma-ray and neutron hodoscopes can be combined with a recently developed neutron diagnostic probe system, based on a unique associated-particle sealed-tube neutron generator (APSTNG) that interrogates the object of interest with a low-intensity beam of 14-MeV neutrons, and that uses flight-time to electronically collimate transmitted neutrons and to tomographically image nuclides identified by reaction gamma-rays. Gamma-ray spectra of resulting neutron reactions identify nuclides associated with all major chemicals in chemical warfare agents, explosives, and drugs, as well as many pollutants and fissile and fertile special nuclear material.

I. INTRODUCTION

New developments in hodoscope radiation detection and neutron diagnostic probe technologies offer some rather unique capabilities for a wide range of applications, including arms control treaty verification, remediation of radwaste and pollutants,

[1]Argonne National Laboratory is owned by the U. S. government and operated by the University of Chicago under the provisions of a contract with the Department of Energy. This work was performed partly under sponsorship of the U. S. Department of Energy Office of Arms Control and Office of Environmental Restoration and Waste Management as part of a research and development program and does not imply current or future policy decisions or technical preferences of any agency of the U. S. government.

and detection of explosives, drugs, and other contraband. In the hodoscope concept, an array of radiation detectors is used to image or detect objects inside opaque containers. Argonne interest in hodoscopes stems from the fast-neutron hodoscope used at the Transient Reactor Test (TREAT) Facility for many years to image motion of reactor fuel inside thick steel capsules undergoing destructive testing that simulates hypothetical core-disruptive accidents. The TREAT reactor heats up the test fuel by the fission process, and a two-dimensional hodoscope array views the test fuel through a thick collimator behind slotted TREAT fuel elements and samples fission neutrons from the test fuel at millisecond intervals.

A diagram of the TREAT fast-neutron hodoscope is shown in Fig. 1. Only a representative number of the 360 detection channels is shown (10 columns by 36 rows). Two redundant detector arrays are used, a bank of proportional counters and a bank of Hornyak buttons, with discriminators set to detect neutrons above 0.5 MeV.[1] Currently the collimator and detection system are being extended to 14 columns and being modified for new TREAT tests.

For non-reactor hodoscope applications however, relatively weak radiation sources and little or no shielding and collimation are generally sufficient. Laboratory measurements have demonstrated a range of potential treaty verification applications. With radioisotope sources, gamma-ray transmission hodoscopes can inspect canisters and railcars to monitor rocket motors, can detect nuclear warheads by their characteristic strong gamma-ray absorption, or can count nuclear warheads inside a missile by low-resolution tomography. Intrinsic gamma-ray radiation from warheads can also be detected in a passive mode. Neutron hodoscopes can use neutron transmission, intrinsic neutron emission, or reactions stimulated by a neutron source, in treaty verification roles.

Gamma-ray and neutron hodoscopes can be combined with a recently developed neutron diagnostic probe system to satisfy a wide range of van-mobile and fixed-portal applications for NDA (nondestructive analysis). The probe is based on a unique associated-particle sealed-tube neutron generator (APSTNG) that interrogates the object of interest with a low-intensity beam of 14-MeV neutrons generated from the deuterium-tritium reaction and that detects the alpha-particle associated with each neutron. Gamma-ray spectra of resulting neutron reactions identify nuclides associated with all major chemicals in chemical warfare agents, explosives, and drugs, as well as many pollutants and fissile and fertile special nuclear material. Flight times determined from detection times of the gamma-rays and alpha-particles yield a separate low-resolution tomographic image of each nuclide identified in the time-correlated gamma-ray spectrum. The APSTNG also forms the basis for a compact fast-neutron transmission imaging system that can be used along with or instead of the emission imaging system.

II. Treaty Verification Hodoscopes

The criteria that a fielded verification radiation detection system for arms control treaties must satisy are different than for other NDA applications, because the system must be accepted and used by all parties to the treaty, and each party wants to protect its own interests and secrets as well as to verify adherence to the treaty by the other parties. A high-confidence measurement is needed that is deception resistant, but an instrument that is also nonintrusive (will not reveal hidden detailed design secrets) and transparent (simple to understand and employ) is favored. Other criteria include lack of sensitive technology, portability or transportability, high reliability, easy operation and maintenance, personnel safety, and development and deployment costs commensurate with applications.

Hodoscope technology can meet these criteria rather well. Intrusion is controlled because spatial resolution is determined by the visible fixed spacing between detectors and lack of a need for any detailed energy spectra, and relatively short measurement times are provided by the simultaneous counting of a number of relatively efficient detectors. The use of relatively weak radioisotope sources eliminates any need for complex bulky accelerator equipment and yields low radiation exposure. The instrumentation is commercially available, highly reliable, relatively low cost, transportable, and simple to operate and maintain.

Most ANL work in the treaty verification area has involved gamma-ray transmission hodoscopes consisting of linear arrays of 2.54 cm x 2.54 cm NaI detectors viewing transmission of a 10 to 20 mCi ^{60}Co source through objects of interest. Figure 2 depicts the results of an early experiment demonstrating the concept of hodoscope verification that a cruise missile that has been declared to be conventional does not contain a nuclear warhead. In a cruise missile mockup, transmission through a simulated generic nuclear warhead (buried in simulated propellant) was much less than that through propellant or a conventional warhead. A nuclear warhead, even if hidden in a fuel tank, should be detectable in a cruise missile that has been declared conventional.

Thus, nuclear warheads are detectable by their characteristic high-Z gamma-ray attenuation. This is useful, because there are likely to be cases for which sufficient radiation is not emitted from nuclear warheads to allow confident detection or counting by passive means. Figure 3 illustrates the concept of counting nuclear warheads on a ballistic missile by rotating a linear gamma-ray transmission hodoscope around the missile to obtain different views for low-resolution tomographic reconstruction (in Fig. 3, "RV" means "re-entry vehicle") . In experiments conducted at ANL on mockups, the optional collimator and source/detector positions shown in Fig. 3 were not necessary, and measurements were completed in a few minutes. This method of counting warheads was found to be deception-resistant against hidden warheads and decoys.

Active-source radiation interrogation systems have not yet been accepted for treaty verification, except for US operation of a gamma-ray radiography facility at Votkinsk in the USSR. The Votkinsk facility, which is used to measure diameter and length of rocket motors inside rail cars, is based on a high-current linear accelerator that produces a relatively high radiation level and requires substantial shielding. For the same or similar measurements, ANL proposes a much simpler, far less expensive gamma-ray transmission hodoscope as depicted in Fig. 4, that emits far less radiation. The rail car is inspected at stops as it rolls by the portal. In addition to the vertical arrays shown for measuring rocket motor diameter, there are horizontal arrays for measuring length. Intrusion is limited by not measuring unnecessary regions. Successful experiments have been conducted on mockups of missiles.

In addition to gamma-ray transmission hodoscopes, neutron-reaction hodoscopes of several types have been proposed for detecting and counting nuclear warheads, in which neutron sources irradiate nuclear warheads and the emitted fission neutrons (or gamma-rays) are detected by a hodoscope. Because emitted radiation is isotropic, these hodoscopes can be placed more arbitrarily with respect to the source than transmission hodoscopes and thus allow measurements in more confined spaces, but a collimator is required to count warheads. Laboratory experiments on mockups and radiation transport calculations indicate that relatively strong special radioisotope neutron sources can be used or a pulsed neutron generator can be used (counting delayed neutrons between pulses).

III. APSTNG CHARACTERISTICS

Recently Argonne has been involved with a newly-developed diagnostic probe from the Advanced Systems Division of Nuclear Diagnostic Systems Inc.

(NDSI), a potentially powerful NDA tool with wide-ranging applications.[2,3] The system is based on a unique associated-particle sealed-tube neutron generator (ASPTNG). As shown in the schematic layout in Fig. 5, deuterons are accelerated into a tritium target, producing 14-MeV neutrons isotropically. Each neutron is accompanied by an associated alpha-particle travelling in the opposite direction. The gamma-ray and neutron detectors are time-gated by pulses from the alpha detector, which forms a cone of flight-time-correlated neutrons through the object. Detector pulses are time-resolved by CFD's (constant-fraction discriminators). Flight times are determined by TAC's (time-to-amplitude converters), digitized by an ADC (analog-to-digital converter), and recorded.

When a reaction occurs in the object along the cone that results in a detected gamma-ray, the time-delay from the alpha pulse yields the position (depth) along the cone where the reaction occurred, since the source neutron and gamma-ray speeds are known (5 cm/ns and 30 cm/ns, respectively). By scanning the alpha detector horizontally and vertically, or by using a two-dimensional (2D) position-sensitive multipixel alpha detector, transverse and depth coordinates of reaction sites can be mapped, providing three-dimensional (3D) emission imaging of reaction densities from measurements at a single orientation. Figure 6 illustrates the electronics and information flow for a multipixel system containing a 2D position-sensitive alpha detector. In Fig. 6, the vectors involved in the reaction location are "Rt", "Rd", and "Rs". The transverse "X" and "Y" coordinates of "Rt" are digitized and stored in the PC computer, along with "TOF" (time-of-flight = "t" - "T") and gamma-ray energy "Eg". The PC controls the experiment, calculates positions, and displays data and images.

Fast-neutron inelastic scattering reactions in the object provide prompt gamma-ray spectra that can identify many nuclides. By choosing gamma lines of specific nuclides, a 3D image of each identifiable nuclide in the time-correlated spectrum can be mapped. By choosing appropriate nuclide intensity ratios, 3D images of compounds can be made. Slow-neutron capture is not time-correlated with the alpha pulses, but provides nonimaging gamma-ray spectra that can aid nuclide identification. (If fissionable materials are present, neutron reaction detectors may be used to detect emitted fission neutrons).

As shown in Fig. 5, by discarding detected neutrons not having the proper flight time to be uncollided, one can perform fast-neutron 2D transmission imaging without a collimator (by scanning, using a neutron detector hodoscope array, or using 2D neutron detectors), since scattered neutrons are removed by "electronic collimation". By measuring at a sufficient number of views around 180 degrees, 3D tomography is feasible. Transmission imaging can be done along with or instead of emissive reaction-density imaging.

The application of the associated-particle method to NDA for neutron inelastic scattering is not new, although it has been relatively undeveloped and confined to the laboratory because of the bulk, complexity, and reliability and maintenance problems of the accelerator equipment required. The replacement of the accelerator in this neutron diagnostic probe system by the sealed-tube APSTNG brings new flexibility to the method and allows it to become a tool for field use. The state-of-the-art APSTNG was developed with considerable effort by the Advanced Systems Division of NDSI.

As diagrammed in Fig. 7, a Penning ion source inside the APSTNG emits a continuous mixed beam of deuterium and tritium ions that is accelerated and focused on a small spot on the target, tritiating the target and producing neutrons and alpha particles. A getter controls the mixture of deuterium and tritium. The alpha detector consists of a ZnS screen inside the tube, with a photomultiplier outside (replaced by a microchannel plate and resistive anode readout, for a 2D detector). The APSTNG is an inexpensive small sealed module with low-bulk support equipment. It has a long mean-time-between-failures (around 2000 hours at a million n/s or 200 hours at 10 million n/s), is easily replaced (allowing simple field operation), and presents low radiation exposure.

A proof-of-principle experiment on gamma-ray emission reaction-density imaging was performed on an interrogation volume containing a carbon block and an aluminum block and plate. Shown in Fig. 8 are the gamma-ray energy spectra for neutron inelastic scattering obtained for C and Al. By using a multi-pixel 2D alpha detector, transverse x and y coordinates of reaction locations along the correlation cone were simultaneously obtained. By mapping reaction locations from flight-time along the correlation cone (z coordinate) for energy windows enclosing C and Al gamma lines, the objects were correctly identified and 3D-imaged, as shown in Fig. 9.

IV. APSTNG APPLICATIONS

APSTNG technology has the capabilities for identification and 3D imaging of many individual nuclides and compounds, with flexible positioning of reaction detectors with respect to the neutron source (on the same side, perpendicular, or opposite side), as well as capability for fast-neutron transmission imaging. The source and emitted radiation are high-energy and penetrate highly absorbing objects. Proof-of-concept laboratory experiments have been successfully done for a number of applications: nuclear warhead detection, chemical ordnance identification, explosive detection and identification, contraband drug detection, uranium borehole logging, corrodent detection on steam-turbine blades, kerogen analysis of shale,[4] on-line assay of coals, and bulk soil remediation of radwaste and pollutants.[5]

Based on data from proof-of-concept laboratory experiments, it is interesting to estimate the measurement times required for detection of contraband items using a fielded APSTNG system, in this case, one having a multipixel alpha-particle detector and six relatively large gamma-ray detectors. A plot of the ratio of nitrogen to oxygen to that of carbon to oxygen is useful for differentiating contraband drugs or explosives from ordinary items expected to be seen, such as Fig. 10. Materials that would normally appear in luggage or foodstuffs are separated from explosives (open squares) and cocaine.

The boxes shown in Fig. 10 represent count statistics for a 15-second measurement of 1 kg C-4 explosive, the larger box enveloping five standard deviations (5 sigma), the smaller box enveloping two standard deviations. The C-4 is definitely identified as an explosive. In fact, even a 4-second measurement would distinguish the C-4 from items normally found in luggage, so if luggage is being examined, suspicion is indicated. In 480 seconds of measurement time, the C-4 would be differentiated from other common explosives.

In Fig. 11, boxes are drawn for two and five standard deviations of count statistics for a 2-second measurement of 1 kg of meat. With high probability, the meat is identified as a foodstuff rather than explosives or contraband, indicating a very low false alarm rate for monitoring foodstuffs. In Fig. 12, a two-standard-deviation box is shown for a 4-second measurement of 1 kg of cocaine in fish. The item is identified as suspicious, since it is not just fish, and is thought probably to be cocaine, since it is not amphetamines (it could be plastic, but why would plastic appear in fish?).

For the most part, the proof-of-concept experiments have been conducted using only time-correlated, or imaging, reaction gamma-ray spectra (from neutron inelastic scattering for nearly all applications). This is called the IGRIS (inelastic gamma-ray imaging and spectroscopy) mode. Analysis of the soil remediation experiments included the uncorrelated gamma-ray spectrum, called the CGRS (capture gamma-ray spectroscopy) mode. The FNTI (fast-neutron transmission imaging) mode has so far not been much used, but it may find use in the future for simultaneous mode measurements, to correct IGRIS images for neutron attenuation or for multimode image analysis, or in a separate system for imaging extended or highly absorbing objects.

The IGRIS mode is not very suitable for imaging extended objects much over a meter or so in all three dimensions or highly absorbing objects. For large objects, the double solid angle reduction (source-to-object and object-to-detector) substantially reduces signal count rate. For large objects, accidental counts become limiting, and the raw images exhibit amplitude reductions and increased fluctuations in regions where neutron or gamma-ray attenuation are significant.

In the FNTI mode, the signal is proportional to the source-to-detector solid angle. It may be feasible to combine FNTI hodoscope arrays with GRTI (gamma-ray transmission imaging) hodoscope arrays so as to obtain Z-sensitive images of large volumes, such as a truck or cargo container, by employing the differences in attenuation Z-dependence (tomographic imaging may be necessary to do this). In some applications, this combination of FNTI and GRTI may allow determination of suspicious regions inside the volume, with a low false alarm rate. Then a two-stage interrogation process could be applied, in which the suspicious region would be offloaded and examined using a separate system based on the IGRIS mode.

V. CONCLUSIONS

With radioisotope sources, hodoscope technology has been shown to provide effective instruments for some arms control treaty verification applications, meeting the special criteria of high confidence, nonintrusiveness, transparency, transportability, reliability, easy operation and maintenance, personnel safety, and relatively low cost, in these applications. Combining hodoscope technology with APSTNG technology opens avenues to a much wider range of applications, not only for treaty verification, but also for detection of contraband drugs and explosives and remediation of radwaste and pollutants.

However there are some limitations in the IGRIS mode of the APSTNG system that can be significant for some applications, even for interrogation of volumes that are not large. Presently attainable depth resolution is limited, for a small gamma-ray detector, to about 5 cm (because the system has an overall time resolution of ~ 1 ns and a 14-MeV neutron travels 5 cm in 1 ns), and measurement times can be rather long to obtain sufficient gamma-ray counts. The gamma-ray signal count rate is limited by reaction cross-sections, solid angles subtended by the alpha detector and gamma-ray detectors, gamma-ray detector efficiency, and neutron source strength, but usable source strength is limited by detector accidental counts and pileup.

A gamma-ray hodoscope detector array can be used to substantially increase the signal count rate to lower measurement times, when necessary. However, small detectors will have a small energy-peak efficiency for the high-energy gamma-rays detected, while large detectors of the standard form will degrade the time resolution (and thus the depth resolution) substantially. Detector configurations are being investigated that will substantially improve the signal count statistics, while retaining as much time resolution as possible.

VI. Acknowledgments

The support and direction of M. F. O'Connell, Project Manager for the Office of Arms Control, U. S. Department of Energy are greatly appreciated. We acknowledge, with many thanks, the continuing cooperation and support of the NDSI staff, A. H. Aitken, C. C. Blackmon, and C. J. Henderson. We also appreciate the continuing direction and support provided by Argonne Arms Control Program Manager A. Travelli and Technical Manager A. DeVolpi.

VII. References

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4. C. M. Gordon and C. W. Peters, "Instrumental Assay of Kerogen in Shale Using Fast Neutrons", *Int. J. Radiat. Appl. Instrum. Part E* **2**, 123-128 (1988).
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Activities at DOE Applicable to Mixed Waste", submitted for publication in proceedings of the Hazardous Materials Conference/South (Atlanta, Georgia USA, October 2-4, 1991).

Figure Captions

Fig. 1. Elevation and plan views of the fast-neutron hodoscope at north face of the TREAT reactor.

Fig. 2. Concept of detecting a nuclear warhead inside a cruise missile that has been declared to be conventional, using a gamma-ray transmission hodoscope.

Fig. 3. Concept of counting of nuclear warheads using a gamma-ray transmission hodoscope.

Fig. 4. Concept of verification of dimensions of rocket motor inside rail car, using a gamma-ray transmission hodoscope.

Fig. 5. Schematic layout of APSTNG-based interrogation system.

Fig. 6. Electronics and information flow for basic multipixel APSTNG-based system with 2D position-sensitive alpha-particle detector.

Fig. 7. Diagram of interior of APSTNG (Associated-Particle Sealed-Tube Neutron Generator).

Fig. 8. APSTNG system gamma-ray energy spectra of C and Al targets, for neutron inelastic scattering.

Fig. 9. Top and side views of 3D location of C and Al targets as mapped from APSTNG gamma-ray emission data. Points indicate mapped reaction sites.

Fig. 10. APSTNG N/O vs. C/O for 15-second measurement of 1 kg C-4 explosive. Large box envelops 5-sigma statistics and small box envelops 2-sigma statistics.

Fig. 11. APSTNG N/O vs. C/O for 2-second measurement of 1 kg of meat. Large box envelops 5-sigma statistics and small box envelops 2-sigma statistics.

Fig. 12. APSTNG N/O vs. C/O for 4-second measurement of 1 kg of cocaine in fish. Box envelops 2-sigma statistics.

MODIFIED 1.2 m (48 in) HODOSCOPE

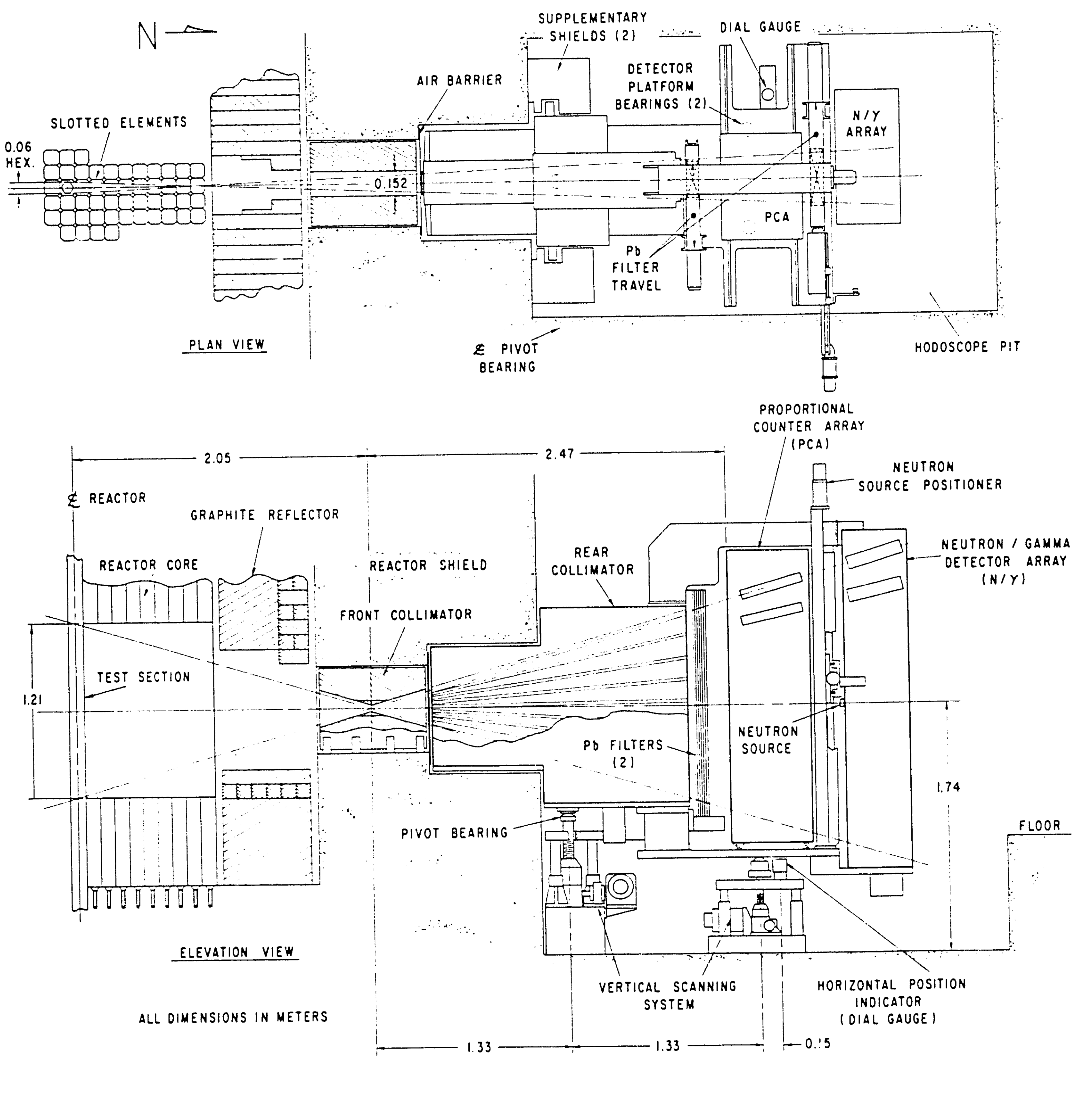


Fig. 1

VERIFICATION OF CONVENTIONAL CRUISE MISSILES

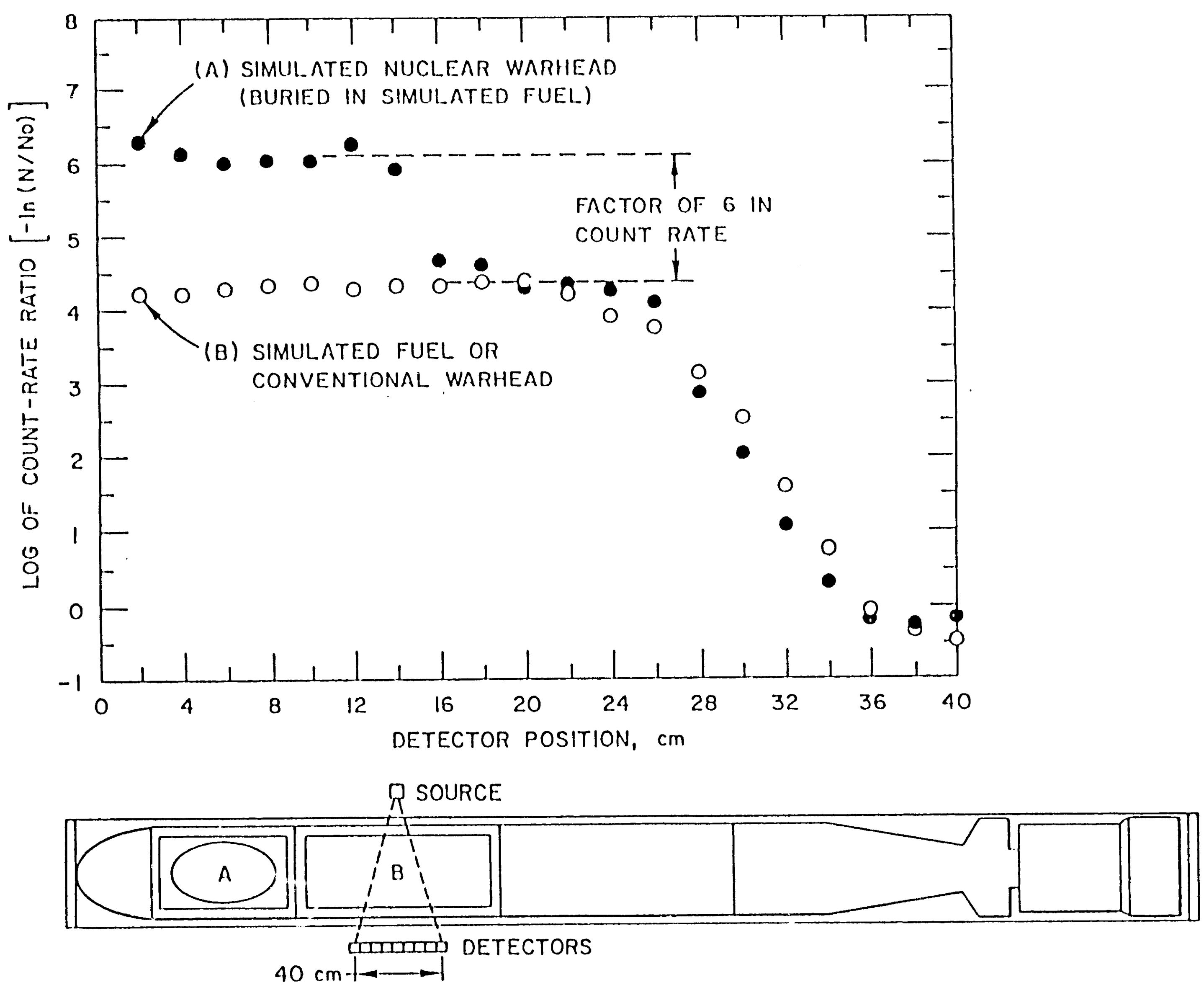
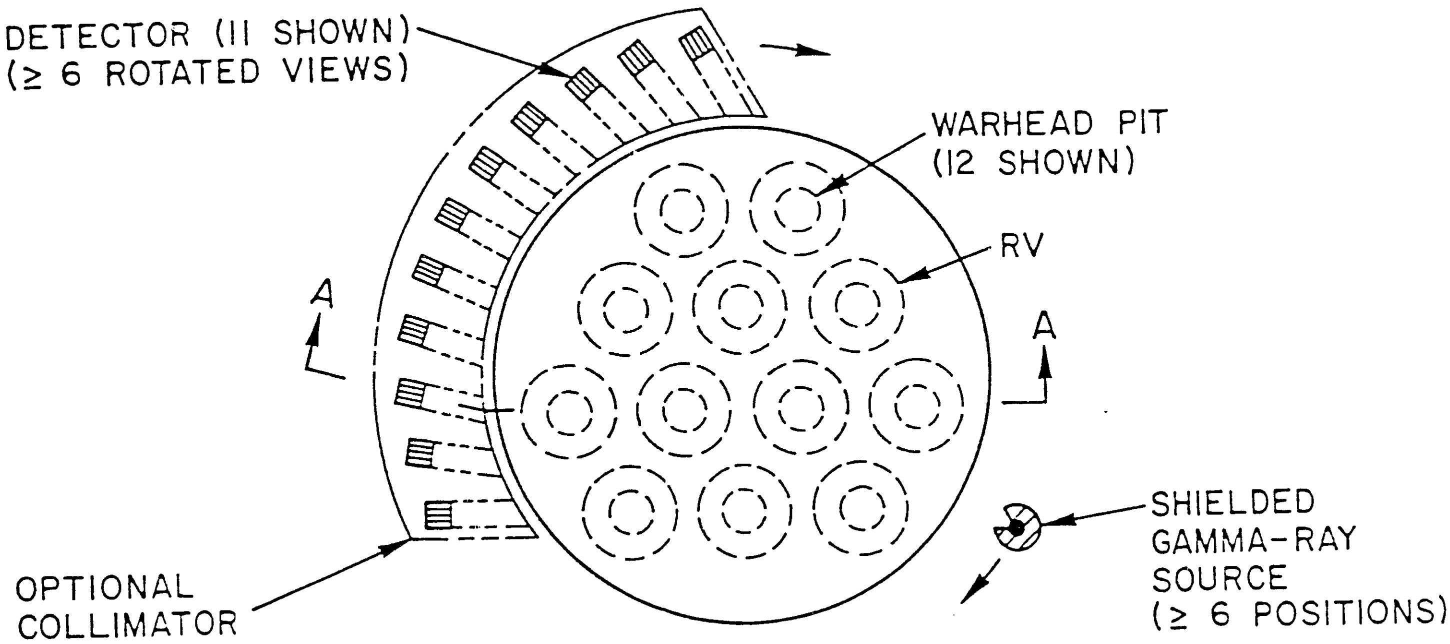
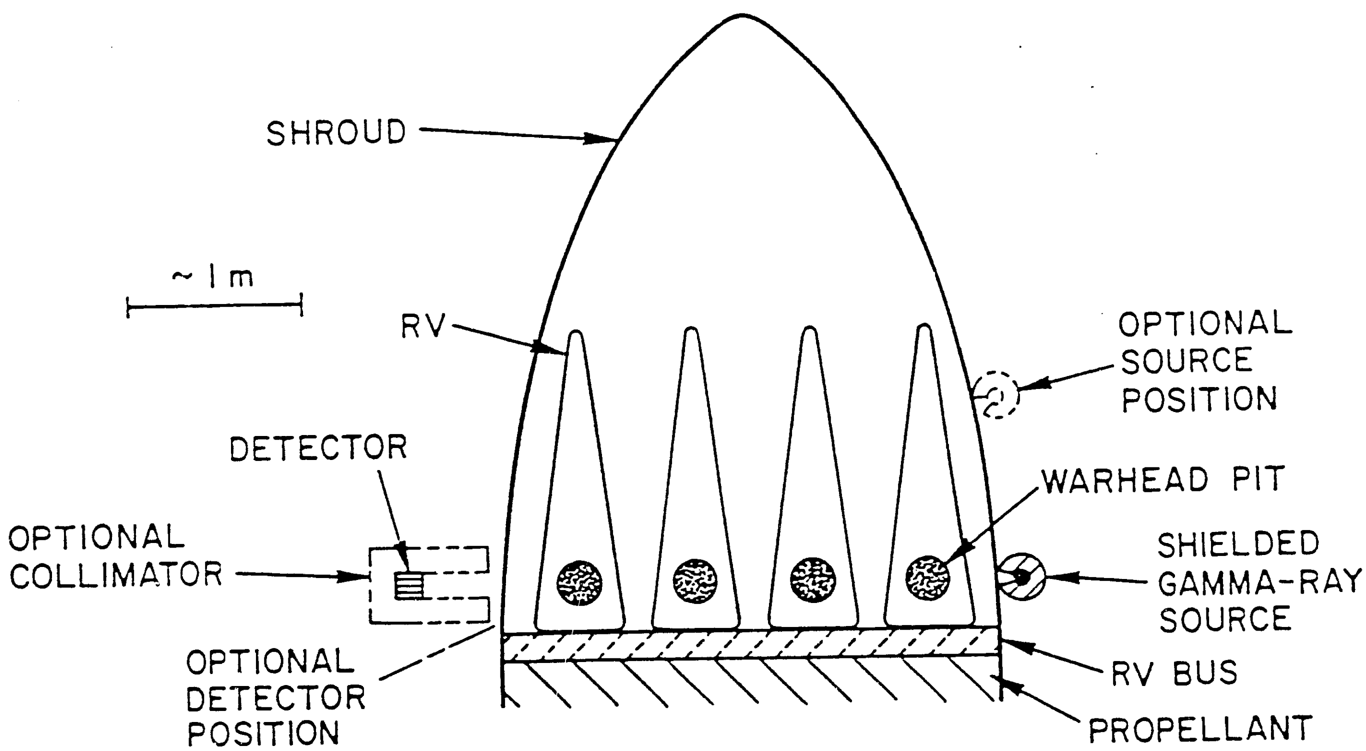


Fig 12

GAMMA-RAY TRANSMISSION HODOSCOPE CONCEPT



TOP VIEW
(CROSS SECTION)



SECTION A-A

Fig. 3

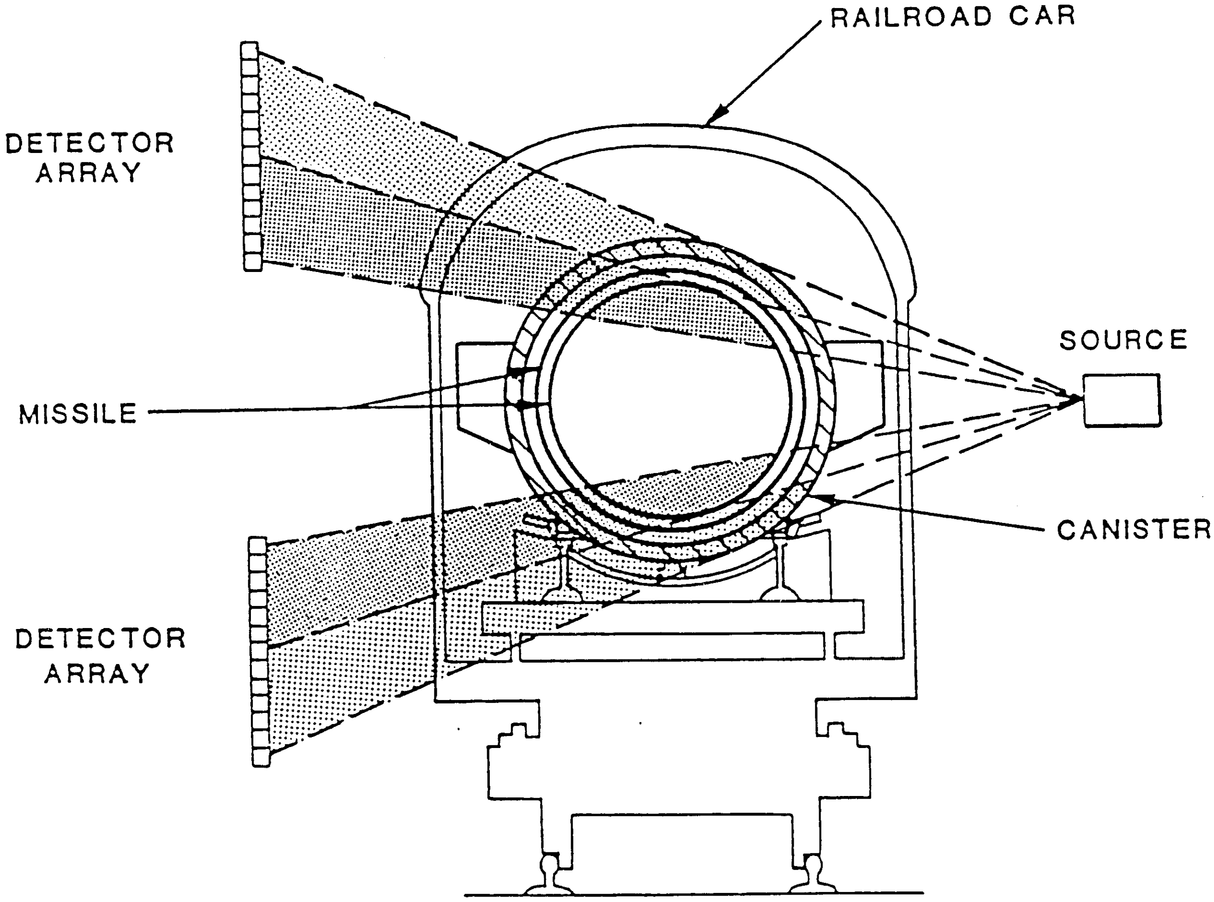

RAILROAD CAR
DETECTOR ARRAY
SOURCE
MISSILE
CANISTER
DETECTOR ARRAY

Fig 4

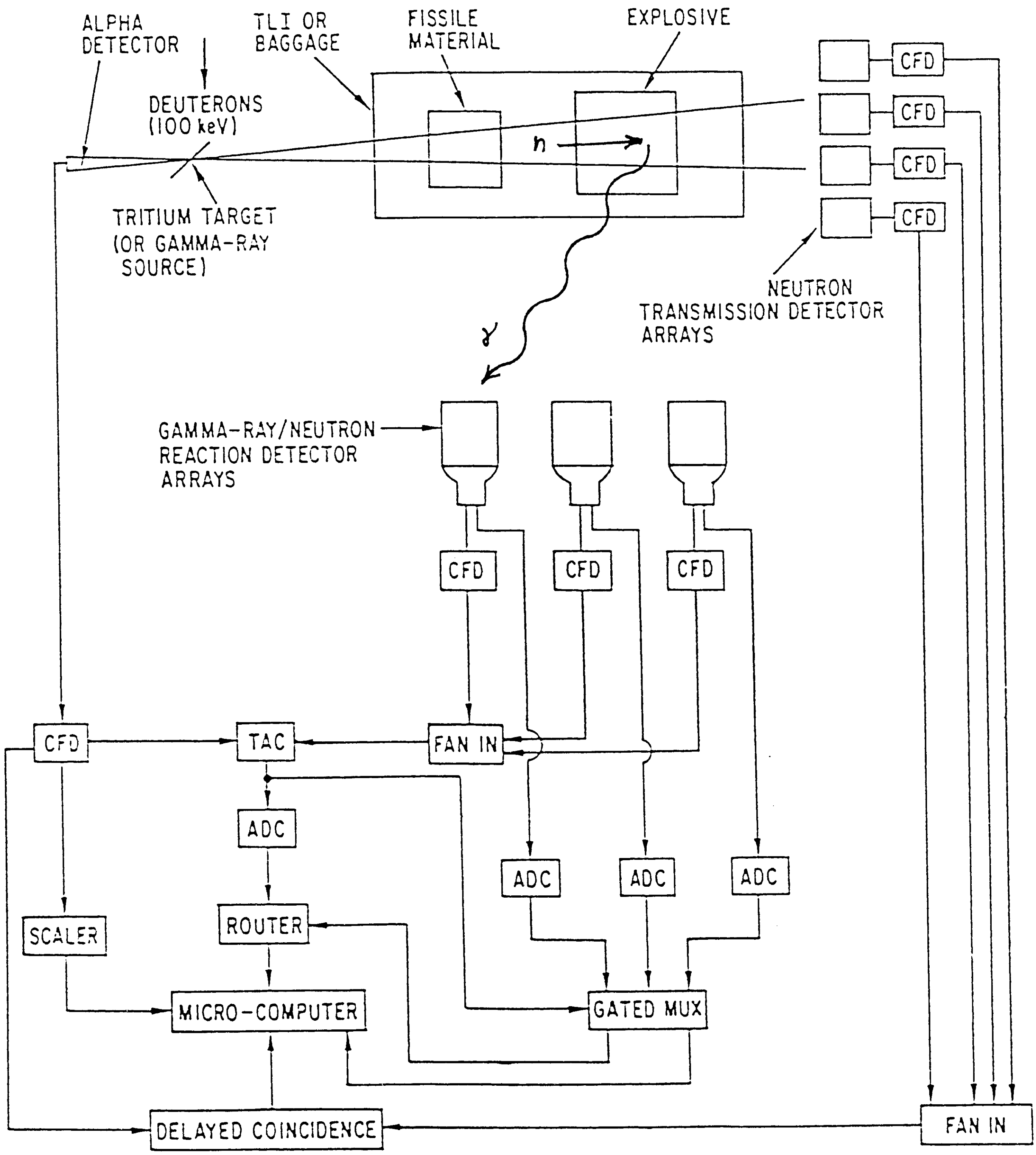

ALPHA DETECTOR
DEUTERONS (100 keV)
TLI OR BAGGAGE
FISSILE MATERIAL
EXPLOSIVE
CFD
CFD
CFD
CFD
n
TRITIUM TARGET (OR GAMMA-RAY SOURCE)
NEUTRON TRANSMISSION DETECTOR ARRAYS
γ
GAMMA-RAY/NEUTRON REACTION DETECTOR ARRAYS
CFD
CFD
CFD
CFD
TAC
FAN IN
ADC
ADC
ADC
ADC
SCALER
ROUTER
MICRO-COMPUTER
GATED MUX
DELAYED COINCIDENCE
FAN IN

Fig. 5

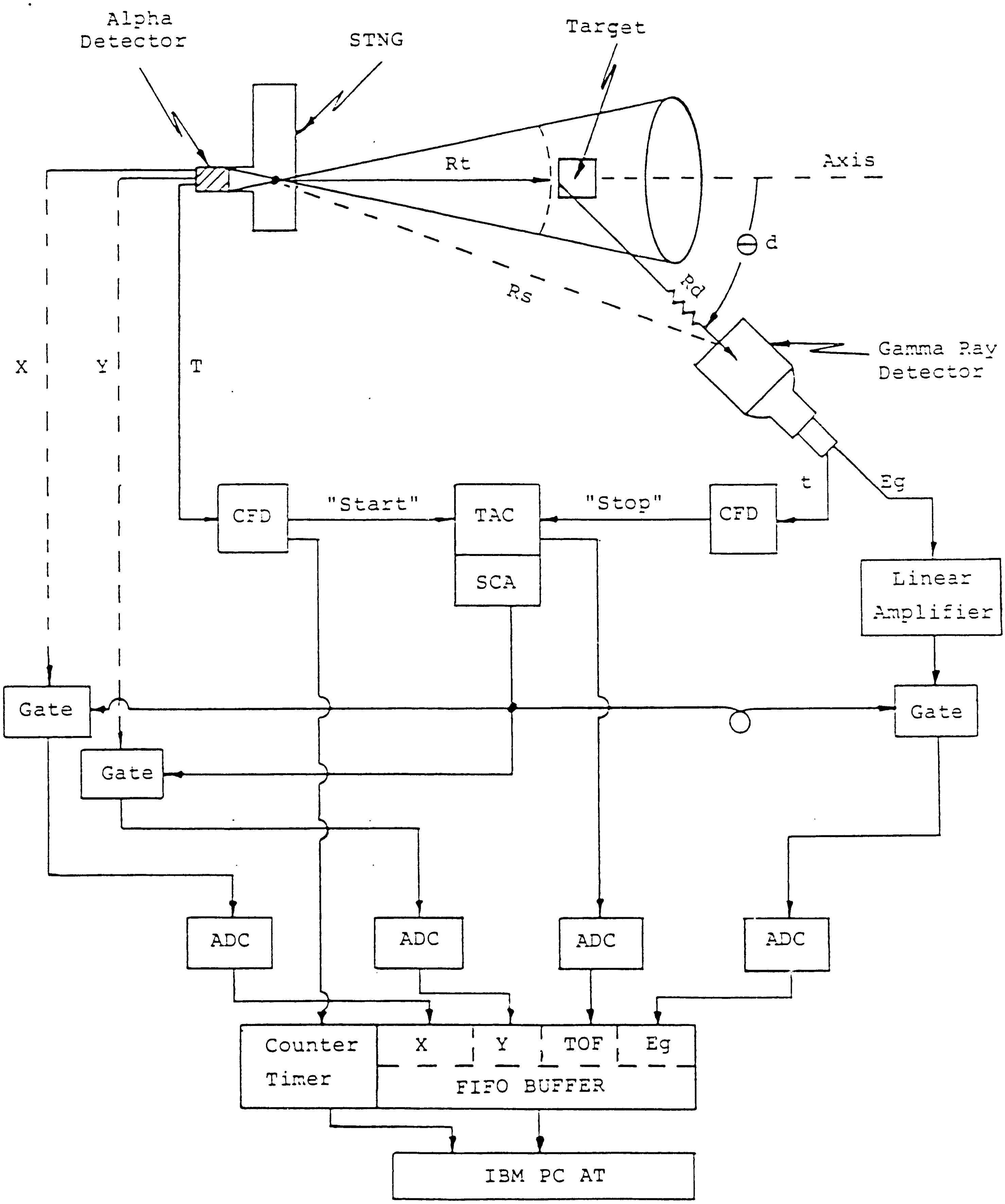

Alpha Detector
STNG
Target
Rt
Axis
θd
Rd
Rs
Gamma Ray Detector
X
Y
T
t
Eg
CFD
"Start"
TAC
"Stop"
CFD
SCA
Linear Amplifier
Gate
Gate
Gate
ADC
ADC
ADC
ADC
Counter Timer
X
Y
TOF
Eg
FIFO BUFFER
IBM PC AT

Fig. 6

SEALED TUBE NEUTRON
GENERATOR

STNG

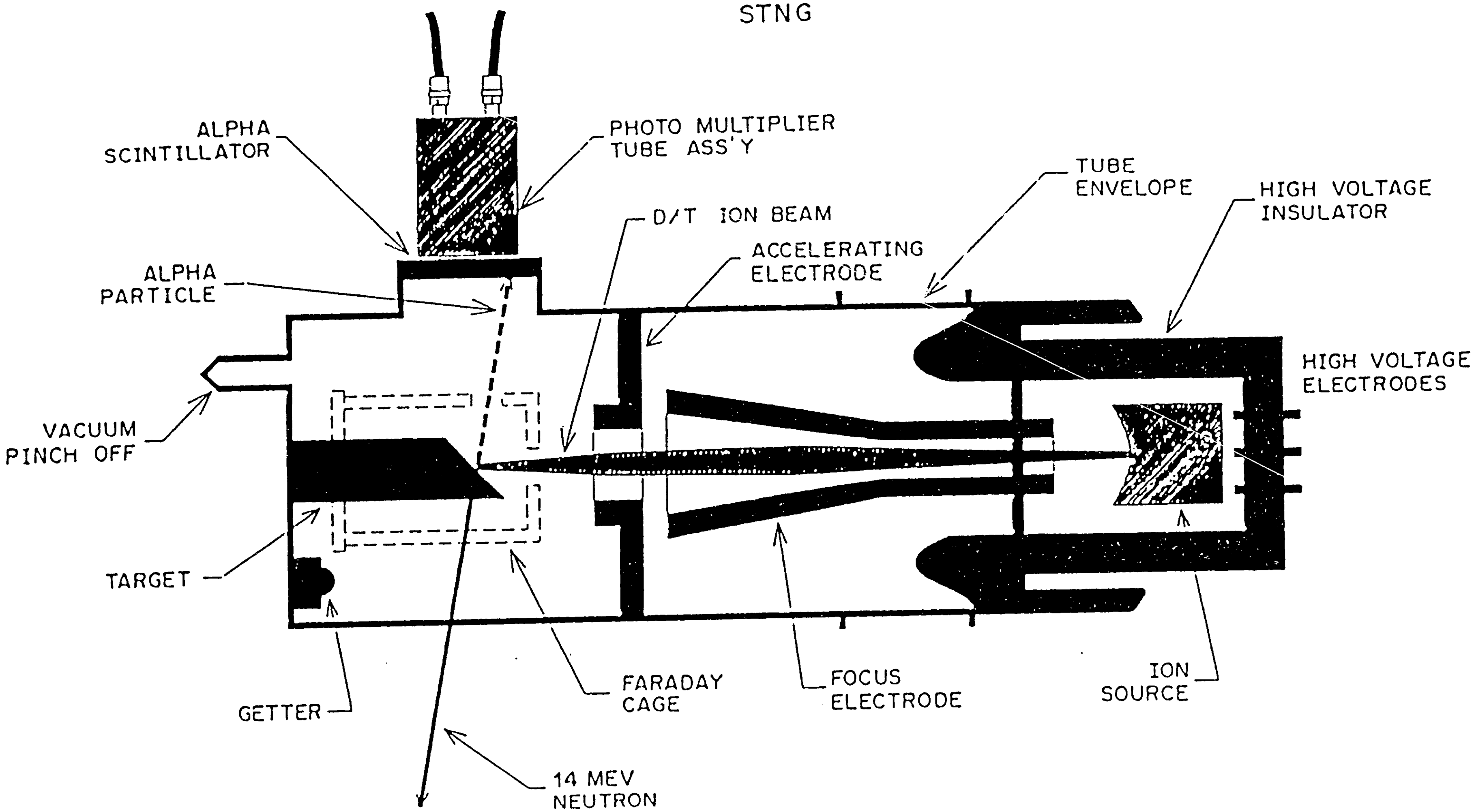
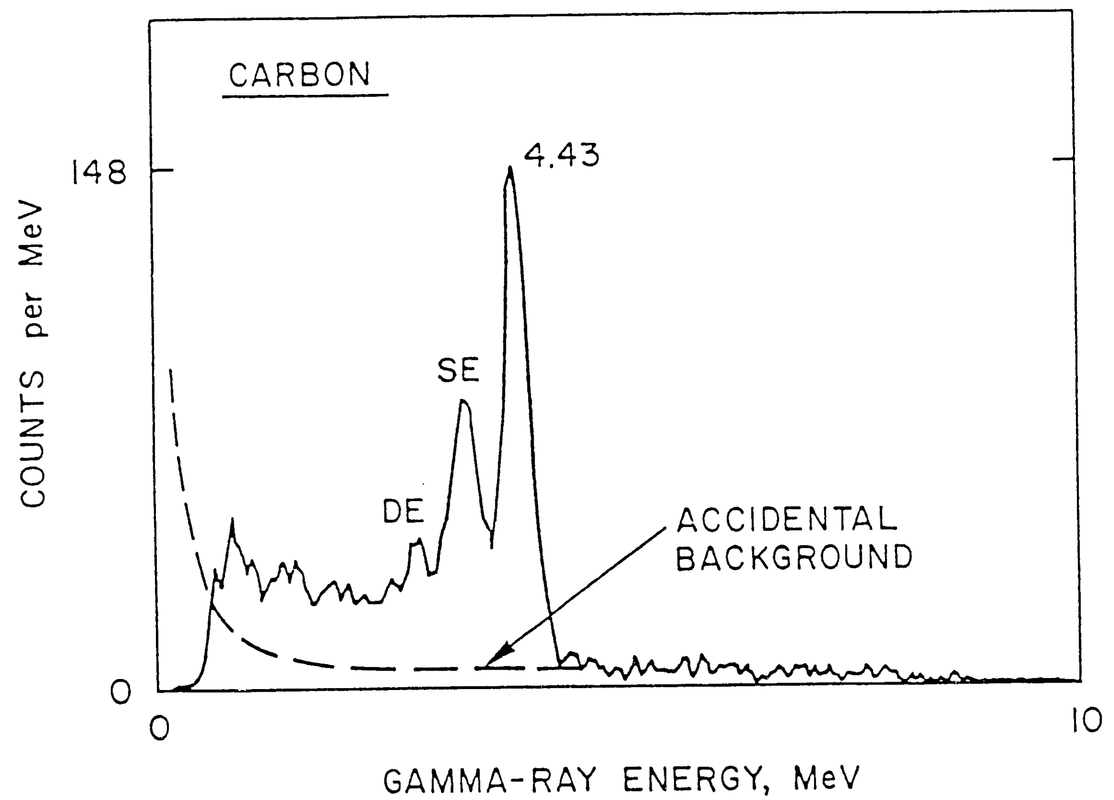


Fig. 7


CARBON
148
4.43
COUNTS per MeV
SE
DE
ACCIDENTAL
BACKGROUND
0
0
10
GAMMA-RAY ENERGY, MeV

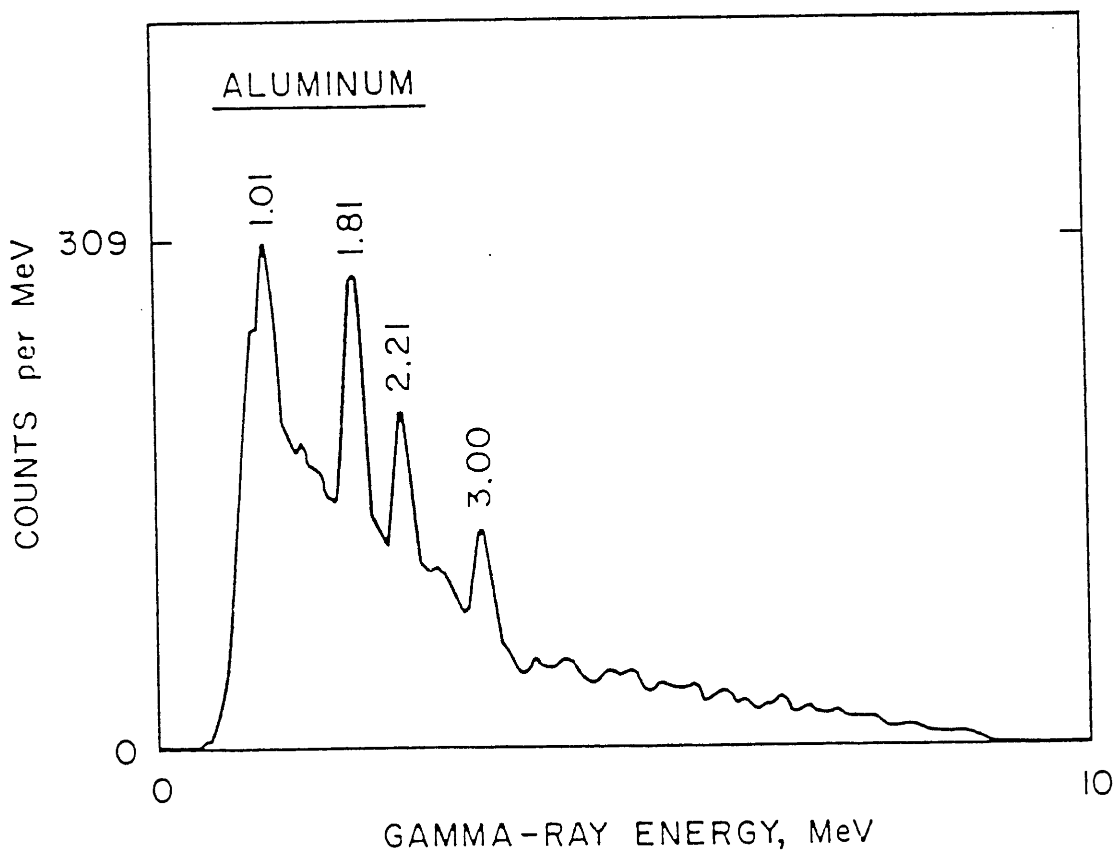

ALUMINUM
309
1.01
1.81
2.21
3.00
COUNTS per MeV
0
0
10
GAMMA-RAY ENERGY, MeV

Fig. 8

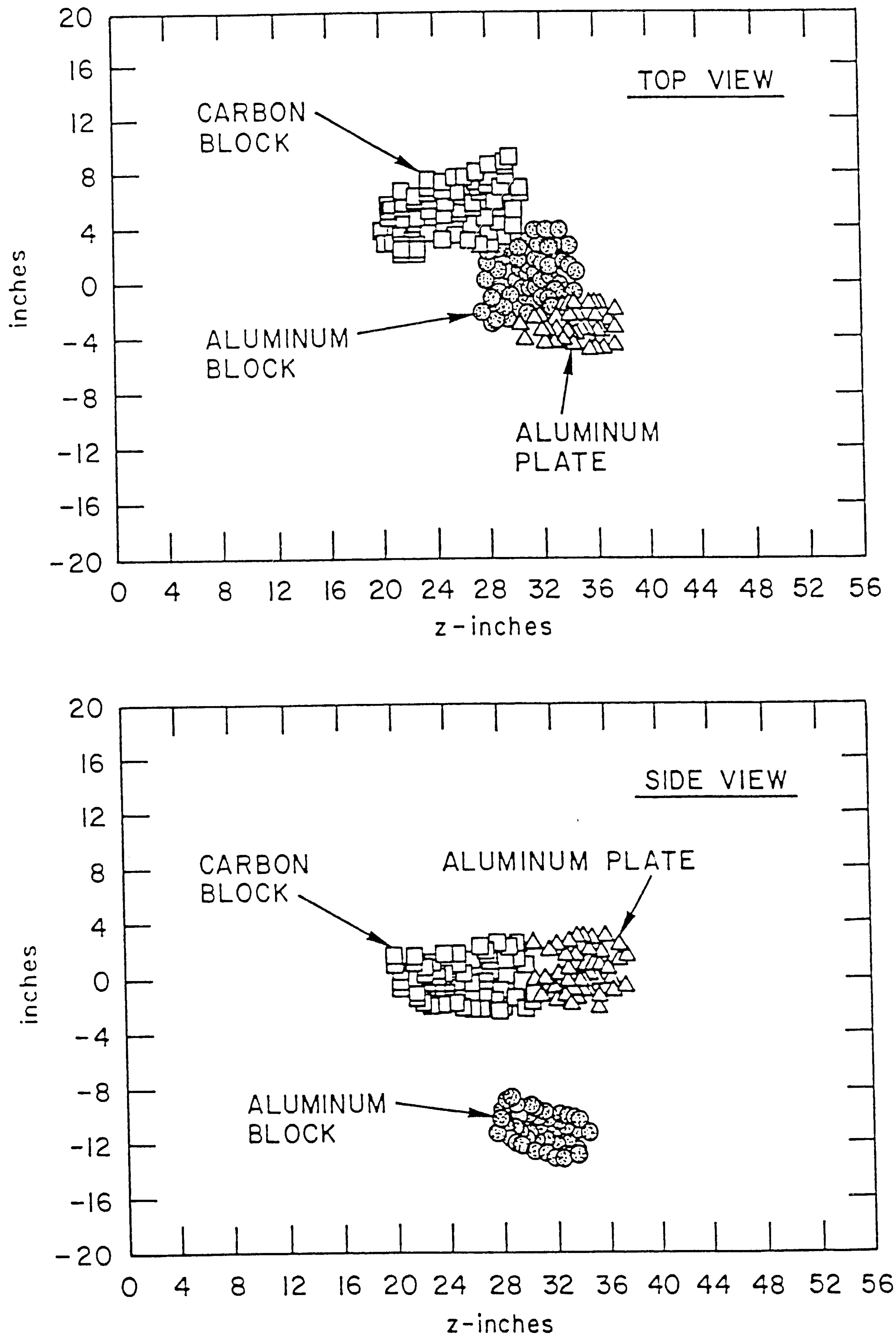

TOP VIEW
CARBON BLOCK
ALUMINUM BLOCK
ALUMINUM PLATE
inches
z-inches
20 16 12 8 4 0 -4 -8 -12 -16 -20
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56
SIDE VIEW
CARBON BLOCK
ALUMINUM PLATE
ALUMINUM BLOCK
inches
z-inches
20 16 12 8 4 0 -4 -8 -12 -16 -20
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56

Fig. 9

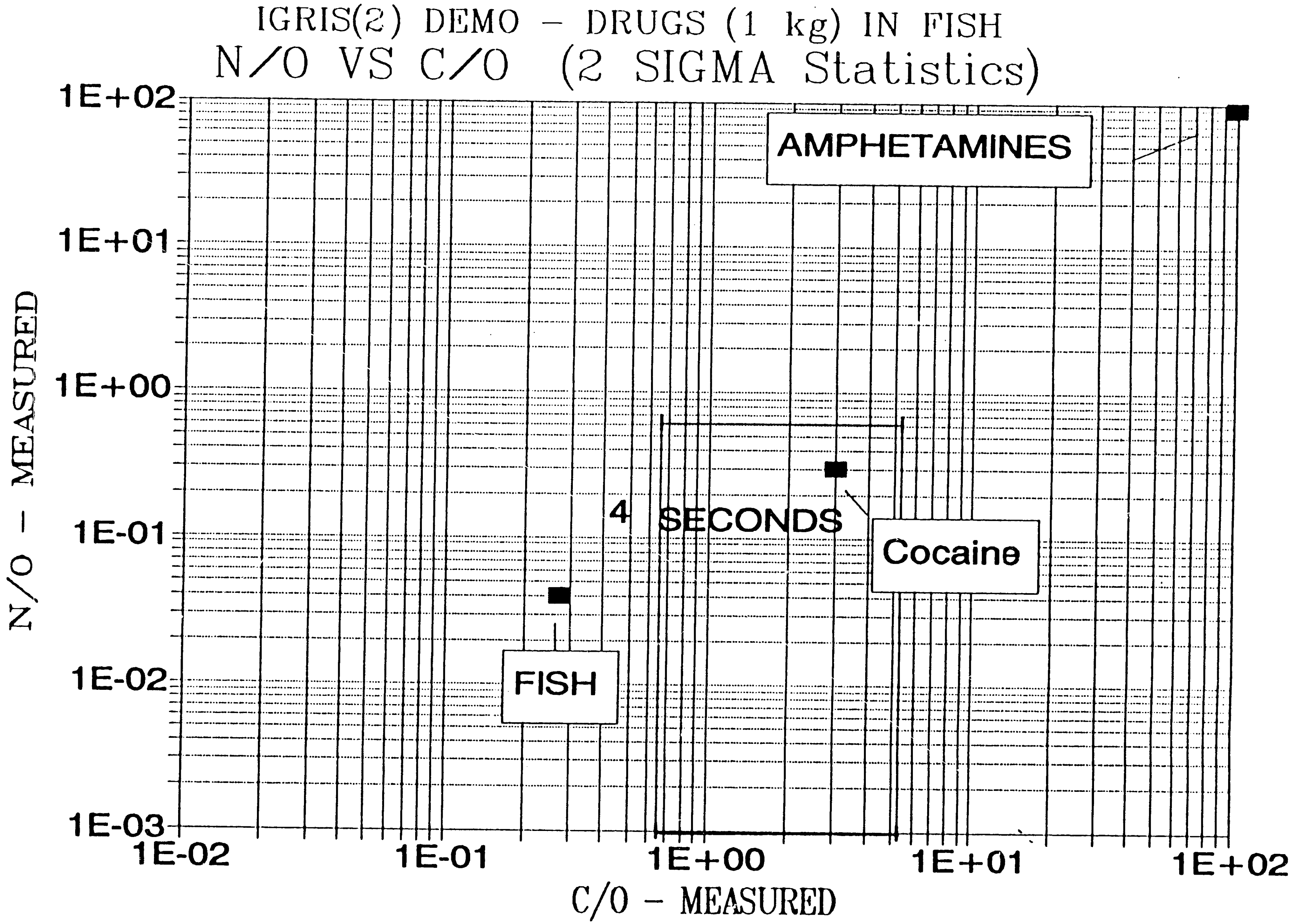
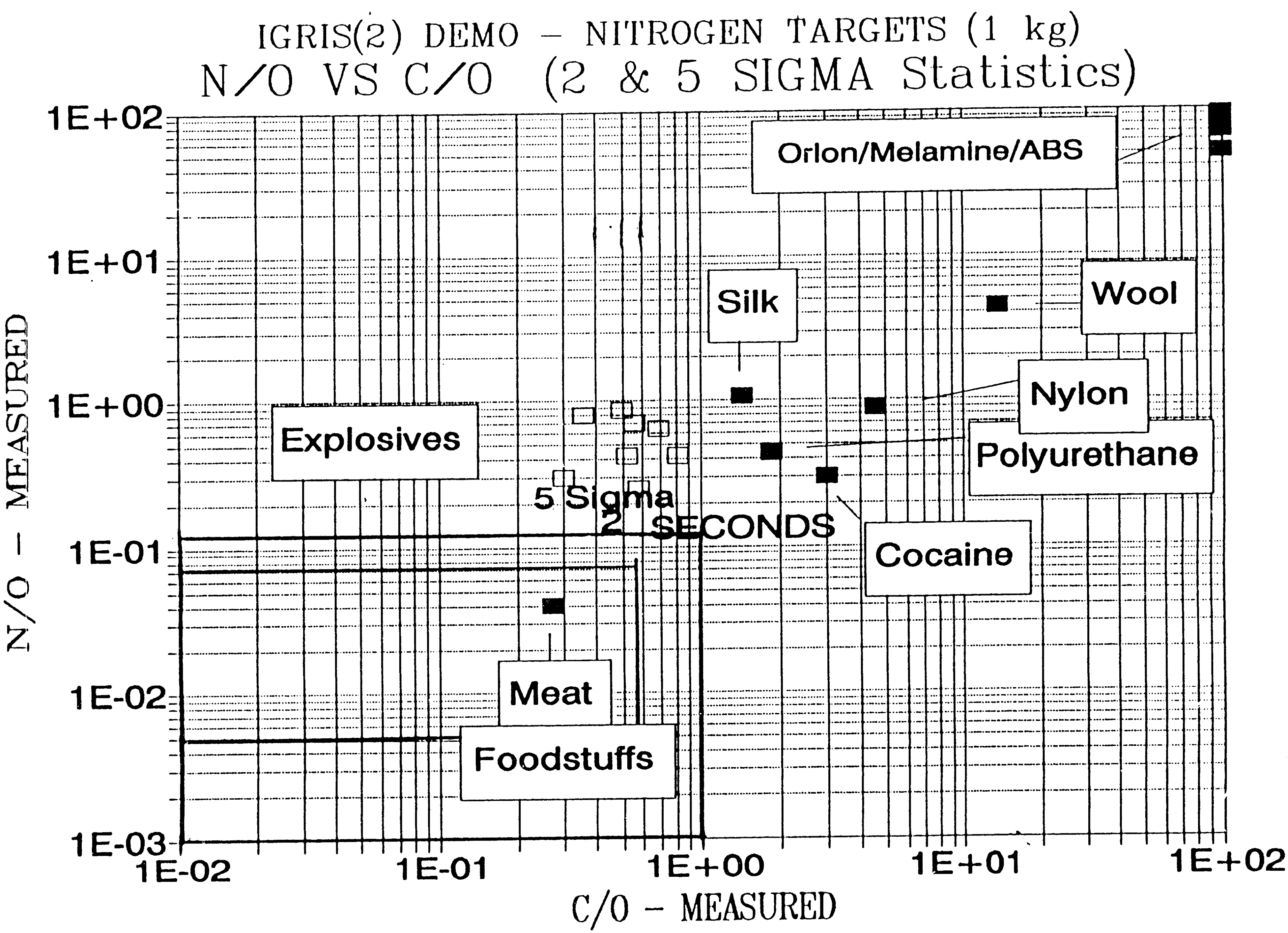
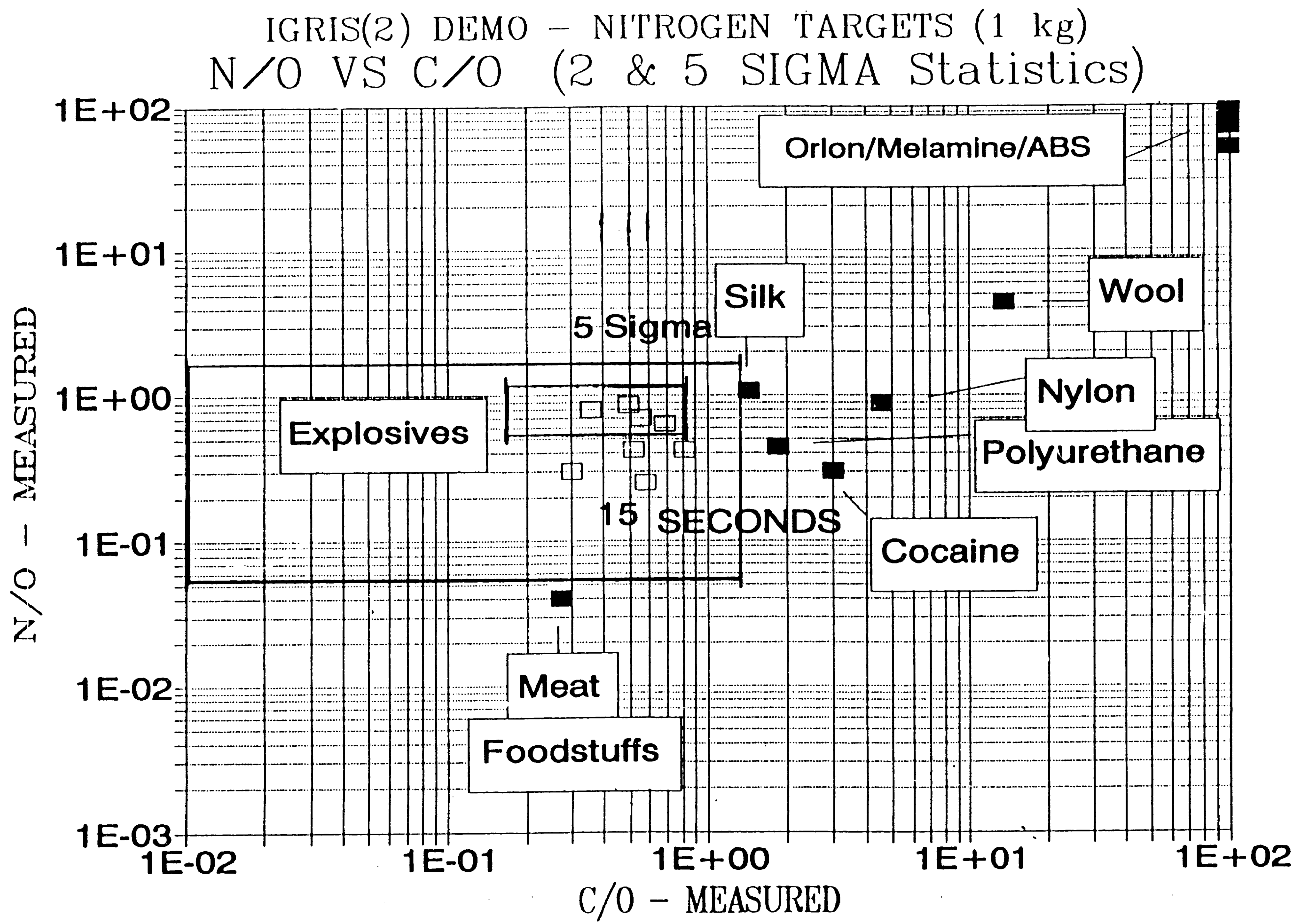

IGRIS(2) DEMO - DRUGS (1 kg) IN FISH
N/O VS C/O (2 SIGMA Statistics)
AMPHETAMINES
4 SECONDS
Cocaine
FISH
1E+02
1E+01
1E+00
1E-01
1E-02
1E-03
N/O - MEASURED
1E-02
1E-01
1E+00
1E+01
1E+02
C/O - MEASURED

Fig. 10



TARGET: 1 kg MEAT

Fig. 11



TARGET: 1 kg C-4

Fig. 12

END

DATE FILMED

01/27/92