DETECTION OF HIDDEN EXPLOSIVES AND DRUGS
(Advanced Mass-Spectrometry Methods)

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INTRODUCTION

An initial collaborative effort among RF MINATOM, the Kurchatov Institute, and Argonne National Laboratory (ANL) culminated in the First International Symposium On Nuclear Physics Methods For Detection Of Smuggled Explosives & Nuclear Materials, held in Obninsk, Kaluga Region, Russia, April 8-11, 1996.

The Symposium assessed

- the need to optimize both policy and technical means in the detection (prevention of smuggling and unauthorized use) of chemical explosives and nuclear materials (the "second line of defense"), starting with the development of requirements;

- R&D now being performed in this area, and the potential of many organizations to implement this R&D effectively, using methods and technologies of nuclear physics in detection of explosives and special nuclear materials;

- opportunities to organize an international collaborative project to compile and assess the scientific methods for detecting explosives and nuclear materials;

- opportunities to organize an international pilot project, to be performed jointly by the relevant RF and US institutions, on the detection and removal of unexploded ordnance at a few selected commercial development sites in Russia.

In the course of follow-up discussions, it was suggested that the requirements for advanced detection technologies shall be developed based on:

- qualification and quantification of threats presented to various agencies;

- assessment of "threat reduction versus detection performance;"

- comparative analysis of the ability of off-the-shelf technologies to meet the detection requirements above and the corresponding threat reduction;

- assessment of probable detection performance of advanced technologies that may be developed in the future, as a function of cost;

- assessment of probable threat reduction as a function of cost (investment in the "second line of defense").

It was also suggested that the next steps in developing fast neutron alternative technologies and optimal synergistic detection systems for the "second line of defense" shall include the following:

- an experimental synergistic system that may combine any of the following -- metal detector, vapor detector, neutron-generator, neutron-passive system, or X-ray generator;

- testing of that system under various Russian/FSU conditions;

- testing of that system under various US conditions;

- several conceptual designs tailored to the needs of different agencies under different conditions.

The technical discussion presented in this paper is a part of the effort above, and includes (1) general assessment of detection applications of neutronic techniques, (2) the Argonne inelastic scattering approach, (3) the Kurchatov elastic-scattering approach, and (4) benefits of combining the Argonne and Kurchatov approaches.

APPLICATIONS OF NEUTRONIC TECHNIQUES

Detecting hidden storage of explosion devices and explosives is a complicated problem, particularly, in view of the development of plastic casings and plastic explosives. The most promising methods for solving this problem are, in our opinion, nuclear physics methods. However the current methods using nuclear radiation, including the widely used neutron-activation method, cannot be considered as fully meeting the requirements for the detection of concealed explosives -- both in regard to their expressiveness and sensitivity and, particularly, in regard to their reliability.

Neutrons can penetrate deeply into luggage and cargo, and neutrons are able to produce telltale interactions with the chemicals in explosives. Neutrons are thus unique as a tool for interrogation of objects; neither x-rays, gamma-rays, nor electromagnetic sources have these fundamental advantages for definitive characterization of explosives. This is why neutronic techniques are being developed for application to detection of explosives, contraband, and other dangerous chemicals.

For inspection of cargo containers that cross international borders (including transport by ship), Khan[1] has carried out extensive reviews of neutronic systems. Container-inspection systems are relatively large installations, exemplified by the SAIC-developed pulsed-fast-neutron system.[2]

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Various neutron scattering (inelastic and elastic) and transmission techniques are valuable for contraband detection in checked luggage. Since several types of interactions invariably take place when neutrons are targeted on an object, these interactions can be used for simultaneous, synergistic detection of contraband.

Active neutron-generating techniques alone have the capability of detecting all categories of illicit substances. Some active techniques that use pulsed fast neutrons can distinguish between explosives and other contraband.

Neutronic interrogation can also be sensitive to nuclear materials.[3] Neutronic methods, especially operated simultaneously with other techniques, such as x-ray imaging, are powerful approaches to universal detection of illicit materials in luggage.

There are several possibilities for synergistic operation of detection systems. A system that detects multiple types of contraband offers better security value and cost-effectiveness. Inasmuch as active neutron probes have limited spatial resolution, concurrent x-ray imaging would augment the identification of objects.

While active interrogation could induce a very small amount of residual radioactivity, short bursts of fast neutrons coupled with high detection efficiency would minimize any residual effects and bring them to acceptable levels. Thermalized neutron sources cause a greater proportion of radiation activation. Reduction of radiation exposure to operators and objects will come about by more complete utilization of the neutrons produced in the source; this means simultaneous detection of fast neutrons and gammas.

The two methods described in this paper have in common a special low-intensity continuous source of fast neutrons; both systems can be combined to optimize respective strengths. One of the methods, the APSTNG, relies on inelastic neutron scattering to produce telltale gamma rays in the object. The other method is a novel approach to neutron elastic scattering that produces mass-spectrometric data from the object.

KURCHATOV NEUTRON ELASTIC-SCATTERING METHOD

In this paper a new method conceived at Kurchatov for determination of flight element nuclear masses is proposed. The method is based on use of elastic scattering of fast monochromatic neutrons. It allows the spectrum of the nuclear masses of the elements of an object to be determined and produces a three-dimensional image of the object. The method can be used for detecting explosive, drugs, and other substances.

To find some mass M, it is necessary to know the scattered neutron energy E_i and scattering angle θ, with the energy E_o, of the scattered neutron known. In accordance with the laws of the elastic scattering of this neutron by a nucleus of mass M we have:

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$$M = 2\frac{\left[1 - (E_i / E_o)^{1/2} \cos\theta\right]}{(1 - E_i / E_o)} - 1$$

In the proposed method, neutrons of the (d,T) reaction

$$^2H + {}^3H = {}^4He + n + 17.5895 \ MeV$$
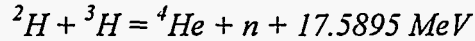
will be used as monochromatic fast neutrons with an alpha-particle emerging in the opposite direction.

A diagram of the possible setup is shown in Figure 1. A principle new feature of the setup proposed is the use of position-sensitive alpha detectors and position-sensitive detectors of fast neutrons, both having high spatial and temporal resolutions.

These detectors are used to determine the birth point and the vector along which the neutron emerging from the thin flat layer of the titanium-tritium target is moving. They are also used to determine the time-of-neutron-flight to a position-sensitive neutron scattering detector D_{n1} and the time-of-neutron-flight to a position-sensitive neutron detector D_{n2}. These data are sufficient to determine the scattered neutron energy E_i and the scattering angle θ, as well as the coordinates of the point where the scattering occurred.

One of many paths traversed by the neutron from the instant of its emergence from the target to the moment of its recording is shown in Figure 1. The point of the neutron's emergence from the target and the direction of the neutron flight are determined by a system consisting of two semiconducting position-sensitive alpha-detectors - $D_{\alpha 1}$ and $D_{\alpha 2}$. One detector is of the time-of-flight through-type ($D_{\alpha 1}$). The detectors are set at distances l_1 and l_2 from the target, respectively.

The position-sensitive alpha detector of the flight-through type ($PSD_{\alpha 1}$) represents a matrix of solid silicon transistors set on a thin (5-7 μm) silicon membrane. The $PSD_{\alpha 1}$ is described in more detail in another paper to be presented at this conference.[4] The other alpha detector-- $D_{\alpha 2}(PSD_{\alpha 2})$ -- is more easily realized.

The position-sensitive fast neutron detectors (PSD_n) are made of organic optofibers laid in single layers, with the fibers oriented at right angles to each other. The PSD_n principle of operation is based on recording scintillations from recoil protons in two adjacent fibers lying in different layers. The spatial resolution of the detector is equal to two diameters of the scintillating filaments (~1 mm). More detailed information about the PSD_n is given in another paper to be presented at this conference.[5]

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Figures 2 and 3 show the results of the numerical Monte Carlo experiment assigned to detect trinitrotoluene and azidodinitroinethyl samples, each with mass 200 g, and covered with 1 cm iron. Figure 4 gives results for a 200 g acrylic plastic sample. In the calculations, the following data were used: $l_1 = 25$ cm and $l_2 = 50$ cm; resolutions $\Delta x = \Delta y = 0.5$ mm and $\Delta x = \Delta y = 1$ mm for detectors D_{a1} and D_{a2}, respectively; spatial resolution in the measurements of the coordinates by the fast neutron detectors $\Delta x = \Delta y = \Delta z = 1$ mm, accuracy of time measurement: 0.1 ns; volumes of detectors D_{n1} and $D_{n2} \sim 0.2$ m^3; the differential scattering cross sections were taken from the literature[6,7]. The analysis of these calculations shows that the presence of 200 g or more of explosives enclosed in a 1-2 cm thick iron container can be reliably determined in 10 seconds. However, in addition to the explosives, the integral mass spectrum of all objects may be registered, and, therefore the direct identification may be somewhat difficult. The method proposed permits one to solve this problem by allowing a longer time for the accumulation of better statistics.

In the measurement of the explosive mass spectrum, the background associated with neutrons scattered by objects outside the container will appear. It should be pointed out that the background will not have any clearly expressed dependence on the nuclear masses. Therefore the spectrum we are interested in will be on a smoothly changing pedestal. The size of this pedestal depends on the field of neutrons with energies above the registration threshold (~0.3 MeV). The calculations of this field were carried out for the case of a neutron source and the setup in the center of an airless sphere with a radius of 150 cm. Taking into account that each neutron released in the direction towards the container is followed by the position-sensitive detectors -- D_{a1}, D_{a2}, D_{n1}, D_{n2} -- in space and time from the point of emerging from the target to the point of the registration in detector D_{n2}, a time gate is provided for the registration of the actual events, whose duration will be much shorter than the average time between neutrons emerging towards the container. All these circumstances lead to a rather low background, expected to be about 1%.

ARGONNE NEUTRON INELASTIC-SCATTERING METHOD

The Associated-Particle Sealed-Tube Neutron Generator (APSTNG) has been developed through several generations of improvements in reliability and lifetime.[8,9] It is a type of accelerator neutron source that makes a useful compromise between fieldability, cost, and utility. Figure 5 contains a block diagram of the primary components.

The APSTNG is not yet available off-the-shelf. Based primarily on associated-particle time-of-flight measurements, the inelastic neutron scattering technique provides 3-dimensional mapping of chemical components in objects with the size typical of luggage or shipping packages. Figure 6 is a photograph of a new generator tube and power supply manufactured for Argonne by MF Physics.

Inelastic scattering cross-sections are reasonably high and uniform for all chemical elements with atomic numbers above that of boron. Also, the 14-MeV source neutrons and the reaction-product radiation are highly penetrating. The inelastic-scattering approach is effective in sorting the characteristic elements from background, delivering information on ratios of chemical constituents. These chemical ratios are definitive in identifying explosives and other contraband. Since fission and radiative capture are also detectable, the associated-particle technique offers sensitivity and versatility to the full range of potential smuggled goods.

Examples of calculated data confirmed with measurements are provided in Figs. 7 and 8[10]. Figure 7 shows how chemical explosives can be distinguished from common substances found in luggage and air cargo. The ratios of C, O, and N -- detected by inelastic scattering of neutrons -- are definitive and sufficient for identifying explosives, despite a background of other materials[11]. Figure 8 demonstrates the ability to analyze the same accumulated data to distinguish illicit drugs from accompanying materials in luggage.

While the technical capabilities of the inelastic-scattering method have been established, further demonstrations and improvements are being sought for installation at airports. Merging this system, which has a capability for coarse three-dimensional imaging, with a high-resolution x-ray system would be a logical next step.

CONCLUSION

In order to optimize detection capability and cost-benefit, comparative modeling needs to be carried out for the two neutronic approaches and their combination. This should result in an optimal arrangement of neutron and gamma detectors to make maximum use of each neutron produced in the common accelerator source. By gaining the most information possible from each neutron, the required source intensity -- and thus the potential for radiation fields -- would be diminished. Also, experimental work, which has begun on testing of a synergistic system, should be expanded.

The specific features of the analytical methods proposed are the following:

- Expressiveness;
- Contactlessness;
- Non-destructive evaluation of the object investigated;
- Versatility (all elements from hydrogen to fluorine are determined with equal efficiency).
- Possibility of analyzing an object in any physical and chemical state;
- Possibility of analyzing an object in a closed container or screened and obtaining its three-dimensional image;
- Insensitivity to the radioactive radiation background;
- High reliability of the analytical results.

The methods proposed surpass all known methods of explosive detection and possess an enormous potential for application in many fields of science and for practical purposes.
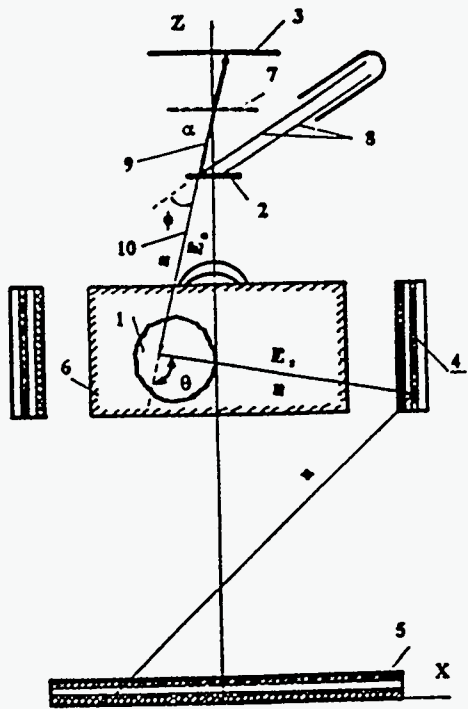
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11. E. Rhodes, C. E. Dickerman, T. Brunner, A. Hess and S. Tylinski, "APSTING: Associated Particle Sealed-Tube Neutron Generator Studies for Arms Control, Final Report on NN-20 Project ST 220", Argonne National Laboratory report ANL/ACTV-95/1 (December 1994).

LISTS OF FIGURES

Fig.1. Block diagram of a neutron double elastic-scattering method alternative

1 - sought object; 2 - target; 3 - second detector of α-particles; 4 - first neutron detector; 5 - second neutron detector; 6 - suitcase; 7 - first detector of α-particles; 8 - deuteron beam; 9 - α-particle path; 10 - neutron trajectory

TNT: $C_6H_2(NO_2)_3CH_3$
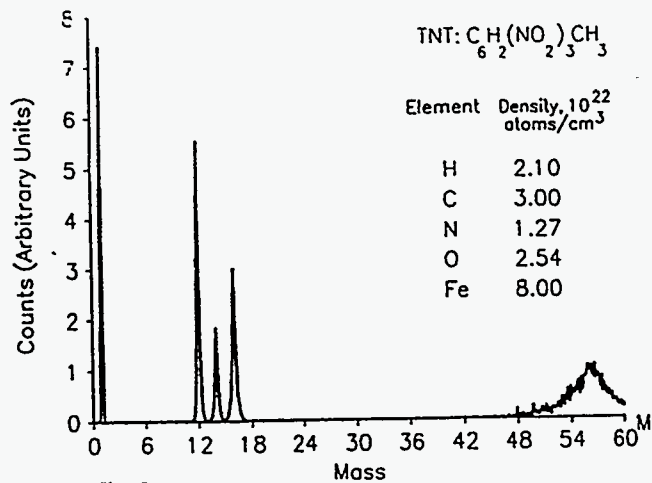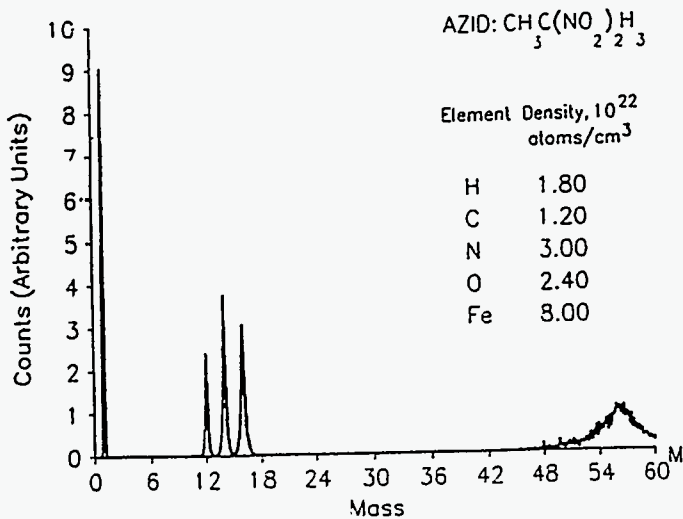
Element	Density, 10^{22} atoms/cm³
H	2.10
C	3.00
N	1.27
O	2.54
Fe	8.00

Fig. 2

AZID: $CH_3C(NO_2)_2H_3$

Element	Density, 10^{22} atoms/cm³
H	1.80
C	1.20
N	3.00
O	2.40
Fe	8.00

Fig. 3

PMMA: $(C_5H_8O_2)_n$

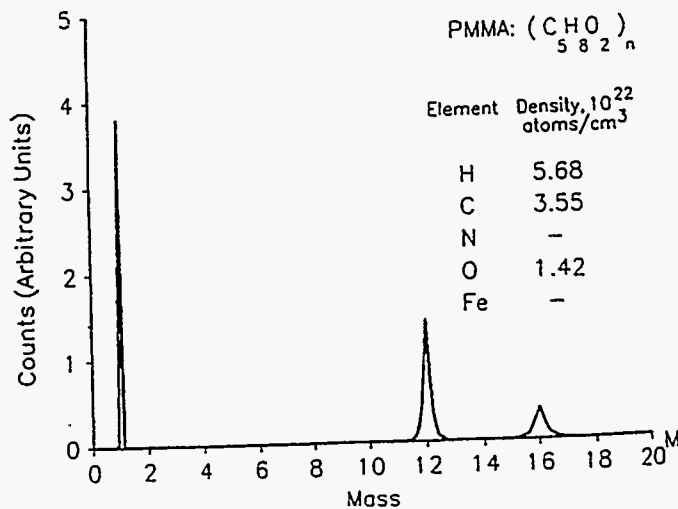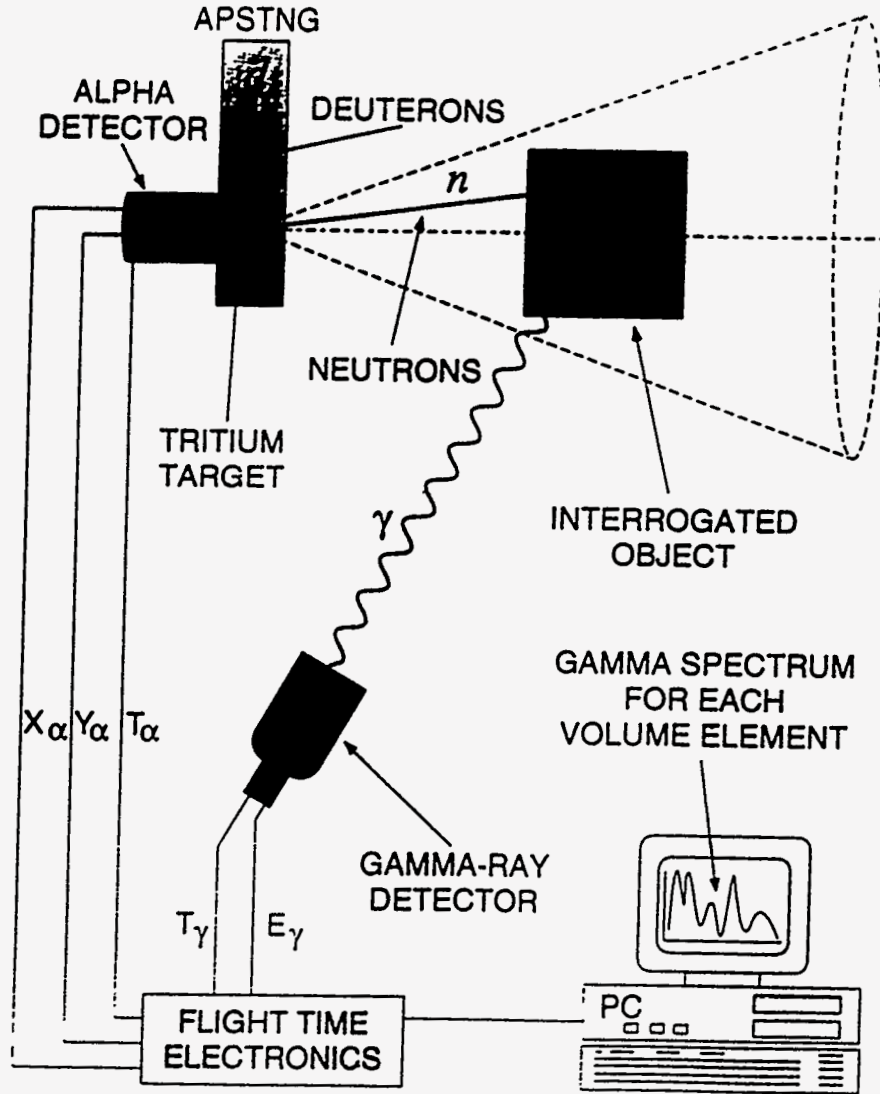| Element	Density, 10^{22} atoms/cm³
H	5.68
C	3.55
N	—
O	1.42
Fe	—

Fig. 4

5

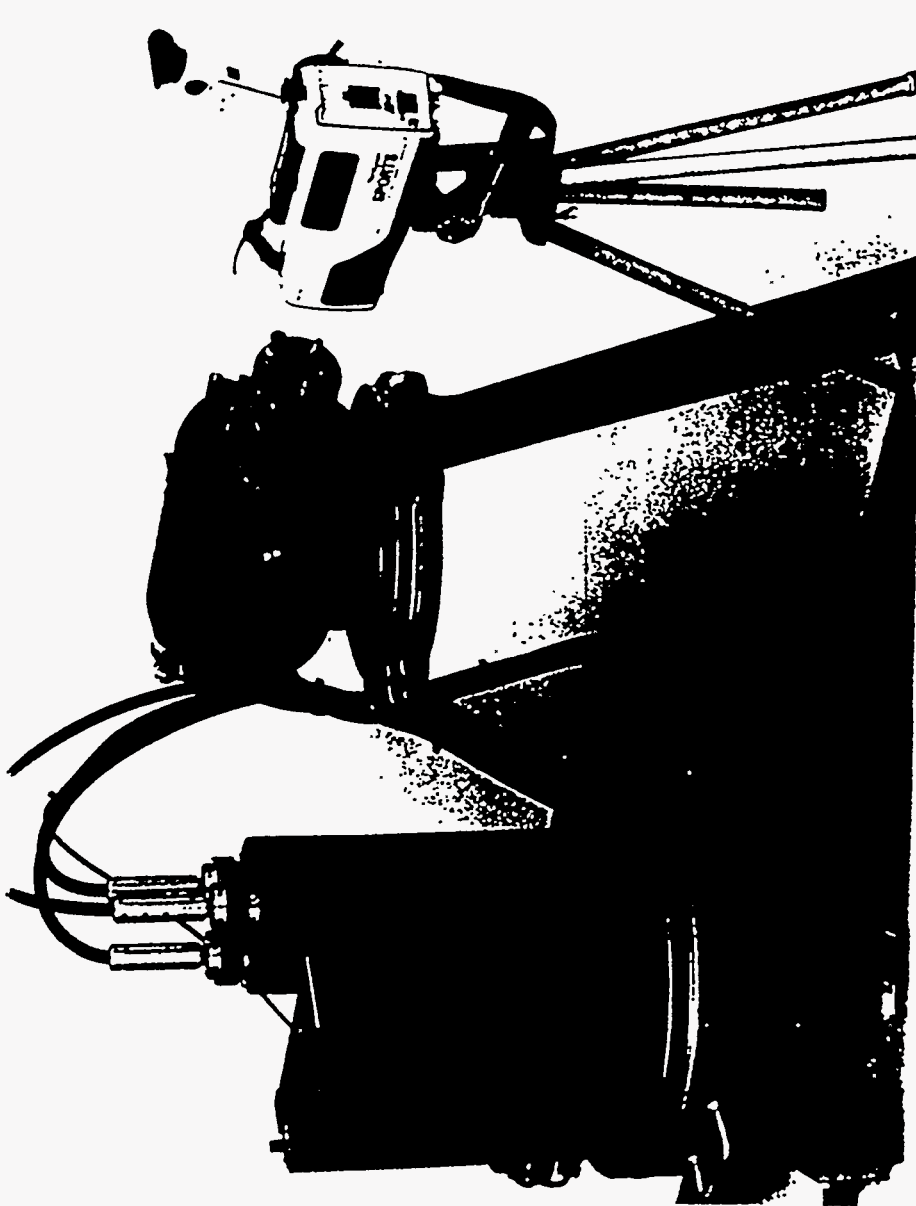# APSTNG SYSTEM OPERATION

Fig. 5.   Block diagram for the primary APSTNG components
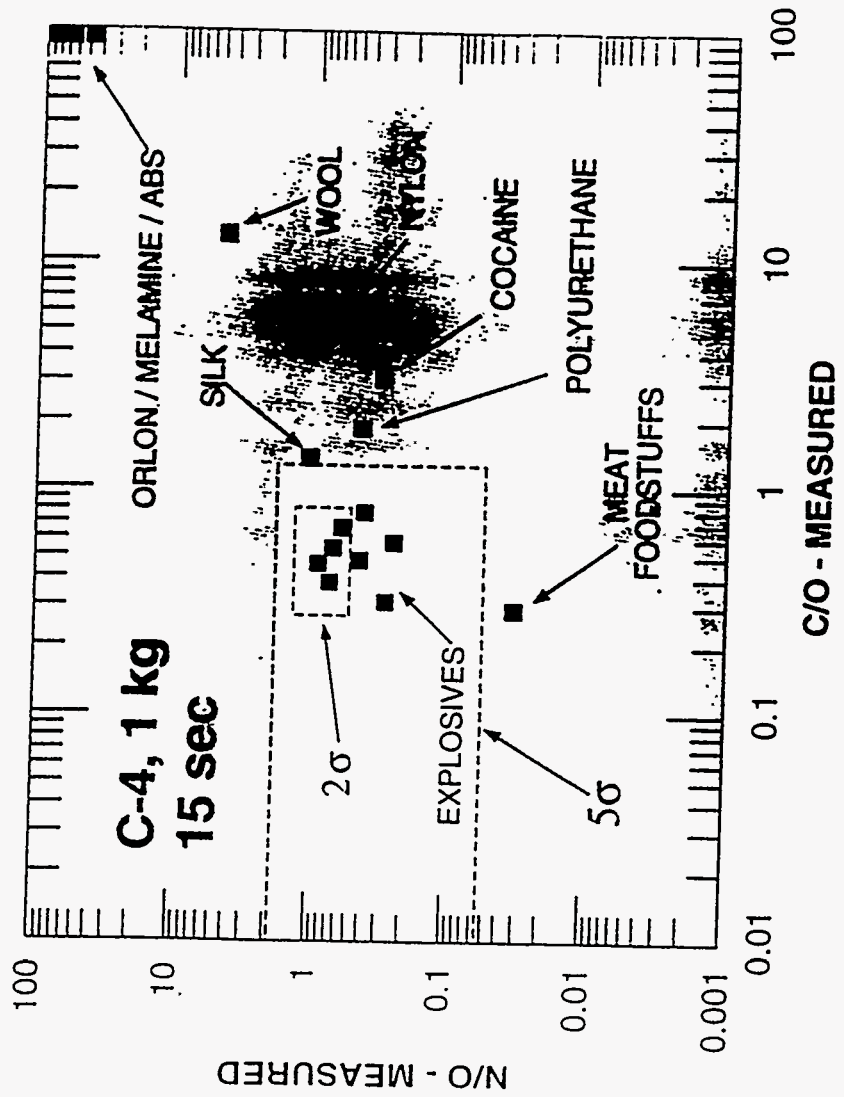
Fig. 6. New APSTNG generator tube and power supply.

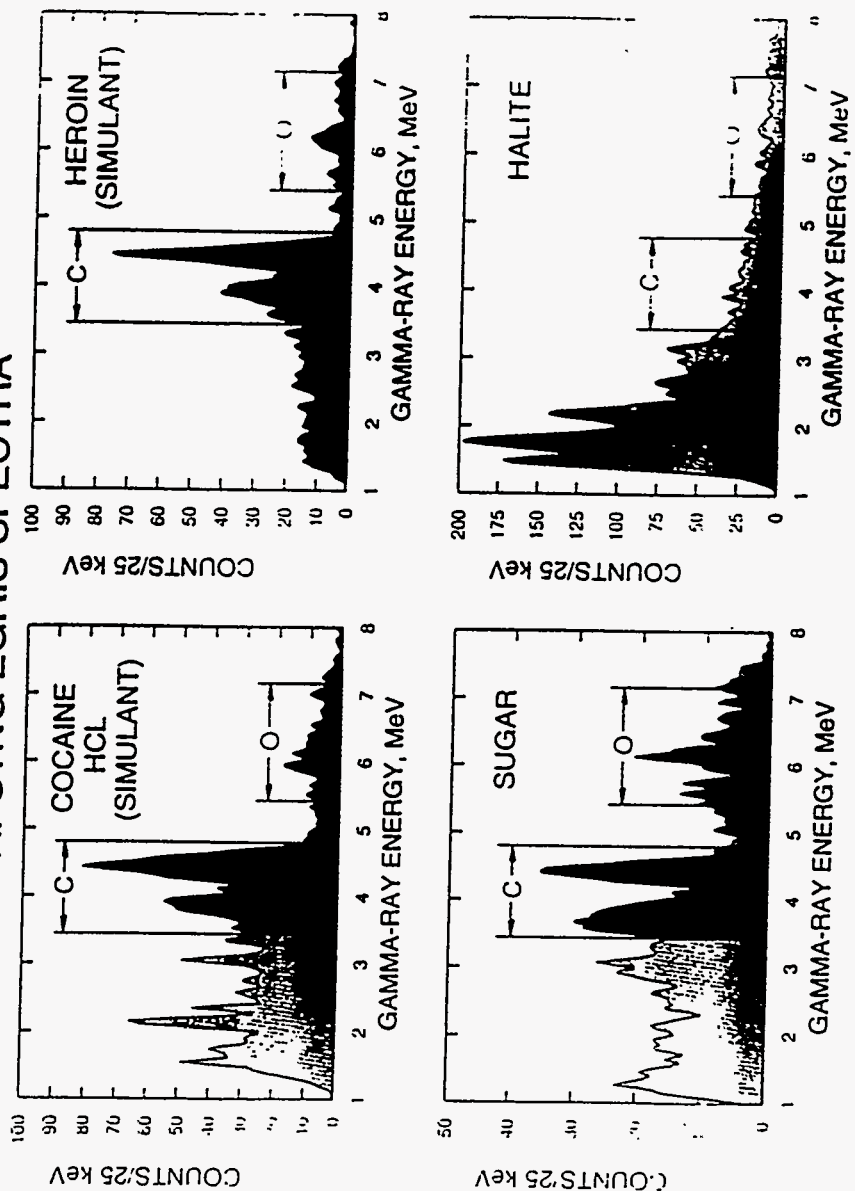Fig. 7. Example 2 of calculated data for APSTNG explosives.

Fig. 8. Example 2 of calculated data for APSTNG drug detection.