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A NEW PROOF-OF-PRINCIPLE CONTRABAND DETECTION SYSTEM *

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ABSTRACT

A new concept for a Contraband Detection System (CDS) has been developed under a Phase I ARPA funded program. Our approach employs the phenomenon of gamma resonance absorption (GRA) to detect certain forms of illegal drugs that may be transported in man-portable containers. We have found that a high detection probability for heroin and cocaine is possible with a device that is simultaneously searching for explosives. We apply the elemental detection of both nitrogen and chlorine, and with the tomographic technique, a 3D density image of the selected elements is generated. In addition, the total density image is developed. These characteristics together may be utilized with considerable confidence in determining if heroin or cocaine is present in the interrogated containers in a relatively small quantity (approx. 1kg).

The CDS employs a high current (≥ 10 mA) DC accelerator that provides a beam of protons at selected energies of either 1.75 or 1.89 MeV. These high energy particles impact upon a target that employs coatings of ^{13}C and ^{34}S. Depending upon which coating and energy are selected, the resultant resonant gamma rays that are produced are preferentially absorbed in either ^{14}N or ^{35}Cl. The resonant gammas come off the target in a conical fan at 80.7 degrees for nitrogen and 82 degrees for chlorine. Since these angles are so close, a common array of segmented BGO detectors is utilized over an arc of 53 degrees to provide input to an imaging subsystem. The tomographic imaging approach makes use of rotation and vertical translation of a baggage carousel holding typically 18 average sized bags for batch processing of the contents. The single proton accelerator and target can supply multiple detection stations with the appropriate gammas, a feature that may lead to very high throughput potential approaching 2000 bags/hr. Each detection station can operate somewhat independently from the others thereby enhancing flexibility.

Our current Phase II contract calls for the construction and testing of a proof-of-principle CDS by late 1996. This paper presents the overall requirements, design, operating principles, and characteristics of the CDS proof-of-principle (POP) device developed in the Phase I program.

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1. Introduction

The ease of transportation of contraband such as high explosives and illegal drugs is a serious national problem that has been steadily on the increase. Further, the ability to conceal these types of materials in man-portable containers such as suitcases, briefcases, and mail pouches raises additional concerns. Explosives constitute an obvious danger particularly in the cases where mass transit and the postal service are involved. The ease of drug transportation, has contributed to the massive illegal drug trade by providing nearly unlimited distribution. To reduce these threats, a capability to determine the presence of these types of contraband in luggage, mail, and other man-portable containers generally associated with air, rail, and bus transport must be developed. Techniques exploiting the presence of nuclear resonances in specific materials of interest have received recent attention, among them is the GRA technique. The interrogation of man-portable containers through the GRA process has been found from previous work [1] [2] [3] to be a potential candidate for determining the presence of explosives. As a result of the work in this project, we have further developed the GRA approach into a system design that offers the potential for detecting a significant portion of illegal drugs.

This paper describes some of the aspects of a CDS device that was developed during a 5 1/2 month Phase I design and analysis program. The effort concentrated on establishing potential user requirements, developing CDS specifications based on those user requirements, defining a POP design using existing or near term technology, and planning a Phase II program that would carry out the construction and testing of the POP CDS device. This device will be able to examine the range of available parameter space for the GRA technique and to provide a sufficient technical data base to permit a solid conclusion on GRA utilization in the real world. Although the proposed CDS is expected to be capable of detecting both explosives and certain illegal drugs, we will discuss primarily its application to illegal drugs in this paper.

2. Technical Approach

In addition to searching the literature, representatives of various agencies concerned with contraband detection were personally contacted to determine what recent or unpublished agency requirements were available [4] [5] [6] [7] [8] [9]. The accumulated information was used to specify various missions to be addressed by a CDS. It was found that each mission has different requirements for contraband detection sensitivity and man-portable container throughput. The key results of this effort with regard to illegal drugs are summarized in Table 1.

There are two primary characteristics that might be used to identify illegal drugs among common materials using GRA. They are material total density, and individual selected element density. When mapped on a two dimensional domain, most illegal drugs of interest were found to occupy a localized region in the nitrogen density vs. total density domain in which most common materials were excluded (Figure 1a). Some forms of illegal drugs which contain a significant density of chlorine can also be segregated from common materials (Figure 1b). In contrast, there are very few common materials that might be shipped that contain significant amounts of chlorine. Since marijuana does not contain any appreciable amount of nitrogen or chlorine, it has been excluded from our list of detectable substances for now.

At the beginning of the study, a method for defining figure of merit in general for gamma resonance reactions was developed. This method included such effects as reaction cross section, resonance line width, gamma ray energy spread, and other parameters that affect the usefulness for imaging by tomography. Most resonant reactions were disqualified based upon their low figure of merit when compared to the most obvious and best resonance reaction, $^{13}C(p,\gamma)^{14}N$, for detection of nitrogen. The figure of merit for this reaction was normalized to 1000. Two resonance reactions for chlorine detection ($^{34}S(p,\gamma)^{35}Cl$) that occur at proton beam energies of 1.89 MeV and 2.79 MeV, have FOMs of 35 and 70 respectively. Although resonance reactions for other elements, such as oxygen and carbon exist, they were eliminated at this time due to their very low figure of merit. This is not to say that these other elements may not be reconsidered at a later date.

Camouflage techniques which include hiding contraband among other materials led to the conclusion that a tomographic imaging approach should be used as a countermeasure. The literature was searched for

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methods to produce resonant gamma rays in a form that can be used in tomography. Since no system of this type exists today, we developed an original concept that uses the Doppler-shifted gamma rays from the resonance reaction in the same way that X-rays are used in medical CAT scanning. By rotating and elevating a carousel full of baggage, the attenuation factor of the gamma rays are recorded at all positions and angles. A 3D image of resonant and normal gamma rays' attenuation factor per unit volume are recorded in the memory of a computer. The container handling subsystem and image reconstruction and interpretation subsystem were designed with this concept in mind.

Methods to produce up to 3 MeV protons were investigated. After performing extensive simulations to obtain the beam current and beam energy spread requirements for high resolution tomography, many techniques (e.g., RFQ and cyclotron) were eliminated. The only viable technique for proton acceleration was an electrostatic accelerator. The beam energy and beam current requirements led to the selection of a tandem accelerator with a vapor stripper system in the high voltage terminal. Since there is no tandem electrostatic accelerator that is presently capable of producing the required beam current and energy simultaneously, we selected the lower energy chlorine resonant reaction to minimize the near term risk of accelerator development. If the POP shows the chlorine reaction is viable, then work toward the higher proton beam energy would improve CDS performance by a factor of 2 for chlorine detection.

Previous experience with target design indicated that the target was a critical and high-risk element of the system. The target materials and the thickness of the various layers were designed to minimize background signal; however, the lifetime of the resulting target coating under constant bombardment by protons was unknown. A rotating target design was selected to maximize lifetime by providing a large area for irradiation to minimize thermal effects. In addition, we conducted an experiment using the pulsed beamline facility at Northrop Grumman to study the target behavior under proposed operating conditions. The experiment was designed to irradiate a target coupon and produce thermal stresses and sputtering effects similar to that calculated for the production target under operating conditions. This experiment showed that with the right combination of substrate material and cooling configuration the coating could withstand the rigorous environment of proton bombardment.

3. CDS Requirements

The counter-drug mission is directed to the seizure of quantities of high value illegal drugs such as cocaine and heroin brought into the country in man-portable containers. The counter-drug mission differs significantly from explosives detection in that the volumes of contraband involved are usually larger when compared to high explosives, minimizing the need for high resolution. The larger volume of contraband associated with drug trafficking permits integration of the 3D scan information over larger slices, thereby enhancing the signal to noise and allowing detection of the relatively low nitrogen densities.

Cocaine and heroin can occur in hydrochloride forms as well, although the exact chlorine content can vary. A CDS device designed to detect both nitrogen and chlorine is a plus for this mission scenario. While nitrogen density measurements must be done to identify the appropriate nitrogen-to-total density ratio, the mere presence of chlorine can signify suspicious baggage.

The key requirements for the CDS device are presented in Table 2. To provide the capability for dual element detection, the energy of the accelerator must be variable. The proton current is a compromise between technical capability and production yield per proton. A higher gamma production yield requires higher currents; however, target lifetime under high heat loads is an issue for consideration. The accelerator required to produce 10 mA of proton current at 2 MeV can be built at reasonable cost using state-of-the-art technologies. A 10 mA proton beam is adequate for detection of nitrogen in high explosives; currents between 10-20 mA are required for the chlorine measurements because of the lower FOM. The discrimination between resonant and non-resonant gamma rays can be achieved by exploiting the fact that the resonant gammas are emitted at a specific angle. Therefore, the detection system is required to be position sensitive. This is accomplished using segmented BGO detectors much like, but improved over PET systems, which provide good spatial resolution and high detection efficiency. The use of tomography requires that the object that is interrogated be rotated and vertically translated through the gamma beam. A baggage carrousel can be sized for an optimum volume to maximize throughput and still maintain sufficient transmission of gamma rays for measurement.

4. Description of POP Device

A top level block diagram of the POP device is shown in Figure 2. There are four major subsystems; beam production, detector and data acquisition, image reconstruction and interpretation, and operational control and support.

The beam production subsystem consists of all of the equipment that is necessary to generate the gamma rays that are used for detection of contraband. This subsystem includes an ion injector, a tandem accelerator, a High Energy Beam Transport (HEBT), and a target. With this subsystem a proton beam is generated and accelerated to a precise energy. The proton beam is then projected onto a suitable target material (^{13}C, or ^{34}S) where a reaction takes place to generate the required gamma rays. The resonant gamma rays are emitted in a conical fan shaped pattern around the beam spot as illustrated in Figure 3.

The detector and data acquisition subsystem consists of segmented BGO block detectors (also shown in Figure 3) and the associated electronics which are used for amplitude and position determination of the detected gamma rays. The block detectors are combined into a double decked arc subtending about 53 degrees.

The image reconstruction and interpretation subsystem includes the computer hardware and software necessary to store and process the data from the detector subsystem. In addition, this subsystem contains the algorithms that perform image reconstruction and decision analysis on whether or not contraband has been located.

The operational control and support subsystem provides overall control of the CDS, container handling of test or suspect baggage, power supply and distribution, and equipment/personnel safety and hazard control.

The design of the POP device stresses experimental flexibility at minimum cost. For example, a fieldable CDS should be capable of dual element detection; however, for the POP it is not necessary to provide the automatic controls and complex targets that will be required. Instead we will permit machine down time for manual conversion of a simple target for single element detection and for minor accelerator adjustments. Furthermore, we will reduce the cost of the demonstrator device by mitigating radiation hazards with exclusion distances where possible to reduce the cost of providing shielding.

The side elevation and plan view of the CDS POP device are shown in Figures 4(a) and 4(b) respectively. The centerline of the tandem accelerator is 108 inches above the floor. This configuration provides adequate length in the HEBT section which must be bent at an angle of 80.7 degrees for proper position of the proton beam with the target surface to result in a horizontal gamma ray fan at the area of container inspection. Another choice to have the accelerator at a lower level would require that the target, the detector and container handling equipment be at elevation. We selected the former based upon the feeling that most of the hands-on time with the POP device will be with the target, detectors and container handling. We have located all support equipment (power supplies, electronics, compressors, heat exchangers, etc.) below the CDS support structure and are providing a platform around the entire machine at a level to facilitate hands-on repairs and/or changes. A configuration such as this can be easily adapted for field testing since all functions are conducted on a single level (floor or ceiling penetrations are not required). It should be pointed out that a CDS of this type will not induce residual radioactivity in the scanned material, a feature that the users consider very important where food stuff and other personal belongings are involved.

5. Predicted Performance

The performance of the CDS has been predicted for explosives and for illegal drugs using either nitrogen detection or chlorine detection. The prediction is based upon extensive simulations of particle transport and nuclear interactions and an algorithm for analysis of 3D density image data. For a given set of conditions, the detection probability per object and the false alarm probability are shown in Figure 5 using nitrogen detection for an assumed sensitivity of 2 liters of cocaine (approx. 1820g). The scan time per slice is based upon 10 mA of proton current and an inspection carousel having a 56 inch diameter. Obviously the probability values will change depending upon the value of the proton current and the carousel diameter as well as numerous other parameters. For this set of conditions we can pick a detection probability of 90% which gives a scan time per slice of 1 second. The calculated throughput can be as high as 364 bags/hr for a single detection station assuming an 85% packing efficiency in a carousel 44 inches high. This estimate allows for loading and unloading of the carousel from its CT drive mechanism. Throughput can be increased linearly by increasing proton beam current on target. For example, a modest increase in proton current to 13 mA will provide a throughput of 473 bags/hr with the same detection probability or increased detection probability at the lower throughput value. If four detection stations are driven by a single proton accelerator and target subsystem, the throughput can be as high as 1892 bags/hr. The POP device will benchmark our models and facilitate accurate prediction of fieldable CDS performance.

6. Conclusion

The requirements for a GRA detection system have been reasonably defined from available user data and a design for the first full demonstration of the GRA principle at real operating parameters has been formulated. Although there are some areas of the device that have associated risk and still require development, the POP CDS should serve as a test bed for future enhancements.

7. References

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CHARACTERISTIC	VALUE	RATIONALE
Throughput (bags/hr)	$\geq$ 450	Taken from FAA *
Sensitivity (gm)	1200 (Heroin)	Average seizure (JFK airport)
	3300 (Cocaine)	Average seizure (JFK airport)
	5400 (Marijuana)	Average seizure (JFK airport)
Spatial Resolution (cm)	5	Typical package dimension
False Negative Rate (%)	$\leq$ 30	Goes on the street, does not slow throughput
False Positive Rate (%)	$\leq$ 10	Causes intrusive inspection, slows throughput

* Note: The value obtained from US Customs was >> 30 bags/hour

Table 1. Requirements for Counter Drug Mission CDS

CHARACTERISTIC	VALUE	
Element Detected	**Nitrogen**	**Chlorine**
Nuclear Reaction	$^{13}C(p,\gamma)^{14}N$	$^{34}S(p,\gamma)^{35}Cl$
Target Type	segmented surface	
Selectable Proton Beam Current (mA)	$\geq$10	10 - 20
Selectable Proton Beam Energy (MeV)	1.75	1.89
Proton Beam Energy Spread (keV)	25	12
Detector Field of View (degrees)	53	53
Detector Array Height (cm)	10	10
Detector Radius (m)	2.14	2.14
Position Resolution (mm)	5	5

Table 2. Specifications for the Principle Characteristics of the CDS Gamma Resonance Device

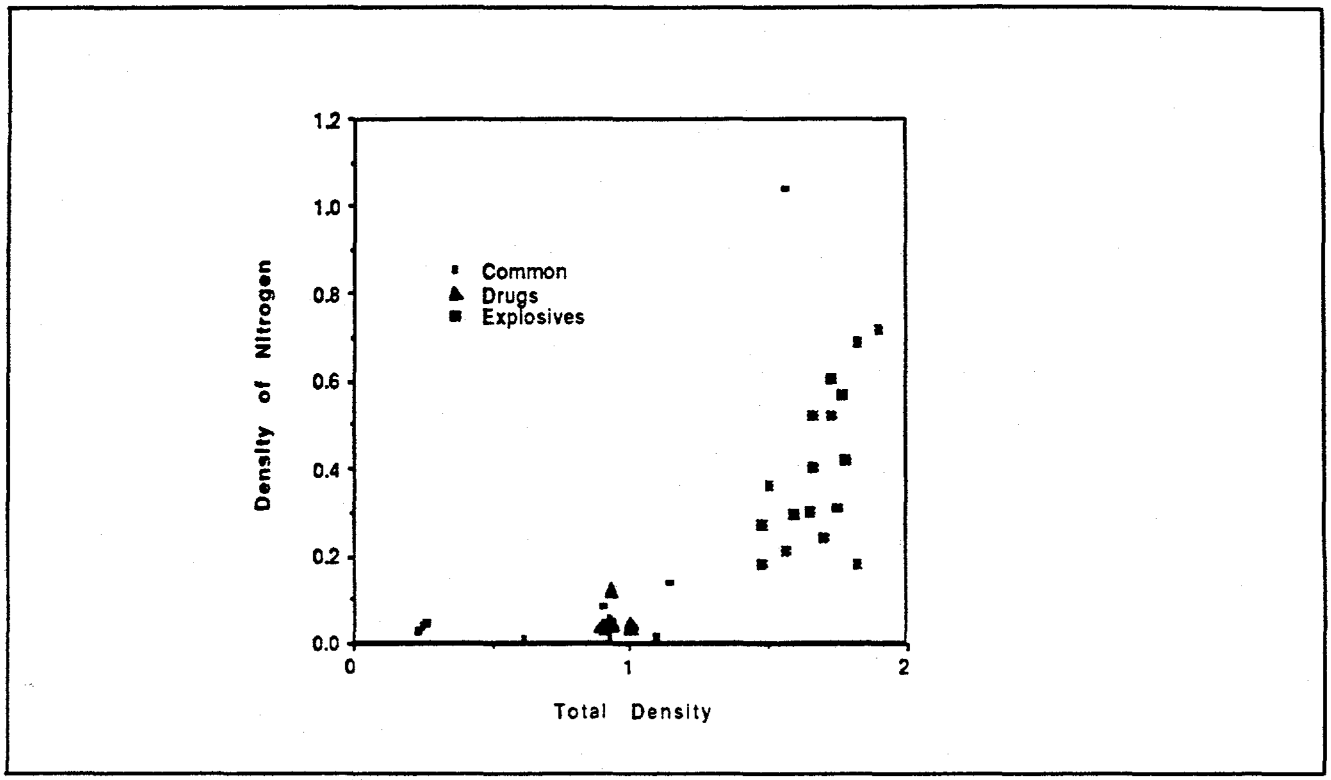

Figure 1(a). Two Dimensional Nitrogen Density Map

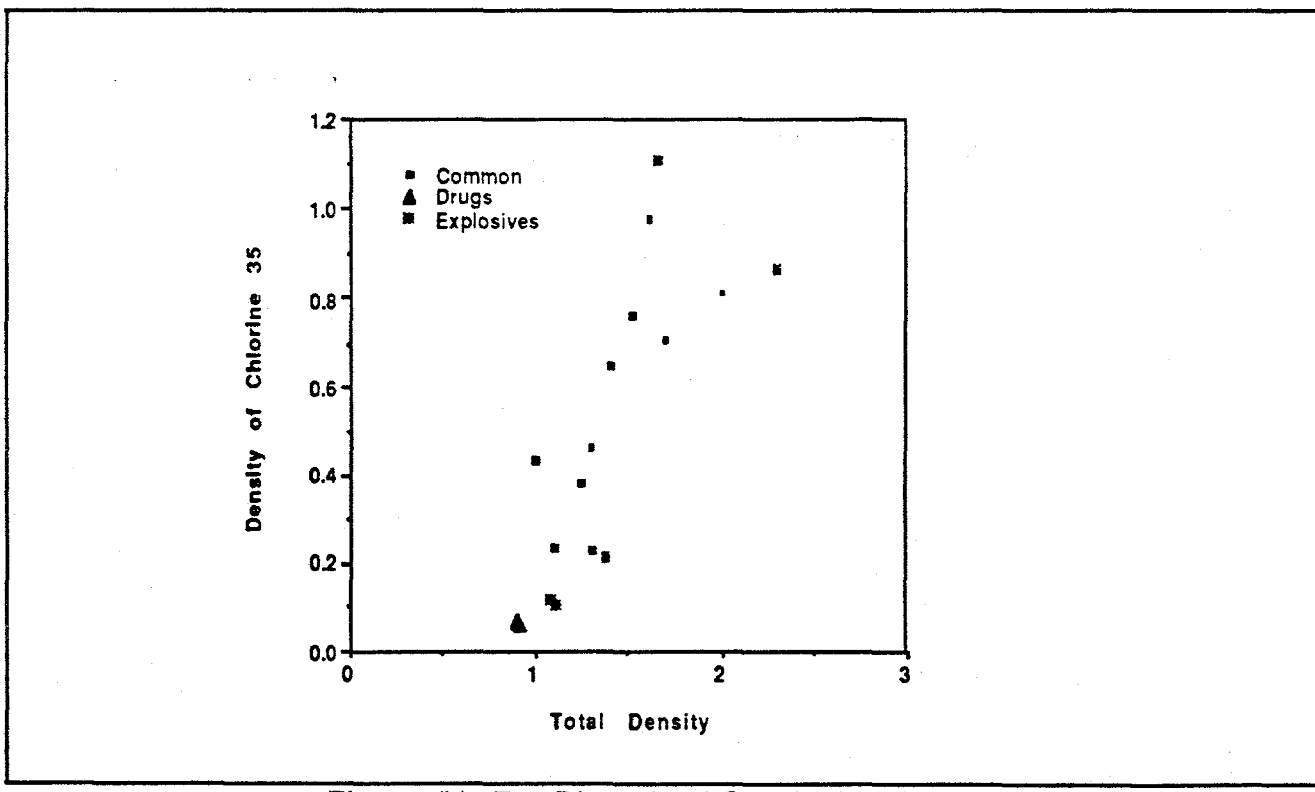

Figure 1(b). Two Dimensional Chlorine Density Map

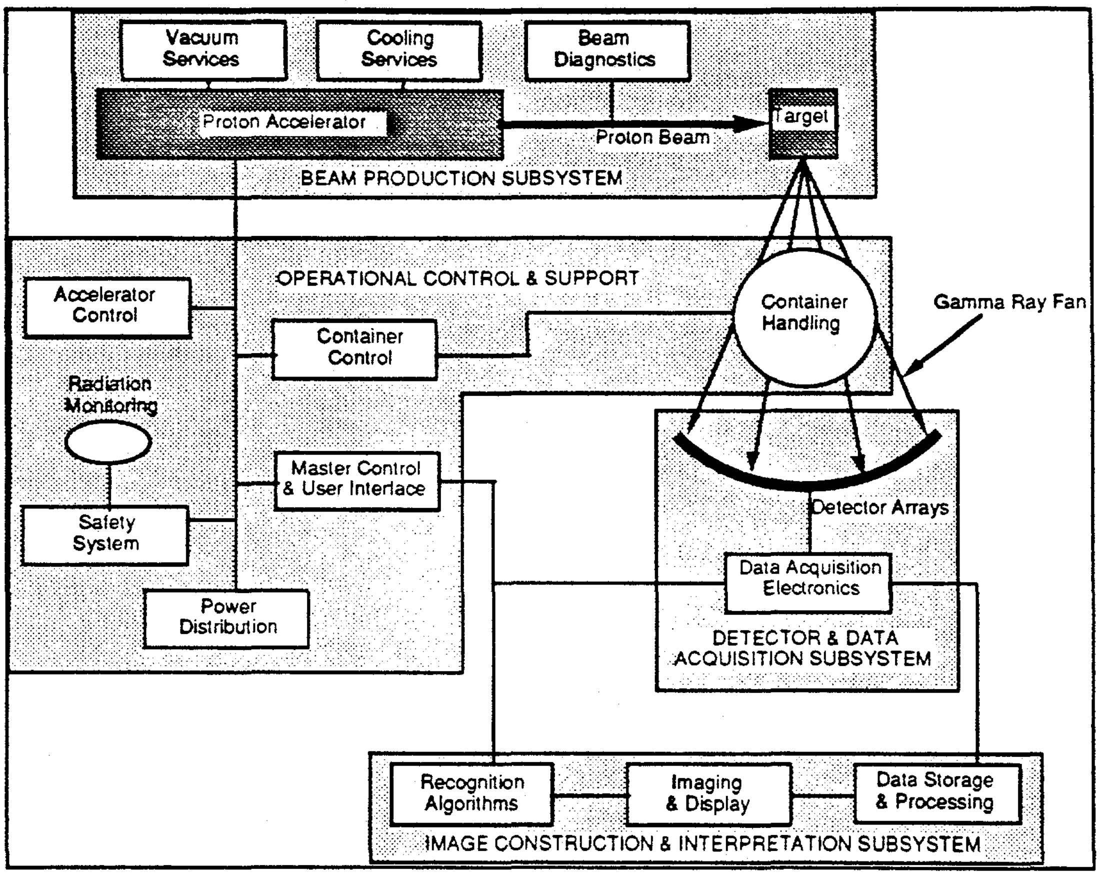

Figure 2. CDS Block Diagram

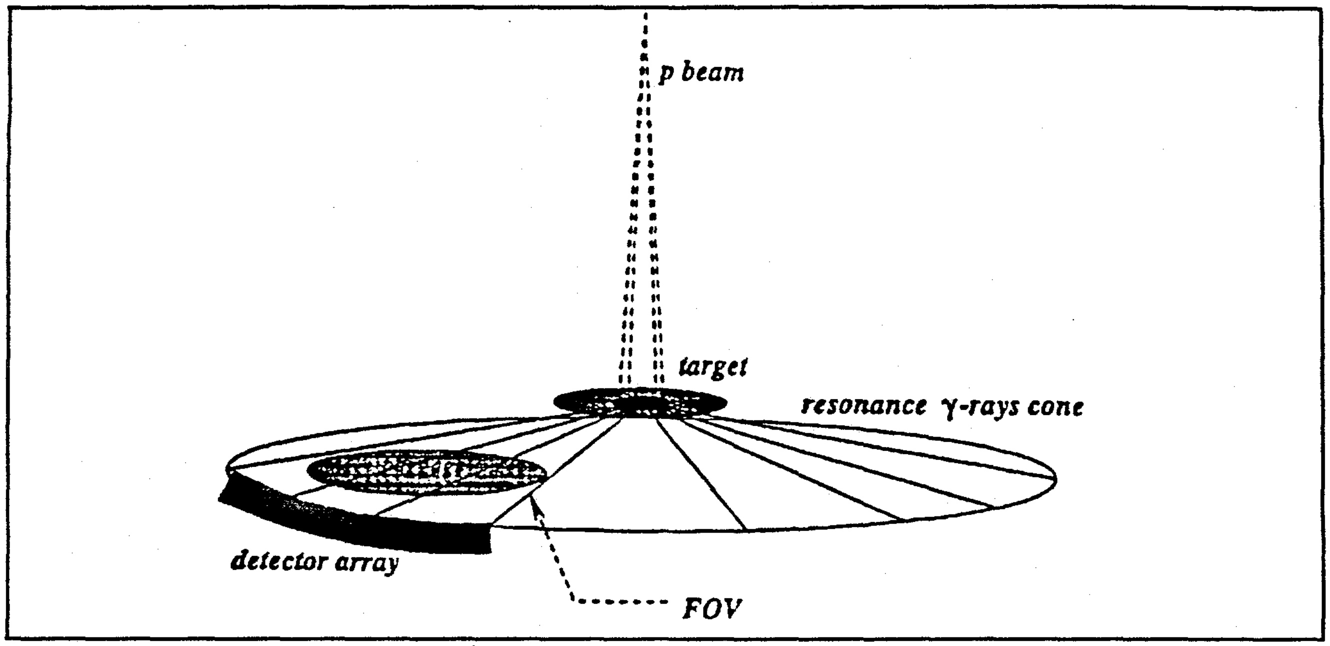

Figure 3(a). CDS Beam Geometry

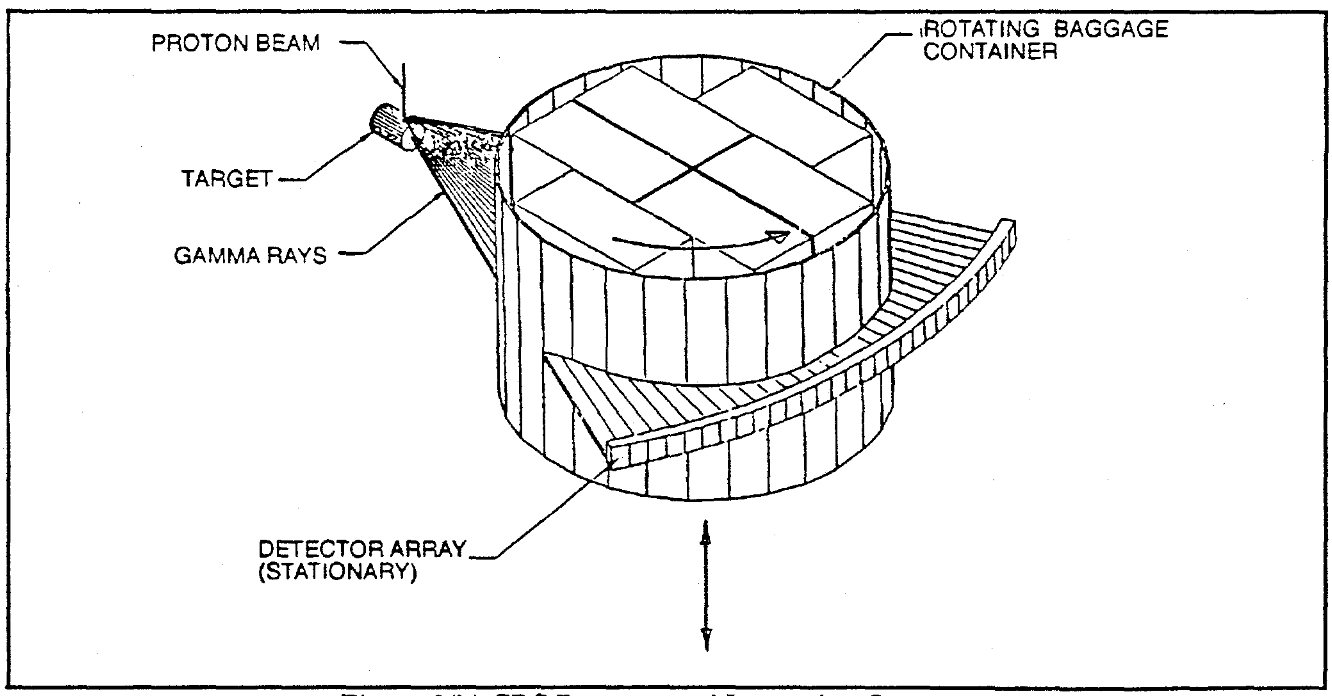

Figure 3(b) CDS Detector and Inspection Geometry

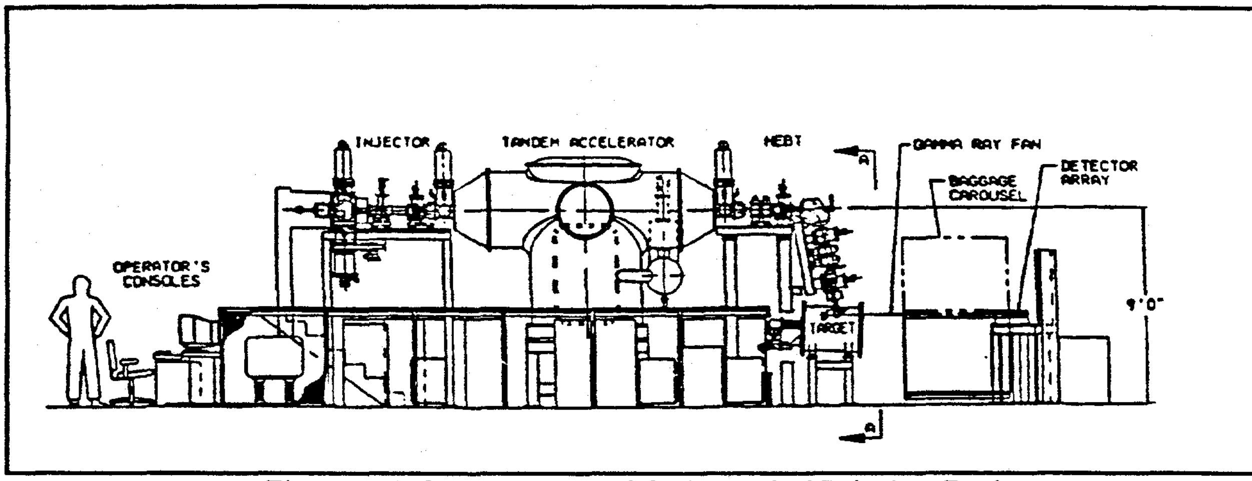

Figure 4(a). Side Elevation of CDS Proof-of-Principle Device

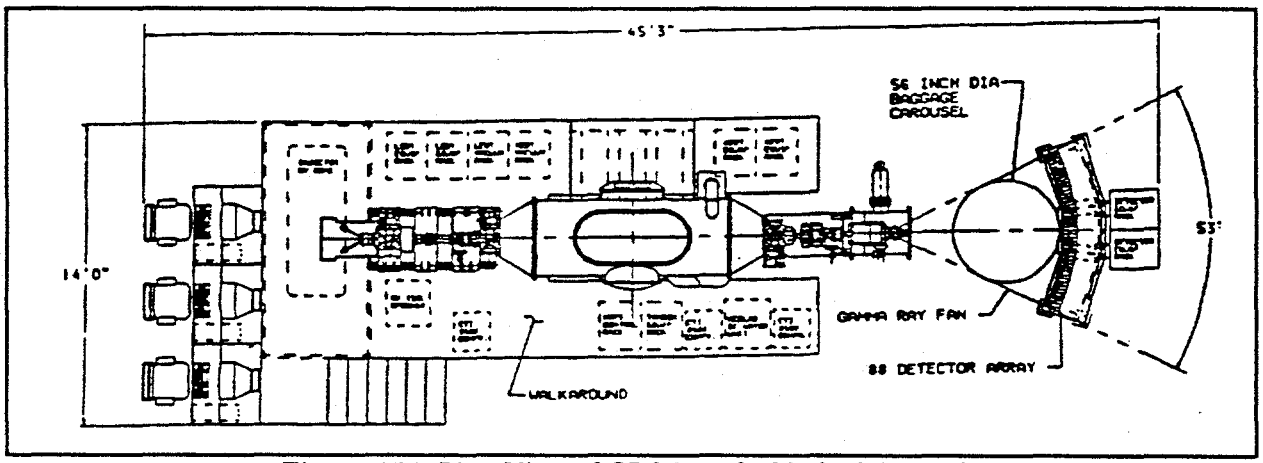

Figure 4(b). Plan View of CDS Proof-of-Principle Device

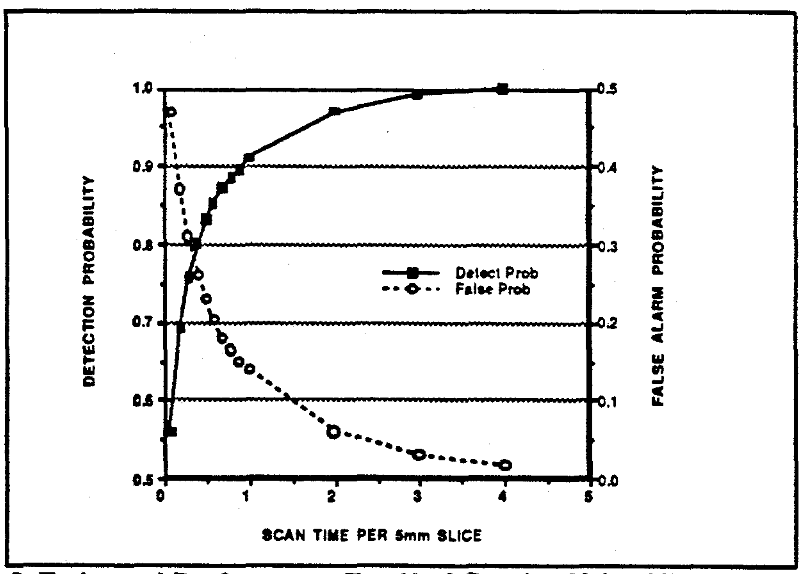

Figure 5. Estimated Performance For 2l of Cocaine Using Nitrogen Detection