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*Evaluation of the NDP System
Final Report*

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EVALUATION OF THE NDP SYSTEM FINAL REPORT OCTOBER 1990

by

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ABSTRACT

The neutron diagnostic probe (NDP), an explosive detection system developed by Consolidated Controls Corporation and based on the associated-alpha-particle technique, was evaluated. Although many problems were found with the prototype system that make it useless for most practical applications, the NDP system may be considered a successful proof-of-principle for the basic explosive detection system design. In addition to evaluating the design and performance of the present system, models were developed to estimate the performance that might reasonably be expected from full scale systems of different conceptual design. Specific examples involved various types of bulk and sheet explosives contained in a suitcase and a large crate. Also considered were the effects of innocuous materials surrounding explosives in different scenarios, including the deliberate use of shielding materials as a countermeasure to detection.

I. INTRODUCTION

The purpose of this study was to evaluate the performance of the neutron diagnostic probe (NDP) developed by Consolidated Controls Corporation (CCC) and to investigate its usefulness in various scenarios for the detection of concealed explosives.

The NDP system is based on the associated alpha particle technique. It consists of a sealed-tube neutron generator (STNG) and a fast position-sensitive alpha-particle detector. The 14-MeV neutrons emitted by the STNG are used as the system's probing radiation. The trajectories of these neutrons are uniquely determined by observing the trajectories of the associated alpha particles, which are measured with the position-sensitive alpha-particle detector. Gamma rays emitted from reactions of the fast-neutron probe with nuclei in the interrogation volume are

detected by a scintillation-type gamma-ray detector. Because the energies of these gamma rays are characteristic of the nuclei from which they are emitted, analysis of the resulting gamma-ray spectra reveals the elemental composition of objects in the system's interrogation volume. By determining neutron trajectories via position-sensitive detection of the associated alpha particles, and by measuring the neutrons' times of flight, the spatial coordinates of the gamma-ray-producing neutron interactions are determined. The elemental specificity of the gamma rays' energy allows the spatial distribution of elements in the interrogation volume to be determined by mapping the detected gamma rays to these coordinates.

In principle, the associated-alpha-particle technique is powerful not only because it reveals the elemental composition of the object being interrogated, but also because it shows the distribution and density of each element detected in the interrogation volume. In practice, however, there are a number of factors that introduce uncertainties into the interrogation results. Among the most significant of these are the uncertainties in the measured neutron trajectories and times of flight. These uncertainties determine the dimensions of the smallest volume element, or voxel, that the system can resolve, which in turn determines the minimum scale on which elemental densities can be measured. The measured density of various elements is likely to provide the strongest discriminant between explosives and nonexplosives. In particular, it is well known that the average nitrogen density in explosives is usually greater than that of nonexplosives. The uncertainties in the measurement of elemental densities, which arise mostly through the limitations of the system's spatial resolution, will therefore be significant factors determining the limits of the system's performance. Not only does the spatial resolution play a key role in determining the threshold mass and thickness of explosive material that can be detected, but it is also a significant factor in determining the overall probability of detection and the probability of false alarm.

The NDP system and its potential usefulness in various applications have been described by CCC in several reports. However, their reports did not indicate the limitations of the system. In particular, they did not specify the system's spatial resolution. This left serious uncertainties regarding the system's performance and its potential real-world applications. In addition, there were many other issues surrounding the system's performance, some subtle and some that are more obvious, that either were not identified or were apparently not given sufficient consideration during the system's development. The evaluation program addressed the most important of these issues to obtain a good understanding of the system's strengths and potential strengths as well as to determine its weaknesses and, when possible, to suggest improvements.

The evaluation program was separated into four phases. In the first phase, the system was assembled and all of its components were tested. During this phase, several malfunctioning electronic modules were repaired and various additional electronic modules were collected. The latter were used throughout the evaluation program as a flexible data acquisition system to independently monitor the system's performance in parallel with the NDP system's own data acquisition hardware. Several parameters critical to the overall performance of the NDP system were measured during the second phase. These parameters include (1) the position resolution of the alpha-particle detector, (2) the time resolution of the system and the time resolution of each of the major components of the system, and (3) a measurement of the neutron-generator yield. This phase of the program required the fabrication and assembly of specialized tools and the use of

specialized equipment, including image-processing hardware, a "long counter," and an NE 213 detector. Two computer programs were also written during this portion of the evaluation: one estimated the intrinsic time resolution associated with the detection geometry for the alpha particles emitted from the STNG target and the distribution in the energies of these alpha particles, and the second program estimated the maximum neutron-output rate of the STNG. During the third phase of the evaluation program, experiments were performed in which various materials, including simulated explosives, were irradiated. The gamma-ray spectra of these experiments were analyzed and the gamma-ray yields, timing, and spatial distribution were compared with analytical calculations. Finally, in the fourth phase of the evaluation program, calculations were performed to project the ability of two conceptual systems to detect various sheet and bulk explosives in different scenarios. These calculations were followed by an analysis of the effects that surrounding materials might have on the ability of the conceptual systems to detect explosives and how countermeasures in the form of composite shields fabricated from common materials might affect the systems' performance.

Section III describes the NDP system, and Sec. IV presents an outline of the evaluation program and some of the experiments that were performed. Section V describes two conceptual designs for full-scale systems similar in principle to the NDP system. In addition, performance estimates for these conceptual systems are developed in Sec. V for several scenarios involving the detection of both sheet and bulk explosives. These projections were developed for various orientations of the explosives and with a number of different assumptions about the spatial resolution of the system and about the types of materials surrounding the explosive. While the discussion in Sec. V does not represent an exhaustive analysis of all of the different scenarios that might arise in applications of a system like the NDP, it does suggest the effects that will be most important to consider, and it gives an impression as to the type of performance that may be expected. Recommendations are presented in Sec. VI for both hardware and software improvements, the most important areas for future research and development, as well as for the applications of the system that should be given the greatest consideration. A summary and conclusions are presented in Sec. VII.

II. SUMMARY

In addition to evaluating the performance of the existing NDP system, models were developed during the experimental program to estimate the performance that might be achieved with full-scale systems in various explosive-detection scenarios and to identify those aspects of the present system that must be improved to realize a useful full-scale system. Specific recommendations were made based on estimates of the evaluation and performance for types of improvements that should be made to the system, the areas where continued development should be focused, and the types of applications that might be considered for systems based on the associated-alpha-particle technique.

During the evaluation phase, the components of the NDP system were tested individually and together, using independent electronic equipment that was assembled to collect data in parallel with the NDP system. This phase involved the testing and repair of various electronic components, including amplifiers, preamplifiers, the logic unit, and other standard nuclear physics

instrumentation. In addition, the work involved determining the performance characteristics of the system's elements, including the output capability of the neutron generator; the energy resolution of the gamma-ray detectors; the time resolution of the gamma-ray detectors, alpha-particle PMT, and other electronics; and the spatial resolution of the MCP. As a check to ensure that the system's performance was well understood, computer models representing the system's timing capabilities and the neutron-generator output were developed. The major conclusions of the evaluation phase of the program are the following:

- The maximum neutron output of the STNG is estimated to be about 3×10^6 n/s when operated at its maximum operational design limits. This estimate is based on extrapolations from experimental observations taken far from the operational design limitations. Although higher maximum neutron output rates have been reported, there have also been reports that the STNG's lifetime is severely shortened when operated at its design limits.
- The NaI(Tl) detectors have energy resolution of about 9.3% at 0.662 MeV and 7.9% at 1.17 MeV. Their time resolution is about 2.0 ns.
- The system's overall time resolution was reduced to about 2.3 ns, which is dominated by the 2.0-ns time resolution of the NaI(Tl) and its PMT. The system's overall time resolution corresponds to a radial spatial resolution of about 11.7 cm.
- The system's "intrinsic" timing uncertainty, which is due to geometrical and physical effects of the $T(d,n)^4\text{He}$ reaction in the STNG target and the detection of alpha particles, is very small compared with other sources of timing uncertainty (about 0.6 ns).
- The MCP is capable of resolving 1.2-mm features on the ZnS(Ag) scintillator screen, which is equivalent to an angular resolution of about 1.6° for alpha-particle and neutron trajectories. This resolution is much poorer than the spatial resolution the MCP is capable of providing and is probably caused by the crude manner in which the alpha-particle-detector assembly's optics form the image of the ZnS(Ag) screen upon the face of the MCP.
- Whereas the MCP was shown to have 1.6° angular resolution by itself, the system's overall angular resolution in the dimensions imaged by the MCP was found to be about 3.0° for objects located in the interrogation volume. This reduction in the spatial resolution is probably due to the uncertainty in trajectories associated with the STNG's beam spot size. An analysis of the images formed by the NDP system indicates that the diameter of the STNG's beam spot is about 1.9 mm.
- There is a large nonuniformity in the light output of the ZnS(Ag) screen that is probably due to a nonuniformity in the deposition of the ZnS(Ag) over the scintillator screen. This nonuniformity will result in variations in the system's overall detection sensitivity. Therefore, great care should be taken in the design of future systems to ensure the uniform thickness of the scintillator. The cause of the nonuniformity in the present system may be due to sublimation of the ZnS(Ag) during tube bakeout.

- The NDP system's maximum counting rate is severely limited by the maximum throughput rate of the MCP's position computer. This limits the present system to data acquisition rates less than about 10 kHz, whereas a useful system would have to acquire data at about 1 - 3 MHz to be practical.
- The NDP system's software is not fully developed and has many errors. More importantly, its basic design and implementation are inadequate and inappropriate to realize the associated-alpha-particle technique's full potential.

Although the prototype system developed by CCC has a number of shortcomings that prevent it from being useful in practical applications, the system does demonstrate the technique's feasibility. Following the evaluation phase, models were developed to estimate the performance of various conceptual full-scale systems. Although no estimate of these systems' PD and PFA could be provided within the current scope of work, it was possible to develop simple models to provide rough estimates of other measures of these systems' performance. These models were based on considerations of geometry, cross sections, spatial resolution, and counting statistics. These analyses presumed that the neutron generator for each full-scale system would be capable of providing 5×10^7 n/s and that the alpha-particle detector would not be limited at the resulting counting rates. Some important results of these analyses are listed below:

- A full-scale system should be capable of providing a high probability of detection and a low rate of false alarm for 1.5 lb of bulk C4 explosive inside a typical suitcase or a 10-lb mass of high explosive concealed inside a 4- by 4- by 4-ft crate, within a reasonable interrogation time and at a reasonable cost.
- Although there is reason to believe that sheet explosives could be detected by a system similar to the first conceptual system considered, such detection would be complicated by the fact that its spatial resolution would be much coarser than the thickness of sheet explosives. This system would have to rely heavily on image processing to reliably detect a 3-mm-thick, 1.5-lb mass of sheet explosive. Suggestions were made as to how the systems' geometry could be tailored specifically to sheet explosive detection.
- While it appears possible to shield an explosive from detection by the conceptual associated-alpha-particle systems considered here, an example considered in this section of the report suggests that effective masses of shielding material may be more easily detected than an unshielded threshold mass of explosive material. In practice, the detection of possible countermeasures would certainly lead to further scrutiny and would focus attention upon the shielded volume of space. In this instance, detection of shielding materials would ultimately lead to the detection of the explosive or to the appropriate disposal of the potential threat. More detailed study should be performed to determine whether it will always be possible to detect an effective mass of shielding material within the same interrogation time that would otherwise be required to detect the threshold mass of explosive.

- The interaction of secondary neutrons may become a significant source of background in some situations, and this may ultimately limit the maximum thickness of material that can be effectively probed by the system.

Finally, a number of recommendations to improve the system and some applications that might be considered for this type of system were made. These included the following:

- The system should be simplified by eliminating the cumbersome optics in the alpha-particle-detector assembly. This should be done by taking the timing signal directly from the position-sensitive alpha-particle detector.
- Consideration should be given to other types of position-sensitive alpha-particle detectors because of the counting rate limitation of the MCP's position computer. Arrays of discrete scintillators coupled to either discrete PMTs or to multianode PMTs should be considered.
- ZnO(Ga) should be considered as a potential candidate for the alpha-particle detector's scintillating material because of its superior timing characteristics, but care should be taken to ensure its uniformity. Particular attention should be paid to its behavior at high temperature, where, as with ZnS(Ag), it may sublime at temperatures lower than its melting point.
- Neutron generator development should be pursued. For the system to be practical, reliable performance and long life must be provided by the neutron generator at outputs in the range of 5×10^7 to 10^8 n/s. To achieve good spatial resolution, the beam spot should remain as small as possible (~ 1 to 2 mm), which may require active target cooling. There are a number of ways to significantly improve the system's overall time resolution. One would be to couple smaller (3-in.) PMTs to the large NaI(Tl) detectors presently used in the system by using lucite light guides. This would preserve the advantages afforded by large scintillators while providing the better timing characteristics of smaller PMTs. Further improvement could be achieved by replacing some or all of the NaI(Tl) detectors with BaF₂ detectors.
- Spectrum-unfolding routines must be included as part of the data processing system to achieve automated explosive detection.
- The data acquisition system, from the MCP's position computer to the data analysis computer, should be carefully redesigned to provide real-time or near real-time data acquisition at 1 - 3 MHz.
- The data analysis and display software should incorporate not only gamma-ray-spectrum unfolding routines, but also a number of utilities that would allow true four-parameter manipulation, gating, and display of the data. The software should allow the automatic identification of elements within the interrogation volume, and it should allow spatial correlations of multiple elements to be displayed in various two- and three-dimensional display formats. It would also be useful to have the ability to correlate images acquired

from different perspectives, particularly in instances where shielding materials are present. Finally, image-processing and discriminant analysis software should be developed for the enhanced and automated detection of contraband materials.

III. DESCRIPTION OF THE MULTIPIXEL NEUTRON DIAGNOSTIC PROBE SYSTEM

A. Principles of Operation

The multipixel Neutron Diagnostic Probe (NDP) produced by CCC¹ is a nondestructive, remote interrogation system based on the associated-alpha-particle technique and the detection of gamma rays emitted when 14-MeV neutrons react with nuclei in the interrogation volume. The multipixel NDP provides three-dimensional spatial information about the interrogated object through the combined use of time-of-flight (TOF) spectroscopy and a position-sensitive particle detection system. The system analyzes neutron TOF data and the gamma rays produced in the interrogation volume to determine the concentration and distribution of elements within the volume.

The NDP probes the interrogation volume with a highly-penetrating flux of energetic neutrons produced by the $T(d,n)^4He$ fusion reaction in a sealed-tube neutron generator (STNG). The associated-alpha-particle technique is based on the fact that recoil alpha particles produced in the STNG by the $T(d,n)^4He$ reaction are ejected in directions nearly opposite to those of the neutrons. The trajectories of the emitted neutrons may therefore be deduced by determining the trajectories of the ejected alpha particles, which impinge upon a highly efficient scintillator screen. A position-sensitive detector views the screen and records the positions where the alpha particle interactions with the screen occur. Although the reaction $T(d,n)^4He$ produces neutrons nearly isotropically, a cone of useful neutrons (and hence the interrogation volume) is defined by the solid angle subtended by the scintillator. This arrangement is illustrated in Fig. 1.

The neutrons emitted from the STNG may interact in a number of ways with the materials through which they pass. These interactions include the reactions (n,n') , (n,p) , (n,d) , (n,α) , and other reactions. The recoil nuclei that are produced by these reactions may be left in excited states and may de-excite to lower-energy states by emitting gamma rays. The energy of an emitted gamma ray is equal to the difference between the energy level of the excited state and the energy level of the final state of the nucleus from which it is emitted. These gamma rays are detected and analyzed by the NDP. The gamma rays that are emitted have energies that are characteristic of the nuclides from which they are emitted. Therefore, it is possible to determine the composition of a sample by measuring the energy of the gamma rays emitted. In addition, the number of gamma rays emitted at each energy level is proportional to (1) the cross section (or probability) for inelastic scattering, (2) the abundance of gamma rays produced in the decay process, (3) the quantity of each nuclear species present in the interrogation volume, and (4) the flux of neutrons through the interrogated material. Because the neutron flux, the cross sections, and the gamma-ray abundances for the reactions of interest are well known, the number of gamma rays detected at each energy (after correction for detector response) provides sufficient information to determine the quantities of the sample's various constituents.

Fig. 1. Deuterons impinge vertically upon the neutron generator's target, reacting with tritium in the target to emit neutrons and alpha particles. Although neutrons are emitted almost isotropically from the target, a cone of useful neutrons (the interrogation volume) is defined by the solid angle subtended by the scintillator screen.

In the NDP, the direction of emitted alpha particles is observed by viewing a silver-activated zinc sulfide (ZnS(Ag)) scintillator screen with a position-sensitive detector. This arrangement is illustrated in Fig. 2. Alpha particles emitted from the target within the angle subtended by the scintillator screen have a 100% probability of interacting with the ZnS(Ag), and cause the screen to scintillate along the path of each alpha particle. Because the starting point of the alpha particles' trajectories at the target is known, the locations of the scintilla on the ZnS(Ag) screen allow the trajectories of the alpha particles to be determined. From the trajectories of the alpha particles, the initial trajectories of the associated neutrons may be inferred. The position-sensitive detector that views the ZnS(Ag) is a microchannel plate (MCP), which is a high-gain, multiple-pixel imaging device. Signals from the MCP are processed by a dedicated position computer to determine the location of the scintilla, providing the information necessary to determine the initial trajectories of the associated neutrons. The known trajectories of the emitted neutrons determine the location of detected neutron reactions in two dimensions.

Additional information is required to determine the location of an inelastic scattering event in three dimensions: a measurement of the time that elapses between the emission of the neutron and the detection of a gamma ray associated with an inelastic scattering event. Because the energy of the emitted neutrons is known, the TOF from the target to the location of the inelastic scattering event is an indirect measure of the distance separating these two positions. The neutron TOF is measured indirectly by measuring the time interval between the detection of the alpha particle and the detection of a gamma ray. As shown in Fig. 3, this measured time interval differs from the desired time interval by an amount corresponding to the TOF of the alpha particle to the ZnS(Ag)

Fig. 2. Trajectories are determined in the NDP system by a position-sensitive detector, which views a ZnS(Ag) scintillator screen. Distance from the target to the neutron interaction site is determined by measuring the neutron's time of flight. The resulting coordinate system is "quasi-spherical".

Fig. 3. The neutron's TOF is determined by measuring the time interval that elapses between the detection of the alpha particle at the ZnS(Ag) screen and the detection of a gamma ray at the NaI(Tl) detector. This value is the sum of the neutron and alpha particle's time of flight, t_n and t_α , and the time taken for the gamma ray to reach the detector from the interaction site, t_γ . The neutrons TOF is determined by subtracting t_α and t_γ from the total measured time.

scintillator plus the time for the gamma ray to reach its detector from the location where it originated. The alpha particles' total TOF is approximately 3 ns, and the propagation time for the gamma rays is even smaller because they travel so much faster (30 cm/ns) than either the alpha particles or the neutrons. Thus, the corrections for the alpha-particle and gamma-ray TOF are small in comparison to the TOF of the neutrons, which travel at approximately 5.1 cm/ns. Both the alpha-particle TOF and the correction for the gamma ray's path length (from the scattering site to the detector) can be determined by considering the position of each scattering event in the other two dimensions. Subtracting these time intervals from the measured time interval produces a good estimate of the neutron TOF (and hence the radius from the target) to the scattering nucleus.

The indirect measurement of the neutron TOF completes a four-dimensional vector that localizes the inelastic scattering event in space and identifies the energy of the emitted radiation. It is this energy information, taken over a large population of scattering events, that makes it possible to identify the nuclides in the samples being examined as well as their concentrations relative to each other. Considered together with the known point of origin of each gamma ray, this information also determines the density distribution of each nuclide in the interrogated object.

B. System Design

A block diagram of the NDP system architecture is shown in Fig. 4. The system can be separated into a neutron generator, three detectors and their associated electronics, and the computer and its associated interface unit.

The sealed-tube neutron generator (STNG) is a very compact device designed to accelerate deuterons through a potential of approximately 100 kV to a target of tritiated titanium. The accelerated deuterons fuse with the tritium in the target, resulting in the emission of energetic neutrons and alpha particles, as described in the previous section. Alpha particles are detected by a ZnS(Ag) scintillator screen, integrally mounted to the STNG, as shown in Fig. 5.

Light from the scintillator is viewed by two detectors, the light being split between the two by a partially reflecting mirror, as shown in Fig. 6. One of the detectors, a fast photomultiplier tube, generates a "start" signal for the time-to-amplitude converter (TAC) when an alpha particle interacts with the ZnS(Ag) screen. The other detector, a microchannel plate (MCP), determines the position of each alpha particle detected on the ZnS(Ag) screen. Because the area of the MCP is smaller than the area of the ZnS(Ag) screen, the image of the ZnS(Ag) screen must be focused onto the surface of the MCP through a converging lens.

Gamma rays are detected by a 5- by 5-in. thallium-activated sodium iodide (NaI(Tl)) detector. The anode signal from the NaI(Tl) generates the "stop" signal for the TAC, and the dynode signal measures the energy spectrum of the detected gamma rays. The TAC output is a voltage level that is proportional to the time interval between the generation of the "start" and the "stop" pulses. This time interval is itself directly related to the time interval between the detection of the alpha particle and the gamma ray. From the TAC output, the distance from the source to the site of the inelastic scattering event may be determined.

The outputs of the three detectors are processed by their respective electronics, as shown in Fig. 4. These electronics are standard pulse-shaping and fast-timing electronics commonly used in nuclear physics. The outputs provide two-dimensional position information from the MCP, one-dimensional position information from the output of the TAC, and a fourth dimension, the energy of the gamma rays, from the NaI(Tl). The coincidence unit, a custom-built circuit, matches each of these signals to their corresponding signals. The coincidence unit generates a gate pulse whenever a complete set of signals has been acquired within a specific coincidence window; it also prevents incomplete data transmission by suppressing the gate pulse if an incomplete set of signals has been received or if the computer interface unit (described below) is generating a busy signal.

When the coincidence unit determines that a complete set of signals has been generated, it passes a gate pulse to the direct-memory-access (DMA) data interface unit. Upon receiving the gate pulse, the DMA interface begins processing the signals in preparation for buffering and eventual transfer to the computer system. The DMA interface uses additional logic to ensure that a valid coincidence has occurred and that all of the signals have been generated and received. Valid signals from each source are stored in their respective first-in-first-out (FIFO) buffers. If an incomplete set of signals is received by the interface unit or if the data received is not accompanied by a valid-data gate signal from the coincidence unit, a reset is sent to the up-stream ADCs, and none of the data is stored in the FIFO buffers. This ensures that only complete sets of data are stored in the buffers and that the sequencing of data across buffers is identical.

The DMA interface sends a DMA transfer request to the IBM PC/AT when 50 valid sets of data have been stored in the FIFO buffers. Corresponding bytes of data are transferred together in four-byte blocks to the computer. As the contents of each buffer register are transferred, the buffer is cleared, enabling it to receive data again. Once all 50 blocks of data have been transferred, the interface unit sends a signal to the computer indicating that the transfer is complete. This frees the interface unit to acquire new data and frees the computer to proceed with display and analysis tasks.

C. Software Design

The NDP data processing software operates on an IBM PC/AT computer that is linked to the rest of the system by the custom-built DMA interface and the commercially produced Metrabyte PDMA-16 card, which is resident within the computer. The NDP software provides a set of functions tailored to the NDP application. Because no source code and virtually no documentation on the program were made available, the discussion of the software features and design that follows is necessarily generalized.

The NDP program is a version of the software that was previously developed for the single-pixel explosive detection system (SPEDS). In the multipixel version, each datum is a four-byte word consisting of eight-bit values for energy, time, azimuth (X), and altitude (Y). These data points are transferred to the computer through the DMA interface described previously. The NDP software manipulates these data words to present the data as either a histogram of time or energy, or as a two-dimensional plot of the position where the alpha particles have been detected. Up to 10 display screens are available. Because all of these screens are kept resident in the

computer's RAM module in the form of "virtual screen" records, the display may be quickly switched from one screen to another. When data are not being transferred to the computer, the system runs independently and can perform any necessary display functions as well as user-specified menu functions.

The software provides utilities that allow the user to further manipulate the data by displaying the points in one dimension that correspond to a region-of-interest (ROI) in either one or two of the other dimensions. The software also provides other utilities for data manipulation, such as linear background subtraction, spectrum subtraction, and simple smoothing routines. NDP functions are executed through a menu-style command procedure. Interactive input is required for some input and output (I/O) functions and for functions requiring the placement of cursors. Appendix A lists the various functions of the software.

Fig. 4. Block diagram of the NDP System.

- a. SSL 24012: Surface Sciences Laboratories Model 24012 pre-amplifier.*
- b. SSL 2401 X-Y Computer: Surface Sciences Laboratories Model 2401 position computer.*
- c. MCP: ITT F4146 "Mepsicon" 200 x 200 resistive-film anode microchannel plate.*
- d. Thorn EMI 9821B: Thorn EMI Model 9128B photomultiplier tube.*
- e. NaI(Tl): 5-in. by 5-in. Harshaw/Filtrol NaI(Tl) detector crystal optically coupled to a Hamamatsu Model R1250 photomultiplier tube; Bertan Model PMT-20A high-voltage supply; resistive divider dynode supply; LeCroy Model VTV 100B pre-amplifier.*
- f. ORTEC 934 QUAD CFD: Ortec Model 934 quad constant fraction discriminator.*
- g. ORTEC 567 TAC/SCA: Ortec Model 567 TAC/SCA.*
- h. ORTEC 800 ADC: Ortec Model 800 analog-to-digital converter.*
- i. CANBERRA 1413 SPEC AMP: Canberra Model 1413 spectroscopy amplifier.*
- j. ORTEC 542 GATE & STRETCHER: Ortec Model 542 linear gate and stretcher.*
- k. COINCIDENCE UNIT: CCC custom-built fast-gate coincidence unit.*
- l. DMA INTERFACE: CCC custom built direct memory address interface.*
- m. IBM PC/AT: IBM PC/AT computer.*

Fig. 5. Deuterons are accelerated vertically downward into the TiT_x target, where alpha particles and neutrons are produced nearly isotropically in the reaction $\text{T}(d,n)^4\text{He}$. The scintillator screen detects those alpha particles whose trajectories fall within the solid angle defined by the ZnS(Ag) screen. The interrogation volume corresponds to the cone of neutrons associated with the alpha particles detected by the scintillator.

IV. DESCRIPTION OF EVALUATION PROGRAM

A. System Assembly

Most of the components of the NDP system were shipped from the Naval Explosives Ordnance Disposal Technical Center (NAVEODTECHCEN) at Indian Head, MD, during the latter half of March 1989; they were received at LANL at the beginning of April. These components included the neutron generator, its control system, high-voltage power supply, the various nuclear electronics components and NIM bins, alpha and gamma-ray detectors, the position computer, and the data analysis computer. Miscellaneous other equipment, including the mounting rack for the neutron generator, detector high-voltage power supplies, three nuclear-electronics modules, and the dielectric insulating fluid for the neutron generator, was delivered to LANL at the end of July.

Assembly of the system began during the last week of June. Repairs were made to the equipment as necessary, and the missing components were requested. The repairs included replacement of bad connectors, as well as the replacement of three FETs in the MCP amplifier. In addition, the unipolar output of the EG&G Ortec Model 572 linear preamplifier was found to be malfunctioning, and a Canberra 1413 spectroscopy amplifier was substituted.

Fig. 6. The ZnS(Ag) screen emits light along the tracks of the alpha particles. Some of this light is transmitted directly to the photomultiplier tube for timing purposes, while the remainder is reflected through a converging lens that focuses the image of the ZnS(Ag) screen onto the MCP to determine the position of each scintillation.

During the time prior to the arrival of the missing components, evaluations were performed on some of the equipment that had already been received. The energy and time resolution of the sodium iodide (NaI(Tl)) gamma-ray detectors was measured, and the operation of the fast photomultiplier tube (PMT) used for timing was verified. A preliminary test of the MCP's position computer and the timing circuitry was also performed.

At the beginning of August, the system was moved to a new location in a radiation dosimetry lab. The dosimetry lab was designed to provide a low-scattering, low-background environment for detector calibration, but was chosen as the site for the NDP evaluation primarily because it provided a suitable set of facilities in an open (unclassified) part of the laboratory. The remainder of the system evaluation was performed at this location.

In addition to the components of the system that were shown in Fig. 4, which were delivered as part of the NDP system, other equipment was added to the system to allow data to be monitored and recorded in parallel with the NDP system. This equipment included a fast oscilloscope, a

storage scope, MCAs, and various pulse-shaping and timing electronics modules. These additions provided a flexible experimental setup for thoroughly testing the system. This hardware was rearranged as necessary for each experiment. Photographs of the experimental setup are shown in Figs. 7a-c. The MCA collected time-gated gamma-ray energy spectra from the NaI(Tl) in parallel with the NDP data acquisition system, and it was also used to record the time spectrum of alpha particle/gamma-ray coincidences. The storage scope provided an independent display of the MCP position-computer's output.

Fig. 7a. A view of the laboratory setup showing the IBM PC/AT used to collect NDP data, the storage scope, and the oscilloscope in the background; racks of electronics in the center; an NE 213 liquid scintillator detector on top of the nearest rack of electronics; a fast oscilloscope on the floor in the foreground; the neutron generator stand in the background to the right of the electronics racks; a NaI(Tl) detector on top of the two shipping crates; and a long counter used to measure the neutron generator's output.

Fig. 7b. A view of the electronics racks showing (from top to bottom and left to right) the CCC coincidence unit, the MCP's position computer, two NIM bins of electronics modules, the neutron generator's power supply, and the neutron generator's controller in the rack on the left, and various electronics modules (some of which are unused) mostly associated with the NE 213 detector in the rack on the right.

Fig. 7c. The neutron generator is in the background. Attached to the neutron generator is the alpha-particle-detector assembly, whose PMT is visible to the left. In the left foreground is the NE 213 liquid scintillator detector next to the NaI(Tl) detector in the center foreground. The long counter is shown on the right.

B. Description of the Testing Program

1. Determination of STNG Output. The CCC design of the STNG is similar to that described by Reifenschweiler in Ref. 2. To this design, CCC added electric-field optics that provide extraction and focusing of the deuterium-tritium ion beam. The system operates at a maximum total accelerating potential (extraction/focus plus accelerating potential) of 120 kV and a maximum target beam current of 10 μA . Through the course of the present evaluation program, the STNG was typically operated at a 70-kV acceleration potential, with a 15-kV to 18-kV extraction/focus potential, and at a target beam current of between 3.0 μA and 3.5 μA . The maximum acceleration potential applied was 75 kV. This range of generator operational parameters was far from the design limits of the system, but allowed safe and reliable operation of the system with the minimum requirement for shielding and lab space. Operation at acceleration potentials higher than 70 kV caused occasional arcing, which affected the instantaneous neutron generation rate and which was felt to be detrimental to the longevity of the tube.

Using two different types of equipment, the output of the STNG was measured several times throughout the course of the experimental program. A "long counter" (Fig. 7c), previously calibrated with a $^{238}\text{Pu-Li}$ source, was first used to determine the generator's output. These results were later verified through an independent set of experiments using an NE 213 liquid-scintillation detector whose neutron response had been calculated. Neutron output calibrations were obtained with the NE 213 detector by using pulse-shape discrimination to record only those signals associated with detection of neutrons. Figure 8 shows the time spectrum for neutron and gamma-ray pulses detected by the NE 213. The figure shows the clear separation in time between the gamma-ray signals (on the right) and neutron signals (on the left). In this figure, the time scale is reversed because the alpha-particle signals have been delayed and used as the TAC stop.

Figure 9 shows the time spectrum produced by setting the time window of the TAC to a position surrounding the neutron time peak shown in Fig. 8. The results of the various neutron-generator output calibrations for different acceleration potentials are presented in Fig. 10, where all results have been normalized to a 3.0- μ A beam current at the target. The output of the neutron generator throughout the experimental program was typically in the range of 3.5×10^5 n/s.

Deuterons lose energy as they penetrate into the TiTi_x target. Because the STNG's target thickness is large in comparison to the range of the accelerated deuterons, the energy distribution of the deuterons in the $\text{T(d,n)}^4\text{He}$ reaction ranges from 120 keV (near the target surface at maximum accelerating potential) down to thermal energy (for deuterons that are completely stopped in the target). The cross section for the $\text{T(d,n)}^4\text{He}$ reaction as a function of energy is shown in Fig. 11. Because the cross section for the $\text{T(d,n)}^4\text{He}$ reaction is a strong function of energy between 0 and 120 keV, deuteron energy loss in the target has a strong effect upon the reaction rate. A computer program was written to model the output of the STNG based on the deuteron energy distribution in the target. The model used to describe the production of neutrons was

Fig. 8. TOF spectrum from NE 213 showing separation between gamma-ray signals (on the right) and neutron signals (on the left). The time scale is reversed in the figure because the alpha-particle signals have been delayed and used as the TAC stop.

Fig. 9. Time spectrum of neutron pulses from NE 213 with gamma-ray signals rejected.

Fig. 10. The neutron generator's neutron yield as a function of total accelerating potential. The curve represents calculated projections of the system's performance. Triangles are experimental data points plotted with the assumption that the extraction voltage is added to the acceleration potential. Squares are data points plotted against the acceleration potential alone. The data points indicate that the extraction potential does accelerate the ions somewhat.

Fig. 11. The cross section for the $T(d,n)^4\text{He}$ reaction as a function of the deuteron's kinetic energy.³

$$N(E_0) = k \int_0^{E_0} \sigma(E(x)) \cdot \left[\frac{dE}{dx}(E(x)) \right]^{-1} dE \quad ,$$

where N is the total number of neutrons produced, E_0 is the maximum incident deuteron energy, σ is the $T(d,n)^4\text{He}$ cross section, and dE/dx is the stopping power for deuterons in the target. Both σ and dE/dx are evaluated at energy $E(x)$, where x is the depth of deuteron penetration into the target. The cross section for the reaction as a function of deuteron energy was taken from Liskien and Paulsen.³ The stopping power values were based on the work of Anderson and Ziegler⁴ and

were taken as $R \text{ (mg/cm}^2\text{)} = 0.026 \cdot E_d^{0.596} \text{ (keV)}$. The factor k relates to the deuteron current on the target and to the tritium loading in the target. The ratio between titanium and tritium atoms in the target was assumed to be 1:1.7. The neutron yield predicted by the program as a function of deuteron energy is also shown in Fig. 10. Extrapolating from operational conditions used (i.e., 70-kV acceleration potential, 15-kV extraction/focusing potential, and 3- μ A target current), the neutron output predicted at the maximum operational design limits was $(2.8 \pm 0.4) \times 10^6$ n/s, although higher outputs up to 5×10^6 have been reported.⁵ The discrepancy between this estimated maximum generator output and the maximum outputs previously reported is attributable to various factors related to the age of this particular tube. These factors include contamination of the drive-in target, tritium decay since the unit was built, and degradation of the internal components as the result of sputtering and plating due to ion bombardment of surfaces within the tube. Although it is certainly possible to operate the STNG at output rates higher than those used during this evaluation program, there is insufficient data available to offer a judgment as to how this would affect tube life. There are indications,⁵ however, that tubes may survive only a very short time (~ 1 h) when operated near the design limits.

2. Determination of NaI(Tl) Energy Resolution. Each of the 5- by 5-in. NaI(Tl) detectors is coupled to a Hamamatsu R1250 PMT. High voltage (~ 1350 V) to each PMT is provided by a Bertan PMT-20A resistive-divider dynode power supply. Anode signals pass through a LeCroy VTV 100B preamplifier to improve time resolution, while signals from the 12th dynode are passed through a generic linear preamplifier built by CCC. As noted previously, dynode signals are amplified by a Canberra model 1413 amplifier, which replaces the EG&G Ortec model 572 amplifier that was found to have a faulty unipolar output.

The resolution of the detectors was measured by using the 0.662-MeV gamma ray of ^{137}Cs and the 1.17-MeV and 1.33-MeV gamma rays of ^{60}Co . The results are presented in Table I, below.

The large size of the detectors leads to good energy resolution, as well as greater efficiency and a larger peak-to-total-energy ratio than could be obtained with smaller detectors. However, better time resolution could be achieved by using smaller detectors. The peak-to-total-energy ratio for the detectors used is approximately 0.3 at the 4.4-MeV energy of ^{12}C gamma rays⁶

Table I. Energy resolution of the NaI(Tl) detectors.		
Energy (MeV)	Resolution (%)	
	Detector 1	Detector 2
0.662	9.2	9.3
1.17	8.0	7.8

3. Determination of System Time Resolution

a. Intrinsic Time Resolution. It is the ability of the associated alpha particle technique to provide spatial imaging that makes it a particularly attractive candidate for remote nondestructive interrogation applications. Because one dimension of its spatial imaging capability is based on TOF measurements, the time resolution of such systems determines the imaging fidelity that is achievable.

Numerous experiments were performed through the course of the evaluation program to measure the time resolution of the NDP system. In addition, calculations were performed and a computer model was developed to determine the sources of the observed timing uncertainty. This computer model calculated the intrinsic time resolution (i.e., it accounted for the sources of timing uncertainty that are intrinsic to the associated-alpha-particle technique in general, as well as those that are specific to the NDP system's geometry). It did not take into account the sources of timing uncertainty associated with hardware, such as the NaI(Tl)'s large volume, jitter in the electron transit time in the PMTs, and jitter in the zero-crossing of the constant-fraction discriminators (CFDs). The total intrinsic timing uncertainty of the NDP system is caused by the angular anisotropy of neutron and alpha-particle energies and by variations in the path lengths of alpha particles and gamma rays to their respective detectors. The anisotropy of neutron and alpha-particle energy has several causes. One cause is the intrinsic kinematic anisotropy of the energy distribution of the reaction products in the laboratory frame of reference. Another cause is a consequence of the penetration of deuterons into the target, which has the following effects:

- 1) a small reduction in energy of the reaction products, and
- 2) a more significant loss of energy experienced by alpha particles as they pass through the target.

The first effect is very small, while the second effect is much greater. Alpha particles originating in the target must pass back through the target material before they can reach the ZnS(Ag) screen and be detected. Because the range of the emitted alpha particles is much greater than the range of the incident deuterons, the thickness of material through which the alpha particles must pass is much smaller than the thickness required to stop them. Nevertheless, the energy lost by the alpha particles cannot be neglected. Alpha particles leave the surface of the target with a range of energies, and the distribution of alpha-particle energies is determined by kinematics and by the position within the target where the interaction occurred. In addition, the amount of material that an alpha particle traverses prior to reaching the surface of the target is proportional to the secant of its angle of emission with respect to the normal to the target surface. Because the ZnS(Ag) subtends a large solid angle and the alpha particles are emitted nearly isotropically, this leads to an additional variation in the energy, and hence the TOF, of the alpha particles that reach the ZnS(Ag). An additional anisotropy in the TOF of detected alpha particles is introduced because the target in the NDP system is oriented at 45° to the ZnS(Ag) screen. Thus, alpha particles emitted from a given depth in the target that reach the bottom of the ZnS(Ag) screen must pass through a greater thickness of material than those that strike the top of the scintillator screen. Finally, because the scintillator subtends such a large solid angle at the target,

there is considerable variation in the path length from the target to the ZnS(Ag) screen. This leads to an additional variation in the measured TOF.

All of the factors noted above were modeled in a computer program, which predicted the total intrinsic timing uncertainty associated with these factors to be ~ 0.6 ns. This time resolution corresponds to a radial position uncertainty of about 3.1 cm.

b. Time Resolution Resulting from Hardware. The greatest contribution to the timing uncertainty in the NDP system is not, however, intrinsic to either the associated-alpha-particle technique or to the NDP's geometry, but rather is due to the signal-processing hardware. This hardware includes both the Thorn EMI 9821B PMT used as the alpha-particle detector and the NaI(Tl) detector and its associated Hamamatsu R1250 PMT. In experiments using nearly ideal geometry, the best time resolution achieved for the system has been 2.3 ± 0.1 ns, which corresponds to a radial position resolution of approximately 12 cm. Of this, the signal-processing hardware contributed the most to the uncertainty, and uncertainties associated with the NaI(Tl) were by far the most significant. Table II, below, lists the significant sources of timing uncertainty in the NDP system. The values cited for the uncertainty associated with alpha-particle and neutron velocity and path length variations are based on the computer model described earlier. The value for the 9821B photomultiplier is based on manufacturer's specifications, while the values associated with the NaI(Tl) and the CFD are based on experimental observations. The total time resolution of the system is obtained by assuming independence between the various components and by adding the individual contributions in quadrature. It is obvious from Table II that the NaI(Tl) degrades the time resolution much more than any other single element of the system. This is somewhat surprising, given the manufacturer's specification that the jitter in transit time for the R1250 PMT is 1.2 ns. If this were indeed the case, and no other uncertainty were associated with the NaI(Tl) signals, then the resolution would improve to approximately 1.8 ns, which would give a radial position resolution of about 9 to 10 cm. In fact, there is some timing uncertainty introduced through effects related to the large volume of the NaI(Tl) crystal (due to jitter of light emitted

Table II. Estimated contributions to the timing uncertainty of the NDP system.	
Source	Time Resolution, FWHM (ns)
α -particle PMT (Thorn EMI 9821B)	1.0
NaI(Tl) PMT (Hamamatsu R1250)	2.1 ± 0.1
CFD (Ortec 934)	0.2
Path length and energy variations	Intrinsic time resolution: 0.6
Total	2.3 ± 0.1

isotropically in the crystal and reflected internally several times before it reaches the PMT's photocathode), but this has a very minor effect. Although the 2.3-ns resolution achieved is significantly better than the best resolution reported by CCC⁷ (3.3 ns, or 17 cm), significantly better time resolution could be reasonably expected by choosing different components.

4. Experimental Verification of Time Resolution Models

a. Time Resolution of the NaI(Tl) Detectors. Because the 2.3-ns timing uncertainty observed for the NDP system was much greater than was expected on the basis of calculations and manufacturers' specifications, experiments were performed to identify the cause of the unexpectedly poor time resolution.

The full-width at half maximum (FWHM) of the coincidence time spectrum obtained when two detectors view a ⁶⁰Co source gives a direct measure of the detectors' time resolution. If the two detectors used can be assumed identical and their noise independent, then the FWHM for an individual detector is given simply by the FWHM of the coincidence spectrum divided by the square root of two.

In one experiment, the ⁶⁰Co source was placed between the two NaI(Tl) detectors. The anode signals from each detector were input to an EG&G Ortec model 934 CFD. One of the CFD channels was delayed and used as the input to the "stop" channel of an EG&G Ortec model 567 TAC/SCA; the other CFD output was used as the start. A Canberra Series 35 Plus MCA recorded the TAC output. The time spectrum collected in this experiment is shown in Fig. 12. To calibrate the spectrum, a 14-ns delay was added to the stop channel, and the resulting time distribution was superimposed upon the first time peak. The 145 channels between the two peaks corresponds to the 14-ns delay in the stop channel. Thus, the 31-channel FWHM of the first time peak represents a time resolution of 2.99 ns for the two sodium iodide detectors. The statistical uncertainty (2σ) of this value is approximately two channels, or about 0.2 ns. Assuming that the detectors have identical response and that their responses are independent, this value corresponds to a time resolution for each detector of ~2.1 ns.

Fig. 12. Superimposed coincidence spectra for the NDP's two NaI(Tl) detectors viewing a ⁶⁰Co calibration source. The peaks are separated by 14 ns. The FWHM of each peak is about 3.0 ns, which indicates that the time resolution for the NaI(Tl) detectors is ~2.1 ns.

Because the preamplifier for one of the NaI(Tl) detectors did not work, it was replaced with an EG&G Ortec model 474 timing filter amplifier, and there was some doubt as to whether the response of the two detectors was indeed identical. A second experiment was therefore performed in which the NaI(Tl) with the malfunctioning amplifier was replaced with a BaF₂ detector, which was known to have a time resolution of approximately 0.4 ns, FWHM. The spectrum obtained in this experiment is shown in Fig. 13. Using the same calibration as in the experiment with the two NaI(Tl) detectors in coincidence, the FWHM of this spectrum is 2.0 ± 0.2 ns. From this calculation, the time resolution of the NaI(Tl) is $((2.0)^2 - (0.4)^2)^{1/2} = 2.0$ ns. This is within the experimental uncertainty of the previous experiment in which the coincidence time spectrum of the two NaI(Tl) detectors was measured.

b. Total System Time Resolution. The total system time resolution was measured by hanging a thin (12.5- by 100- by 100-mm) plate of sintered graphite at a fixed distance from the STNG and recording the time spectrum of the 4.43-MeV gamma rays emitted from the $^{12}\text{C}(n,n'\gamma)^{12}\text{C}$ reaction. The geometry for this experiment is shown in Fig. 14. The time peak for the graphite plate was isolated from other sources of gamma rays by gating the time spectrum on an energy ROI centered at 4.43 MeV.

The graphite plate was hung 17.5 cm from the STNG to achieve good efficiency, which reduced the acquisition time necessary to obtain good statistics. However, because the graphite was so close to the generator, there was an overlap between the graphite time peak and the time peak caused by gamma rays originating in the material in the generator and close to the target, as shown in the spectrum in Fig. 15. To ensure that an accurate value for the resolution was obtained from the time spectrum, it was necessary to subtract the contribution of the generator time peak from the total time spectrum. This was done by fitting the generator time peak to a Gaussian distribution and subtracting this distribution from the raw data. After subtraction, the residual spectrum was fit to a Gaussian, and the FWHM of the Gaussian was calculated. By this method, the FWHM of the graphite time peak was found to be 2.3 ns. The effect of the plate thickness on the time spread

Fig. 13. The coincidence time spectrum between a BaF₂ detector and one of the NDP system's NaI(Tl) detectors. The time calibration is the same as in Fig. 12, and the FWHM of the peak is about 2.0 ns.

Fig. 14. The experimental setup for the measurement of the system's overall time resolution.

Fig. 15. Time spectrum for the thin graphite plate illustrated in Fig. 14. The first large peak at left originates in the neutron generator's structural materials; the second peak corresponds to the graphite plate.

was not significant ($((2.3 \text{ ns})^2 - (0.24 \text{ ns})^2)^{1/2} \approx 2.3 \text{ ns}$). The full-width at tenth-maximum (FWTM) of the graphite peak was found experimentally to be 4.1 ns. The time resolution of the total system, from all sources, was calculated from the FWHM of the time peak by folding the intrinsic time spread with a Gaussian distribution with FWHM equal to 2.3 ns. The computer model of the time resolution previously described was modified to include the time resolution of the NaI(Tl) that had been determined experimentally, as well as the time resolution of 1.0 ns quoted by Thorn EMI for the model 9821B PMT. Both the FWTM and the FWHM values obtained from this experiment correspond well with the values of 2.4 ns and 4.3 ns, respectively, predicted by the computer model. This indicates that the system is modeled well by the computer program and that the values listed in Table II reflect well the sources of timing uncertainty in the NDP system.

5. Determination of Two-Dimensional Spatial Resolution. As noted previously, the spatial resolution of the NDP system in each dimension determines the overall imaging fidelity of the system, and this bears a direct relation to the system's achievable detection threshold. Figure 2 shows that the images formed by the NDP system have a "quasi-spherical" geometry. Positions in the radial dimension are resolved through TOF measurements, while azimuth and altitude from the target are resolved by the MCP. The MCP, an ITT F4146, has 200 resolvable pixels across an active diameter of 25.4 mm. This gives a total of approximately 31 000 resolvable pixels over the detector's active area. Each pixel of the MCP responds to light emitted from a small area of the ZnS(Ag) screen, and each of these small areas subtends a solid angle at the target. Thus, each pixel of the MCP responds to alpha particles emitted within a small solid angle whose vertex is located at the target. Each pixel may therefore be mapped to a particular azimuth and altitude from the target.

Although the manufacturer claims that the MCP provides spatial resolution of $\leq 62 \mu\text{m}$ with 200 resolvable pixels over a 25.4-mm active diameter, these figures apply to the MCP alone and are certainly obtained from carefully designed test procedures. In the NDP system, the MCP views the reflection of the ZnS(Ag) screen in a partially reflecting mirror. The image of the 45-mm-diameter ZnS(Ag) screen is focused onto the face of the MCP by a lens that also reduces the size of the image to the 25.4-mm diameter of the MCP's active area. In this configuration, the MCP's achievable resolution is affected by several factors related to how well the image of the ZnS(Ag) screen is formed on the face of the MCP. The resolution quoted for the MCP by the manufacturer may be taken as an upper limit for the resolution of the system as a whole.

There are a number of factors that affect the quality of the image formed upon the face of the MCP, including the position of the lens, mirror, ZnS(Ag) screen, and MCP relative to one another; the quality of the lens and mirror; and the presence of internal reflections within the detector assembly (which have been noted by CCC). Of these factors, the only one that can be adjusted in the present system is the position of the MCP and lens with respect to the mirror and ZnS(Ag) screen. This can be done by sliding the MCP housing in the ring that holds it to the aluminum block that forms the main body of the detector assembly. This is an awkward adjustment, however, and probably was not intended as an adjustment at all.

Incorrect positioning of the MCP and lens would degrade the observed spatial resolution of the system. It was therefore necessary to determine how to properly position the MCP and lens in the

detector assembly before a correct evaluation of the system's spatial resolution could be made. Because there was no design documentation for the detector assembly (including such information as the dimensions of the assembly, the position of the mirror, and the focal length of the lens), it was necessary to determine the proper positioning of the MCP and lens experimentally prior to evaluation of the system's spatial resolution.

a. Determination of the Lens' Focal Length. To make this determination, accurate measurements of the detector assembly were made, and experiments were performed to determine the focal length of the lens. A light-tight tube with a light source and a mask was used to determine the focal length of the lens. The tube, shown in Fig. 16, was made from a brass pipe and an aluminum pipe which threaded together to form a tube with adjustable length. At the end of the aluminum section, several LEDs were mounted on an end cap to provide a source of light to be detected by the MCP. The MCP housing was attached to a flange at the opposite end of the brass section of the tube. Between the MCP lens and the LEDs was mounted a stainless-steel mask with slots ranging in size from 0.2 to 7 mm. The dimensions of the mask are shown in Fig. 17. A flat Plexiglas[®] lens was placed between the LED and the mask to diffuse the light that passed through the mask.

To determine the focal length of the lens, the length of the tube was changed in approximately 1-mm increments, and the light pattern detected by the MCP was displayed on the storage scope. Photographs of the display were taken for each position of the mask relative to the lens and MCP. Each photograph was digitized by a JVC model GR-C1 CCD video camera and a frame grabber. To obtain better statistics, the images were projected into one dimension perpendicular to the pattern of alternating bright and dark bands. The focal length of the lens was determined by finding the

Fig. 16. The focusing tube used to determine the lens' focal length and the MCP's spatial resolution is shown in the center of the photograph. The tube was attached directly to the MCP housing by the flange at the far end of the tube. One of the two stainless-steel masks used in the evaluation program can be seen inside the tube. An identical mask is to the left. Leaning against the focusing tube is a Plexiglas lens that was used to make the light source more uniform. To the right is the tube's end plate upon which three LEDs were mounted. A tool that was used to remove the retaining rings is also shown.

Fig. 17. Dimensions of the mask used in the focusing experiments.

mask position that provided the greatest separation between successively closer bands of light. The measure of separation chosen for this evaluation of the image quality was the peak-to-valley ratio of the light intensity corresponding to the narrowest distinguishable bands on the image.

Figure 18 shows a photograph of the image produced with the lens located 87.8 mm from the mask. The corresponding plot of the light distribution is shown in Fig. 19. In this figure, the 7-mm aperture falls outside the field of view of the MCP, and the broadest band of light that appears corresponds to the 5-mm mask aperture. The narrowest distinguishable bands in the plot correspond to the 1-mm and 2-mm bands of the template, which are separated by 1 mm. The peak-to-valley ratio for these bands is plotted in Fig. 20 for several mask positions. The figure

Fig. 18. Storage scope display of the pattern produced by light passing through the mask in the focusing tube.

Fig. 19. Projection of the average pixel intensity in the image of Fig. 18. The projection shows the 1- and 2-mm lines are well separated, and some separation exists between the 0.5- and 1-mm lines, but the 0.5-, 0.3-, and 0.2-mm lines cannot be resolved from one another.

Fig. 20. Peak-to-valley ratios for (a) the ratio of the average light intensity in the 0.5-mm band to the average intensity in the space separating it from the 1-mm band, and (b) the ratio of the average light intensity in the 1-mm band to the intensity in the space separating it from the 2-mm band. The ratio was evaluated for several values of the separation between the mask and the lens and shows a weak peak in the system's resolution near 91 mm.

shows that the image is focused best when the distance between the mask and the lens is approximately 91.9 mm. Very little degradation of the image is observed when the mask is moved by ± 2 mm from the optimal position of 91.9 mm.

In each photograph, there was a bright spot near the center of the image, and this degraded the image resolution locally. An effort was made to minimize the bright spot by using different light sources and light diffusing mechanisms, but the results were inadequate. Analysis of the images was eventually performed by using a template to define regions of interest in the image that excluded the bright spot from the analysis.

Figure 21 shows a sketch of the alpha-particle detector and its dimensions, as measured. The length of the light path from the ZnS(Ag) screen to the MCP lens can be adjusted between 87.8 and 103.0 mm by tightening the MCP retaining ring to different positions on the MCP housing, making it possible to position the MCP at the optimal position with respect to the mirror and the ZnS(Ag) screen. As was noted before, however, this adjustment is extremely cumbersome, and there is only one position (corresponding to 87.8 mm) where the position is accurately known and where proper alignment is ensured. For this reason, the spatial resolution of the MCP was evaluated by mounting it at the 87.8 mm position, as described in the next section. It should be noted that the plot of the peak-to-valley ratios presented in Fig. 20 shows that the effect of small displacements from the optimal focal length have only a small effect upon the spatial resolution of the system. The result of the experiments that were conducted to determine the focal length of the lens did verify that the lens and MCP are positioned correctly in the detector assembly with respect to the mirror and ZnS(Ag) screen.

Fig. 21. Schematic representation of the alpha-particle-detector assembly and the dimensions important for assuring that the MCP is correctly positioned.

b. Determination of the MCP Spatial Resolution. From the experiments that were performed to determine the focal length of the lens, it appeared that the MCP was capable of resolving features (located at the lens' focal point) having dimensions of approximately 1 mm. In the light patterns created in the focusing experiment, however, the narrow-width apertures were so close together that the light distributions from adjacent lines overlapped. This made it difficult to accurately determine the spatial resolution of the system. To measure the resolution with greater accuracy, a new mask was made, as shown in Fig. 22. The width of the apertures on the new mask was 0.2 mm (which was known to be approximately a factor of five smaller than the spatial resolution of the MCP for images formed at the position of the ZnS(Ag) screen). This mask was placed directly over the ZnS(Ag) screen, and the neutron generator was operated at low output. The light pattern detected by the MCP was displayed on the storage scope and photographed. From the photographs, line spread functions were determined in the vertical and horizontal dimensions for analysis.

Figure 23 is a photograph of the storage-scope display, and Fig. 24 is a plot of the intensity distribution of the projection of the vertical band of light in the image. The resolution of the MCP was determined by measuring the FWHM of the peak in Fig. 24. Because the dimensions of the pattern on the mask were very accurately known, the endpoints of the lines in the images were used as the references in determining the spatial calibration of the images in each dimension. From this analysis, the spatial resolution of the MCP was found to be 1.2 ± 0.2 mm, FWHM, at the lens' focus. From a similar analysis of the horizontal line in the image, the resolution in the vertical dimension was found to be nearly the same. This corresponds to image resolution of $1.6^\circ \pm 0.3^\circ$ of arc at the center of the ZnS(Ag) screen, or 1.4 ± 0.2 cm for an object positioned 50 cm from the target.

Fig. 22. Schematic of the second light mask, which was used to determine the MCP's spatial resolution.

Fig. 23. A photograph of the storage scope display of the light pattern formed with the second mask.

Fig. 24. Projection of the average pixel intensity in the image of Fig. 23. The projection shows the vertical band of light clearly separated from the horizontal band. The nonuniformity in the scintillator's light output is clearly seen in the projection of the horizontal band.

The MCP's ability to resolve 1.2-mm features on the ZnS(Ag) screen means that the resolution of the image formed at the face of the MCP is approximately 0.68 mm. Although this is far below the manufacturer's claim for the device's performance, this does not imply that the MCP is defective or that it has deteriorated with use. In fact, for the light intensity to which the MCP has been exposed in the NDP system, the MCP should not show any sign of deterioration for many more years. It is much more likely that the mirror and lens form an image upon the face of the MCP that is either not perfectly focused or suffers from some degree of aberration. These problems could arise through improper positioning of the lens with respect to the MCP, improper coupling of the light from the lens to the MCP, or if the mirror were to somehow distort the image by having some curvature. Because nothing is known of the manner in which the optics have been designed and assembled, nothing more can be said about the cause of the observed resolution.

c. Nonuniformity of Response and Image Artifacts. In addition to revealing the spatial resolution of the MCP, the images obtained with the second mask showed several other significant characteristics of the images formed by the MCP. Most important of these is the variation in light

intensity in the images. One of the main reasons for placing the mask directly over the ZnS(Ag) screen (instead of using the LEDs in the focusing tube) was that the ZnS(Ag) was expected to provide a very uniform source of light. Figure 23, however, shows that the light intensity was much lower near the outside ends of the two mask apertures than it was near the center of the image. Another photograph, Fig. 25, of the ZnS(Ag) screen was taken without the mask in place and with the neutron generator running at low output. This photograph shows that there is a very large, nonuniform variation of light intensity across the MCP's field of view. Figure 26 is a histogram of the optical density of the image shown in Fig. 25, which shows graphically the nonuniformity in the light distribution within the MCP's field of view.

Fig. 25. Photograph of the storage scope display of the ZnS(Ag) screen with no mask present. The nonuniformity in the image's light intensity is obvious.

Fig. 26. Plot of the optical density of the image in Fig. 25. Only those parts of the image corresponding to the position of the ZnS(Ag) screen are included in the plot. The plot shows a broad, nonuniform distribution of pixel intensities.

To determine whether the variation in light intensity was caused by nonuniform deposition of ZnS(Ag) on the window of the STNG, or whether it was caused by variations in the sensitivity of the MCP to light over its active area, two photographs (Figs. 27a and 27b) were taken of the storage-scope display of the image of the ZnS(Ag) screen. In the second photograph, the MCP was rotated approximately 90° . The rotation of the light pattern between Figs. 27a and 27b shows that the nonuniformity in light output arises not from the MCP, but from the nonuniform deposition of ZnS(Ag) on the STNG window. The most important consequence of this nonuniformity is that it causes an unnecessary additional nonuniformity in the detection threshold for samples placed in different positions within the interrogation volume. The nonuniform deposition of ZnS(Ag) on the STNG window has the effect that alpha particle-gamma ray coincidences are much more likely to be detected at positions within the interrogation volume that correspond to areas of high ZnS(Ag) concentration, while such coincidences will be much less likely to occur in positions corresponding to low ZnS(Ag) concentration. Thus, the detection threshold for elements within the interrogation volume of the present system will vary greatly with their position.

Another feature noted in the photographs was a "ghost image" of the horizontal line. This image was found just above the horizontal line. Also noted in each image was a bright spot just below the center of the horizontal line. These features are identified in Figs. 28a and 28b and do not appear to be artifacts of the camera or of the storage-scope display. Instead, they appear to be

(a)

(b)

Fig. 27. Two photographs of the storage scope display of the ZnS(Ag) screen. The image in (b) was recorded after rotating the MCP 90° from the position recorded in image (a).

Fig. 28. (a) A photograph of the storage scope display with the second light mask in place. (b) A composite representation of (a) illustrating the location of the bright spot (c) and the "ghost image (d)."

associated with the image formed by the MCP itself. To verify that these features were really associated with the MCP image, and not with the camera or the storage scope, the images were moved on the display screen, and the scale of the image was changed on the storage scope. Both features maintained their size and position in relation to the rest of the image as these adjustments were made, indicating that both features are actually associated with the image formed by the MCP. These features may be caused by reflections in the detector assembly, by scratches on the lens, or by improper coupling of the lens to the MCP. The bright spot may be caused by some defect in the MCP itself. The significance of these features is that they may cause some additional distortion in the image formed by the MCP during normal operation by convolving points in the image in such a manner as to form a "ghost image" just above each object's correct position or by producing a spurious point in the image that is not really correlated with objects in the interrogation volume.

d. Other Factors that Affect Position Resolution in the MCP Image. The experiments discussed in Sec. IV.B.5 showed that the MCP is capable of resolving 1.2-mm features in images formed on the ZnS(Ag) screen. If no other factors affected the fidelity of images formed by the system, the resulting voxel dimensions in the interrogation volume would be given as a function of distance from the target by the expression

$$s = 0.028r + 0.005r, \quad (1)$$

where $s \equiv$ the length of the side of a voxel, and

$r \equiv$ the radius to the edge of the voxel from the target,

and where s and r are measured in consistent metric units.

The results of experiments in which objects were suspended within the interrogation volume of the NDP system, however, produced images whose resolution was somewhat poorer than is predicted by Eq. 1.

In one experiment (to be discussed in greater detail in the next section), a 1.0-cm-thick Semtex sheet-explosive simulant was suspended in the NDP's interrogation volume by strings tied to the floor of the laboratory's mezzanine level. The simulant was aligned with the neutron generator such that the simulant would be viewed by the NDP system along the axis of its longest dimension, as shown in Fig. 29. In this experiment, the NDP system viewed the simulated explosive for approximately 6.4 h. The image of the simulant appears in the X-Y plot (Fig. 30) as the dark vertical band near the center of the image. (The dark spot at the lower left is an artifact of the nonuniform ZnS(Ag) deposition, which intensifies the background in this part of the image.)

The width of the image in Fig. 30 may be determined by comparing it with the width of the field of view at the distance corresponding to the position of the explosive simulant. The simulant was 43 cm long and was positioned with its leading edge at 29 cm from the STNG target. Because of the effects of neutron scattering and attenuation in the simulant (shown in the next section to be very significant) and the geometric reduction in neutron flux with increasing distance from the STNG target, it is apparent that the image formed by the NDP system is dominated by that part of the explosive simulant located nearest the source of neutrons. At this point (29 cm from the STNG

Fig. 29. Experimental setup for spatial resolution experiment using a suspended simulated sheet explosive. The leading edge of the sheet explosive was positioned 29 cm from the STNG target. The center of the simulated explosive was positioned 43.7 cm from the center of the front face of the NaI(Tl) detector.

Fig. 30. NDP display screen showing the image of the sheet explosive in the dimensions viewed by the MCP. The sheet explosive appears to the right of center in the figure. The dark area at the lower left edge of the image is caused by the nonuniformity of the ZnS(Ag) screen.

target), the diameter of the MCP's field of view is 27.1 cm. The FWTM of the image of the explosive simulant has been identified subjectively and is indicated in Fig. 30 by parallel vertical lines. Also, because the extreme portions of the MCP image are clipped in the NDP display, it was necessary to extrapolate from the boundaries appearing in the display to estimate the full width of the MCP's field of view. Dividing the distance separating the parallel lines in Fig. 30 by the diameter of the field of view shown in the figure, the result is that the FWTM of the image of the sheet-explosive simulant is 0.11 ± 0.01 times the width of the field of view. Multiplying this by the 27.1-cm width of the field of view, the apparent width of the image of the explosive simulant is found to be 3.0 ± 0.3 cm.

If the spatial resolution of the NDP system were determined by the resolution of the MCP alone, then the width of the image of the explosive simulant in Fig. 30 could be predicted by convolving a normal distribution of proper width (given by Eq. 1) with a rectangular function of width corresponding to that of the simulant. In the case of the present example, Eq. 1 gives a value for the FWHM of the normal distribution of 0.82 ± 0.14 cm. Convolving this distribution with a rectangular function of width 1.0 cm (the width of the simulant), the FWTM of the resulting distribution is found to be 1.95 ± 0.19 cm. This corresponds to 0.071 ± 0.007 times the width of the field of view, which is $65\% \pm 9\%$ of the width of the observed image.

To explain the discrepancy between the experimental result and the result predicted on the basis of Eq. 1 alone, the effect of the finite size of the beam spot on the STNG target was considered. As shown in Fig. 31, the finite size of the beam spot on the STNG target leads to an uncertainty in the measured values of the neutron and alpha-particle trajectories. In other words, two alpha particles may be detected at the same position on the ZnS(Ag) screen, and yet their angles of emission from the target may have been significantly different from one another because they may have been emitted from different locations within the beam spot.

Fig. 31. The finite diameter of the STNG's beam spot leads to uncertainty in the trajectories of the neutrons and alpha particles. Two deuterons are illustrated impinging upon the target on opposite sides of the beam spot. Both react with tritons in the target to emit an alpha particle and a neutron. Although each alpha particle is detected at the same point on the ZnS(Ag) screen, the trajectories from the target of the alpha particles and their associated neutrons are different from one another. Note that the scale has been greatly exaggerated in this figure for illustrative purposes.

According to CCC reports,⁸ the deuterium-tritium beam in the STNG is focused to a 1- to 2-mm diameter upon the target. If the cross section of the beam were approximated by a normal distribution, then the blurring of the image caused by the associated angular uncertainty could also be represented by a normal distribution. Assuming the beam-spot blurring of the image to be independent of the blurring associated with the MCP assembly, the normal distributions representing each source of blurring could be convolved with the other to determine the distribution that describes the combined blurring effects associated with the MCP and the finite beam-spot size. Because the two distributions are assumed to be normal, the convolution is simple, and the result is another normal distribution whose FWHM is obtained by adding the values of the FWHM of the two original distributions in quadrature. If no other factors degrade the image resolution, then convolution of the resulting distribution with a rectangular function representing the explosive simulant should predict the width of the image produced by the NDP system. Conversely, having measured the width of the image formed by the NDP system and having a model for the amount of blurring attributable to the MCP assembly alone, it would be a straightforward matter to determine the width of the normal distribution that would represent the effect of beam-spot blurring on the image. From this distribution, an estimate could then be made of the FWHM of the STNG beam spot.

The apparent width (FWTM) of the image of the sheet-explosive simulant in Fig. 30 is $3.0 \text{ cm} \pm 3 \text{ cm}$, and the width of the normal distribution associated with the MCP resolution is given by Eq. 1 to be $0.82 \pm 0.14 \text{ cm}$, FWHM. It can easily be verified that the observed width of the image would result if the FWHM of the normal distribution representing beam-spot blurring were $1.26 \pm 0.14 \text{ cm}$ at the position of the explosive simulant. The corresponding beam-spot size is $1.85 \pm 0.25 \text{ mm}$, which matches well with the assertion by CCC that the diameter of the beam spot is between 1 and 2 mm. Based on this conclusion, the width of the normal distribution describing the combined effects of the MCP resolution and the size of the beam spot is given by the expression

$$s = 0.052r \pm 0.005r, \quad (2)$$

where s and r are defined as in Eq. 1. This is the expression that will be used in later analyses to describe the length of the sides of the voxels in the dimensions perpendicular to the radial dimension. It is noted that the length of the side of a voxel given by Eq. 2 is approximately 85% larger than the value given by Eq. 1. Thus, the size of the beam spot has a significant effect upon the resolution that is achievable in the NDP system. Moreover, it can be shown that even if the resolution of the MCP were perfect, voxel dimensions would be given approximately by the expression $s = 0.043r$. Thus, in the present system, position resolution is dominated by the diameter of the beam spot, and it is the beam spot that provides the greatest limitation to the achievable resolution. Indeed, to make the effect of beam-spot size upon image resolution negligible, the diameter of the beam spot must be smaller than one-half the size of a pixel projected onto the ZnS(Ag) screen. This constitutes a significant challenge to any efforts that may be made to significantly improve the resolution of the system, especially if increased neutron output is also desired.

By way of comparison, another experiment, performed and reported to the NAVEOD Technical Center by CCC,⁹ was considered. In this experiment, two 1.27-cm-thick steel bars were suspended within the NDP's interrogation volume as illustrated in Fig. 32. The irradiation of the bars lasted approximately 1.5 h, and the image produced by the NDP is shown in Fig. 33. Proceeding with an analysis similar to the one described above for the image of the sheet-explosive simulant, the spatial resolution for the NDP system as implemented by CCC was evaluated. In this instance, however, the analysis could be conducted somewhat more objectively because, the report of the experimental results included a histogram (shown in Fig. 34) in which the image shown in Fig. 33 was projected onto the horizontal axis. This made the objective measurement of the widths of the images of the objects a very simple matter. In addition, the small dimensions of the steel bars (5.08 cm) in the radial dimension reduced the uncertainties in the width of the field of view, which had to be determined in order to relate the width of the objects in the image to a unit of length.

The analysis of Fig. 34 is based on the image of the bar positioned closest to the STNG, which is located on the left side in the figure. (Notice that the image is reversed from the positions indicated in Fig. 32.) Based on an analysis similar to the one applied previously, it was found that the FWHM of the corresponding peak in Fig. 34 represents an apparent width of approximately $2.75 \pm 0.25 \text{ cm}$. This width would be achieved if the FWHM of the kernel representing the combined blurring effect from all sources were approximately 2.55 cm at the position of the steel bar. Based upon this result, the length of the sides of the voxels in the dimensions perpendicular to

Fig. 32. The geometry for an experiment reported by CCC.⁹

Fig. 33. Image formed by the NDP system after irradiating the steel bars illustrated in Fig. 32⁹ for 1.5 h.

the radial dimension may be expressed as $s = 0.072r$ (units are metric, as before) in the case of the experiment performed by CCC. Although this represents resolution significantly poorer than that which was achieved in the present evaluation program, it does indicate that the expression presented in Eq. 2, above, is a reasonable estimate of the best resolution achievable with the NDP system, as it is presently constituted.

Fig. 34. Histogram of the image shown in Fig. 33.

There are other factors in the NDP system that could conceivably degrade the resolution of images formed by the MCP, some examples of which are the effects of the interactions of scattered neutrons and the effect of the finite grain size of the ZnS(Ag) crystals. The effect of the latter upon image resolution is certainly negligible, since the dimensions of the ZnS(Ag) crystals used in the system are probably on the order of 10-20 μm , which is much smaller than the resolution of the MCP for images formed on the scintillator screen. But the effects of neutron scattering within the interrogation volume could be significant. In the examples discussed above, the effect of neutron scattering is minimized because of the idealized geometry and the absence of surrounding materials. In a more complicated environment, however, the effect of neutron scattering could be much more significant. This effect is discussed in greater detail in Sec. V.G., however, in the context of its relation to the system's detection threshold.

V. ESTIMATES OF SYSTEM PERFORMANCE IN DETECTING VARIOUS TYPES OF EXPLOSIVES

A. Factors Affecting System Sensitivity

The issue of the NDP system's sensitivity is a complicated matter that is affected by many factors. These factors include (1) the neutron output rate, (2) the time allowed for the interrogation, (3) the type, quantity, and distribution of materials located in and around the interrogation volume, (4) the achievable spatial resolution, and (5) the geometrical configuration of the detection system. The limits of the system's performance are defined by the confidence with which the threshold quantity of contraband material is to be detected and by the maximum rate of false alarm that is to be allowed. Ultimately, the sensitivity of the system is determined by its

ability to interpret the data that are collected, and this relates to the ability to accurately unfold gamma-ray spectra, to apply image-processing techniques (including pattern recognition), and to produce the most useful display of the interrogation results.

Because determination of the system's sensitivity involves so many variables, it is not feasible, within the scope of the present program, to evaluate the performance of the system over the entire range of operational parameters that might reasonably be encountered. The present system, with its single NaI(Tl) detector and low neutron production rate, has a very low rate of data acquisition, and it is therefore of little use for practical applications. For the purposes of the present evaluation, therefore, the NDP system has been evaluated in the context of several specific scenarios in which a system like the NDP, expanded to a useful scale, might be employed. Two sets of evaluations were performed: one for the case in which the spatial resolution of the up-scaled system is the same as that of the current system and one in which the system's resolution has been improved to the level believed to be achievable with modest improvements.

The evaluation was made in the context of three specific situations: one involving the detection of 1.5 lb of bulk explosive within a suitcase, a second involving the detection of a 1.5-lb mass of 3-mm-thick sheet explosive inside of a suitcase, and a third involving the detection of a 10-lb explosive within a 4- by 4- by 4-ft box that also contains an ordinary automobile battery. The original intention was to evaluate the system's detection threshold on the basis of experimental and calculated results obtained for each of the configurations described above. To this end, many experiments were performed throughout the evaluation program. In these experiments, samples with high concentrations of individual elements of interest such as C, N, and O, which are found in explosives and other common materials, were examined. In addition, some other elements, such as Al and Fe, were examined, which are of interest because they are common structural materials that might form part of the matrix in which contraband materials could be concealed. Finally, experiments were performed using both Semtex sheet-explosive simulants and another high-explosive simulant in bulk form. In these experiments, however, it was difficult to determine from the NDP data the mass of the explosives being examined because it was found that the data-acquisition electronics of the NDP system lose some significant fraction of the gamma-ray signals produced by the detectors. Because of this, it was necessary to evaluate the system's sensitivity by using calculated projections rather than by extrapolating from experimental results.

As an example of an experiment in which the NDP system lost a significant number of gamma-ray counts, Fig. 35 shows the raw-energy spectrum that was produced by the NDP system when a 1465-g graphite sample was placed in the interrogation volume. According to the NDP display shown in the figure, during the 5647-s acquisition time there were 7651 gamma-ray signals produced in the ROI that included the 4.43-MeV full-energy peak and the 3.92-MeV first-escape peak of ^{12}C . As noted earlier, however, a Canberra Series 35 Plus MCA was used for gamma-ray and time-spectrum acquisition, independent of the NDP's coincidence unit, DMA interface unit, and IBM PC/AT. Figure 36 shows the display of the Canberra MCA corresponding to the NDP display shown in Fig. 35. Although the shape of the spectrum produced by the Canberra MCA appears to closely match that of the spectrum produced by the NDP system, the Canberra MCA shows that the true acquisition time for the experiment was 6220 s. The Canberra MCA's display also shows that at least 11 398 gamma-ray signals were generated by the NaI(Tl) in the ROI that

Fig. 35. Raw energy spectrum from the NDP system's display and analysis software showing 7651 counts in the full-energy and first-escape peaks of a 1465-g block of ^{12}C after a 5647-s acquisition.

Fig. 36. Screen from the Canberra MCA used to independently monitor the performance of the NDP system in parallel with the NDP's data acquisition system. This spectrum was acquired concurrently with the spectrum acquired by the NDP system shown in Fig. 35. The Canberra display, however, shows that the true acquisition time for the experiment was 6220 s, and that at least 11398 gamma-ray signals were generated by the NaI(Tl) in the ROI considered in Fig. 35.

includes the 4.43-MeV full-energy peak and the 3.92-MeV single-escape peak of ^{12}C . In this instance, there was approximately a 10% discrepancy in the elapsed-time measurement, while there was approximately a 33% discrepancy in the number of counts recorded between the two data acquisition systems.

Although this general pattern of discrepancies was observed throughout the experimental program, the magnitudes of the discrepancies between the two data acquisition systems were not constant and did not appear to be related to the data acquisition rate, which was always exceedingly low. No great effort was expended to identify the cause of the discrepancies, but one

plausible explanation is that the coincidence unit improperly rejects a large fraction of the total number of true coincidences that occur. This might happen if there were either a large dead-time in the data acquisition system or if the coincidence unit frequently failed to receive valid position, time, and energy signals within the 15- μ s window of the DMA interface unit. Because the total signal-processing rate was always exceedingly low, it seems unlikely that there could be any significant dead-time for the system. And because no losses were apparent in the time and energy spectra collected by the Canberra MCA, it appears that these signals were being properly generated and transmitted to the coincidence unit. It therefore seems reasonable to speculate that for some reason the MCP's position computer often does not produce the "valid-data" signal that the coincidence unit requires as part of a complete data set.

Regardless of the cause of the discrepancies, an evaluation of the present system's detection threshold, with its unpredictable data losses, would be of little value. Of greater value would be an evaluation of the detection threshold that might be achieved by the system if a properly functioning data acquisition system were to be used. Unfortunately, although a parallel data acquisition system was used in the evaluation program, it was not a multiparameter data acquisition system; instead it consisted of a single-parameter MCA and a separate storage scope. The data collected by the parallel system could not be combined to form the type of multiparameter data sets that a properly functioning NDP data acquisition system would produce. Therefore, it was not possible to use experimental data collected with the parallel data acquisition system to evaluate the NDP system's performance. To evaluate the system's performance, it was necessary to make projections on the basis of calculations, rather than on the basis of extrapolations from experimental results.

B. Conceptual System and the Basis for the Performance Projections

Even given a fixed geometry for the system, the potential variability in the geometry and content of interrogation samples makes the projection of such a system's performance difficult. In the following analyses, the discussion is focused upon two conceptual designs for a full-scale implementation of the NDP system. One design is intended for interrogating small articles, such as suitcases, while the other design is intended to be more versatile and might be used to interrogate larger objects of variable geometry. To provide an evaluation with the broadest utility, the results will be parameterized so that they may be easily adapted to various system configurations and interrogation samples other than those that will be explicitly considered here.

The geometry for the first conceptual design of a full-scale NDP system is shown in Figs. 37a and 37b. The design consists of an array of NaI(Tl) detectors that are located just outside the cone of the interrogation volume. These detectors are shielded by a composite shield of iron and borated polyethylene. The shield would minimize the interaction of the direct flux of neutrons in the detectors. This would be achieved by scattering the fast neutrons out of the path of the detectors, as well as by slowing and capturing the neutrons in the shield's borated polyethylene. Gamma rays produced in the neutron shield would be attenuated by several centimeters of lead positioned between the detectors and the neutron shield, reducing the gamma-ray background. The interrogation volume is defined by a cone whose vertex angle is approximately 56°, and the surface of the detector array has been set back from the surface of this cone by -2 cm. For the purposes of

Fig. 37. Conceptual design for a full-scale system used to interrogate parcels and luggage. (a) Isometric view. (b) Cutaway view showing conveyor belt.

the present discussion, the length of the interrogation volume has been somewhat arbitrarily defined as being 1 m in length, as measured along the central axis of the interrogation volume. The two ends of the interrogation volume correspond to the projection of the endpoints of the detector array onto the central axis. The smallest radial dimension of the interrogation volume is therefore ~70 cm at the end nearest the neutron generator — large enough to accommodate most luggage.

The geometry for the second conceptual design is illustrated in Fig. 38. This design is different than the previously illustrated one in that the detectors do not cover the surface of the interrogation volume, but are deployed in smaller discrete arrays that may be arranged in modular fashion around larger objects as necessary. This conceptual design will be discussed in greater detail in Sec. V.F.

Fig. 38. Conceptual design for a mobile full-scale system used to interrogate large or irregularly shaped objects. (a) Top view. (b) Front view.

The evaluation was based on a modest neutron-generator output rate of $5(10^7) \text{ s}^{-1}$, and the parameterized results were normalized to an output of 10^6 s^{-1} . Explosives were modeled at total mass densities of 1.6 g/cm^3 to 1.7 g/cm^3 , while parameterized results were normalized to an areal density of 1 g/cm^2 when projected along the radial dimension. The solid angle subtended at the neutron-generator target by the sample was normalized in the parameterized results to $4\pi \text{ sr}$, as was the solid angle subtended at the sample by the gamma-ray detectors. The effects of multiple neutron reactions and neutron and gamma-ray attenuation upon the results are not easily

parameterized because these are functions of the size and shape of the explosive, as well as the composition and distribution of the materials that surround the explosive. Therefore, these issues will be addressed only in general terms at the end of the present discussion. The evaluation will be made on the basis of two voxel sizes: one based on the resolution of the present system, and one based on the resolution that might be achieved if modest improvements were to be made to the system.

Any evaluation of the performance of a system such as the NDP must be made in terms of the level of confidence with which the presence or absence of the threshold quantity of contraband material is to be established. This would ordinarily be based upon the probability of detection (PD) of the threshold quantity of contraband material and upon the probability of false alarms (PFA) for samples that do not contain the threshold quantity of contraband material. These measures of performance, however, are strongly affected by systematic errors and sources of background that are highly dependent upon the matrices within which the contraband material is concealed, as well as upon the hardware and software that is used in the system. Because the PD and PFA are so strongly dependent upon sample, application, and site-specific parameters, it is not useful (nor is it practically possible) to provide an analytical evaluation of the performance in terms of the PD and PFA. An evaluation in these terms would be more amenable to experimental determination, and the results would vary for the same system and the same operational parameters from one application to the next. Alternatively, given a well-known matrix of materials within which the contraband material is to be concealed, and given a well-defined system configuration, the problem may also be addressed by more sophisticated computer modeling than has thus far been attempted in regard to the NDP application. Considering the large number of potential applications for a system like the NDP, a more tractable approach to the question of the system's sensitivity would be based only upon the randomly distributed errors associated with its performance, such as those related to the counting statistics of gamma-ray spectroscopy and those associated with the system's spatial resolution.

Two sets of performance criteria were considered for the present evaluation. The first made no requirement upon the imaging capability of the system; it was based upon the detection of the mass of each element that would be present in the threshold-quantity of explosive. It was chosen as the length of time necessary (with a given geometry and neutron-output rate) for the system to measure this quantity of each element with a 90% probability (based on counting statistics alone) that the error in the resulting mass estimate would be less than 10% of the true mass. The second detection criterion was similar to the first, but it required that the masses of the elements in each voxel be measured with 90% probability of being accurate to within 10%.

The "90-10" detection criteria that were chosen as the basis for the evaluation are somewhat arbitrary, and the 90-10 criterion for imaging, in particular, is likely to be much more rigorous than what is necessary for the system to achieve a high rate of detection and low rate of false alarm. Even determining the statistical requirements necessary to achieve a given level of performance would require a more thorough review of the imaging techniques that would be applied and of the models that would be used to discriminate between explosives and innocuous materials. It is difficult, therefore, to put the performance projections for the system into a more useful perspective until more is known about the detection requirements for such a system. For the

moment, however, the projections obtained through this analysis can give order-of-magnitude impressions of the capabilities of the system.

C. Detection of C, N, and O

In most applications of a system such as the NDP, the discriminants between contraband and noncontraband materials would be based on the content of C, N, and O in each volume of space interrogated. Therefore, before addressing the sensitivity of the system to explosives *per se*, it is useful to consider individually the detection of the elements that will provide the strongest signatures of the presence of explosives: carbon, nitrogen, and oxygen. Normalized values for each of the significant lines of C, N, and O are presented in Table III for estimating the full-energy-peak gamma-ray yields for each of these elements in spectra acquired by the NDP system. These values are normalized in the manner described in Sec. V.B. Included in these values are estimates of the peak-to-total ratios for the detectors. The estimated values for the peak-to-total ratios were based on the graphs given by Marion and Young⁶ for 5- by 5-in. NaI(Tl) detectors. As noted previously, the values presented in the table do not account for the effects of multiple neutron scattering or neutron or gamma-ray attenuation. These effects are accounted for separately.

Table III. Normalized values for the detection of C, N, and O gamma rays by a NaI(Tl) array. Tabulated values are estimates of the full-energy-peak counts per second, normalized to 10^6 n/s, 4π source-sample solid angle, 4π sample-detector solid angle, 1 g/cm^2 areal density for samples when projected radially, 80% detector efficiency, and peak-to-total ratios given by Marion and Young ⁶ for 5- by 5-in. NaI(Tl) detectors.			
E (MeV)	Normalized Peak Counts for Carbon (s^{-1})	Normalized Peak Counts for Nitrogen (s^{-1})	Normalized Peak Counts for Oxygen (s^{-1})
2.31	—	710	—
2.75	—	—	470
3.09	—	—	190
3.68	—	330	580
3.85	—	—	270
4.43	1680	—	140
4.46	—	550	—
5.1	—	430	—
5.8	—	—	180
6.13	—	—	970
6.92	—	—	270
7.12	—	—	350

There are several sources of systematic error in interpreting the gamma-ray spectra, and these errors will result in larger uncertainties in the measured counting rates for some gamma-ray lines listed above than will be observed for others. As a result, it is likely that (at least for initial system implementations) only a few of the gamma-ray lines listed in Table III will be of use in detecting contraband materials. Another source of error that will generally tend to reduce the observed counting rates from those predicted by the values listed in Table III is the variation in the peak-to-total ratio with the gamma rays' angle of incidence upon the scintillation detectors. The values listed in Table III are based upon normal gamma-ray incidence. The true value of the peak-to-total ratio, however, will tend to decrease as the angle of gamma-ray incidence becomes more oblique. While gamma rays originating from a sample in the interrogation volume may have nearly normal incidence upon some of the detectors in the array, this will not be the case for many of the detectors. It is therefore expected that lower counting rates would be observed experimentally than are indicated by the values listed in Table III.

Despite the considerable number of caveats listed above for the limitations of the present analysis, Table III still provides a useful guide to the performance that could be expected from a full-scale system. The values presented in Table III may be scaled to estimate the total number of counts that will appear in the full-energy peaks of the gamma-ray spectrum for samples of a given mass, size, and position in the interrogation volume. To do this, the values presented in Table III must be multiplied by the following factors:

Ω_1 The ratio of the solid angle subtended at the neutron-generator target by the sample to 4π sr.

Ω_2 The ratio of the solid angle subtended at the sample by the detector array to 4π sr.

R_o The ratio of the neutron-generator output rate to 10^6 s^{-1} .

R_N The mass of the sample in grams divided by the area in cm^2 of the average sample cross section taken perpendicular to the radial dimension.

Values of Ω_2 for samples placed near the central axis of the interrogation volume may be taken from Table IV, below, for the conceptual configuration illustrated in Fig. 37. Values of Ω_2 for sample positions off of the axis of the interrogation volume are more difficult to calculate, and these positions will not be explicitly considered in the following discussion except to note that on-axis values for Ω_2 at a given distance from the neutron-generator target will always be smaller than off-axis values (and hence this aspect of the gamma-ray yield projections is conservative).

Table IV shows that for samples positioned near the center-line of the interrogation volume at a distance of 70 cm from the neutron-generator target, ~16% of the gamma rays will be emitted from the sample in the direction of one of the detectors. For samples positioned 165 cm from the target, ~32% of the gamma rays produced in the sample will be emitted in the direction of the detector array. From the standpoint of the efficiency of gamma-ray detection, it is therefore most favorable to position samples at the greatest distance from the source. But since gamma-ray production is directly proportional to the neutron flux through the sample, it is easily verified that

the system's sensitivity would be much greater in the position closest to the neutron generator than it would be at larger distances. In fact, for a given sample, ~2.7 times more gamma rays would reach the detector array by placing the sample at the 70-cm position than would reach the detectors if the sample were to be placed at the 165-cm position.

With Tables III and IV, estimates may be made of the gamma-ray detection rate that would be expected from samples having various contents of C, N, and O. This is only a part of the information, however, that is necessary to estimate the system's ability to discriminate between contraband and noncontraband materials. As was noted at the beginning of this section, any system such as the NDP will discriminate between contraband and noncontraband materials on the basis of the measured content of C, N, and O in each resolved volume of space (i.e., mainly on the basis of elemental densities). To achieve a high rate of detection and a low rate of false alarm, there must be a clear separation (within the volumes resolvable by the system) between the C, N, and O content in contraband and noncontraband materials.

Table IV. Values of Ω_2 for samples placed at various distances from the neutron-generator target along the central axis of the interrogation volume.

Distance from Target (cm)	Ω_2
70	0.160
80	0.170
90	0.197
100	0.228
110	0.253
120	0.272
130	0.285
140	0.296
150	0.306
160	0.318
165	0.325

It is well known that most explosives can be distinguished very well from most common innocuous materials on the basis of their carbon, oxygen, and in particular, their nitrogen content. However, if the spatial resolution of a system such as the NDP is coarse in comparison to the dimensions of an explosive, two effects will reduce the system's detection and discrimination capability. The first adverse effect of coarse spatial resolution is that the explosive's image becomes distributed over a volume of space that is larger than the volume actually occupied by the explosive. Not only does this blurring of the explosive's image make it more difficult to determine the true size and location of the explosive, but it also results in an apparent dilution of the explosive's C, N, and O content. In the case of nitrogen, which has a relatively high concentration in most explosives as compared to most nonexplosive materials, this dilution has the effect of making the explosive appear more like an innocuous material because of the reduced nitrogen density in the explosive's image.

The second adverse effect of coarse spatial resolution is related to the blurring of the image of the materials that surround the explosive. The result of this blurring is to superimpose some fraction of the image of the innocuous surrounding materials upon the image of the explosive. This

superposition of signals further reduces the system's detection capability by producing an image in the volume occupied by the explosive that is composed of a combination of signals from both explosive and nonexplosive materials. The superimposed signals from the innocuous surrounding materials may be viewed as a source of background in the volume of the image that is actually occupied by the explosive. The net effect of this superposition of signals is to further reduce the separation between the thresholds that would indicate the presence of explosives and the thresholds that would indicate their absence.

Because the blurring effects caused by limited spatial resolution minimize the differences between the signatures of contraband materials and the signatures of noncontraband materials, the spatial resolution of a system such as the NDP is one of the primary factors that determines the threshold quantity of contraband material that may be detected. In considering specific applications of such a system, the apparent dilution of the chemical contents of contraband materials will therefore be central to each application's viability.

D. Detection of 1.5 lb of Bulk C4 Explosive in a Suitcase

Calculations were performed to estimate the performance of the NDP system in detecting 1.5 lb of C4 explosive. The nominal density for this type of explosive is 1.65 g/cm^3 , and the composition assumed was 3.6% H, 21.9% C, 34.5% N, and 40.2% O by weight. The shape of the explosive chosen for the evaluation was that of a rectangular prism with sides 4.5 by 4.5 by 20.35 cm. The explosive was assumed to be located within a suitcase whose dimensions were 25 by 50 by 60 cm. An evaluation was performed for various orientations of the suitcase to account for the differences in the neutron attenuation within the explosive itself and to account for variations in performance caused by the changes in the signal density that would result from the reorientation of an irregularly-shaped explosive. No accounting was made for the effects of neutron and gamma-ray attenuation in the suitcase. As noted previously, these effects are highly variable and will be discussed in general terms later.

In the first position considered, the explosive was oriented with its longest dimension perpendicular to the direction of neutron flight. The diameter of the interrogation volume is large enough that the suitcase may be easily accommodated while standing upright at the end of the interrogation volume closest to the neutron generator (i.e., at a distance of approximately 70 cm from the neutron generator). The least favorable position for detection of the explosive, given this orientation of the suitcase, is near the central axis of the interrogation volume, adjacent to the side of the suitcase that is farthest from the neutron generator. Given the dimensions of the suitcase and the dimensions of the conceptual system shown in Fig. 37, this puts the explosive at a distance of ~90 cm from the neutron-generator target, as shown in Fig. 39. Table V lists some of the assumptions that were made for the calculations performed for this scenario.

Table VI lists some of the results of the calculations. The table shows that although the combined effects of neutron and gamma-ray attenuation in the explosive are significant for this orientation of the explosive, these effects are not prohibitive.

Fig. 39. Orientation of the C4 explosive and suitcase in the interrogation volume for the first scenario considered.

Table V. Assumptions made in calculations of the NDP system's ability to detect a 1.5-lb mass of C4 plastic explosive.

Explosive's Density	1.65 g/cm ³
Explosive's Dimensions	4.5 x 4.5 x 20.4 cm
Hydrogen	3.6%
Carbon	21.9%
Nitrogen	34.5%
Oxygen	40.2%
MCP Resolution	0.052r x 0.052r (3° of arc), FWHM
Radial (Time) Resolution	11.7 cm (2.3 ns)

Table VI. Calculated results based on 1.5 lb of C4 explosive located 90 cm from the neutron-generator target and positioned as illustrated in Fig. 39.

Macroscopic Cross Section	0.13 cm ⁻¹
Average Neutron Transmission	76%
Average Gamma-Ray Transmission	94 - 98%
Average Voxel Dimensions	4.7 x 4.7 x 11.7 cm, FWHM
Dimensions of the Explosive's Image	5.8 x 20.4 x 12.1 cm, FWHM
Number of Voxels Occupied by Explosives Image	5.5

Based on the results shown in this table, combined with the gamma-ray production rates listed in Table III and the solid angles listed in Table IV, estimates were made of the gamma-ray detection rates for each of the significant lines of the C, N, and O present in the sample. These estimates are presented in Table VII and are based on an assumption that there are no surrounding materials. In most cases, however, it is expected that there will be innocuous materials surrounding the explosive and that they will contain significant masses of the same elements that are found in the explosive itself. In these cases, the counting rates actually observed are likely to be greater than those listed in the table.

Table VII. Estimated counting rates for the C, N, and O full-energy gamma-ray peaks from 1.5 lb of C4 explosive positioned as illustrated in Fig. 39.			
Gamma-Ray Energy (MeV)	Carbon (s^{-1})	Nitrogen (s^{-1})	Oxygen (s^{-1})
2.31	—	11.5	—
4.43	17.3	—	—
5.1	—	7.0	—
6.13	—	—	18.6
6.92	—	—	5.2
7.12	—	—	6.7
TOTAL	17.3	18.6	30.4

Calculations of the time necessary to detect 1.5 lb of C4 at the 90-10 probability level were made on the basis of the results presented in Table VII. The results of these calculations are presented in Table VIII. In most cases, with surrounding materials present, the time for each element that would be necessary to establish the presence of each element in the 1.5 lb of explosive at the 90-10 probability level would be shorter than those presented in Table VIII.

Table VIII. Estimated time necessary to detect with 90-10 confidence the presence of the quantities of C, N, and O present in 1.5 lb of C4 oriented as shown in Fig. 39.			
Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	17.3	—	—
2.31 and 5.1	—	16.2	—
6.13, 6.92, and 7.12	—	—	9.9

Table VIII shows that for a bare 1.5-lb C4 explosive in the position illustrated in Fig. 39, the maximum time expected to be necessary to measure the mass of C, N, and O present at the 90-10 confidence level is 10 - 20 s. If, after an interrogation of perhaps 15 - 25 s, the system had not detected the threshold quantity of each of these elements, it would be possible to clear the object without further interrogation. In practice, because surrounding materials could significantly attenuate emitted gamma rays or could shield an explosive from the probing neutrons, a somewhat longer interrogation may be required prior to clearing a bag.

If, during the initial interrogation, the threshold quantity of each element is detected, then a longer interrogation would be required to image the distribution of each element in the sample. The objective of the imaging would be to determine whether (in any resolvable volume of the space occupied by the sample) there is a sufficient mass of C, N, and O to indicate the possible presence of an explosive. (In practice, the detection of explosives would also be based on the analysis of derived values, such as the ratios between the masses of C, N, and O in each resolvable volume of space. The analysis here, however, will focus upon the primary information provided by the NDP system: the mass and distribution of elements contained in the interrogation sample.) Table IX shows the estimated time necessary to achieve 90-10 confidence in the mass of each element contained in each voxel, based on the present system's spatial resolution.

Table IX. Estimated time necessary to image the C, N, and O contained in 1.5 lb of C4 with 90-10 confidence of the mass of each element in each voxel. The explosive is assumed to occupy approximately 5.5 voxels whose average dimension is 4.7 by 4.7 by 11.7 cm. The explosive is also assumed to be positioned as illustrated in Fig. 39.			
Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	102	—	—
2.31 and 5.1	—	95	—
6.13, 6.92, and 7.12	—	—	58

Table IX shows that the conceptual system would require a 60- to 100-s interrogation to image each element in a 1.5-lb C4 explosive oriented in the manner illustrated in Fig. 39 at the 90-10 confidence level. As was noted earlier, however, the 90-10 criterion for the imaging of each voxel is likely to be greatly in excess of what would actually be necessary for the system to provide a high rate of detection and a low rate of false alarm. Less conservative estimates must follow research and development regarding the imaging requirements of the application, as well as the determination of the image-processing techniques that should be applied.

For this orientation of the explosive, the length of the explosive in the radial dimension (4.5 cm) is much smaller than the radial spatial resolution of the system (11.7 cm), so the blurring of the image in the radial dimension is significant. In the other two dimensions, the blurring of the explosive's image is not as large because the MCP resolution in these dimensions is much finer in comparison to the dimensions of the explosive. The net effect of this blurring is a dilution of the explosive's apparent density. In this case, the true volume of the explosive is only about 29% of the volume occupied by the image of the explosive, and there is a corresponding reduction in the apparent density of the explosive. In addition, when the dimensions of the explosive are comparable to, or smaller than, the resolution of the system in any dimension, a significant fraction of the signals from the explosive will appear outside the volume defined by the FWHM of the image. In the limit of an infinitesimally small explosive, only about 45% of the signals from the explosive would appear within the volume defined by the FWHM of the image. In the present example, due to the dimensions and orientation of the explosive, the additional dilution caused by this effect is only ~60%, giving a total apparent density for the explosive that is about 17% of the explosive's true density. Therefore, any separation between explosives and nonexplosives as far as their content of C, N, and O would be reduced by a factor of approximately five to six times. In other words, due to the blurring of the images of the explosive and the nonexplosive surrounding materials, the difference between the apparent density of each element in the image of the explosive and the density of each element in the image of the surrounding materials would be reduced to only 17% of the actual difference between the composition of the explosive and the composition of the surrounding nonexplosive materials. For a given spatial resolution, this limitation is independent of the amount of time allowed for the interrogation, and therefore the ultimate limitation of the system's detection threshold will be largely determined by the resolution achievable by the system.

Based on the present evaluation of the system, it appears that by making only modest modifications to the current system's hardware, the spatial resolution of the system might be improved from approximately 3° of arc to under 2.5° of arc for the MCP, and from 2.3 ns to about 1.3 ns for the time resolution. Greater improvements could be achieved by making significant modifications to the currently implemented hardware. To estimate the improvement in performance that could be achieved with modest modification and effort, calculations were performed on the basis of a conservative assumption that the MCP resolution could be improved to 2.6° of arc and that the time resolution could be improved to 1.5 ns. The results of these calculations are listed in Table X, below.

To achieve 90-10 certainty of the mass of an element in each voxel would require approximately 300 signal counts per voxel. With improved spatial resolution, the image of the explosive would occupy a larger number of voxels. It might therefore be expected that to achieve 90-10 imaging of the explosive with improved spatial resolution, the total number of signal counts (and therefore the interrogation time) would have to increase in direct proportion to the increase in the number of voxels occupied by the image of the explosive. However, Table X indicates that the total interrogation time is expected to be shorter when the system's spatial resolution is improved to 2.6° of arc and 1.5 ns. The explanation lies in the fact that a greater fraction of the total number of signals from the explosive would fall within the FWHM of the image if the spatial resolution were to be improved. Thus, although the number of voxels occupied by the image would increase

Table X. Estimated time necessary to image the C, N, and O contained in 1.5 lb of C4 with 90-10 confidence of the mass of each element in each voxel. The explosive is assumed to occupy approximately 7 voxels whose average dimension is 4.1 by 4.1 by 7.7 cm. The explosive is also assumed to be positioned as illustrated in Fig. 39.

Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	64	—	—
2.31 and 5.1	—	59	—
6.13, 6.92, and 7.12	—	—	36

from 5.5 to 7 voxels, the apparent density of the explosive would increase from 17% to 27% of the explosive's true density. The 30% increase in the number of counts necessary to achieve 90-10 imaging would be more than offset by the 60% increase in the signal density within the image of the explosive.

These results indicate how an improvement in the system's spatial resolution would improve the system's performance. First, due to the reduction in the apparent dilution of the object being imaged, the time necessary to satisfy a given imaging criterion can be reduced in some instances. Second, the improved spatial resolution has the added benefit of increasing the separation in "decision space" between the characteristics of the explosive's image and the characteristics of the image of the nonexplosives. The result would be a reduction of the statistical criterion necessary to distinguish explosives from nonexplosives, thereby reducing the interrogation time necessary.

It is obvious that the system's performance will be very dependent upon the achievable spatial resolution. The system will perform best when the spatial resolution in each dimension is fine in comparison to the corresponding dimensions of the objects being imaged. Because the system is not likely to have the same spatial resolution in each dimension, the ability to detect irregularly-shaped objects will therefore be dependent upon their orientation in the interrogation volume. For this reason, and in consideration of the change in performance that would result from different neutron attenuation in the explosive itself, calculations were performed for a second orientation of the explosive. In this orientation, illustrated in Fig. 40, the explosive was assumed to be located in the center of the 25 by 50 by 60 cm suitcase, and the explosive's longest dimension was assumed to lay in the radial, or time, dimension of the interrogation volume. The position of the explosive for this orientation of the suitcase would be about 95 cm from the neutron-generator target. Table XI lists some estimates of the system's performance for this orientation of the explosive, based on the system's presently achievable spatial resolution.

Fig. 40. Orientation of the C4 explosive and suitcase in the interrogation volume for the second scenario discussed in the text.

Table XI. Calculated results based on 1.5-lb C4 explosive located 95 cm from the neutron-generator target and positioned as illustrated in Fig. 40.	
Macroscopic Cross Section	0.13 cm^{-1}
Average Neutron Transmission	35 - 45%, depending upon the precise orientation
Average Gamma-Ray Transmission	95%
Average Voxel Dimensions	4.9 x 4.9 x 11.7 cm, FWHM
Dimensions of the Explosive's Image	6.0 x 6.0 x 20.9 cm, FWHM
Number of Voxels Occupied by Explosive's Image	2.6

With this orientation of the explosive, the self-attenuation of the neutron flux by the explosive is much more significant than before, resulting in the gamma-ray detection rates listed in Table XII, which are significantly lower than the detection rates predicted for the previous orientation of the explosive.

Because of these lower gamma-ray detection rates, the time necessary to determine the total mass of each element in the 1.5-lb explosive to within the 90-10 confidence level would be increased to the values listed in Table XIII.

While the estimated time necessary to detect the presence of a sufficient quantity of C, N, and O to warrant more detailed imaging is about twice the time that was required for the previous orientation of the explosive, this is balanced by the improvement in the resolution of the explosive's image and the associated reduction in the time required to produce an image of the explosive at the 90-10 confidence level. Added to this would be the reduction in interrogation time that could be realized by the relaxation of the imaging criterion associated with the reduction in the background

Table XII. Estimated counting rates in the C, N, and O full-energy gamma-ray peaks from a 1.5-lb C4 explosive positioned as illustrated in Fig. 40.

Gamma-Ray Energy (MeV)	Carbon (s^{-1})	Nitrogen (s^{-1})	Oxygen (s^{-1})
2.31	—	5.2	—
4.43	7.8	—	—
5.1	—	3.1	—
6.13	—	—	8.3
6.92	—	—	2.3
7.12	—	—	3.0
TOTAL	7.8	8.3	13.6

Table XIII. Estimated time necessary to detect with 90-10 confidence the presence of the quantities of C, N, and O in 1.5 lb of C4 oriented as shown in Fig. 40.

Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	38.4	—	—
2.31 and 5.1	—	35.9	—
6.13, 6.92, and 7.12	—	—	22.1

counting rate provided by the improved spatial resolution. Table XI shows that even though the explosive is positioned 5 cm farther from the neutron generator than in the previous example, the number of voxels occupied by the image of the explosive is reduced from 5.5 in the previous example to only about 2.6 for the present orientation. Not only is a sharper image of the explosive produced with this orientation, but the number of counts necessary to achieve the 90-10 level of image fidelity is significantly reduced. The estimated interrogation time necessary to image each element in the 1.5-lb C4 explosive sample for this orientation is listed in Table XIV.

Table XIV shows that although approximately twice as much time would be required to determine the total mass of each element for this orientation of the explosive, the improved matching of the system's spatial resolution with the dimensions of the explosive would allow 90-10 imaging of the explosive to be achieved with only a 40% increase in the interrogation time over the time required for the previously considered orientation of the explosive. The benefit is an image of the explosive that occupies less than half the volume of the image that was produced when the

Table XIV. Estimated time necessary to image the C, N, and O contained in 1.5 lb of C4 with 90-10 confidence of the mass of each element in each voxel. The explosive is assumed to occupy approximately 2.6 voxels whose average dimension is 4.9 by 4.9 by 11.7 cm and is assumed to be oriented as illustrated in Fig. 40.

Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	142	—	—
2.31 and 5.1	—	133	—
6.13, 6.92, and 7.12	—	—	82

explosive was oriented as in the previous example. This added image fidelity would significantly improve the detectability of the explosive, and it would also be of great diagnostic value if an attempt were to be made to open or defuse the explosive device. In addition, for the reasons discussed above, the improvement in the image fidelity would actually reduce the statistical requirements necessary to detect the explosive, thereby reducing the interrogation time. The 40% increase in interrogation time necessary to image the explosive is therefore a conservative estimate. The primary cause of this 40% estimated increase is the increased attenuation of neutrons in the explosive itself, which is based on the assumption that the longest dimension of the explosive is perfectly aligned with the direction of flight of the neutrons. With only a 20° misalignment, the attenuation of unreacted neutrons would be reduced sufficiently to allow imaging to be performed in the same time as was required with the previous orientation of the explosive, yet the sharpness of the image produced with the 20° misalignment would be virtually the same as that which would result with perfect alignment.

As with the previous orientation of the explosive, improvement of the system's spatial resolution would be accompanied by a significant improvement in the system's performance. If, as was assumed in the previous example, the spatial resolution of the system were improved to 2.6° of arc for the MCP and 1.5 ns (7.7 cm) for the time (or radial) spatial resolution, then the average dimensions of a voxel at the location of the explosive would be reduced from the dimensions listed in Table XI to 4.3 by 4.3 by 7.7 cm. Because of the smaller voxel size, the number of voxels occupied by the explosive's image would increase from approximately 2.6 to about 3.3. The estimated time necessary with this spatial resolution to achieve 90-10 imaging of each element in the explosive is listed in Table XV.

As was the case for the previous orientation of the explosive, the interrogation time required to achieve 90-10 imaging of the explosive is expected to be smaller with the improved spatial resolution assumed in this example. While the number of voxels occupied by the image of the explosive would increase from 2.6 to 3.3, the apparent density of the explosive would increase from 27% of the true density of the explosive to 46% of the explosive's true density. The 27% increase in the number of voxels occupied by the image of the explosive is more than offset by the 70%

Table XV. Estimated time necessary to image the C, N, and O contained in 1.5 lb of C4 with 90-10 confidence of the mass of each element in each voxel. The explosive is assumed to occupy approximately 3.3 voxels whose average dimension is 4.3 by 4.3 by 7.7 cm. The explosive is also assumed to be positioned as illustrated in Fig. 40.

Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	83	—	—
2.31 and 5.1	—	78	—
6.13, 6.92, and 7.12	—	—	48

increase in the signal density of the explosive's image. In practice, there would again be an added reduction in the total interrogation time required because the increased signal density in the explosive's image would enhance the differences between the image of the explosive and the image of the surrounding nonexplosive materials.

To summarize, the results presented above for the conceptual system illustrated in Fig. 37 indicate that such a system would be capable of detecting and imaging a 1.5-lb explosive concealed within a suitcase with an interrogation time of between 1 and 2.4 min if the neutron and gamma-ray attenuation of surrounding materials were insignificant. The results indicate that the total time required for the interrogation depends strongly upon the position and orientation of the explosive in the cavity, as well as upon the spatial resolution that is achievable. In addition, the achievable spatial resolution determines the dilution of the signal density in the explosive's image. Regardless of the interrogation time allowed, this dilution will largely determine the ultimate ability of the system to distinguish threshold quantities of explosives from nonexplosive surrounding materials.

E. Detection of a 3-mm-Thick Sheet Explosive in a Suitcase

To estimate the ability of the conceptual system to detect sheet explosives, calculations were performed based on a 1.5-lb sample with thickness equal to 3 mm. The chemical composition of sheet explosives, and the nitrogen fraction in particular, may vary greatly depending upon the amount of plasticizer used in a given formulation. The model for this evaluation was based on PETN sheet explosive with 4.2% H, 29.8% C, 16% N, and 50% O by weight. In terms of nitrogen fraction, this sample ranks toward the lower end of the range of that which might typically be encountered in a sheet explosive. Typical values for the nitrogen fraction in sheet explosives might range between approximately 12% for PETN mixed with a large quantity of plasticizer and approximately 25% for some Semtex sheet explosives. The explosive was modeled as being 53 cm in length and 26 cm in height, with a density of 1.64 g/cm^3 . Given these dimensions, this explosive could be made to line either the sides of or a divider inside the 25- by 50- by 60- cm suitcase considered in the previous examples. The calculations were performed for two orientations of the suitcase to consider the differences in performance that might be encountered as the result of different spatial resolution in each dimension and as the result of differences in the attenuation

within the explosive itself. Again, the effects of neutron and gamma-ray attenuation within the suitcase itself were not explicitly considered.

As in the previous example, the first position considered was with the longest dimensions of the explosive oriented perpendicularly to the direction of neutron flight. Because the diameter of the interrogation volume is large enough to accommodate the suitcase in its upright position at the end of the interrogation volume nearest to the neutron generator, it was assumed that the suitcase would be placed in this position. The least favorable position for detecting the explosive, given this orientation of the suitcase, would be in the side of the suitcase that is farthest from the neutron generator. As for the previous examples with the C4 explosive, this places the explosive at a distance of approximately 90 cm from the neutron-generator target, as shown in Fig. 41. Table XVI lists some of the assumptions that were made for the calculations performed for this scenario.

Fig. 41. Orientation of the sheet explosive and suitcase in the interrogation volume for the first scenario considered.

Table XVI. Assumptions made in calculations of the NDP system's ability to detect a 1.5-lb mass of sheet explosives.	
Explosive's Density	1.64 g/cm ³
Explosive's Dimensions	0.3 x 26 x 53 cm
Hydrogen	4.2%
Carbon	29.8%
Nitrogen	16.0%
Oxygen	50.0%
MCP Resolution	0.052r x 0.052r (3° of arc), FWHM
Radial (Time) Resolution	11.7 cm (2.3 ns)

Some results of these calculations are listed in Table XVII.

Table XVII. Calculated results based on a 1.5-lb sheet explosive located 90 cm from neutron-generator target and oriented as illustrated in Fig. 41.	
Macroscopic Cross Section	0.13 cm^{-1}
Average Neutron Transmission	98%
Average Gamma-Ray Transmission	~100%
Average Voxel Dimensions	$4.7 \times 4.7 \times 11.7 \text{ cm}$, FWHM
Dimensions of the Explosive's Image	$26.0 \times 53.0 \times 11.7 \text{ cm}$, FWHM
Number of Voxels Occupied by Explosive's Image	63

For the geometry of this example, neither neutron nor gamma-ray attenuation is a significant factor. In Table XVIII, the estimated gamma-ray detection rates for this geometry are listed for the gamma-ray energies most likely to be useful for the detection of explosives. As with the corresponding tables for the examples based on C4, the detection rates listed are the estimated values for the full-energy photopeaks only.

Although the gamma-ray detection rate for nitrogen is somewhat smaller in this example because the nitrogen fraction is less than 50% of the value assumed in the previous examples with the C4 explosive, the gamma-ray detection rates for carbon and oxygen are much greater because

Table XVIII. Estimated counting rates for the C, N, and O full-energy gamma-ray peaks from a 1.5-lb sheet explosive positioned as illustrated in Fig. 41.			
Gamma-Ray Energy (MeV)	Carbon (s^{-1})	Nitrogen (s^{-1})	Oxygen (s^{-1})
2.31	—	7.3	—
4.43	32.2	—	—
5.1	—	4.4	—
6.13	—	—	31.2
6.92	—	—	8.7
7.12	—	—	11.3
TOTAL	32.2	11.7	51.2

of the larger fraction of each of these elements and the greatly reduced effect of neutron attenuation within the explosive itself. While the gamma-ray detection rate for nitrogen is smaller than in the previous examples, the strong carbon and oxygen signals may still provide excellent discriminants of the presence of the explosive.

Based on the detection rates given in Table XVIII for this example, Table XIX shows the estimated time necessary to establish the presence of the threshold quantity of each element in the explosive at the 90-10 probability level. These values presume the (unlikely) absence of other surrounding materials containing these same elements. As was explained above, this determination of the gross elemental composition might constitute the first level of interrogation by which an object could be rejected as having a concealed explosive (on the basis that the total mass of one or more of the elements in the suitcase is insufficient to constitute a significant threat).

Table XIX. Estimated time necessary to detect with 90-10 confidence the presence of the threshold quantities of C, N, and O in the interrogation volume.

Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	10	—	—
2.31 and 5.1	—	26	—
6.13, 6.92, and 7.12	—	—	6

Based on these projections, an interrogation of 10 - 20 s may be adequate to determine whether a sufficient quantity of each element is present in the sample to warrant a more detailed interrogation and imaging of the object. This estimate is independent of the system's spatial resolution, since this is simply the time necessary to detect the gross quantity of each element present, and is not based upon any imaging requirement. In practice, it is not likely that the system would usually require this amount of time to determine whether more-detailed imaging is required. This is because it is likely that there will frequently be a sufficient mass of C, N, and O in innocuous materials within a suitcase to signal the possible presence of an explosive. Of course, this does not imply that the interrogation process will be shorter on average, but rather that it will, in fact, be longer overall than 10 - 20 s because more time-consuming and detailed imaging will be required whenever the threshold quantity of each element is detected. Table XX shows the estimated time necessary to achieve 90-10 confidence of the mass of each element contained in each voxel for this geometry and spatial resolution.

The greatest difficulty in the present example arises not in the ability of the system to detect the threshold quantities of C, N, and O in the sheet explosive, but rather in the ability of the system to resolve the position of these elements in space. For this orientation of the explosive, the length of the explosive in the radial dimension (0.3 cm) is much smaller than the spatial resolution of the system in the radial dimension (11.7 cm, FWHM). In the other two dimensions, the length of

Table XX. Estimated time necessary to image the C, N, and O contained in a 1.5-lb sheet explosive with 90-10 confidence of the mass of each element in each voxel. The explosive is assumed to occupy approximately 63 voxels whose average dimension is 4.7 by 4.7 by 11.7 cm. The explosive is also assumed to be positioned as illustrated in Fig. 41.

Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	480	—	—
2.31 and 5.1	—	1320	—
6.13, 6.92, and 7.12	—	—	300

the explosive (26 cm and 53 cm) is large in comparison to the spatial resolution of the system (4.7 cm, FWHM). Therefore, the blurring of the image is significant only in the radial dimension. Because there is such a large difference, however, between the explosive's thickness and the resolution in the radial dimension, the ratio of the true volume of the explosive to the volume defined by the FWHM of the image of the explosive is only 0.026. Because only about 76% of the total signal from the explosive appears within the limits of the image defined by the FWHM of the image, the total apparent dilution factor of the explosive's density is 0.019, which is approximately one-fiftieth the true density of the explosive.

Table XX indicates that the elements that constitute the explosive in this example could each be imaged to the 90-10 confidence level with interrogations that might range from 5 - 22 min. Although this might be an acceptable investment of time in some cases, the result of the interrogation in this instance would be less than ideal due to the large dilution of the apparent density of the explosive's constituent elements. In a suitcase whose thickness in the radial dimension is only 25 cm, the ability to produce an image in which only 76% of the signals from a sheet explosive appear within 6 cm of the true position of the explosive leaves much to be desired, particularly since the apparent density of the elements that comprise the explosive would be a factor of 50 less than the true density. In the presence of other C-, N-, and O-containing materials, the change in the apparent density of each of these elements (due to the distributed image of the sheet explosive) over the apparent densities that would result from the innocuous materials alone is not likely to be identifiable. It is therefore unlikely that a sheet explosive could be detected with a system having the spatial resolution assumed in this example if the explosive were oriented in the manner illustrated in Fig. 41.

In this instance, an improvement in the MCP's resolution provides no significant improvement in the explosive's detectability because it is the system's time resolution that causes the greatest blurring for this orientation of the explosive. If the time resolution were to be improved to 1.5 ns, the volume defined by the FWHM of the explosive's image would be reduced to approximately 25 times the true volume of the explosive. The thickness of the explosive would still be very much

smaller than the resolution of the system in the radial dimension, so there would still be only approximately 76% of the total signal appearing within the volume defined by the FWHM of the image. The apparent density of the C, N, and O in the explosive would still be approximately a factor of 35 - 36 times smaller than their true density in the explosive. Although this would result in an image in which approximately three quarters of the signals from the explosive would appear within less than 4 cm of the true position of the explosive, the large apparent dilution of the explosive's density is still likely to make detection difficult. The orientation of the explosive illustrated in Fig. 41 is clearly not favorable for detection by the NDP system. To the extent that the concealed mass of sheet explosive can be maximized by lining the broad, flat panels of a suitcase as has been assumed, it is unfavorable from the standpoint of sheet-explosive detection to orient the suitcase as shown in this figure.

Clearly, from the example presented above, the optimal detection of sheet explosives requires that the smallest dimension of the sheet explosive be oriented in such a manner as to coincide with the dimension in which the system provides the finest spatial resolution. To achieve the greatest probability of detecting a sheet explosive concealed within a suitcase in the manner of the previous example, it would therefore be desirable to orient the suitcase in the interrogation volume as illustrated in Fig. 42. Given a 50-cm-tall suitcase, this places the center of the explosive at a minimum distance of approximately 95 cm from the neutron-generator target, 5 cm farther from the target than in the previous example. Table XXI presents some results for calculations performed with this orientation (Fig. 42).

With the sheet explosive reoriented as shown in Fig. 42, the length of the explosive in the radial dimension (26 cm) would be large in comparison to the spatial resolution of the system (11.7 cm, FWHM), so the blurring of the image in this dimension would be very small. The width of the explosive (53 cm) would also be large in comparison to the system's spatial resolution in the corresponding dimension (4.9 cm, FWHM). Although the system's spatial resolution in the vertical dimension would still be large in comparison to the 2.3-cm thickness of the sheet explosive, the situation is greatly improved over the previous orientation of the explosive. Now the ratio of the true volume of the explosive to the volume defined by the FWHM of the image would be 0.06,

Table XXI. Calculated results based on a 1.5-lb steel explosive centered 95 cm from neutron-generator target and oriented as illustrated in Fig. 42.

Macroscopic Cross Section	0.13 cm ⁻¹
Average Neutron Transmission	28-98%, depending upon precise geometry
Average Gamma-Ray Transmission	~100%
Average Voxel Dimensions	4.9 x 4.9 x 11.7 cm, FWHM
Dimensions of the Explosive's Image	4.9 x 53 x 26 cm, FWHM
Number of Voxels Occupied by Explosive's Image	24

Fig. 42. Orientation of the sheet explosive and suitcase in the interrogation volume for the second scenario discussed.

which is an improvement of about 2.3 times over the value obtained with the previous orientation of the explosive. Although the apparent density of the explosive in this orientation increases to approximately 4.6% of the explosive's true density, detection of the explosive with this dilution factor is still likely to be difficult if the decision is to be made only on the basis of simple thresholds on the number of gamma rays detected at each energy. Of course, much more information may be extracted if more sophisticated pattern-recognition techniques (including image processing) are applied to the data.

Because the dilution in the apparent density of sheet explosives is directly related to the spatial resolution that is achievable, this will certainly provide the motivation for continued improvement of the system's spatial resolution. With the improvement in spatial resolution that appears to be within the reach of a modest effort at the present, the ratio of the true volume of the explosive to the volume of the explosive's image could be increased to 0.07 for the configuration illustrated in Fig. 42. The apparent density of the explosive would then be approximately 5.3% of the explosive's true density, which would still be likely to make detection difficult. With a more ambitious set of modifications, the system might realistically be tailored to the effective detection of sheet explosives, but this would include substantial changes to the current system, and the geometry for detection would be significantly different than that of the conceptual design illustrated in Fig. 37.

F. Detection of a 10-lb Bulk Explosive in a 4- by 4- by 4-ft Box

The last scenario for which the performance of an NDP system is to be considered is that of a 10-lb explosive concealed within a 4- by 4- by 4-ft box. Because of the large size of this container, it would not be practical to apply a system such as the one considered for the previous two scenarios, which was designed for the interrogation of smaller objects. For the present scenario, a different conceptual system, illustrated in Fig. 38, was considered. In contrast to the previously considered conceptual design, this mobile system could be moved to the location of a suspicious object without disturbing the object itself. Furthermore, the design of this conceptual system would be modular,

allowing it to interrogate objects that differ in size and shape from the 4- by 4- by 4-ft cube currently being considered.

The conceptual system illustrated in Fig. 38 would consist of three rectangular arrays of 45 5- by 5- by 5-in. detectors. Each array would be mounted on a wheeled cart that could be easily moved by a single operator, and each cart would include mechanisms that would allow the detector arrays to be raised or lowered to the optimal height and orientation for interrogation of the suspicious object. One of the carts would be designed in such a manner as to allow its detector array to be positioned above the object to be interrogated.

In use, operators would move the detector system into nearby positions surrounding the object to be interrogated. The neutron generator and associated electronics could be mounted on one or two wheeled carts. Once the position of the neutron generator had been chosen, the detector arrays could be rolled into position near the object to be interrogated, yet outside the interrogation volume. Mobile neutron-shielding modules could then be rolled into position to minimize the background counting rate associated with the interaction of neutrons in the detector arrays. Finally, electrical connections could quickly be made between the detector arrays and the electronics carts by the use of cable harnesses having only a single multiconductor connector at each end. The interrogation could be monitored remotely with display and control electronics that could also be mounted on a mobile cart. Communication between the remote display-and-control electronics and the other electronics carts located near the object of the interrogation could be achieved either through a direct cable-harness link or through suitable telemetry.

The composition of the explosive was assumed to be 2.1% H, 36.2% C, and 29.4% each for N and O by weight. The density was taken as 1.68 g/cm^3 , and the shape was assumed to be cubic with sides 13.9 cm long. For the present scenario, the 10-lb high explosive was assumed to be located within a 4- by 4- by 4-ft box as illustrated in Fig. 43. The assumed position of the neutron generator and the detector arrays is also illustrated in Fig. 38. With the arrangement illustrated in Fig. 43, the distance from the neutron-generator target to the center of the explosive would be

Fig. 43. Position of the box and explosive for the scenario developed for the second conceptual design.

approximately 216 cm. The average distance from the center of the explosive to the face of each detector array would be about 116 cm.

In a realistic scenario, it is plausible that there may not be access to all sides of the object to be interrogated. For example, if the box in Fig. 43 were to be positioned adjacent to a wall, or worse, if it were to be located in a corner of the room adjacent to two walls, one could not have access to some sides of the box without disturbing it. For the purposes of the present analysis, therefore, the conservative assumption was made that there is access to only three sides of the box, which is the situation that would result if the box were located in the corner of a room. In this instance, only two of the three detector arrays might be used, with the result that the total interrogation time required would be increased about 50% over the time required if all three arrays could be used. The location of the neutron generator and detector arrays illustrated in Figs. 38 and 43 allows 98.5% of the volume of the box to be interrogated during the first inspection. To view the entire volume of the box in a single interrogation, it would be necessary to move the neutron generator approximately 60 cm farther from the box, thereby reducing the neutron flux through the box and increasing the required interrogation time. It would also be necessary to move the detector arrays about 25 cm farther from the box, which would require an additional increase in the interrogation time. These increases in the interrogation time and the accompanying reduction in the resolution and sensitivity would be both prohibitive and unnecessary.

The shape of the volume that would remain uninterrogated after the first examination is somewhat irregular, and it is illustrated in Fig. 44. Although only 98.5% of the volume of the box falls within the interrogation volume for this position of the neutron generator, it would be difficult to conceal a single 10-lb mass of explosive entirely within the volume that remains uninterrogated after the first inspection. And even though two interrogations would be required to examine the entire box, it is likely that the total interrogation time required would be shorter with two interrogations than the interrogation time that would be necessary to examine the box's entire volume in a single interrogation.

Fig. 44. Shape of the uninterrogated volume for the scenario considered for the second conceptual design.

Table XXII summarizes some of the assumptions that were made in projections of the conceptual system's ability to detect a 10-lb mass of high explosive within a 4- by 4- by 4-ft box, for the geometry described by Figs. 38 and 43.

Table XXII. Assumptions made in projections of the NDP system's ability to detect a 10-lb mass of high explosive sequestered within a 4- by 4- by 4-ft box.	
Explosive's Density	1.68 g/cm ³
Explosive's Dimensions	13.9 x 13.9 x 13.9 cm
Hydrogen	2.1%
Carbon	36.2%
Nitrogen	29.4%
Oxygen	29.4%
MCP Resolution	0.052r x 0.052r (3° of arc), FWHM
Radial (Time) Resolution	11.7 cm (2.3 ns)

Some of the results of the calculations are listed in Table XXIII. Because of self-attenuation in the explosive, the neutron flux in the explosive, averaged over the explosive's volume, would be only about 47% of that which reaches the explosive. Self-attenuation of gamma-rays by the explosive would reduce the observed number of gamma rays by a factor of about 15%.

Table XXIII. Calculated results based on a 10-lb mass of high explosive located 216 cm from the neutron-generator target.	
Macroscopic Cross Section	0.13 cm ⁻¹
Average Neutron Transmission	47%
Average Gamma-Ray Transmission	85%
Average Voxel Dimensions	11.2 x 11.2 x 11.7 cm, FWHM
Dimensions of the Explosive's Image	15.6 x 15.6 x 15.9 cm, FWHM
Number of Voxels Occupied by Explosive's Image	2.6

The estimated gamma-ray detection rates for the most significant lines of C, N, and O are listed in Table XXIV. Despite the large self-attenuation of neutrons and the relatively large distances between the explosive and the neutron generator and gamma-ray detectors, the gamma-ray detection rates are not prohibitively small.

Table XXIV. Estimated counting rates for the full-energy gamma-ray peaks of gamma rays emitted from a 10-lb mass of high explosive positioned as illustrated in Figs. 38 and 43.			
Gamma-Ray Energy (MeV)	Carbon (s^{-1})	Nitrogen (s^{-1})	Oxygen (s^{-1})
2.31	—	1.8	—
4.43	5.2	—	—
5.1	—	1.1	—
6.13	—	—	2.5
6.92	—	—	0.7
7.12	—	—	0.9
TOTAL	5.2	2.8	4.1

These gamma-ray detection rates do not take into account the effects of attenuation of neutrons and gamma rays by materials surrounding the explosive. These effects will be considered at the end of the present analysis.

Using the gamma-ray detection rates listed in Table XXIV, projections were made of the maximum time that would be necessary to detect the quantities of C, N, and O present in the 10-lb mass of high explosive, given the situation illustrated in Fig. 43. The numbers listed in this table are the times estimated to be necessary simply to detect the presence of the C, N, and O in the explosive at the 90-10 confidence level of the total mass, and they do not include any requirement for imaging. It is also assumed for the moment that there are no other C-, N-, or O-containing objects present in the interrogation volume.

With the explosive, neutron generator, and detector arrays positioned as illustrated in Figs. 38 and 43, Table XXV shows that approximately 1 - 2 min would be necessary to detect the presence of the quantity of C, N, and O that would be present in a 10-lb mass of high explosive (if the

Table XXV. Estimated time necessary to detect the presence of the C, N, and O contained in a 10-lb mass of high explosive for the detection geometry illustrated in Figs. 38 and 43. Detection is based on the counting statistics necessary to achieve 90-10 confidence of the total mass present.			
Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	58	—	—
2.31 and 5.1	—	105	—
6.13, 6.92, and 7.12	—	—	74

neutron and gamma-ray attenuation of surrounding materials were not severe). If, after a few minutes, the system had not detected a sufficient mass of each of these elements to constitute a potential threat, then it would be possible to either continue the interrogation to establish whether there might be a smaller mass of explosive or to proceed with the interrogation of the small volume of the box that remains uninterrogated. If, during the first few minutes of the interrogation, the threshold mass of each element were detected within the box, then a longer interrogation would be required to determine the distribution of each element within the box. Table XXVI shows the time estimated to be necessary to image each element in the explosive with 90-10 confidence of the mass present in each voxel, given the spatial resolution presently achieved by the NDP system.

Table XXVI. Estimated time necessary to image the C, N, and O contained in a 10-lb mass of high explosive with 90-10 confidence of the mass of each element in each voxel. The explosive is assumed to occupy approximately 2.8 voxels whose average dimension is 11.2 by 11.2 by 11.7 cm. The explosive is also assumed to be positioned as illustrated in Fig. 43.			
Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	180	—	—
2.31 and 5.1	—	325	—
6.13, 6.92, and 7.12	—	—	230

At 216 cm from the neutron-generator target, the spatial resolution due to the MCP would be about 11.2 cm, which is comparable to both the NDP's time resolution and to the length of the explosive in each dimension. The signal density of the explosive's image with this spatial resolution would be approximately 32% of the explosive's true density, which may be adequate for this application of the system. Table XXVI indicates that in the absence of significant attenuation of neutrons and gamma rays by materials surrounding the explosive, the C, N, and O in the 10-lb mass of high explosive could be imaged at the 90-10 confidence level in each voxel with an interrogation time of between 3 and 7 min.

The performance of the system would be improved if better spatial resolution were possible. Table XXVII lists the estimated interrogation times that would be necessary to image the 10-lb mass of high explosive for the detection geometry of Figs. 38 and 43 if the spatial resolution were improved to 2.6° of arc for the MCP and 1.5 ns for the time resolution.

The signal density with this spatial resolution is expected to be 45% of the explosive's true density. Table XXVII indicates that interrogation times of between 2 and 4 min would be necessary to image the explosive at the 90-10 confidence level of the mass of each element in each voxel of the explosive's image. Furthermore, the statistical criterion for imaging would be relaxed with

Table XXVII. Estimated time necessary to image the C, N, and O contained in 10 lb of high explosive with 90-10 confidence of the mass of each element in each voxel. The explosive is assumed to occupy approximately 4.3 voxels whose average dimension is 9.7 by 9.7 by 7.7 cm, and it is assumed to be positioned as illustrated in Fig. 43.

Gamma-Ray Energies (MeV)	Carbon (s)	Nitrogen (s)	Oxygen (s)
4.43	130	—	—
2.31 and 5.1	—	235	—
6.13, 6.92, and 7.12	—	—	165

improvements in the spatial resolution, allowing an added reduction in the necessary interrogation time. With reduced background counting rates, the statistical requirement for the number of counts necessary in each voxel to produce a good image would be relaxed.

G. Some Effects of Materials Surrounding an Explosive upon the Conceptual System's Ability to Detect Explosives

The analyses presented in Secs. V.C. - V.F. were simplified by neglecting the effects of surrounding materials on the detection of an explosive. In fact, these effects are not likely, in general, to be negligible. While it is possible to develop a highly accurate model of these effects for a known composition and distribution of materials, performance of such modeling is beyond the scope of the current evaluation program. It is possible, however, to draw general conclusions about the effects of materials surrounding the explosive for the examples of Secs. V.C. - V.F. by applying a much simpler model of the interactions of neutrons and gamma rays with these materials.

For the purposes of the present analysis, two main effects of surrounding materials upon the detection of explosives will be considered: (1) shielding effects and (2) background-enhancing effects of gamma rays produced in reactions that involve secondary neutrons. The consequences of the first are obvious. Materials surrounding the explosive attenuate the probing flux of neutrons, thereby reducing the rate of gamma-ray production in the explosive. Likewise, these materials attenuate the gamma rays that are emitted from the explosive, reducing the number of gamma rays that would otherwise reach the detectors. Both of these attenuation effects reduce the gamma-ray detection rate and therefore increase the time that is required to complete an adequate interrogation. The production of gamma rays in reactions involving secondary or scattered neutrons may result in a significant background because the trajectories of these neutrons are unknown. The points of origin of these gamma rays will therefore be identified incorrectly in the image produced by the system.

To make a rough estimate of how materials surrounding an explosive might affect each conceptual system's ability to detect explosives, some assumptions were made about the composition and quantity of materials that could be expected to surround the explosive in each of the scenarios discussed in Secs. V.C. - V.F. In the first two examples considered in Sec. III, explosives were assumed to be concealed inside a suitcase. The total mass of the suitcase in each example was assumed to be 13.4 kg, with a mass density of 0.18 g/cm^3 . The composition of the suitcase's nonexplosive contents was assumed to be 3.5% H by weight, and the remainder of the mass was assumed to be a combination of C, N, and O. These assumptions were based on the characteristics found to be typical of luggage that was scanned during airport tests of other explosive detection systems.¹⁰

For the first orientation of the suitcase considered in Sec. III.B., the average thickness of material traversed by neutrons prior to reaching the C4 explosive was assumed to be approximately 23 cm. Calculations indicate that about 28% of the flux of 14-MeV neutrons would be attenuated prior to reaching the explosive upon passing through this thickness of the material assumed to surround the explosive. The average path length of gamma rays through the suitcase was assumed to be about 12.5 cm. Approximately 3% of the gamma rays emitted from the explosive would be absorbed by passing through this thickness of material. The combined effect of this neutron and gamma-ray attenuation in the materials surrounding the explosive would be a reduction in the observed gamma-ray detection rates to about 79% of those presented in Table VII. This would increase the initial interrogation time required to approximately 14 - 25 s. The time necessary for imaging the explosive at the 90-10 confidence level would increase to about 85 - 150 s. With the spatial resolution improved to 2.6° of arc and 1.5 ns, the interrogation time required for 90-10 imaging would be about 50 - 90 s.

For the second orientation of the suitcase considered in Sec. III.B., the average path length of neutrons through the suitcase prior to reaching the explosive was assumed to be approximately 30 cm, while the average gamma-ray path length through the suitcase was assumed to remain about 12.5 cm. In this case, the neutron attenuation would be increased to about 35%, while the average gamma-ray attenuation would remain at about 3%. The rate of detection of gamma rays emitted from the explosive would thus be about 63% of the rates indicated in Table XII. Because of the reduced gamma-ray detection rate, the initial interrogation would require approximately 35 - 60 s, while the interrogation time required for imaging of the suitcase would increase to about 130 - 225 s. With the improvement in spatial resolution that was assumed achievable with modest improvements to the system, the imaging time would be about 75 - 130 s.

In Sec. III.C., the blurring of the sheet explosive's image was shown to pose the greatest obstacle to detection, and the overall rate of gamma-ray detection was not a primary limitation of the system's performance. Therefore, this example will not be considered with regard to the effects of materials surrounding the explosive.

The composition of the materials surrounding the 10-lb explosive in the example of Sec. V.F. was chosen on the assumption that the explosive might be concealed within a large appliance such as a document photocopier. The detailed composition and distribution of the box's content were not modeled, but attenuation effects were estimated by assuming that the box contained 270 kg (about

600 lb) of iron distributed evenly over the box's volume. The average path length through the box was assumed to be about 115 cm for both neutrons and gamma rays. With these assumptions, the estimated reduction in neutron flux would be about 38%, while the reduction in the number of gamma rays reaching the detector arrays would be about 21%. The gamma-ray detection rate in the presence of these materials would therefore be approximately 49% of the values listed in Table XXIV. The initial interrogation time required would increase from the 1 - 2 min indicated in Table XXV to between 2 and 4 min, and the interrogation time necessary for imaging would increase to about 6 - 11 min. With the improved spatial resolution assumed in Table XXVII, the imaging time would be about 4 - 8 min.

In these examples, the effects of neutron and gamma-ray attenuation in materials surrounding the explosive are considerable, but they probably do not make the system inviable for certain applications. With a known composition and distribution of materials, it is a fairly simple matter to estimate how much additional time must be spent to adequately interrogate each object. In practice, of course, if the composition and distribution of the materials in an object were known, its interrogation would be unnecessary. In fact, the actual composition could be very different from that which has been assumed in the examples considered above. Common aggregations of materials such as copper, iron, polyethylene, wax, and water are very effective attenuators of fast neutrons, while materials having a high atomic mass number (such as iron, copper, lead, and bismuth) could be very effective attenuators of the gamma rays emitted from an explosive. If a combination of these materials were to surround an explosive, it is possible that the explosive could be very effectively shielded from detection by a system like the NDP. Fortunately, the NDP system should be capable of identifying the presence of significant masses of these shielding materials by detecting the gamma rays that would be emitted from them in fast-neutron interactions. For example, if, in the scenario described in Sec. V.F., a typical automobile battery were to be placed between the neutron-generator target and the 10-lb explosive, the neutron flux reaching the explosive would be significantly reduced. Likewise, if the battery were to be placed between the explosive and one of the detector arrays, the effect would be to significantly attenuate the gamma rays (emitted from the explosive) that would otherwise have reached the detector array.

Calculations were performed in which the attenuation of neutrons and gamma rays was estimated for penetration through a 17-kg battery consisting of 9.5 kg of lead and 7.5 kg of a solution of water and sulfuric acid. With the detection geometry illustrated in Fig. 43 for the conceptual system, a single automobile battery would not be capable of simultaneously shielding both the explosive from neutrons and the detector arrays from the gamma rays emitted from the explosive. For this reason, two positions of the battery were considered in the analysis: one in which the explosive would be shielded from exposure to the probing flux of neutrons and another position in which one of the detector arrays would be shielded from the gamma rays emitted from the explosive. The dimensions of the battery were assumed to be 16 by 18 by 23 cm, and for each position considered, the orientation of the battery was assumed to be such that the 16-cm dimension of the battery would be aligned with the direction traveled by the neutrons or gamma rays being shielded. This orientation was chosen because it would cast the largest shadow and would therefore be the orientation of the battery that could most easily shield the entire explosive. With this orientation of the battery, the lead plates inside the battery would be perpendicularly

oriented with respect to the trajectories of the neutrons and gamma rays being shielded, resulting in more uniform attenuation.

The results of the calculations indicate that the battery would reduce the useful neutron flux reaching the explosive to about 16% of the flux that would otherwise reach the explosive. The calculations also showed that if the battery were to shield a detector array from the gamma rays emitted by the explosive, the number of gamma rays detected would be reduced to about 17% of the number that would otherwise be detected. In fact, because a single automobile battery would not be capable of shielding more than a single detector array, the reduction in the gamma-ray detection rate would be smaller than that which is suggested by the calculations.

In this example, the shielding caused by the automobile battery would increase the interrogation times required to thoroughly interrogate the box by a factor of up to about 6.5 over those that were suggested in the analyses presented in Sec. V.F. Thus, the initial interrogation time necessary might increase to between 6 and 11 min; the 90-10 imaging time with the spatial resolution of the current system might range from 19 - 35 min, and the imaging time with the improvements in spatial resolution assumed in the previous examples might be between 14 and 25 min. While it may be argued that these results are still not prohibitive for the application being considered, it is obvious that only a slightly greater cost and effort on the part of a terrorist would be required to achieve essentially perfect shielding of the explosive. This could be accomplished by surrounding the explosive with batteries or other shielding materials instead of using just the one battery that was assumed in the example considered here. Furthermore, with the reduced rate of detection of gamma rays emitted from the explosive that would be caused by the presence of shielding materials, it would be necessary to examine in closer detail whether an acceptable signal-to-background ratio could be achieved. The important question here is not whether the explosive could be detected in a reasonable amount of time in the presence of countermeasures, but rather it is whether such shielding materials could be identified and localized by the system within the same interrogation time that would otherwise have been required to image the explosive in the absence of countermeasures. If this were possible, then the information provided would constitute a valuable diagnostic as to how to proceed with the interrogation of the box or the elimination of the potential threat.

In the case described above of the automobile battery, there are a number of very strong gamma-ray lines that might be used to detect the presence of lead. In fact, some of the gamma rays emitted by lead in fast-neutron reactions are many times stronger than the strongest lines of C, N, and O (a characteristic that may be of use in the detection of explosives such as lead azide and lead styphnate). Unfortunately, the strongest gamma-ray lines of lead appear at relatively low energy and would therefore be superimposed upon a larger Compton continuum, which might make them difficult to use. On the positive side, these gamma rays are fairly close to each other in energy and would probably appear in gamma-ray spectra as a distinctively broad and irregularly shaped peak. For larger masses, there can be little doubt that detection would be a simple matter. For now, the question is whether an automobile battery could be detected within the same time that would be necessary to detect a 10-lb explosive in the absence of countermeasures. The estimated gamma-ray detection rates for a single battery, listed in Table XXVIII, suggest that even a single automobile battery at the relatively large distance from the neutron generator that has

been assumed in this example would have a high probability of detection within the time that would otherwise be required to detect the explosive in the battery's absence.

Table XXVIII. Estimated counting rates for the most prominent full-energy gamma-ray peaks emitted from the lead in a typical automobile battery positioned in close proximity to the explosive illustrated in Fig. 43.	
Gamma-Ray Energy (MeV)	Lead (s^{-1})
0.81	8.6
0.89	4.8
0.99	3.0
1.06	9.5
1.77	1.8
2.62	2.4
TOTAL	30.2

Table XXIV from Sec. V F., which listed the gamma-ray detection rates for the most significant lines of the C, N, and O in a 10-lb explosive that would be expected in the absence of neutron or gamma-ray shielding is repeated below (as Table XXIX) for comparison with Table XXVIII.

A comparison of Tables XXVIII and XXIX shows that even a single automobile battery, which would constitute only a modest attempt to shield an explosive, would have an identifiable signature that may be many times stronger than that of the explosive itself. Certainly the 2.6-MeV gamma rays of lead would be a usable signature for detecting the presence of the lead, and these gamma rays alone are estimated to have a full-energy-peak detection rate that would be comparable to the sum of the detection rates of the most significant lines of the nitrogen contained in the explosive. In addition, the oxygen content of the automobile battery would be about twice that of the explosive. Although this would be balanced by the self-attenuation of neutrons and gamma rays in the battery (which would be about 2.5 times greater than the self-shielding effect in the explosive), the oxygen gamma-ray signals could certainly be expected to provide an additional strong signature of the presence of the battery.

Assuming no improvement in the spatial resolution of the conceptual system considered here over that which is achievable with the current lab system, the time required to image the battery on the basis of the signatures of its lead content alone would range between about 20 and 200 s, depending upon which gamma rays were used for imaging. If all of the most significant gamma rays listed in Table XXVIII could be used, then the interrogation time required to image the lead

Table XXIX. Estimated counting rates for the full-energy gamma-ray peaks of gamma rays emitted from a 10-lb mass of high explosive positioned as illustrated in Fig. 43.

Gamma-Ray Energy (MeV)	Carbon (s^{-1})	Nitrogen (s^{-1})	Oxygen (s^{-1})
2.31	—	1.8	—
	5.2	—	—
5.1	—	1.1	—
6.13	—	—	2.5
6.92	—	—	0.7
7.12	—	—	0.9
TOTAL	5.2	2.8	4.1

at the 90-10 confidence level might be as short as 20 s, whereas if only the 2.6-MeV line were to be used, the imaging time would be closer to 200 s. These are shorter interrogation times than the 180- to 325-s interrogation times that were estimated to be required to detect the 10-lb explosive in the absence of shielding materials. This is a very important aspect of the system's performance because information regarding the presence of shielding materials would be crucial to the interpretation of the interrogation results and would provide an extremely valuable diagnostic as to how much additional time would be required to adequately interrogate any shielded volumes of space. Of course, the ability of the system to reveal the manner in which shielding materials are distributed would also be a very useful diagnostic as to whether shielded volumes of space could be interrogated more effectively from a different perspective.

As was noted at the beginning of this section, the discussion that has just been presented is based upon very simple models and assumptions about the materials that might surround the explosive in each of the scenarios considered in Secs. V.C. - V.F. Nevertheless, the results of the analyses upon which the discussion was based suggest that while materials surrounding an explosive may effectively shield it from being directly detected, there is reason to believe that such countermeasures could themselves be detected by a system based on the associated alpha particle technique. Not only would the detection of such potential countermeasures result in more detailed scrutiny of any object within which they are detected, but the imaging that an associated alpha particle system could provide of shielding materials would provide information important to either the further interrogation of the object being examined or to the determination of the best means of eliminating the possible threat. As is the case with the detection of explosives, it is the detection of the threshold mass of shielding material that will be the limiting parameter in the system's performance, since larger masses will be readily detected and smaller masses will be less effective.

As mentioned at the beginning of this section, there is another possibly significant effect of materials surrounding an explosive that will be considered here. As the 14-MeV neutrons penetrate through increasing thicknesses of material, the number that have not reacted with the materials through which they have passed (referred to here as primary neutrons) drops exponentially. In most of the fast-neutron reactions that occur, incident neutrons will be scattered either elastically or inelastically, as illustrated in Fig. 45. (The elastically or inelastically scattered neutrons, as a group, will be referred to in the remainder of the discussion as secondary neutrons.) Thus, the number of secondary neutrons can be expected to increase exponentially as the number of primary neutrons decreases. Because the secondary neutrons often remain quite energetic even after multiple reactions, their reaction cross sections are comparable to those of the primary neutrons. Therefore, as the probing flux of primary neutrons penetrates to increasing depths, an increasing fraction of the gamma rays detected can be expected to originate from reactions that are induced by secondary neutrons. Unfortunately, the trajectories of these neutrons are not uniquely

Fig. 45. Illustration of the effect of secondary-neutron interactions. A primary neutron (n_0) is emitted from the STNG target and scatters from a nucleus in the interrogation volume at position A. The scattered neutron (n_1) subsequently scatters from another nucleus at position B_1 . There is no way, however, for the NDP system to correctly identify the point of interaction of the scattered neutron because its trajectory is unknown. The gamma ray emitted from B_1 is indistinguishable from one that might have been emitted from B_2 , for example. The NDP system will, in any case, map the position of the secondary neutron interaction to a point (B) along the trajectory of the initially emitted neutron, corresponding to the sum of the primary and secondary neutrons' times of flight.

correlated with the known trajectories of the primary neutrons, so the locations of the gamma-ray-producing reactions of the secondary neutrons cannot be identified in the same way that the reaction sites of the primary neutrons are determined. Gamma rays emitted as a result of the interactions of the primary neutrons are not distinguishable from those that are emitted in reactions that involve secondary neutrons, with the exception that some of the secondarily emitted gamma rays will be mapped to radial coordinates that clearly fall outside the volume of the object being interrogated. A gamma ray emitted in a reaction that involves a secondary neutron and that is detected within the coincidence window of the data acquisition system will therefore be mapped to the position in space that the corresponding primary neutron would have occupied had it continued on its initial trajectory for the measured TOF. Gamma rays originating from secondary-neutron reactions can therefore be expected to constitute an ever-increasing source of background with increasing thicknesses of material to be interrogated. In other words, the signal-to-background ratio of the image can be expected to decrease as the thickness of material penetrated by the neutron probe increases. Because the only discernable difference between gamma rays originating from primary-neutron-induced reactions and those originating from secondary-neutron-induced reactions would be in their times of detection, the only possibility that currently exists to discriminate between these gamma-ray signals is to reject those signals that are clearly mapped to positions outside the object that is being interrogated. This, however, will usually allow only a fraction of the total number of secondary-neutron-induced gamma rays to be rejected. In the next section, an alternative conceptual design will be described that should be effective in significantly reducing the background signals associated with secondary neutrons. For the moment, a heuristic analysis of the significance of secondary-neutron-induced gamma-ray background effects will be presented for the examples that were considered in Secs. V.C. - V.F., and earlier in Sec. V.G.

The expected mean free path of 14-MeV neutrons would be about 70 cm in the material (3.5% H by weight with a combination of C, N, and O to give a total mass density of about 0.18 g/cm^3) assumed to surround the explosive in the previous examples in which an explosive was concealed within a suitcase. Thus, about 30% of the neutrons entering the suitcase could be expected to interact prior to escaping. The trajectories of secondary neutrons would not be isotropically distributed, but rather would be biased in the directions corresponding to the trajectories of the primary neutrons. In the first orientation of the suitcase considered, the average thickness of material that a secondary neutron would have to traverse before passing out of the suitcase might therefore be about 12 - 15 cm. If the average thickness of material traversed by secondary neutrons were 15 cm and if the mean free path of the secondary neutrons were the same as that of the primary neutrons, then about 20% of the secondary neutrons (about 6% of the primary neutron flux) could be expected to react with nuclei in the suitcase. (Following this line of reasoning, the ratio of the number of tertiary-neutron interactions to the number of primary-neutron interactions within the suitcase would probably be less than 1%.) Assuming that the rate of gamma-ray production would be essentially the same for secondary neutrons as it would be for primary neutrons, the background signal rate attributable in this example to secondary neutrons would be about 6% of the gamma-ray signal rate associated with primary neutrons. This background would usually be concentrated in the region of the C and O lines because of the organic nature of the surrounding materials.

In the second orientation of the suitcase, about 50% of the neutrons entering the suitcase would react with the contents of the suitcase prior to escaping. If the average thickness of material traversed by secondary neutrons in this example were about 25 cm, and assuming the mean free path of the secondary neutrons would be the same as that of the primary neutrons, then about 30% of the secondary neutrons (about 15% of the primary neutron flux) could be expected to react within the suitcase. Again assuming that the rate of gamma-ray production is essentially the same for the primary and secondary groups of neutrons, the background signal rate estimated to be attributable to secondary neutrons would be about 15% of the signal rate associated with the primary neutron flux.

Some of these gamma ray signals could certainly be rejected because of their late time of detection, but the point here is not to provide a precise estimate of the effect of secondary-neutron interactions, but rather to illustrate that the signal-to-background ratio (S/B) may be significantly degraded with increasing depth and to suggest that this is a potentially significant effect that should be examined in greater detail.

For the example of the 10-lb explosive concealed in the 4- by 4- by 4-ft box, the explosive was assumed to be surrounded by iron with a mean density of 0.15 g/cm^3 . The mean free path of 14-MeV neutrons in this material would be about 240 cm. About 40% of the primary neutron flux might therefore be expected to interact within the box. Assuming that the average thickness of material traversed by secondary neutrons would be only about 60 cm, then about 20% of the secondary neutrons would react within the box. In other words, in this example, the number of secondary-neutron-induced background gamma rays might be as much as 8% of the number of primary-neutron-induced gamma rays detected, although as in the previous example, some fraction of the background gamma rays could be rejected on the basis of their times of flight.

Before concluding this chapter, it must be emphasized that the last discussion regarding the potential effects of multiple neutron interactions was highly subjective, and the calculations upon which the discussion was based can only be considered to provide a crude representation of the complicated physical processes that are involved. Indeed, because there has been almost no development to date of the image-processing techniques that would be applied to the data acquired by a system such as the NDP, there is little basis for determining what an acceptable background rate would be and whether the rates that this analysis suggests might be possible would prevent the system from effectively detecting explosives. Although more detailed modeling of these effects is beyond the scope of the current evaluation program, it seems to be clear that consideration of these effects should be a part of future evaluations and should also play a part in consideration of the range of applications to which the associated alpha particle technique could be usefully applied.

VI. RECOMMENDATIONS

The NDP system demonstrates the feasibility of using systems based on the associated alpha particle technique in applications such as explosive detection. However, the current laboratory prototype suffers from many shortcomings and limitations that make it impractical for such applications. Various improvements are recommended here for each component of the current system's design to make the system more useful for realistic applications. These improvements

generally address three aspects of the system's performance: efficiency, spatial resolution, and data handling and analysis. Also suggested are areas where further research and development efforts should be committed, and some applications to which the associated alpha particle technique may be best suited.

A. Neutron Generator

Obviously, the neutron generator is central to the associated alpha particle technique. The design and capabilities of the neutron generator are major factors in determining the overall performance of the system. To be practical, an associated alpha particle system such as the NDP must offer reliability, a continuous neutron output rate between about $5(10^7)$ and $1(10^8)$ n/s, and (depending upon the alpha-particle detection geometry) a beam-spot size no larger than about 1 - 2 mm, FWHM. A neutron-output rate in the range $\sim 5(10^7)$ to $1(10^8)$ n/s is required if interrogations are to be completed in a reasonable amount of time, while the constraint on beam-spot size arises because of the spatial resolution that is likely to be required in practical applications. Additional desirable qualities would include simplicity of design, ease of use, compactness, and low cost. Unfortunately, there is probably no existing system that satisfies all of these needs, although different subsets of these qualities are offered by a number of existing neutron generators.

While the NDP system's STNG does enjoy a number of desirable characteristics, such as small (~ 2 mm, FWHM) beam-spot size, compactness, simplicity of design, ease of use, and relatively low cost, its ability to reliably provide a continuous output in the range of $5(10^7)$ to $1(10^8)$ n/s has not been demonstrated. During the evaluation, the performance of the STNG was found to be adequately reliable when operated at low neutron-output rates [$\sim 3(10^5)$], but a significant reduction in its neutron-output rate was observed after about 300 - 400 h of operation. This was probably caused by contamination of the target by materials sputtered from other surfaces that are exposed to ion bombardment. (It should be noted that this system's STNG was presumably operated for some large number of hours prior to its shipment to Los Alamos.) Despite this generally reliable performance, however, there is good reason to believe that when the generator is operated at the high neutron outputs required for practical applications, the lifetime of the generator would be prohibitively shortened.

Active mechanisms such as a rotating target or closed-loop water or freon cooling will probably be necessary to dissipate enough heat from the target to provide both reliable neutron-output rate in the range between $5(10^7)$ and $1(10^8)$ n/s and a beam spot of between 1 and 2 mm. Whereas heat is dissipated from the target in the present system through the high-conductivity copper post upon which it is mounted, the beam-spot power density of a practical system would be 2 - 3 orders of magnitude greater than that of the present system, and a passive heat sink such as the copper post would probably not provide target cooling adequate to prevent damage. Because of the need to increase the neutron-output rate while minimizing beam-spot size, neutron-generator development should be emphasized in short-term system-development efforts. While the need for more effective target cooling will certainly add somewhat to the cost, complexity, and size of the neutron generator, the technologies for target rotation and liquid cooling are well-developed and probably do not represent a large obstacle to the creation of a practical full-scale system.

B. Alpha-Particle Detection and Detection Geometry

Effects related to the beam-spot size play the most important role in determining how accurately neutron trajectories are measured in the NDP system, and this is likely to be true of future systems as well. Although this provides the motivation to continue efforts to minimize the beam-spot size, considerations of heat transfer from the target will limit the improvements that can be made in this regard. As was shown in Sec. IV, however, the present laboratory prototype also suffers from other factors that significantly degrade the spatial resolution. In the dimensions imaged by the MCP, the most significant of these (other than that which may be attributed to the size of the beam spot) appears to be related to the poor coupling of the image of the ZnS(Ag) scintillator screen to the MCP. To minimize these effects, the design and geometry of the alpha-particle detector should be reviewed and modified.

The re-evaluation of the detector's design should begin with a reconsideration of the original motivation for the alpha-particle detector's present design, which was ostensibly based on the need to achieve good time resolution. According to a report by CCC,⁷ the MCP would not be capable of providing suitable timing signals at the alpha-particle detection rates expected in most applications because of the small value of the anode current available. It is well known, however, that the MCP's design provides it with very good timing characteristics, and the MCP's manufacturer (ITT Electro-Optics) refers customers to a paper¹¹ by W.G. McMullan et al., in which 500-ps time resolution (FWHM) was demonstrated with an MCP almost identical to the one used in the NDP system. Whereas there are a number of reasons why it would not be practical to obtain time signals from the resistive anode of the MCP, this paper suggests that with a very simple circuit, timing signals could be obtained from the transient positive voltage that develops across the last of the three MCPs that are cascaded in the ITT Model F4146 MCP. There is no apparent reason why this would not work in the NDP application, as this approach would have an insignificant effect upon the MCP's performance even at the detection rates anticipated in practical applications. It was shown in Sec. IV that the timing uncertainty associated with the NaI(Tl) detector dominates the present system's time resolution. Therefore, use of the MCP for timing would not result in a great improvement in the system's overall time resolution. It would, however, result in a significant improvement in the system's spatial resolution if the present system's cumbersome optics could be simplified and improved by eliminating the mirror and by either improving or eliminating the focusing of the lens, since these components appear to degrade the current system's performance.

In the NDP system, the image of the ZnS(Ag) screen was reduced through a lens to the same size as the MCP's active area. If the MCP could be used for timing purposes, the need for the mirror could be eliminated, but it would still be necessary to match the size of the ZnS(Ag) image to the active diameter of the MCP. If a lens were still to be used for this purpose, the focusing mechanism should be designed very carefully. Particular care should be taken in the choice of the lens to be used and how it is coupled to the MCP. In addition, the focusing mechanism should be easily adjustable. To meet these needs, the focusing mechanism may require a compound lens and a suitable aperture as is found in a camera's focusing mechanism. It is not likely that a simple lens like the one in the present system will provide adequate resolution.

Another alternative would be to eliminate the lens from the system completely. This could be achieved either by proximity focusing of the ZnS(Ag) image onto the MCP (which would restrict the size of the interrogation volume to the solid angle subtended at the STNG target by the MCP) or by coupling one or more MCPs to the ZnS(Ag) screen via coherent bundles of optical fibers. For the present system, this latter technique would require about three MCPs like the one presently used to cover the entire area of the ZnS(Ag) screen. Another option that should be considered would be to replace the ZnS(Ag) screen with a face plate of scintillating fibers, again fiber-optically connected with one or more MCPs.

There are obviously a number of possibilities for the ultimate design of the alpha-particle detector, and each design has its own advantages and disadvantages with respect to the others. Because of the different requirements of the many potential applications of a system such as the NDP, the final choice for the design of the alpha-particle detector will depend on each system's intended application. The factors that will affect the design most will be considerations of the required spatial resolution, the solid angle that must be covered by the interrogation volume, and the time that will be allowed for the interrogation (because this will determine the alpha-particle counting rate in the MCP). For example, a simple way to improve the spatial resolution and reduce the chance coincidence rate of the system is to move the ZnS(Ag) screen farther from the neutron generator's target. This reduces the solid angle subtended at the scintillator by the beam spot, thereby reducing the uncertainty in the neutrons' measured trajectories. Likewise, moving the scintillator farther from the neutron generator's target would reduce the alpha-particle detection rate in each MCP because each MCP would then view a smaller solid angle about the target. In each case, however, to continue to cover a fixed interrogation volume, the area of the scintillator screen would increase as the square of the distance between the scintillator and the neutron generator's target. In this instance, the number of MCPs required to view the entire screen would necessarily increase at the same rate. This has obvious consequences in both cost and complexity.

C. Alpha-Particle Scintillator

Because the start signals for the TOF measurements (which give the radial spatial coordinate of the gamma-ray-producing neutron interactions) originate with the emission of light from the scintillator, this scintillator should naturally be chosen to be as fast as possible. But because the scintillator is incorporated into the STNG, which must be baked at a high temperature to obtain a good vacuum, the scintillator must also be capable of withstanding such heat. Unfortunately, although organic scintillators are typically very fast (~1- to 4-ns decay constant), the temperature at which they become soft or begin to melt is very low (~75 - 100 °C), and they cannot survive the temperatures of tube bakeout, which may be up to several hundred degrees. The only alpha-particle scintillators that are capable of withstanding temperatures of several hundred degrees or more are inorganic crystals, and of these, ZnS(Ag) has nearly the highest melting point (1850 °C). In addition, ZnS(Ag) is known for its high scintillation efficiency (~17%), but it has a relatively long main decay constant of about 200 ns. The only other scintillator that may perform better is ZnO(Ga), which has a melting point of 1975°C and a main decay constant of 1.5 ns (comparable to very fast plastics), while giving a light output that is about 30% of ZnS(Ag) light output. This light output is probably adequate if other aspects of the scintillator's performance are suitable (little afterglow, suitable grain size). Although there have been no deficiencies attributed

to the relatively slow response of ZnS(Ag) during the evaluation program, ZnO(Ga) should be considered in this application.

Regardless of the scintillator used in future systems, great care should be taken to ensure that the scintillator's thickness is uniform over the entire scintillation screen so that the system's response will be uniform over the entire interrogation volume. In addition, the scintillator's thickness (grain size in the case of ZnS(Ag) or ZnO(Ga)) should be on the order of the alpha particles' range (at maximum energy) to maintain high efficiency while allowing minimum dispersion of light within the scintillator itself. [For ZnS(Ag), the grain size should probably be chosen to be between about 8 and 10 μm .] Likewise, to minimize light dispersion and to produce the sharpest image possible, the plastic substrate upon which the scintillator is deposited should be as thin as possible and match the refractive index of the ZnS(Ag) scintillator.

D. Microchannel Plate (MCP) Detector and Position Computer

The MCP provides very good spatial resolution (currently available MCPs offer resolution as fine as 30 μm) and very good timing capabilities (~ 0.5 ns), which make it attractive for this application. Not only will the detection of explosives and other contraband materials depend upon the system's energy and spatial resolution, but it will also depend on the system's ability to accurately measure the mass of each element detected. Because these masses are measured by counting the number of gamma rays characteristic of each element that are detected, it is very important that the system should have insignificant dead-time losses, or that these losses be accurately known and small enough to allow interrogations to be completed within the time constraints of the application. While the need for reasonable interrogation times in most practical applications of the system will require high neutron-output rates on the order of $5(10^7)$ to $1(10^8)$ n/s (and hence high rates of position-sensitive alpha-particle detection), the present system is severely limited by the position computer's low counting-rate capability. This is a significant limitation to the system's performance and viability. Even if $5(10^7)$ to $1(10^8)$ n/s could be obtained from the neutron generator, the NDP system's position computer would be far from capable of handling the alpha-particle detection rate.

Surface Sciences Laboratories (SSL) is the primary manufacturer of commercially available position computers at this time, and their Model 2401 X-Y Position Computer is currently used in the NDP system. While a practical system will require the MCP to operate at about 1 - 5 MHz (depending upon the neutron-generator output rate, the solid angle to be covered by the alpha-particle detector, and the number of MCPs to be used), dead-time signal losses with this position computer start to become significant at about 10 kHz. Not only is this an unacceptably low counting rate for practical applications, but it was also found to be unacceptable even for the laboratory system which was operated at only about 1% of the neutron-output rate estimated to be required for a practical system. (Because of this, in fact, the signal losses described at the beginning of Sec. V were not initially attributed to the position computer. These losses occurred at such low counting rates that they were assumed to be caused by some malfunction within the system rather than by the normal dead-time effects in the position computer that now appear to have been responsible for these losses.) To accommodate the counting-rate requirements anticipated for practical systems, several alternatives to the current alpha-particle detection

system should be considered, including the use of a faster position computer, the use of multiple MCPs to view the scintillator screen, and the use of other position-sensitive alpha-particle detectors.

Although SSL currently offers a position computer that is faster than the Model 2401, there are new products now available or soon to be available from Chesapeake Photon Sciences that may provide significantly higher counting rates. Regardless of the position computer chosen, its performance should be optimized for this application to maximize the counting rate without significantly degrading the system's overall spatial resolution. Specifically, it should be possible to achieve significant improvements in the counting rate in exchange for an acceptable degradation in the MCP's position resolution. These improvements could be achieved in two ways: (1) by reducing the voltage on the first MCP plate and (2) by shortening the charge-integration time of the position computer. Both of these steps would degrade the system's position resolution somewhat, but as long as the MCP's resolution is equal to or better than about 0.5 mm, the system's overall spatial resolution will still be dominated by the size of the neutron generator's target beam spot, and the MCP's resolution will have little effect on the system's overall performance. By optimizing the charge-sensitive amplifier and the position computer's performance in this way, the counting rate of the system may be improved by a factor of two or more over that which would otherwise be achievable. The expected upper limit for position computer performance is expected to be on the order of 1 - 1.5 MHz.

The other alternative that should be considered is the use of a different type of position-sensitive alpha-particle detector. Although other types of detectors have their own limitations, such as their time resolution, cost, complexity, and reliability, there are a number of options that merit further consideration. Some of these alternatives include the use of a PIN diode array or an array of discrete scintillators (perhaps scintillating fibers) connected to either a single multi-anode or resistive-anode PMT, or to multiple individual PMT's. Although the use of a single multianode PMT with multiple scintillators has the advantage of simplicity, compactness, and relatively lower cost, the use of multiple individual PMT's has the advantage of faster timing and higher counting-rate capability. Of course, there are many variations that may be made with respect to the type and number of scintillators and PMT's that may be used, and there are other types of position-sensitive detectors that may be viable. This application's requirements will challenge different aspects of each alternative's capabilities. The final choice for the alpha-particle detector will therefore be a complicated matter and may involve various compromises; this choice should take a high priority in further development efforts.

E. Gamma-Ray Detectors

Just as the MCP should be used to resolve three spatial dimensions, the role of the system's gamma-ray detectors is to resolve both the radial position (in conjunction with the MCP) and the energy dimension of the detected gamma rays, each of which is central to the system's overall performance. While the time resolution of the gamma-ray detectors is significant in determining the system's overall spatial resolution in the radial dimension, the energy resolution of the gamma-ray detectors has a fundamental effect on the system's ability to identify the elements that are present in the interrogation volume. In addition, other features of the gamma-ray detectors' response (such as the full-energy peak-to-Compton-continuum ratio and the peak-to-escape ratio)

will also affect the system's ability to interpret the gamma-ray energy spectra. To choose a gamma-ray detector for the system, it will therefore be necessary to balance considerations of time resolution and energy response. The relative importance of each will depend upon the particular application and upon the software available for unfolding of the gamma-ray-energy spectra. Added to this will obviously be consideration of the cost, which is influenced not only by the type of detector chosen, but also by detector size and the solid angle covered (which will determine the number of detectors and associated electronics).

In the present laboratory prototype, the greatest contribution to the system's overall timing uncertainty arises from the time jitter of the NaI(Tl) detector's PMT and (to a lesser extent) the jitter associated with the large volume of the detector. Although the 2.1-ns time resolution of the Hamamatsu R1250 PMT is good for a PMT with such a large diameter, a smaller-diameter PMT would be capable of providing significantly better time resolution. Three-in.-diam PMTs could be used with 5-in. scintillator crystals by using commercially available Lucite light guides. This would significantly improve the system's time resolution, while preserving the advantages in energy response and efficiency afforded by the large detectors.

The overall time resolution could also be significantly improved by using a scintillator with a shorter decay constant, such as BaF_2 , which is intrinsically much faster than NaI(Tl). If BaF_2 were to be used in a system instead of NaI(Tl), and if small, fast PMTs were used, it should be possible to improve the system's overall time resolution to 1 ns (~ 5 cm) compared with the present system's 2.3-ns time-resolution capability (~ 12 cm). This would be done at a cost of slightly poorer energy resolution in BaF_2 as compared with NaI(Tl) (because of BaF_2 's lower light output) and a significant increase in price [BaF_2 costs several times more than NaI(Tl)]. Although the cost would be much greater for a BaF_2 -based system, this cost would have to be weighed against the needs of the application for enhanced spatial resolution. In some applications, it may be desirable to use two types of detectors so that both good timing and good energy resolution could be achieved by folding the data from each type of detector together.

The last major consideration that must be made is with regard to the size of the detectors to be used. Large detectors offer a number of advantages over smaller detectors. The photopeak efficiency of large detectors is greater than that of smaller detectors because of their lower escape probability. This makes the interpretation of large-detector gamma-ray spectra simpler than that of the corresponding spectra obtained from smaller detectors. And while the cost of the detectors' large volume to the system's time resolution can be small if smaller-diameter (~ 3 -in.-diam) PMTs are used, large-volume detectors also offer a significant potential cost advantage because fewer PMTs, preamplifiers, amplifiers, and data acquisition channels are necessary to cover a fixed solid angle than would be required if smaller detectors were used. It is therefore recommended that large-volume gamma-ray detectors be used in the system in conjunction with smaller-diameter PMTs.

F. Detection Geometry and System Design

The associated-alpha-particle technique is potentially quite versatile in that it may be adapted to a large number of different detection scenarios. Potential applications include not only the

detection of explosives in suitcases and small packages, but also the detection of explosives and other contraband materials (such as drugs) in larger, irregularly shaped containers or spaces (such as large boxes, automobile trunks and tires, and the walls of cargo containers or ships). Whereas the interrogation time and energy resolution may be the most critical performance parameters in some applications (such as the detection of bulk explosives in airline luggage), other applications may not require such short interrogation times and may instead require very good spatial resolution. The requirements of these applications can be accommodated through the proper choice of detection geometry and other operational parameters such as the neutron-generator output and the type and number of detectors used.

Two conceptual systems were considered and analyzed in Sec. V, but these designs were by no means optimized for their particular applications and were only intended as examples of the performance that might be achievable with a full-scale system. Furthermore, these systems are not suitable for many applications. It was shown in Sec. V, for example, that detecting a sheet explosive with either of these two conceptual systems would probably be difficult because these systems would blur the explosive's image, thereby reducing its apparent density and rendering it indistinguishable from surrounding nonexplosive materials. As an example of how the system's geometry may be adapted to a particular application, Fig. 46 illustrates how the spatial resolution could be improved to achieve a high sheet-explosive detection rate with a low rate of false alarm.

Fig. 46. A conceptual design to improve the system's spatial resolution in one dimension and to minimize the background caused by the interactions of secondary neutrons.

This could be done by collimating the probing neutron flux into a narrow (perhaps 1-cm-wide) fan beam, as illustrated in the figure. Not only would such a system provide enhanced spatial resolution, but it could also enjoy the advantage of a lower cost and complexity because (1) the MCP could be replaced by a linear array of alpha-particle detectors; (2) it may be possible to relax the constraint on the neutron generator's beam-spot size (which might also shorten the interrogation time by allowing higher neutron-output rates to be used); and (3) fewer gamma-ray detectors and their associated electronics would be required to effectively cover a large solid angle about the object being interrogated. The system would scan an entire object either by moving it continuously past the collimator at a slow rate or by moving it in small, discrete increments past the collimator.

This is just one example of how the design of an associated alpha particle system might be well-tailored to a particular application. Not only would a system such as the one described above provide enhanced spatial resolution, but it would also increase the signal-to-background ratio (S/B) of the system by (1) reducing the background signals from secondary neutrons mapped to each "slice" of the object being scanned and (2) reducing the dilution of the explosive's image (since all of the gamma rays detected would be constrained to the plane of the collimator). In addition, although a longer interrogation time would certainly be required, the increased S/B would result in a total interrogation time significantly shorter than the product of the number of 1-cm segments and of the interrogation time projected previously for a system that would examine the entire object at once. Finally, the system's imaging fidelity (and hence its probability of detection and rate of false alarm) could be dramatically improved by interrogating an object from orthogonal perspectives and cross-correlating the data.

This example and the examples of Sec. V suggest a number of ways in which the system's design may be effectively adapted to particular applications. Therefore, it is obvious that in designing a full-scale system, careful consideration should be given to the means of optimizing the geometry and other design parameters to achieve the best performance possible.

G. Fast Logic Unit and Data Acquisition System

The fast logic unit used in the NDP system should be redesigned to enable the system to operate at high counting rates and should not be separated from the rest of the data-acquisition system. The logic unit should be combined with the data-acquisition system into a single unit that follows the CAMAC standard. Such a system would be suitable for handling multiparameter data and communicating efficiently at high input-output rates with a fast computer. Given an appropriate input-output controller, such a standardized system could also greatly simplify the interface between the data acquisition and analysis system and the coincidence unit, coincidence gates, and the A/D converters for the energy, time, and position parameters measured by the system. Data would be transferred to the computer via a DMA controller card which should be connected to a VME bus, which is very fast.

H. Display and Analysis Software

The element of the NDP system that bears the greatest criticism is the display and analysis software. The greatest problem with the NDP system's software does not lie in the large number of utilities that either function improperly or do not function at all (although this is certainly an important problem), but rather that the software's organization and architecture is inadequate and unsuitable for this application. Rather than enumerating the various shortcomings of the present system here, recommendations are made below as to the features that should be present in a software package appropriate to the needs of this application. A description of the NDP's software package can be found in App. A. This includes a tabulation of the utilities present in the NDP software, as well as notes that indicate whether each utility functions correctly or not.

1. The software should allow each parameter or group of parameters to be gated by any other parameter or group of parameters. For example, it should be possible to gate the energy spectrum by a window in three-dimensional space so that the contents of an arbitrary volume of space may be analyzed. The NDP's present software package only allows the energy spectrum to be gated by either a window in the radial dimension (time) or by a horizontally oriented rectangular window in the azimuthal dimensions (measured by the MCP). One of the greatest strengths of the associated-alpha-particle technique is its potential ability to analyze the elemental content of arbitrary volumes of space. The absence of the ability to perform this function represents a significant and unnecessary handicap on the system's performance. In addition, the system should not be constrained to the use of horizontally oriented rectangular windows. There has been commercially available software capable of defining arbitrarily shaped windows for several years, and such flexibility should be available for this application.
2. The software should include a sophisticated gamma-ray-spectrum unfolding routine which should incorporate a good model for the gamma-ray detectors' energy response. Such an unfolding routine is essential for interpreting gamma-ray spectra and identifying elements in the interrogation volume because a large number of elements will typically be present and the gamma-ray spectra will be very complicated, making interpretation of the spectra difficult without an unfolding routine. The unfolding routine would increase the system's effective S/B by accurately discriminating the counts in gamma-ray peaks from those in the Compton continuum and also by mapping some of the counts in the first- and second-escape peaks to the full photopeak energy instead of rejecting them as background. A system would probably be ineffective without this type of a utility, and this utility is absolutely essential if there is to be any automated analysis of elemental distribution as would be required to detect contraband automatically.
3. The system should produce an isometric image of the contents of the interrogation volume. The operator should be able to adjust the perspective of the display (a feature that is available in commercial software packages), and the image should be gated by any combination of parameters. In other words, the user should be able to view the content of any volume of space by defining that volume and by choosing the gamma-ray energies to be displayed. In this manner, the elemental distribution of nitrogen in a given volume, for

example, could be visualized by setting windows around the 2.3-MeV and 5.1-MeV regions of the energy spectrum. The image may be either black-and-white with grey levels corresponding to the number of photons detected in the isometric projection or it may be a similar type of pseudocolor display that would allow the visualization of the spatial correlation of multiple elements simultaneously. There are a number of other similar utilities common to imaging systems that should also be available.

4. The system should be able to cross-correlate images formed from multiple interrogations from different perspectives. This could significantly improve the system's effective spatial resolution and would be useful in instances where, for example, simple configurations of shielding materials are present.
5. Algorithms should be developed to automatically detect explosives and other contraband materials, as well as potential countermeasures. This algorithm should be based on the physical characteristics of both contraband and noncontraband materials, as well as the characteristics of materials that would be effective shields of either neutrons or gamma rays.
6. Significant improvements to the system's performance may be achieved by applying image-processing techniques to the data. These techniques, including various types of spatial filters and pattern recognition algorithms, may be very effective in revealing smaller masses of contraband material than would otherwise be possible. These techniques have been demonstrated to be very effective in other applications, including explosive-detection applications, and should be considered in this instance as well. Depending upon the techniques to be applied, this may require the use of a dedicated image processor, but many very useful techniques could be effectively implemented on a fast PC or work station as well.

VII. SUMMARY AND CONCLUSIONS

Both the existing multipixel NDP developed by CCC and the designs of several conceptual full-scale systems were examined during the evaluation program. In each case, a number of parameters relating to performance, reliability, and cost were considered. The most important of these parameters included (1) the system's three-dimensional spatial resolution; (2) their efficiency (primarily for detecting various masses, shapes, and types of explosives); (3) their ability to locate and identify elements in a complex matrix; (4) their ability to correctly measure the density of the elements identified; (5) the interrogation time required in various scenarios; and (6) their cost and reliability.

The experimental program proceeded in several phases, beginning with the evaluation of individual components of the NDP system. This phase revealed several components that did not work properly, and these were repaired or replaced. From these tests, the neutron-output rate of the STNG was found to be about $3(10^5)$ n/s at 15-kV extraction and focusing potential, 70-kV acceleration potential, and 3.5- μ A target current. The energy resolution of the NaI(Tl) gamma-ray detectors was found to be about 9.2% at 662 keV, and the time resolution of the NaI(Tl) gamma-ray detector was found to be about 2.1 ns, FWHM.

In the next phase, the NDP system's overall performance was evaluated, beginning with the system's overall time resolution. Two paths were followed in doing this. The first path involved experimental determination of the system's overall time resolution and the major factors that determine the time resolution (including the time resolution associated with the NaI(Tl) detector and its PMT, the alpha-particle detector's PMT, and the time jitter in the various other electronic components of the system). The second path involved developing some simple computer-based models which were used to (1) verify that the system's overall time response was well understood and (2) estimate the components of the system's overall time resolution that could not easily be determined by direct measurements (such as the TOF uncertainty associated with variations in alpha-particle energy and path length to the ZnS(Ag) screen). The experimental results agreed well with the predictions of the model and showed that the largest component of the present system's 2.3-ns overall time resolution is associated with the 2.1-ns time resolution of the NaI(Tl) detector. While the NDP system's radial spatial resolution was found to be about 12 cm, FWHM, this showed that improvements in the gamma-ray detector's time resolution could significantly improve the system's overall time resolution.

Another computer model was developed at this time to extrapolate the STNG's maximum neutron-output rate from its measured output rates at accelerating potentials and beam currents far below its design limits. This was done to avoid the risk of destroying the tube by pressing it to the limits of its abilities. This computer program predicted that the tube's maximum neutron output rate would be $\sim 3(10^6)$ n/s at 120-kV total accelerating potential (although this result is based on data taken after the tube had presumably been operated for several hundred hours). Higher neutron output may be achieved with a fresh tube.

The next element of the system's performance to be evaluated was the spatial resolution in the dimensions imaged by the MCP. To do this properly, it was necessary to ensure that the image of the ZnS(Ag) screen was focused upon the MCP as well as possible. This was made somewhat difficult not only by the cumbersome design of the alpha-particle-detector assembly (which made accurate positioning of the MCP and lens difficult), but also by the lack of documentation of the assembly's dimensions and details of how the image of the ZnS(Ag) screen was being focused onto the face of the MCP. Because of this lack of documentation, it was necessary to measure the lens' focal length and the dimensions of the alpha-particle-detector assembly prior to evaluating the system's spatial resolution to ensure that the best spatial resolution would be achieved. To avoid the risk of damaging the MCP, this measurement was performed without removing the lens from the face of the MCP. To do this, a pattern of light was created by passing light through a stainless steel mask which was mounted inside a light-tight tube of variable length. With the MCP housing mounted to the end of the light-tight tube opposite the mask, the lens' focal length was measured by identifying the distance from the lens to the mask at which the sharpest image was produced. This procedure showed the position of the MCP housing that would produce the optimal spatial resolution for the system. In addition, the focusing tube made it fairly simple to isolate the MCP's component of the system's overall two-dimensional spatial resolution from any other factors that might degrade the system's spatial resolution. Experiments with the focusing tube showed that the NDP system's MCP-lens assembly is capable of resolving angles of about 1.6° at the STNG's target. Since the MCP itself should give much better spatial resolution (probably $\sim 0.05^\circ$ for this configuration), it was concluded that the simple optics of the alpha-particle assembly probably do

not focus the image of the ZnS(Ag) screen perfectly upon the face of the MCP. With the MCP-lens assembly properly positioned, experiments were performed to measure the system's overall spatial resolution in the dimensions viewed by the MCP, which was found to be about 3° at the STNG target. The discrepancy between the MCP-lens assembly resolution and the system's overall resolution was attributed to the uncertainties in the measured trajectories associated with the size of the STNG beam spot. By taking the difference in quadrature between the two values of the spatial resolution (1.6° for the MCP-lens assembly alone, and 3° for the system overall), the diameter of the STNG's beam spot was estimated to be 2.5° subtended at the center of the ZnS(Ag) target, which corresponds to a beam-spot diameter of about 2 mm on the target.

The next phase of the evaluation program involved a number of experiments in which spectra from various samples were collected. These samples included simple materials containing C, N, and O (the most common elements expected to be found in both the contraband and noncontraband materials), such as graphite, liquid nitrogen, boron nitride, water, and magnesium oxide; samples of iron and aluminum (typical structural materials); and complex materials including simulated samples of C4 plastic explosive, Semtex sheet explosive, and a bulk high explosive. This phase of the experimental program led to (or reinforced) a number of important conclusions about the NDP system, perhaps the most important of which was that the position computer presently used with the MCP in the NDP system limits the rate of signal acquisition to about 1% of the rate that would be required for the system to be of practical use. It may be possible to eliminate this limitation by using an improved position computer or by using multiple position computers or reducing the solid angle interrogated. However, it may be necessary to use another type of position-sensitive alpha-particle detector for this application until a suitable MCP position computer is developed.

The other conclusions that were reinforced during this phase of the evaluation program were the need for a good gamma-ray-spectrum unfolding program and the need for a true multiparameter data acquisition, analysis, and display program to achieve the system's full potential. The unfolding routine is necessary because even the gamma-ray spectra of relatively simple materials can be very complicated to interpret. Because there may be constraints associated with the allowable interrogation time (which is directly related to the statistical significance of the data collected) and the presence of background signals, it is very important to make efficient use of the information content of the gamma-ray spectra. This can be done most effectively by using an unfolding routine; indeed, such a routine will be essential if an automated analysis of the data collected by the system is to be performed by a computer. Likewise, a true multiparameter display and analysis capability is necessary to allow the greatest freedom to identify patterns in the data set that may indicate the presence of contraband or shielding materials.

Finally, in the last phase of the evaluation program, conceptual designs were presented for full-scale practical associated alpha particle systems, and projections were made of some performance characteristics that might be achieved for such systems. Unfortunately, due to the complexity of the analysis that would be required, it was not practical to project the performance of these systems in terms of the usual performance measures, the probability of detection (PD) of a threshold mass of contraband material and the probability of false alarm (PFA). Such an evaluation is much more amenable to experimental determination than to analytical projection. Instead, a number of parameters that would affect the PD and PFA were varied, and the effects

upon the systems' performance were analyzed and discussed in terms of the signals' statistical uncertainty. These analyses were performed for 1.5-lb masses of a C4 plastic explosive and a 3-mm-thick sheet explosive in a suitcase, and for a 10-lb mass of high explosive inside a 4- by 4- by 4-ft box, for various orientations of the explosives, various amounts of shielding material and innocuous surrounding materials, and with various assumptions regarding the systems' achievable spatial resolution. All analyses were performed with the assumption that the neutron generator would be capable of providing $5(10^7)$ n/s and that the alpha-particle detector would not be limited at this rate, both of which seem to be reasonable assumptions about the present state of technology. These calculations suggest that the detection of 1.5 lb of bulk C4 explosive inside a suitcase and 10 lb of high explosive in a large crate may be accomplished with a full-scale system with high probability in a reasonable time and at a reasonable cost. And although the situation is not as clear with regard to the detection of thin sheet explosives, it is noted that the calculations were very conservative throughout with regard to the statistical requirements for detection and imaging of the explosive. Furthermore, there was no consideration given to the information that may be derived through the application of image processing or discriminant analysis of very large data sets. Even very simple image-processing techniques could significantly enhance the systems' detection capabilities. In practice, if the statistical requirements for detection and imaging are less severe than those assumed in the calculations, thin sheet explosives may be found with a high probability in a reasonable interrogation time in scenarios such as those described in Sec. V. If these requirements can be further relaxed through the effective use of image-processing techniques, commensurate improvements in performance could be expected. In this regard, some encouragement is given by the performance of the explosives detection system manufactured by SAIC,¹⁰ which has spatial resolution much poorer than that which is presently achievable with the NDP system, yet is capable of detecting sheet explosives. On this basis, it seems that if neutron output of $5(10^7)$ n/s can be realized in a system like the NDP, the system's superior spatial resolution and multiple elemental signatures would make prospects very good for detecting explosives with a higher PD and lower PFA than the TNA system.

Calculations were also performed during the final phase of the evaluation program to estimate the effect that shielding materials and secondary neutron interactions might have upon the system's performance. Although these calculations were not exhaustive, the shielding calculations suggest that while explosives or other contraband might be effectively shielded by simple assemblages of materials, the presence of effective masses of shielding materials might be easily detected. The calculations also showed that while the effect of secondary neutron interactions is not likely to be severe in the interrogation of small articles such as suitcases, it may become significant in the case of larger objects if a sufficient mass of material must be penetrated by the neutrons. A means was suggested of reducing the adverse effect of secondary neutron interactions by tightly collimating the probing neutron flux into a narrow fan beam. This would effectively improve the system's spatial resolution in one dimension and thereby improve the system's S/B (at the expense of a longer interrogation time). Both of these factors (shielding and secondary-neutron interactions) may significantly affect the system's performance, and the calculations presented here merely support the need for more thorough analyses.

Among the major conclusions, results, and recommendations of the NDP evaluation were the following:

- The poor coupling of light from the ZnS(Ag) scintillator screen to the microchannel plate (MCP) position-sensitive detector significantly deteriorates the system's overall position resolution. This degradation can be eliminated through a more direct coupling of the scintillator's light to the MCP by various means discussed in the last section. Not only could this result in improved spatial resolution in "X" and "Y" dimensions, but it could also greatly simplify the detector system by eliminating the PMT and the partially reflecting mirror. Using the MCP for timing would also slightly improve the system's overall time resolution.
- Higher neutron output and small beam-spot size are required for a full-scale system to be practical. A greater neutron output rate is required to complete interrogations within realistic time intervals, and the small beam-spot size is required to maintain good spatial resolution.
- The overall time resolution of the present system is about 2.3 ns, FWHM, which is equivalent to a radial spatial resolution of about 12 cm, FWHM. The largest contribution to this uncertainty is due to the time resolution of the PMT of the 5- by 5-in. NaI(Tl) gamma-ray detector. A significant improvement in the system's overall time resolution may be achieved by coupling smaller, faster PMTs to large scintillator crystals instead of matching the size of the PMTs to the size of the scintillators.
- The gamma-ray spectra produced by the system are often very complicated, even when very simple samples are being examined. This is due not only to the presence of background signals (that arise from neutron interactions in surrounding materials and in the detector itself), but also as a result of the form of the scintillator's response to gamma rays. This complicated detector response superimposes the signal to be measured on a continuum of other signals and sometimes upon other peaks (first- and second-escape peaks). This makes the interpretation of the gamma-ray spectra very complicated without the use of a deconvolution algorithm. Because the gamma-ray spectra encountered in realistic scenarios will be even more complicated than those encountered in the laboratory environment, it is essential that a suitable deconvolution, or "unfolding," algorithm be incorporated into future systems' software. This is particularly true if automated detection is to be achieved.
- The data acquisition system, from the MCP's position computer to the data analysis computer system, should be carefully redesigned to provide real-time or near real-time data acquisition at high signal rates on the order of 1 - 3 MHz.
- The data analysis and display software should incorporate not only gamma-ray-spectrum unfolding routines, but also a number of utilities that would allow true four-parameter manipulation, gating, and display of the data, as described in the last chapter. The software should allow the automatic identification of elements within the interrogation

volume, and it should allow spatial correlations of multiple elements to be displayed in various two- and three-dimensional display formats. It would also be useful to have the ability to correlate images acquired from different perspectives. In addition, image processing and discriminant analysis software should be developed for the enhanced and automated detection of contraband materials.

Although the NDP system may be considered successful in demonstrating the basic feasibility of the associated alpha particle technique for remote nondestructive elemental-detection and imaging applications, the laboratory prototype will not be useful in practical applications for a number of reasons. The most significant shortcomings of the system are its poor detection efficiency (which results simply from the small solid angle subtended by its single gamma-ray detector) and its low neutron output, which make very long acquisition times necessary to produce useful images of objects in the interrogation volume. These shortcomings could be eliminated by adding more detectors and using a neutron generator having a neutron-output rate on the order of $10^7 - 10^8$ n/s. One difficulty with rectifying the situation in this manner is that the present system's data acquisition system only allows for a single gamma-ray detector input. Another is that the MCP's position computer is not capable of handling the signal rate that would result from operation at a practical neutron-output rate. Also, the software architecture is both inadequate and unsuitable for a full-scale system. Finally, the alpha-particle-detector assembly should be redesigned to provide better image resolution and timing with a simpler, more reliable, and adjustable mechanism. For these reasons, future systems should include a number of significant improvements over the present system's design, and the present laboratory prototype should not be used as the skeleton for a full-scale system.

Although there are numerous shortcomings in the NDP prototype system, the system has been successful in demonstrating the feasibility of using the associated alpha particle technique for remote nonintrusive and nondestructive interrogation applications. It has also revealed some of the most important considerations that should be made in the design and construction of full-scale practical systems. Although one obvious practical application of the system would be for detecting explosive devices in small packages such as suitcases, the technique could potentially be adapted to a wide variety of other detection and diagnostic applications. For example, the system could be adapted to detect explosives and other contraband materials in large or irregularly shaped volumes to which there is no access, such as voids in bulkheads and walls of ships, buildings, or cargo containers. Other possible applications might range from the interrogation of parcels to the scanning of automobile tires or trunks, to name a few. Because of its flexibility and the unique information that it is capable of providing, the technique is very attractive for such applications. Although a number of areas have been identified where significant improvements are required and where further development will be necessary, no fundamental problems have been identified that would prevent the development of useful full-scale systems, and further development of useful full-scale systems, and further development of this type of system should be aggressively pursued.

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APPENDIX: SOFTWARE

The NDP data processing software operates on an IBM PC/AT computer that is linked to the rest of the system by the custom-built DMA interface and the commercially produced Metrabyte PDMA-16 card, which is resident within the computer. The NDP software provides a set of functions tailored to the NDP application. Unfortunately, the software development is incomplete, and several of the functions that appear on the menu either work incorrectly or incompletely, or do not work at all. In addition, some parts of the program's performance produce inconsistent results, and it is not uncommon for the system to "lock up" when the user attempts to execute some of the functions. To recover from these "lock ups," it is usually necessary to turn the computer's power off, and then to reboot the system.

The purpose here is not to discuss the shortcomings of the program as it exists or the improvements that could be made, but rather to give a brief description of the overall structure of the program and the functions that were intended to be available to the user. Because no source code and virtually no documentation on the program were made available, the discussion of the software features and design that follows is necessarily generalized.

The NDP program is a version of the software that was previously developed for the single-pixel explosive detection system (SPEDS). In the multipixel version, each datum is a four-byte word consisting of eight-bit values for energy, time, azimuth (X), and altitude (Y). These data points are transferred to the computer through the DMA interface described previously. The NDP software manipulates these data words to present the data as either a histogram of time or energy, or as a two-dimensional plot of the position where the alpha particles have been detected. Up to 10 display screens are available. Because all of these screens are kept resident in the computer's RAM module in the form of "virtual screen" records, the display may be quickly switched from one screen to another. When data are not being transferred to the computer, the system runs independently and can perform any necessary display functions as well as user-specified menu functions.

The software provides utilities that allow the user to further manipulate the data by displaying the points (in one dimension) that correspond to a ROI in either one or two of the other dimensions. The software also provides other utilities for data manipulation, such as linear background subtraction, spectrum subtraction, and simple smoothing routines. The NDP functions are executed through a menu-style command procedure. Interactive input is required for some input and output (I/O) functions and for functions requiring the placement of cursors. Table A-1 lists the various functions of the software and also includes a remark for each entry, indicating whether the function exists or works properly.

Table A-1. NDP Software Functions.

Key to remarks on function operation:

- 1 functions correctly and reliably
- 2 usually functions correctly
- 3 usually does not function correctly
- 4 not all parts function correctly
- 5 does not function correctly
- 6 not actually present in software

Key	Function Name	Function Description	Remarks
F1	ACQ-START	Starts NDP data acquisition	2
F2	ACQ-STOP	Stops NDP data acquisition	1
F3	FILE I/O	Provides NDP input and output functions: saving, deleting, and retrieving spectra; printing functions; saving and deleting list-mode data; providing directories	1
F4	SMOOTH	Allows 3-, 5-, 7-, and 9-point weighted smoothing of the currently displayed spectrum	1
F5	TIME ROI	Displays the time spectrum corresponding to a single ROI in the energy spectrum	1
F6	ENERGY ROI	Displays the energy spectrum corresponding to a single ROI in the time spectrum	1
F7	REDRAW	Redraws the "active" screen using raw data; returns the display to single-screen format	1
F8	CLEAR SCREEN	Clears the spectrum display area	1
F9	NEXT SCREEN	Scrolls forward through the ten available screens	2
		SCREEN NUMBER	DISPLAY CONTENT
		0	Energy Histogram
		1	Time Histogram
		2	X-Histogram
		3	Y-Histogram
		4	X-Y "scatter plot"
		5	Energy ROI

Key	Function Name	Function Description		Remarks
		6	Time ROI	1
		7	XY-Time ROI	1
		8	XY-Energy ROI	1
		9	Retrieved Spectrum	1
F10	MORE...	Scrolls through the menu options		1
A/F1	DOS	Exits NDP program and returns computer control to DOS		1
A/F2	SCALE	Allows user to change the scales of the display axes		3
A/F3	CALIBRATE TIME	Allows the user to calibrate the abscissa of the time histogram in units of nanoseconds		1
A/F4	ENERGY CALIBRATION	Allows user to calibrate the abscissa of the energy histogram in units of MeV		1
A/F5	RESTART	Allows NDP software to be reset without exiting to DOS		3
A/F6	SPLIT SCREEN	Displays two spectra simultaneously with either of the spectra designatable as "active"		1
A/F7	SPECTRAL SWITCH	Switches the "active" designator between two spectra displayed in the split-screen format		1
A/F8	SPECTRUM TITLE	Allows the user to specify a title for the currently displayed spectrum		1
A/F9	BACKGROUND SUBTRACTION	Allows the user to perform a linear background subtraction from a range of channels in the currently displayed spectrum		1
A/F10	SPECTRAL SUBTRACTION	Allows the user to subtract one spectrum from another		5
C/F1	NORM	Allows the user to subtract a constant from the "active" spectrum		*
C/F2	OVLAY	Overlays the two spectra on one set of coordinate axes in split-screen mode		1
C/F3	XY TO E	Displays the energy spectrum corresponding to a user-defined region of interest in the two-dimensional "scatter plot"		4

Key	Function Name	Function Description	
C/F4	XY TO T	Displays the time spectra corresponding to a user-defined region of interest in the two-dimensional "scatter plot"	4
C/F5	E TO XY	Produces a two-dimensional display of the coordinates of all of the events that exist within a ROI in the energy spectrum	6
C/F6	T TO XY	Produces a two-dimensional display of the coordinates of all of the events that exist within a ROI in the energy spectrum	6
C/F7	CURSORS	Allows user to mark boundaries of ROIs	2
	MARKER	Allows user to mark an individual channel in a histogram and display the channel's contents	2
	ELAPSED TIME	Displays of the elapsed acquisition time	2
	AREA COUNTS	Displays of the number of counts within a ROI	2

-END-

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