REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	20 Jan 99	Final Report Sept 97 - Jan 99

4. TITLE AND SUBTITLE

Gamma Ray Imaging Prototype Vehicle and Cargo Inspection System (VACIS II)

5. FUNDING NUMBERS

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

DoD Counterdrug Technology Development Program Office
Naval Surface Weapons Center - Dahlgren Division
Dahlgren, VA

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Unrestricted

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report summarizes the development and production of the VACIS II Gamma-ray Imaging System. It includes system specifications, a trade study, and hazard analysis.

14. SUBJECT TERMS

15. NUMBER OF PAGES
66

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLAS	UNCLAS		

CBD # 29

GAMMA RAY IMAGING PROTOTYPE VEHICLE AND CARGO INSPECTION SYSTEM (VACIS II)

Final Report

Contract DAB63T-97-C-0055

January 1999
(Work performed Sept 1997 - Sept 1998)

Report Prepared by

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UNCLASSIFIED

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Section 1 — Introduction

The advanced **Vehicle and Cargo Inspection System**, or **VACIS-II**, is a follow-on effort to the **Vehicle and Cargo Inspection System**, or **VACIS-I**. VACIS-I was delivered to US Customs as a proof of concept experiment in 1996, to determine the feasibility of non-intrusively inspecting the interior of cargo vehicles using a small radioisotopic source and an array of scintillator detectors. The VACIS prototype proved very successful, resulting in a contract to design and build an improved version of the system.

The advanced system was to have improved spatial resolution by increased height and length to accommodate higher and longer vehicles, and improved overall design and operations. A trade study helped to determine the system configuration that would provide optimal performance, while minimizing costs. The preliminary design review resulted in further investigation and several design changes. Development proceeded through the critical design review, where minor changes were made and final development began. A brief summary of the areas addressed in the trade study is shown in Section 2, and the complete trade study is shown in Appendix A. A comparison of VACIS-I and VACIS-II is described in Section 3. The performance specifications and a description of the final system configuration is provided in Section 4, and a summary of the system Hazard Analysis Report is in Section 5. Sample images are shown in Section 6. A Summary of Financial Expenditures is shown in Section 7.

Since the development and testing of VACIS-II, several minor changes have been identified as desirable in future versions of the Operator's Manual (current revision 1.1, 10/02/98). Proposed changes for follow-on units are provided in Section 8, and a summary is in Section 9.

Section 2 — Trade Study and Design Review Results

A trade study was performed to determine various configuration options, their impact on performance and price, and a recommended configuration. The desired performance specifications included the following:

- Resolution of 0.5 inches
- Throughput of 1-ft per second
- Source strength of 1.0 Ci of Cs-137 and 0.5 Ci Co-60
- Able to scan an entire vehicle in a single pass
- Must have variable scan angle

Based on the desired performance specifications, the study examined the variables that contribute to performance, operational impact, ease of use, durability, and costs. Major variables include variations in system geometry, (track width, tower height, source height, and vehicle position within the system); including the number, size and configuration of the detectors; and the rate at which the detectors are polled. A brief summary is provided below, and the complete study is provided in Appendix A.

The study began by examining the overall system geometry. After discussing the typical area of operations for the system, we established a practical maximum system width of approximately 40 feet. The range for the detector tower height was then determined using different practical source heights and the standard height of a vehicle. There were two main objectives in this step: (1) provide the capability to image the entire vehicle in a single pass, and (2) allow flexibility in source height to provide various perspectives. Obviously a higher tower was more difficult to support while moving, but it provides greater imaging capabilities. The optimal tower height was established at 21 feet.

Once the system geometry had been established, the number, size, and configuration of the detectors was adjusted to meet the resolution and throughput criteria. Resolution was increased by changing the number of detectors and decreasing the space between them (the pitch). While increasing the number of detectors increases resolution, it generally requires a reduction in throughput, or scanning speed. Therefore, a balance of detector size, pitch and configuration was used to meet the desired performance. Rather than use a single vertical column of detectors, a new configuration using three vertical columns of detectors was developed, that allowed the use of larger (1.5-inch diameter) detectors, and used software to compensate for the offset. The larger detector size provides higher photon counts, yielding a higher scan rate, and the particular size selected uses a common photomultiplier tube providing the lowest cost. Using this design, a 21-feet detector array of 336 detectors provides both the resolution and throughput desired.

Once the preliminary system geometry and detector configuration were established, analysis was performed on the hardware and software needed to obtain the configuration. The design analysis also considered environmental requirements and manufacturing ease and cost. The analysis lead to the selection of construction materials, wiring and cable selection, and methods to erect the detector tower and position the source.

For maximum environmental protection and structural strength, stainless steel was selected for the detector modules and the trolley enclosures, and aluminum was selected for the track sections. For ease of assembly and environmental protection, the cables were designed with MILSPEC connectors, using unique connectors for different cables, and common cables wherever possible.

Section 3 — Comparison of VACIS-I and VACIS-II

The VACIS systems can be easily divided into several major component areas.

Source

<u>Source Type and Strength</u>. VACIS-I had a 1 Ci Cs-137 source in an Ohmart source holder. VACIS-II was equipped with an identical Cesium source, and a 0.5 Ci Co-60 source. The Cobalt source was provided to examine the results of using a higher energy source (Cobalt is 1.25 MeV, Cesium is 0.662 MeV) for greater penetration. The Ohmart Cesium source holder is equipped with an electrically activated shutter requiring approximately five seconds to open or close. The Ohmart Cobalt source opens with a manually activated plunger. A secondary shutter was included in the design for both sources with VACIS-II. The secondary shutter provides further collimation, and reduces the radiation exposure. The secondary shutter is also electrically operated, but operates in 0.5 seconds, and is closed by a spring, ensuring positive closure in case of loss of power. As with VACIS-I, a flashing red light indicates when the sources are open.

<u>Source Position</u>. The method used to raise and lower the source was drastically improved with VACIS-II, and the capability to position the source at an angle of 0-20° was added. VACIS-I used a manual winch with the capability to raise or lower the source. VACIS-II used an electrical screw jack to raise and lower the source. VACIS-II included an electrical motor to turn (or oblique) the source from 0 to 20° from perpendicular. There are indicators at the source trolley for 0, 10, 15, and 20°. Operators position the source angle from the source trolley, and then align the detector tower using the control console. The source trolley has interchangeable mounts so either source can be quickly replaced.

Detector Array

Height – The height of the tower was raised from 12 feet to 21 feet. This change allows imaging of an entire vehicle in a single pass. The VACIS-I modules were raised with a manual winch. VACIS-II uses an electric hoist. VACIS-I used three 4-ft. modules while the VACIS-II uses seven 3-ft modules. The tower is positioned on the top of the trolley using an optional 3-inch cut-out allowing the tower to be lowered below the top of the trolley. The lowest position of the tower allows operators to image approximately ½ of the tires on a standard vehicle.

Number of Detectors – The number of detectors was increased from 48 in a 12-ft tower (3-in pitch) to 336 detectors in a 21-ft tower (0.75-in pitch). This directly contributed to the increase in resolution and large vehicle capacity

Detector Arrangement. – The location of the detectors was changed to accommodate increased resolution. In VACIS-I the detectors were in a straight vertical line, but those in VACIS-II were set in three offset rows with the offset being corrected by the software.

Detector Design – The detectors were the same, 1 ½-inch diameter by 2 ½-inch deep NaI, but the new design went to a single cable, used to supply high voltage and measure the signal, thus decreasing the detector costs and also decreasing the difficulty in changing out detectors if one should malfunction.

Power Supplies – In VACIS-I the low voltage needed to run the electronic counting boards in the tower was supplied by two voltage supplies at the base of the tower, one for positive 5 volts, the other for negative 5 volts. In VACIS-II, a power supply box was added to each module. The new design prevents voltage drop as the current runs through 21 electronic counting boards.

Module Material. – VACIS-I modules were made from steel shipping containers. The VACIS-II modules were custom designed stainless-steel enclosures, with foam protecting the detectors.

Tracks

The overall footprint of the system was increased to allow inspection of an entire vehicle in a single pass. This included the ability to scan a 13-ft. high truck, up to 70–ft. long, at an angle of 10°. The old system size was 35-ft by 45-ft. The new system is 40-ft by 90-ft.

The width of the detector track was increased from 4-ft. to 6-ft. to provide stability and support for the increased tower height and weight. New leveling feet provide an easier, faster method of leveling each section.

Electrical System

In VACIS-I, the movement of the trolleys was independent of operation of the computer and detectors. In the VACIS-II, a new programmable logic controller that controls the movement of the trolley was added to the system. A software interface was added to connect the system to the control console so the control console could be used to directly control the trolleys. Operators can now position the trolleys independently as well as align them for oblique scans using the new system.

The cables providing communication and power between the tracks, trolleys, and the control console were completely redesigned for greater durability, wear, and resistance to weather. New sealed junction boxes provide more environmental protection, MILSPEC connectors, and heavy gauge cables with numbering and color codes making installation faster and easier. The cable carrier (IGUS chain) was increased in size to accommodate the larger cables. UV resistant plastic was added to the carrier surface to reduce wear.

Electrical controls were added to the source trolley to raise and lower the source. Other controls were added to operate the secondary shutters from either the control console or the source trolley.

Trolleys

The trolleys were redesigned to support the increased weight of the components and to enclose the components. The new trolleys were designed using painted steel (VACIS-I trolleys were aluminum). New motors were selected, which are controlled by a programmable logic controller located in the control center.

Control Console

A 300MHz Pentium II® computer running Windows NT® replaced the previous 486 DOS-based system.

The new software is written with lead tools using C++ software. The user interface was completely redesigned to provide drop-down menus and point and click features. Image enhancing features such as contrast stretch, region-of-interest processing, zoom, edge detection, sharpen, smooth, annotation, and others were added.

The basic display screen was modified to include a video image with each gamma image, and a window that allows operators to quickly select files. Two images are still displayed on the screen.

An audio capability was added allowing operators to append an audio clip to a gamma file with comments.

A video camera was included with the system. The camera provides a real-time image to the monitors in the control center, and a window in the operators console displays a frame from the camera every two seconds. This allows operators to add a video picture to the gamma image.

The camera may be positioned above the control center or it may be placed on tripods or stands up to 100-ft from the control center. Up to four cameras may be added to the system, although only one may be connected to the remote pan and tilt control in the control center.

Control Center

A 30-ft RV was modified to serve as the control center. The furniture in the back room of the RV was removed and replaced with a built-in desk. Additional circuits and a circuit box were added to segregate the control center from the rest of the electrical system. The generator was replaced with a larger (6.5KW) unit capable of running the entire system. Modifications were made to allow operators to run either the VACIS system or the RV using commercial power, or the generator, in any combination. The shower area of the RV was removed and replaced with the electrical control cabinet for the system. The front of the RV was wired to display the video images from the outside camera, and a monitor slaved to the control console in the back of the RV.

The storage areas underneath the RV were filled with foam to store the detector modules during transportation. A camera mount was placed on the roof allowing quick installation and removal of the video camera.

Trailer

A 10,000-lb capacity trailer was purchased to store the system components for transportation. Modifications were made to store the track sections. Equipment tie-downs and cable storage racks were also added. The dealer considerably underestimated the empty weight of the trailer which limited the carrying capacity. As a result, when all the components were added, the original modifications to the trailer increased its weight above the maximum. More modifications resulted in a design that stores all the components; but, it is not nearly as easy to load as the original design. If a trailer is required in future acquisitions, design modifications should include a larger trailer.

Section 4 — System Description and Specification

Performance Specifications

Resolution — Approximately 0.5 inches at vehicle center with nominal configuration.

The nominal configuration for the system is to have 30 ft. between the tracks yielding 35-feet between the source and the detectors and a 40 ft. distance from outside to outside. The nominal placement of the vehicle is with the center of the vehicle 21 ft. from the source. With the 0.75-inch pitch of the detectors, this yields a vertical resolution of 0.43-inches at vehicle center. Objects in the side of the vehicle nearest the source will have slightly more magnification, yielding better resolution. Objects at the far side of the vehicle will have slightly less resolution. When operators configure the system (they enter the nominal parameters), the system automatically determines the vertical resolution (at the center of the vehicle being inspected) and controls the polling of the detectors to match the horizontal resolution.

Penetration — Approximately 2.25 inches of steel

The theoretical penetration of Cesium-137 is 2.5-inches of steel. The system achieves a realistic penetration of 2.25 inches due to attenuation for the source holder, and the steel source and detector tower enclosures. For Co-60, the penetration is increased slightly, to about 2.75 inches; not enough to justify the use of Co-60 (i.e., heavier source shield, higher biological dose and much more frequent source replacement due to shorter half-life).

Throughput — Approximately 0.7-feet per second scan rate

The throughput of the system was set to 0.7-feet per second to ensure adequate counts at the detectors for statistical accuracy. This speed is very conservative. The trolleys may be set faster with very little detectable difference.

Operational Requirements – Various requirements are detailed below

Vehicle Scan Size	– Scan an entire 70-ft long, 13-ft high vehicle in a single scan
Oblique Scan Capability	– Scan vehicles at an angle of 0-20°
Video Image Capability	– Save a video image of the vehicle with each gamma image
Audio Annotation Capability	– If selected, saves an operator's audio clip with the gamma image
Image manipulation	– A suite of image enhancing features, such as zoom, contrast stretch, region-of-interest processing, sharpening, smoothing, annotation

Features and specifications

The major components and the features or improvements are summarized below. An asterisk (*) indicates a safety feature of the VACIS II.

Track and Trolley System

- Scans vehicles 13 ft high, 8 ft wide, and 65 ft long in a single scan
- Scan rate in optimal mode is 0.7 ft/sec, maximum 1.5 ft/sec
- Home switches to ensure automatic, repeatable scan starting position
- Nominal system dimensions (tracks only) are 40-ft wide x 90-ft long, variable
- Nominal source-detector distance of 35 ft, variable
- Detector track is 6-ft wide, source track is 4-ft wide, both are 90-ft long
- Easy-assembly, modular track made of interchangeable 6-ft aluminum sections (easy to lift)
- Each track segment has adjustable leveling feet designed for rapid and easy height adjustment
- High-reliability source-detector synchronization motors accurate to 1- in per scan
- Aluminum rails and steel track connection hardware for increased rigidity and strength
- Cable trays lined with UV resistant plastic to reduce wear on cable carrier
- Ruggedized construction features allow operation during rain
- Source trolley approx. 4 ft. x 4 ft footprint; detector trolley approx. 6 ft. x 6 ft footprint
- Environmental covers protect all trolley components
- Programmable Logic Controller (PLC) uses high-reliability integrated logic and dual-axis motion controller
- Cables in cable carrier are high reliability, long flex life type (100,000 cycles nominal)
- Cable connectors are high reliability mil-spec grade
- Drive motors are brushless DC type with integrally mounted dual-channel optical encoders
- Power requirements: 115 V AC, 1-Phase 60 Hz, 30 A
- Trolleys use variable acceleration rates to maximum velocity
- Manually actuated Emergency Stop (E-stop) buttons, one at each end of each track *
- Forward and reverse travel limit switches *
- Forward and reverse travel power kill switches *
- Shock absorbing hardstops to safely stop trolley in case of over-travel *
- Cam follower detent mechanisms on trolley prevent tipping due to wind loads *

Detectors and Detector Tower

- Detector tower is 21 ft high; made of seven 3-ft-high detector modules
- Modules measure 11" x 12" in cross section

- Total of 336 NaI detectors, 1.5" diameter, 2.5" long, with a pitch of 0.75"
- Provides a vertical and horizontal system resolution of less than 0.5"
- Detector pitch and pattern allows for a 2:1 oversampling of scanned object
- Detectors using single cable design for simplification and ease of maintenance and repair
- Detectors loaded in rugged foam support for electrical (ground-loop-deterrent) isolation, vibration, shock, and temperature protection
- Modules constructed from stainless steel and sealed for corrosion protection
- Access door for servicing internal components
- New, faster data processing board services 16 detectors at a time
- Electronics in enclosed housing for added corrosion protection
- Motorized hoist and guide beam for easily joining and raising detector modules *
- Designed to withstand gusts of wind up to 40 mph *
- For high wind conditions, the detector tower beam has provisions to be lashed via optional cable tie downs and ground mounted eyebolt anchors *

Source

- Two sources provided: 1-Ci Cs-137 (662 keV) and 0.5-Ci Co-60 (1.17 and 1.33 MeV)
- Interchangeable mounts so that either source can be quickly mounted
- Source housing easily removable so that source can be locked up during periods of non-operation
- Motorized lift to raise and lower source position
- Source height indicator scale visible during adjustment procedure
- Source oblique scan angle adjustable from 0 to 20 degrees with detents and indicator lights at 10, 15, & 20 degrees
- Motorized source rotation for oblique scanning
- New dual-shutter system, primary and fast, provided for additional speed, reliability, and safety *
- Both shutters for Cs-137 source provide positive closure in the event of power failure or emergency stop *
- Backup battery, with a shelf life of three years, ensures primary shutter closure *
- Spring-loaded rotation ensures fast shutter closure for secondary shutter *
- Source shutters opened only during a scan and closed at all other times *
- Red indicator lamp illuminated only when source shutter is open *

Control Console

- Console components include: 300 MHz Pentium II CPU, full keyboard, 21" monitor
- CPU runs Windows NT for faster processing and more user friendly operation
- External control pendant allows manual movement of either trolley without console
- Image enhancement features such as zoom, pan, scan, annotation, contrast and more
- CD-based archive system for stored images included
- CCTV video system, to record visual image of vehicle being scanned, included
- Console is stand-alone and can be used in a mobile enclosure or portable building

- Computer code written in C++ for ease of modification, update, and documentation
- Control pad functions include system movement and shutter controls and emergency stop
- Lockout feature preventing override from main CPU *
- UPS provides backup power during power loss for controlled shut down *
- Status indicator lights on control pad *
- Electrical power disconnect physically cuts power to operator's console during servicing *

Section 5 — Hazards Analysis

The contractor completed an analysis of the hazards associated with operating the VACIS system. There were three potential areas analyzed: mechanical, electrical, and radiation. A brief summary is listed below, and the entire analysis is shown at attachment B.

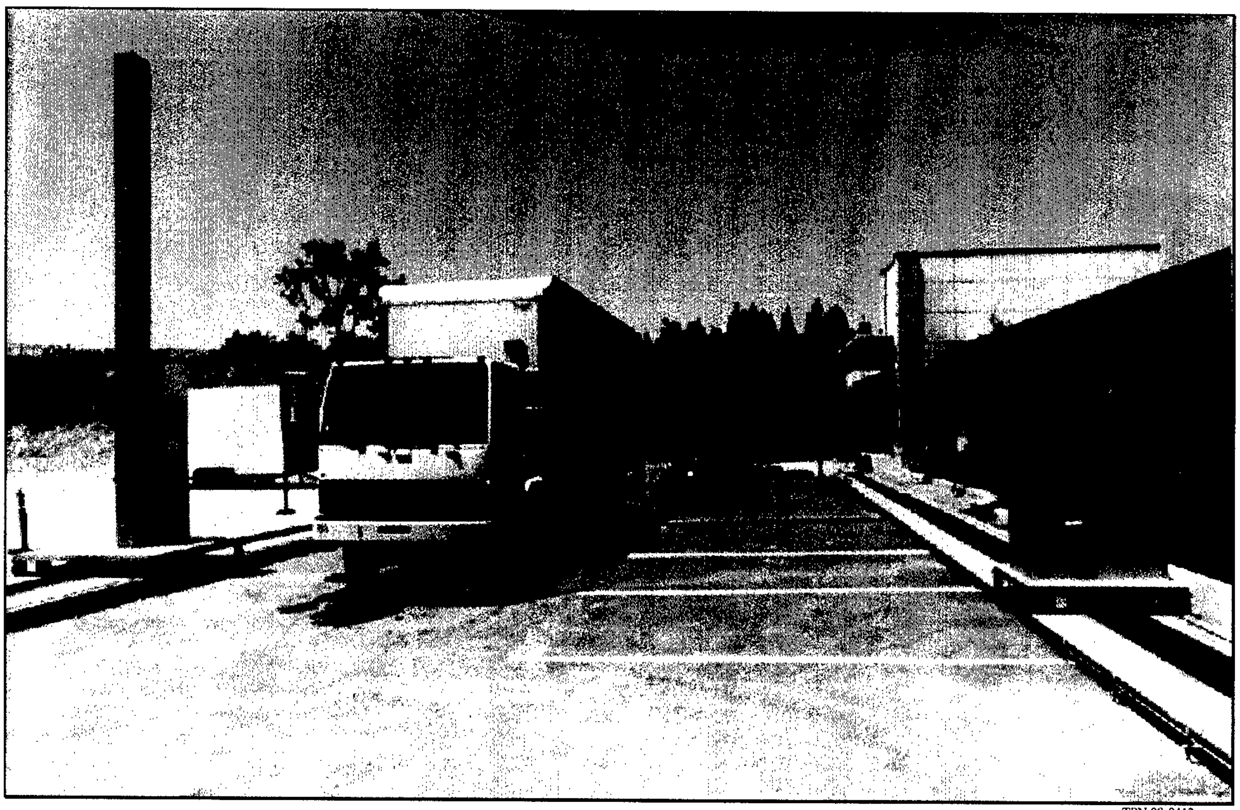
The mechanical hazards are minimal when proper procedures are followed. As with all large industrial equipment, operators must take care around typical hazards such as cables, sharp edges, loose wires, etc, particularly during assembly. Erection of the detector array warrants caution and close attention to detail, but procedures are clearly identified and easy to follow. Concerns about the trolleys are minimized since the trolleys have audible alarms when moving, and are contained within the exclusion zone, limiting access.

The electrical hazards have been minimized through connector design. The major concern is the high voltage power supply, which is located inside the detector trolley enclosure and is not handled or touched during normal operations. If a power supply or associated cable fails, the maintenance technician must exercise the normal cautions when connecting and powering on any voltage supply.

The radiation hazards are clearly defined and summarized in the analysis, including graphs of exposure levels and required exclusion zones. Careful consideration ensures the system is completely safe when typical radiation safety practices are followed. The VACIS –II Radiation Safety Procedures are shown in Appendix C. Both sources have been equipped with a secondary shutter to reduce risk, and the source enclosure on the trolley greatly reduces exposure. The flashing light on the trolley indicates when the shutters are open, and access to the area is generally restricted.

Section 6 — VACIS-II Images

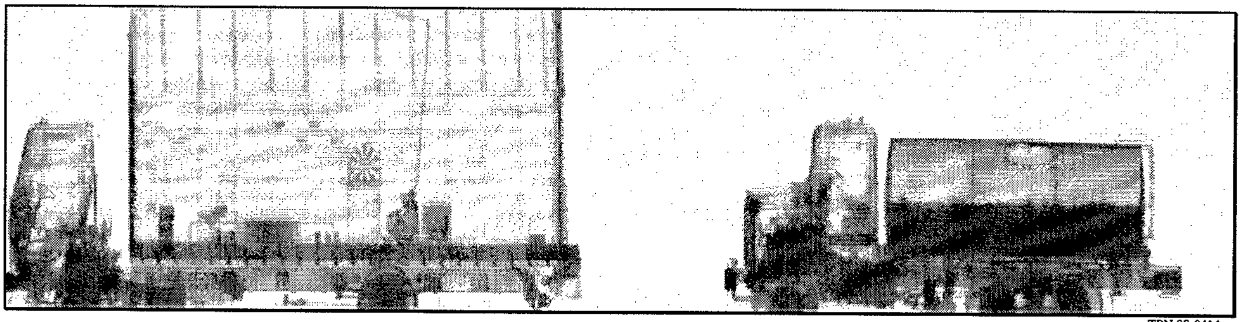
The image shown in Figure 1 below, shows the system in operation in San Diego. The tracks are 90-feet long, enabling them to accommodate a 65-ft. long vehicle at a scan angle of 10°. The tracks are set 40-ft. wide from outside-to-outside and the detector tower, shown on the left side of the tracks, is 21-ft. high to accommodate a 13-ft. high vehicle in a single scan. The source, which is contained on the trolley shown on the right, operates in a range from 14-inches (above ground) to 48-inches, and the horizontal scanning angle can be varied from 0 to 20°. Note the stainless steel enclosures for the source and detector tower, the larger trolleys, and wear resistant cable trays on the tracks.



TPN 08-0413

Figure 1. VACIS II System Operation

The image in Figure 2 shows two vehicles being evaluated in a single scan. A tanker truck was parked behind a cargo van. Note the ability to penetrate the tires, the cab areas of the vehicles, and the easily recognizable objects inside the vehicles.



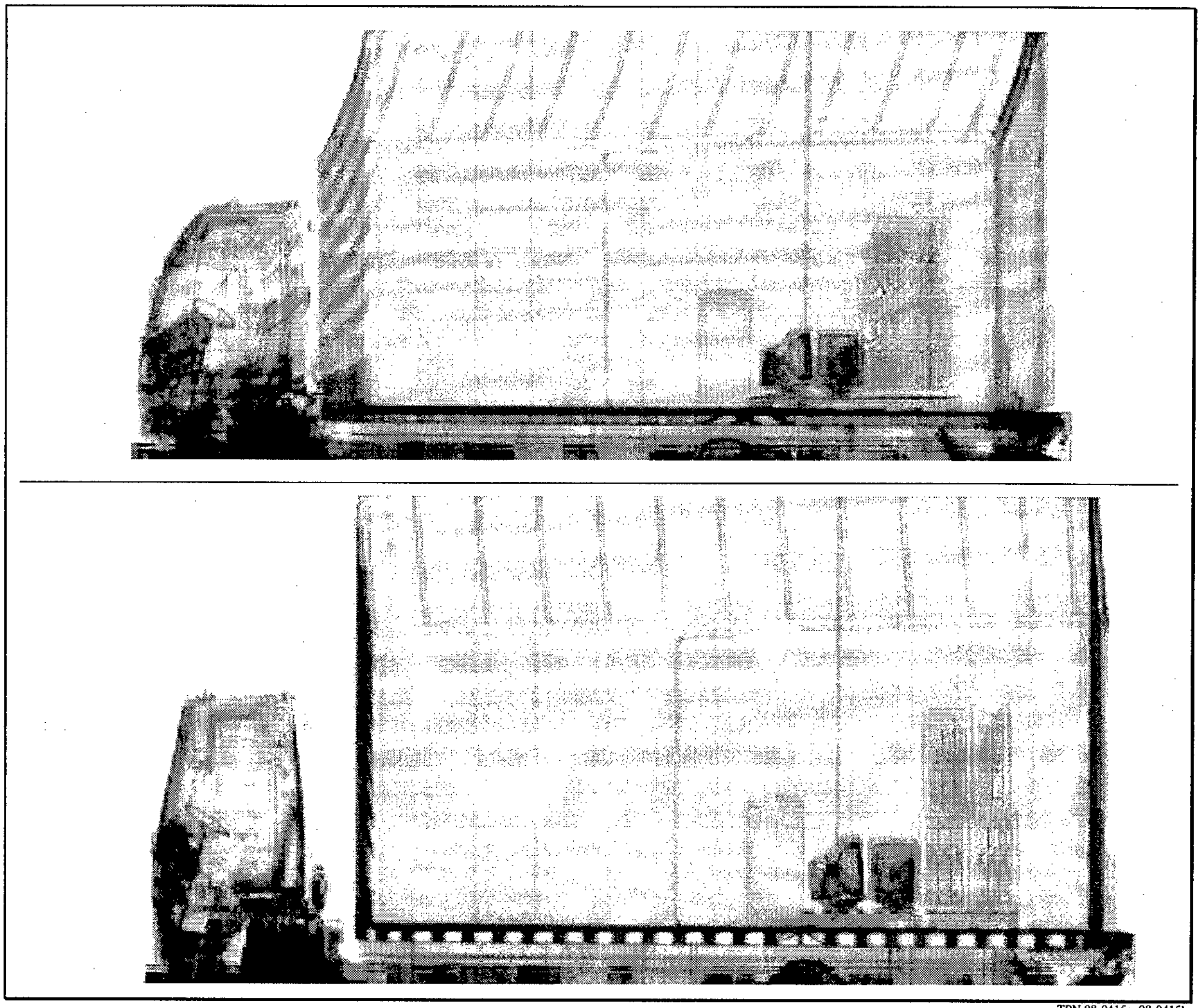
TPN 08-0414

Figure 2. VACIS-II Vehicle Evaluation

In the back of the cargo van is a CRT monitor, and several 1 kilogram packages of cocaine stimulant placed in the cargo area and stacked on the floor. A step wedge was placed approximately 3 ft. from the front of the cargo area which was composed of ½-in steel plates. The plates are positioned to measure the system's penetration, shown to be between 2 and 2 ½ inches of steel.

The images are normally displayed on a 21-inch monitor. Operators have the ability to zoom in on specified regions so this representation is not necessarily the best reproduction of a typical image.

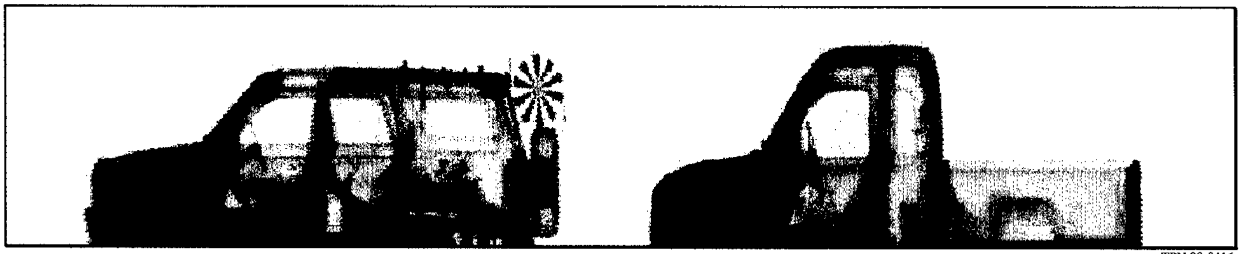
The images in Figure 3 show two views of the same vehicle, the top was taken with the source at a 10° oblique angle. The bottom was taken at a 0 degree scan angle. The oblique view is particularly effective in showing the ends of the container.



TPN 08-0415a, 08-0415b

Figure 3. VACIS-II Images (10° Oblique Angle and 0° Scan Angle)

The images shown in Figures 4 and 5 are the same. Figure 5 shows the image displayed in color mode.



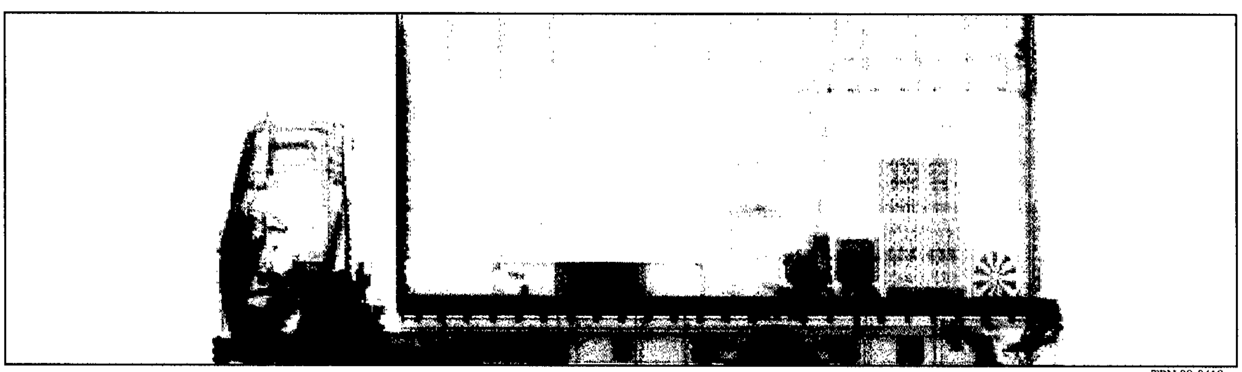
TPN 08-0416

Figure 4. VACIS-II Image (shown in black and white)

TPN 08-0417

Figure 5. VACIS-II Image (shown in color mode)

The image shown in Figure 6 was taken with the source in its lowest position. This low opposition gives the perspective of looking through the bottom of the cargo area and provides the ability to detect hidden compartments or objects located in or under the floor area.



TPN 08-0418

Figure 6. VACIS-II Image with Source in Lowest Position

The image in Figure 7 below shows the effectiveness of the color palettes. Note the guns in two cases. The boxes in the rear contain 1kg cocaine-stimulant located inside packing material.

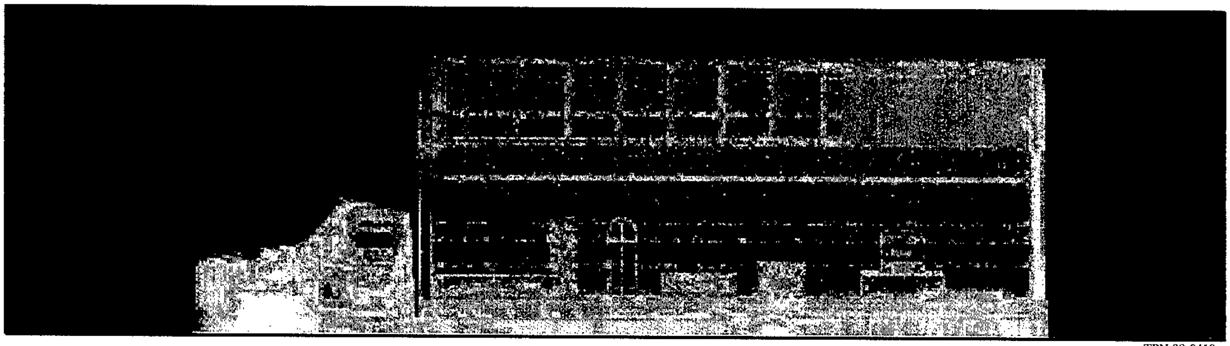


Figure 7. VACIS-II Image (showing color palette effectiveness)

Section 7 — Finance

Original Contract

Mod 0	Cost	$ 849,500.
	Fee	67,959.
	Price	$ 917,459.
Mod 3	Cost	$ 316,958.
	Fee	25,356.
	Price	$ 342,314.
Mod 4	Cost	$ 27,699.
	Fee	2,216.
	Price	$ 29,915.
TOTAL	Cost	$1,194,157.
	Fee	95,531.
	Price	$1,289,688

Actual

Cost	$1,232,221.
Fee	57,467.
Price	$1,289,688

Section 8 — Proposed Changes

Since production and testing of VACIS-II, a review of the completed system revealed several minor changes which could enhance the overall design. A summary of those proposed changes is given below.

Tracks

1. **Guide Pins.** Design change to the guide pins that are used for alignment when bolting track sections. The current steel pins can break when two sections are lifted at the point where they are joined. Replace with either screw in stainless studs or shorter pins.

2. **Track Connecting Brackets**. Currently, the bolts that hold the track sections together are located close to the inner edge of the rail that forms the side of the track section. The bolt heads are so close to the side a wrench must be used. Move the bolts out away from the inner edge of the track rail to provide room for a ratchet or a power (or box-end wrench) wrench to be used for making the connection.

3. **Mirco Switch Locations**. The current tracks have microswitches located on the track end sections. The trolleys contact the switches to perform *home* or stop functions. Move the switches to the trolleys and the contacts to the track ends. This will simplify the wiring for the switches.

4. **Track Section Thickness**. Using 0.090" thick aluminum on the top (versus .060") will reduce the flex and bending caused when people walk on the top of the track.

5. **IGUS Chain Guards**. The current track sections have aluminum guards along the top edge to retain the IGUS chain in its channel. The upright sections have approximately 2 inches at the end of each section bent outward to prevent the IGUS chain from snagging as it passes. The

sections are easily bent if walked on by personnel. A new design should be cut at an angle that allows the IGUS chain to pass by without snagging while providing more support.

6. **E-Stop Arms**. Use hex-head screws to bolt on the arms to standardize the hardware instead of the socket-head screws currently used.

7. **Leveling Feet**. Includes 12 extra feet that are 18 inches long for low spots on the set-up area. During installation, operators may substitute longer feet to cross low-lying areas instead of placing lumber underneath the feet.

8. **Trolley Wheel Extrusions**. The aluminum extrusions that are the rails for the trolley wheels have holes on the top surface that have sharp edges. Countersink or fill the holes from the top to prevent the sharp edges.

9. **Track Section Brackets**. Tighten the tolerances where tracks bolt together for easier alignment during assembly.

10. **Chain Tensioner**. For ease of assembly, include a tensioner at both ends of each track

Trolleys

11. **Trolley Wheel Guides**. The current system uses grooved wheels on both sides of the track. The wheels have a split at the center of the groove on several occasions. The wheels ride on a triangular extrusion that is screwed onto the top of the track. The design should be modified to have the grooves only on one side. This reduces the stress on the wheels. One side should have flat wheels and the other should have grooved. The examination of different wheels and designs further reduce the chance of failure.

12. **Detector Tower Hoist**. The current hoist uses a steel cable that binds and will require frequent maintenance. Change the hoist to a strap versus a cable. Rework the pulley

arrangement for smoother operation. Locate a quieter winch and place a mechanism to hold the module lift pins when they are not in a module.

13. **Trolley Electrical Components**. All electronic components are in a separate enclosure (inside the trolley) to provide further environmental protection.

14. **Trolley Deck Protection**. The current steel design is easily scratched and susceptible to rust. We will place rubber sheeting or another material on the trolley decks.

Electrical Cabling, Servo Drives, and Control

15. **Programmable Interface Controller (PIC).** While the current Giddings and Lewis (G&L) PIC is considered top of the line, it may not be best suited for this particular application. Because the G&L system requires placement of many of the components in the control cabinet, the basic design becomes complicated and hard to troubleshoot. We have redesigned the entire electrical system, using 3 Programmable Logic Controllers (PLCs); 1 slave, and 2 masters that makes the system far less complicated and easier to troubleshoot. The new design yields less cables and smaller cables and allows more controls at each trolley.

16. **Source Oblique and Lift Controls**. Using the new design, it is relatively easy to operate the oblique and lift from the console providing a digital readout on the source trolley or console.

17. **Control Panel**. Replacement of the current industrial panel will be with a smaller box.

Control Console

18. **Icon**. Add a single icon, which allows the image to fill the screen, instead of a smaller viewing window.

Trailer

19. **Weight**. The current trailer weighed considerably more than specified by the dealer, which significantly reduced the payload capacity. The new design will include a gooseneck or fifth-wheel trailer pull that can be pulled by a commercial sized fifth-wheel-hitch equipped truck. The trailer will have the capacity to carry the entire system, including those components that are currently housed in the RV.

Control Center

20. **Recreational Vehicle (RV)**. The RV should be equipped with leveling jacks and have two air conditioners.

Section 9 – Summary

The VACIS-II system is a very effective means of non-intrusively inspecting cargo containers. The images are a valuable tool for performing inspection of lightly or moderately loaded cargo vehicles with adequate penetration and resolution to identify drugs, explosives, or other contraband. The system's throughput allows inspection of a far greater number of vehicles than any other inspection method.

While the system was intended to be a follow-on effort to the first system, it was significantly changed in every aspect. Evaluation of every component resulted in a drastically improved design with greatly improved resolution, far more image manipulating tools, larger vehicle capacity, easier assembly, more reliability, environmental protection, and simpler operation.

Based on the reaction of operators at the acceptance test, nearly every aspect of the system has been greatly improved. With all the improvements in imaging, and image-enhancement features, operators still find the system simple to operate and easy to assemble.

As with any system of this size and complexity, there are items which can be improved in future production. The minor mechanical changes recommended in Section 7 will improve ease of assembly and reliability with minor cost increases. The proposed change to the electrical system will simplify the system as well as provided more automated features.

The cobalt source appears to provide a limited improvement in penetration, but is a somewhat bulky and heavy component to install. Analysis of the images taken with the cobalt source should identify the specific types of loads or cargo where it is most effective. When systems are installed in a location with those types of cargo, a cobalt source could be used.

The additional weight, larger radiation-safety exclusion zone, higher radiation exposure, and shorter source half-life make the cobalt source a less practical option unless the specific type of cargo warrants its use.

Since the Cs-137 source is adequate for light loads, and since neither source can penetrate heavy loads (e.g., a load of gravel, concrete, or potatoes), the in-between loads that might favor the cobalt source are expected to be so rare as to not justify the cobalt source (with its inherent disadvantages (e.g., very heavy source container, great biological dose for the same count rate, higher cost, and much more frequent source replacement)).

Appendix A - Trade Study

ADVANCED VEHICLE AND CARGO INSPECTION SYSTEM

VACIS-II

TRADE STUDY

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1.0 Trade Study

In this trade study we will begin by describing some of the basic operational concepts of the VACIS system and familiarize the reader with some of the parameters used later during the analysis. We follow with a discussion of the design constraints and their origins. We then describe the relationships between various physical parameters of the system and their impact on performance and other design requirements. After a complete analysis of design parameters we will recommend a design configuration that is optimized for cost and performance.

1.1 Basic Description

This section describes some of the basic operational concepts of the VACIS system. The parameters and concepts introduced here will be used later in determining an optimum design. Some of this may be tutorial in nature and can be ignored by the reader familiar with the system physics and the parameters used to measure system performance. We will present the physical geometry of the system, describe how the resolution and throughput are determined, and discuss the gamma ray source.

1.1.1 Geometry

The basic geometry of the system is defined using the following parameters:

a. Source–Detector distance
b. Detector Tower height
c. Source height
d. Vehicle height
e. Vehicle–Source distance
f. Vehicle–Detector Tower distance
g. Detector pitch (center-to-center distance)

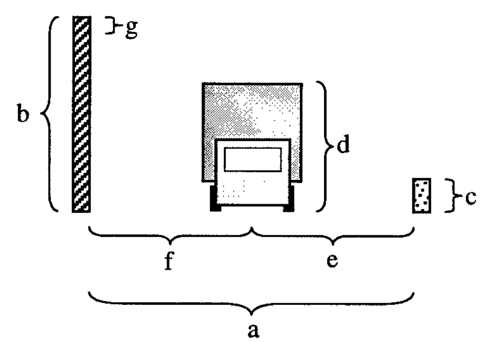

Figure 1. Geometry Measurements

It is clear from the figure that covering the entire object with a gamma ray point source is a tradeoff between the width of the system and the height of the detector tower. It is also clear from the figure that a magnification effect will be incurred in imaging an object positioned between the source and the detectors. The position of the object between the source and the detectors will also affect the height and width of the overall system and this position will also affect the magnification factor. These physical parameters will be used in subsequent discussions and throughout the analysis section in determining the optimal size, resolution, and cost of the entire system.

1.1.2 Resolution & Throughput

The effective spatial resolution for any imaging system is a combination of the physical spacing of the imaging elements and the projection of the target onto the imaging plane. In the VACIS system a tower of scintillator detectors forms the imaging plane and their center-to-center spacing, or pitch, is an important factor in determining the system's overall resolution. In many imaging applications the imaged object is very near the imaging plane. In larger imaging systems, such as VACIS, the true spatial resolution is also determined by the projection of the object onto the imaging plane. Magnification of the object is determined by its physical location with respect to the imaging plane, and will yield a finer spatial resolution of the imaged object.

An imaging system's overall spatial resolution can be represented in terms of both the pitch of the imaging detectors and the magnification. The spatial resolution, r, is determined by the pitch, p, multiplied by the ratio of the distance from the source to the object, d, and the distance from the source to the detectors, D

$$r = p(d/D)$$

Throughput, another important performance parameter, is essentially tied to the system's scan rate. The speed at which the system scans or inspects an object is dependent upon several limitations. Data processing is the primary limitation. As resolution demands increase the number of detectors in the system increases and hence the amount of data to be processed. The communications protocol and data processing board design also constrain the throughput. Finally, the statistical requirements governing how much data needs to be collected for producing an adequate image is an important consideration in determining the throughput. These parameters and others will be discussed and evaluated during the design constraints and analysis sections.

1.1.3 Source

The gamma ray source is described using two parameters, the isotope and the activity. The isotope, in this case Cs-137 or Co-60, defines the energy of the gamma rays emitted by the source. This is a monoenergetic source and not a spectrum of energies as is the case with typical x-ray sources. The gamma ray energy then, defines the penetration of the beam, usually measured in thicknesses of various materials. Cs-137 emits a gamma at 662 keV that penetrates 2" of steel, while Co-60 emits two gammas at 1173 and 1333 MeV that penetrates 2-3/4" of steel. From this we may keep in mind that the penetration distance is not linear with energy.

The source activity, given in curies (Ci), defines the amount of radiation emitted, or the number of disintegrations per second. A single curie of radiation represents 3.7×10^{10} disintegrations per second. A disintegration may result in one or more particles being emitted. In the case of cesium an average of 0.85 gammas is produced per disintegration while cobalt emits two gammas per disintegration. Therefore, cobalt requires only half the activity of cesium to produce the same number of particles. These gamma rays are isotropically emitted and therefore, not all directed towards the intended target, thus, much of the source goes unused. This is why shielding is employed around the source, to prevent extraneous gammas from escaping.

1.2 Design Constraints

There are a number of design constraints generated by the user/customer, the physical size of the vehicles being inspected, considerations of the environment and workplace, and certain engineering design limitations. Below we describe the design constraints that affect the optimal design of the VACIS system geometry along with rationale describing the requirements, specifications, objectives, and considerations. Their use during the tradeoff analysis will be essential in the overall design and function of the VACIS system.

1.2.1 Physical Constraints

- The dimensions of the largest vehicle likely to be encountered at a border crossing are 13' high, 8' wide, and 65' long.
- The footprint of the system depends on the width determined during the analysis, however, a practical limit based on space available at likely installation sites is 50' with an exclusion area of no more than 100'.
- The detector tower, while tall enough to inspect a vehicle, must consider the effects of wind and the engineering required to support and move the tower. A height of 30' is considered the practical limit.
-

1.2.2 Engineering Constraints

- The system electronics is currently limited to polling 1,000,000 times per control board. Each board counts 16 detectors; thus, the effective limit is 62,500 polls per detector per second.
- The communication protocol transferring events to the processor has a current baud rate limit that allows an effective limit of 38,400 detector polls per second.
- Detector statistics are limited to a minimum of 1000 counts per detector poll, if we are to optimize the ability to perceive differences in the image at the same level that the human eye can perceive.
- The speed at which the trolley moves along the tracks is limited to approximately 1 ½ feet per second by the synchronization of the trolley drive motors, and the speed a tall detector tower can safely be moved along the tracks.
-

1.2.3 Customer Requirements

- System resolution must be no less than ½" in both the vertical and horizontal dimensions.
- Scan rate must be no less than 1 ft/sec.
- Detector tower must withstand 40-mph winds.
- Protect the system and associated electronics against environmental conditions.
- Provide oblique scanning capability at 10 degrees.
- Limit cesium source to 1 Ci and cobalt to 0.5 Ci.

- Cobalt and cesium sources are both required and must be interchangeable.
- The source and detector elevation mechanism must be motorized
- Vehicle inspection must be performed in a single pass.

1.3 Analysis

Given the information listed in the previous sections, we can establish some fixed criteria for some of the variable parameters. Once those values are established, we can design around them in order to reach the optimal performance at minimum cost. The figure below illustrates the relationships amongst the myriad of variables we have to work with. Eventually everything comes down to cost. Except for a few limitations of physics and engineering, as well as the absolute minimum requirements of an imaging system, most performance factors come down to cost. Please refer to this chart as we go through some of the analysis factors, as it is easy to see what is affected by a change in operational requirement and where the tradeoffs are.

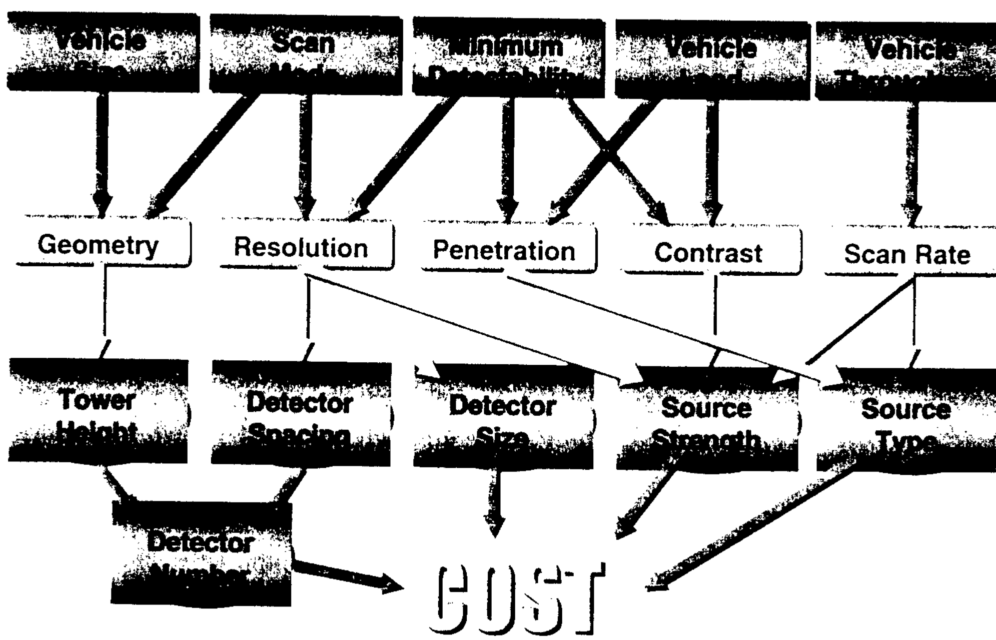

Figure 2. Analysis Flowchart.

1.3.1 Geometry

The width and height of the system determine the height of vehicles which can be inspected. System width is limited primarily by the area it will occupy when installed; the height of the tower is limited by physical size restrictions (allowing for weight and wind impacts), and cost increases. The height of the source determines the angle at which gamma rays pass through the vehicle, and therefore how much of the vehicle will be included in the image. Once limits are established for height and width, various combinations are examinied until the optimal resolution results. One can see from Figure 1, the wider the system is, the lower the detector tower can be.

Since increasing the height of the tower is costly, (more detectors and associated components are needed for a higher tower), the desirable trade is to make the system wider.

The height of the tower is also determined by the location of the vehicle between the source and the tower. Moving the vehicle closer to the tower also allows a shorter tower, and reduces the variation in geometry the image will have, but reduces the resolution. Conversly, moving the truck closer to the source has the opposite effects. Since increasing the resolution is the most desirable variable, the vehicle is moved as close to the source as possible within an acceptable limit for the tower height. Raising the source above ground level also allows reduction in tower height, but raises the minimum height of the area being inspected. Most containers are some distance from the ground, so raising the source a bit is not a problem and still allows nearly full coverage of the vehicle. This allows viewing of the tires from at least halfway up the height of the tires, and since contraband located in tires will most likely be uniformly packed, viewing the upper half is sufficient, and cost effective.

After looking at a number of configurations and analyzing the cost per pixel of resolution of each configuration, an optimal configuration was determined and is show in the figure below.

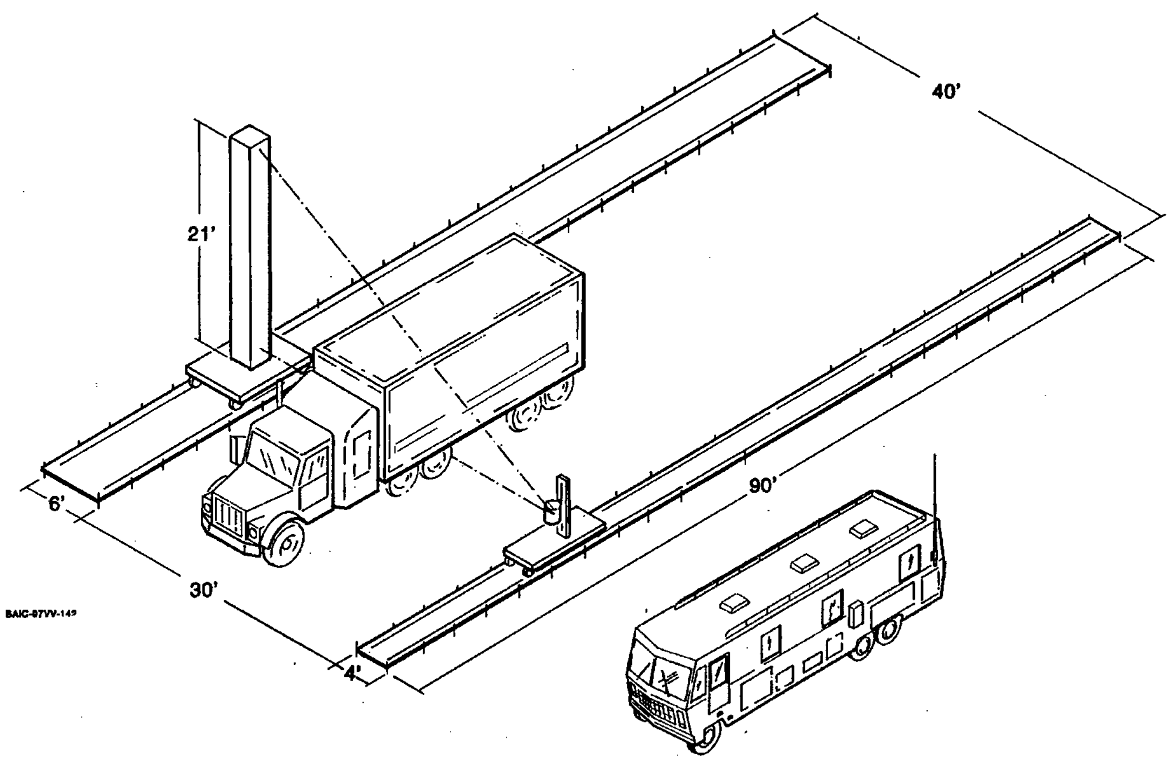

Figure 3. Optimal VACIS-II Configuration

1.3.2 Resolution

Given the baseline VACIS system width of 40 feet, with 35 feet between the source and the detectors, and the standard detector tower height of 21 feet, the system resolution is determined by the pitch and the source-to-object distance. Using standard height and width for a cargo vehicle, 13 feet by 8 feet, and using the centerline of the truck as the object location, we can make comparisons and tradeoffs of detector pitch and magnification distances. This too, directly impacts the number of detectors required and, therefore, the cost of the system.

The resolution as it is defined by detector pitch applies to the image generated in the vertical direction. Since the system is moving, the detectors must be sampled often enough to match the vertical resolution in the horizontal direction. If the detectors are polled slowly, the vertical resolution remains the same, but there would exist a lower resolution in the horizontal direction. Similarly, if the system is polled too fast, the resolution will be unmatched, though better, in the horizontal direction. Ideally, the system will move at a rate that equates horizontal and vertical resolution. For example, if the system has ½" vertical resolution, the detectors should be polled every time the system travels ½". The polling rate influences scan speed, and will be discussed in more detail later.

As stated earlier, the size and number of detectors are the determining factor for the resolution. Disregarding other factors, resolution is most directly increased by decreasing the space between detectors, or pitch. This requires increasing the number of detectors to cover the tower height needed to image an entire vehicle. Smaller detectors can be used to reduce the pitch, but they are generally more costly, and they require a longer sample period to ensure they gather adequate photon counts to provide good statistics, thereby reducing the rate at which the system can scan. Detector cost increases significantly for scintillators smaller than 1 1/8", due primarily to the cost of the associated photomultiplier tubes. The cost for the detectors increase significantly for detectors larger than 2" because of the amount of scintillator material needed for the detector. The table below shows sample resolutions using the most cost effective 1 ½" detectors. Another method to reduce the pitch is to "stagger" the detectors, or slightly offset them. This allows the pitch to be reduced, and the offset distance is recorded by the control unit and compensated for in the image.

Various configurations of detectors were examined to determine the optimal configuration. The table below shows the impact of increasing the number of detectors on resolution. Using the relationships developed earlier the following table was constructed showing the various resolutions available. The requirement for ½" is achieved using the 336 detector configuration.

# of detectors	Pitch	d/D	Resolution	Control Boards
112	2.25"	21/35	1.35"	7
168	1.50"	21/35	0.90"	14
224	1.13"	21/35	0.68"	14
280	0.90"	21/35	0.54"	21
336	0.75"	21/35	0.45"	21

Table 1. Effect of Increasing Number of Detectors on Resolution.

The system uses electronic data processing boards which receive the analog signals from the detectors, modifies and amplifies the signals, converts them to digital signals, processes, and then routes them to the computer for image processing, storage, and display. Each board is currently designed to control 16 detectors, and is located within the detector-housing module. The modules are nominally 3 feet high, so a module with 48 detectors would also have three control boards. To reduce the overall cost of the system, detectors are added in multiples of 16, where possible.

The table above illustrated the practical limits of using 1 ½" detectors in a 3 foot module box. The pitch of the detectors could not be reduced further without decreasing the detector size, which drastically impacts scan rate, as will be shown in the following paragraphs. Establishing the detector size, tower height, and other parameters we can now assess the scan rate.

1.3.3 Throughput

Throughput is determined through the limitations of the electronics and counting statistics that are used to gather data. Whenever data is required by the computer from the detectors it *polls* the detectors through a number of data processing boards via a standard communications protocol. Everything in this path has transmission limits: the detector's ability to count gammas, the number of gammas required to yield a valid signal for imaging, the board limitations on collecting data, and the communication protocol's ability to pass data through. We will discuss each of these bottlenecks below.

The system's electronics control board has a limit at which it can poll the detectors. This rate is currently 1,000,000 times per second for each control board. Since each board controls 16 detectors, the effective limit is 62,500 polls per detector per second. The communication protocol that transfers the events to the processor is more limited at currently 38,400 polls per second. To raise the ceiling on this limitation, the system would have to use a different protocol, such as Ethernet.

The horizontal resolution required of the system (in this case ½") determines how often the detectors are polled. For example, a system with 336 detectors (1/2" resolution), polling every ½", scanning at 1 ft/sec, would require 8064 polls/sec (336 x 24 samples/sec). Table 2 below shows the polls required with various resolutions and various scan speeds.

Resolution	# of Detectors	0.5 ft/sec scan rate (polls/sec)	1.0 ft/sec scan rate (polls/sec)	2.0 ft/sec scan rate (polls/sec)
1.3"	112	1344	2688	4032
0.75"	224	2688	5376	8064
0.5"	336	4032	8064	12096

Table 2. Polls Required at Varying Resolutions and Scan Speeds.

By far the most limiting factor for scan rate is the statistical requirement by the detectors in order to give an unambivalent signal showing image detail discernable by the human eye (~2-3%). The detectors must receive a photon count rate high enough to generate a statistically accurate representation of the object being inspected (similar to an exposure time). This minimum-count criteria, along with the desired resolution, establishes the practical speed the system can scan the object. If we wish to scan faster while maintaining resolution we may do so only by reducing the statistical criteria, or increasing the source strength.

The above criteria for statistical validity, if each set of polled data is to represent a +/-3% accuracy, requires 1000 counts per detector per poll. Scintillator detectors can count single photons emitted by the source. The efficiency of the detectors, and the distance from the source determines the number of counts they receive without interruption from an object. The count rate is the product of the area of the detector, its efficiency, the activity of the source, and the distance the photons travel. At 35 feet, a 1-Ci Cs-137 or 0.5-Ci Co-60 source yields approximately 20000 counts per second (cps) for 1½" diameter detectors, 35000 cps for 2" detectors, and 80000 cps for 3" detectors. Using the geometry and source strength above along with 1½" detectors, the counts received per detector per poll calculations for various resolutions and scan rates are shown in Table 3.

From the table, one can see that the system can move along the trolleys at the rate of 1.0 ft/sec and the detectors will receive just under the required counts for good statistics. This is sufficient for our system description as we have some leeway with some of our other parameters (oversampling, processing speed, source strength, scan rate, etc.).

Resolution		0.5 ft/sec scan rate	1 ft/sec scan rate	2 ft/sec scan rate
0.5"	Time between polls	0.083 secs or 12 polls/sec	0.042 secs or 24 polls/sec	0.028 secs or 36 polls sec
	Counts received at each detector between polls	16600	840*	560*
0.75"	Time between polls	0.125 secs or 8 polls/sec	0.0625 secs or 16 polls/sec	0.042 secs or 24 polls/sec
	Counts received at each detector between polls	2500	1250	840*
1.3"	Time between polls	0.217 secs or 4.6 polls/sec	0.108 secs or 9.2 polls/sec	0.072 secs or 13.6 polls/sec
	Counts received at each detector between polls	4340	2160	1440

*This number of counts is insufficient for the required statistics, slower scan rate required

Table 3. Detector Counts at Varying Scan Rates and Resolutions.

1.3.3 Source

The criteria used to compare the cesium and cobalt sources are shown in the table below. Each source offers some advantages. Cesium is lighter, less costly, and requires a smaller exclusion zone. Cobalt has approximately 37% higher penetration for 2" of steel or 20" of wood. Table 4 compares and contrasts the two sources.

		Cs-137	Co-60
	Activity	1.0 Ci	0.5 Ci
	Weight	115 lbs.	660 lbs.
	Energy	662 keV	~1.17 MeV
Count Rate	**35' Air**	20,000 cps	19,800 cps

2" Steel	1,190 cps	2,260 cps
Penetration Wood	16 in	22 in
Steel	2 in	2.75 in
Contrast Sensitivity light ld	1.00	0.72
Exclusion Zone - 2 mR/hr	38 ft	53 ft
- 0.5 mR/hr	79 ft	110 ft
Cost	$4,645	$11,655

Table 4. Comparison Between Cesium-137 and Cobalt-60 Sources.

The difference in image contrast is another parameter that differs with source. A lightly loaded vehicle will have a larger dynamic range of contrast using the cesium source, while a load that is near the maximum density for penetration will have more contrast with cobalt. Without a good profile of the density of the average load to be inspected, it is hard to determine the exact impact of using cobalt. Calculations can determine its capabilities for each specific use, but there is insufficient data to quantify the type of load to be evaluated. This data will have to be gathered during testing, however, what has been determined is that each source is, using contrast criteria, appropriately suited for its intended purpose.

2.0 System Design SPECIFICATIONS

Once the optimal system design was established, each major component was evaluated to make it more efficient, rugged, cost effective and user friendly. The major components and the features or improvements are summarized below. An asterisk (*) indicates a safety feature of the VACIS II.

2.1 Track and Trolley System

- Scans vehicles 13 ft high, 8 ft wide, and 65 ft long in a single scan
- Scan rate in optimal mode is ~1 ft/sec, maximum 1.5 ft/sec
- Home switches to ensure automatic, repeatable scan starting position
- Nominal system dimensions (tracks only) are 40-ft wide x 90-ft long, variable
- Nominal source-detector distance of 35 ft, variable
- Detector track is 6-ft wide, source track is 4-ft wide, both are 90-ft long
- Easy-assembly, modular track made of interchangeable 6-ft aluminum sections
- Each track segment has adjustable leveling feet designed for rapid and easy height adjustment
- High-reliability source-detector synchronization motors accurate to 0.01 inches
- Track drive (motor speed reducer and brake) mounted directly to trolley
- Aluminum rails and steel track connection hardware for increased rigidity and strength
- Cable trays Teflon coated to reduce wear
- Ruggedized construction features allow operation during rain
- Source trolley approx. 4 ft. x 4 ft footprint; detector trolley approx. 6 ft. x 6 ft footprint
- Environmental covers protect all trolley components
- PLC uses high-reliability integrated logic and dual-axis motion controller
- Trolley PLC cables use standard flexible, center stationary, horizontally mounted cable carrier
- Cables in cable carrier are high reliability, long flex life type (100,000 cycles nominal)
- Cable connectors are high reliability mil-spec grade
- Drive motors are brushless DC type with integrally mounted dual-channel optical encoders
- Power requirements: 115 V AC, 1-Phase 60 Hz, 30 A or 230 V AC, 1-Phase 60 Hz, 15 A
- Trolleys will use variable acceleration rates to maximum velocity
- * Manually actuated E-stop buttons, one at each end of each track
- * Forward and reverse travel limit switches
- * Forward and reverse travel power kill switches
- * Shock absorbing hardstops to safely stop trolley in case of over-travel

- * The electric motor drive train includes a fail-safe brake mechanism
- * During E-stop or power outage the trolley brakes to a stop
- * Cam follower detent mechanisms on trolley prevent tipping due to wind loads

2.2 Detectors and Detector Tower

- Detector tower is 21 ft high; made of seven 3-ft-high detector modules
- Modules measure 10" x 12" in cross section
- Total of 336 NaI detectors, 1.5" diameter, 2.5" long, with a pitch of 0.75"
- Provides a vertical and horizontal system resolution of less than 0.5"
- Detector pitch and pattern allows for a 2:1 oversampling of scanned object
- Detectors using single cable design for simplification and ease of maintenance and repair
- Detectors loaded in rugged foam support for vibration, shock, and temperature protection
- Modules constructed from stainless steel and sealed for corrosion protection
- Access door for servicing internal components
- New, faster data processing board services 16 detectors at a time
- Electronics in enclosed housing for added corrosion protection
- * Motorized hoist and guide beam for easily joining and raising detector modules
- * Designed to withstand gusts of wind up to 40 mph
- * For high wind conditions, the detector tower beam has provisions to be lashed via optional cable tie downs and ground mounted eyebolt anchors

2.3 Source

- Two sources provided: 1-Ci Cs-137 (662 keV) and 0.5-Ci Co-60 (1.17 and 1.33 MeV)
- Interchangeable mounts so that either source can be quickly mounted
- Source housing easily removable so that source can be locked up during periods of non-operation
- Motorized lift to raise and lower source position
- Source height indicator scale visible during adjustment procedure
- Portable lift for transport of the source from storage to the platform included with system
- Source oblique scan angle adjustable from 0 to 20 degrees with detents and indicator lights at 10, 15, & 20 degrees
- Motorized source rotation for oblique scanning
- * New dual-shutter system, primary and fast, provided for additional speed, reliability, and safety
- * Both shutters provide positive closure in the event of power failure or emergency stop
- * Backup battery, with a shelf life of three years, ensures primary shutter closure

- * Spring-loaded rotation ensures fast shutter closure
- * Source shutters opened only during a scan and closes at all other times
- * Red indicator lamp illuminated only when source shutter is open

2.4 Control Console

- Console components include: 300 MHz Pentium II CPU, full keyboard, 21" monitor, system control pad
- CPU runs Windows NT for faster processing and more user friendly operation
- External control pendant allows manual movement of either trolley without console
- Image enhancement features such as zoom, pan, scan, annotation, contrast and more
- CD-based archive system for stored images included
- CCTV video system to record visual image of vehicle being scanned included
- Console is stand-alone and can be used in a mobile enclosure or portable building
- Computer code written in object-oriented C++ for ease of modification, update, and documentation
- Control pad functions include system movement and shutter controls and emergency stop
- * Lockout feature preventing override from main CPU
- * UPS provides backup power during power loss for controlled shut down
- * Status indicator lights on control pad
- * Electrical power disconnect physically cuts power to operator's console during servicing

Appendix B - Hazards Analysis Report

ADVANCED VEHICLE AND CARGO INSPECTION SYSTEM

VACIS-II

HAZARDS ANALYSIS REPORT

Submitted to:

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Appendix B - Hazards Analysis Report

EXECUTIVE SUMMARY

This analysis covers three areas of possible hazards; namely, radiation, mechanical, and electrical. The radiation hazards are completely manageable with the safety features supplied with VACIS-II and the operational procedures designed to minimize accidental exposure of personnel. It should be emphasized that even if the two (primary and secondary) radiation-source shutters were left open (and if somehow the flashing red light were to become non-operational), a person walking through the narrow, fan shaped beam at the location of a truck being inspected would only receive about a 4 microroentgen exposure. This is 10,000 times less than the dose delivered by a 450 kV, 10 mA x-ray beam similarly collimated (and only about 5 millionths of some medical x-ray exposures).

Both the radiation beam and the mechanical (trolley) motions are observed by the computer operator and are completely controllable by this operator, which lends itself to a completely manageable operation. There are no known electrical hazards other than the normal hazards associated with personnel working with a 110 volt system, and a 520 volt DC power supply (30 mA maximum) that is contained in the sealed detector tower.

Since the fabrication, testing and installation of VACIS-II at Florida POEs, the fireproof (all steel and tungsten construction, no lead shielding) and explosion-proof source shield and collimator assembly for the 1-Curie CS-137 source has successfully undergone a blast test near a 7500# TNT-equivalent blast. This is of utmost interest for utilizing the Cs-137 source for force protection (looking for a "truck bomb").

1. INTRODUCTION

This report describes the extent of the possible hazards associated with the operation of the VACIS-II gamma-ray radiographic imaging system. This prototype system was in use, at the time of this writing, for inspecting cargo trucks and cargo containers for drugs being smuggled into USA through ports of entry in Florida. Section 2 of this report describes the physical and operational aspects of VACIS-II. This lays the groundwork for a discussion of the three identifiable sources of hazards, namely radiation, mechanical, and electrical. These are treated in detail in Sections 3, 4, and 5, respectively. Section 6 summarizes this hazards analysis, and compares these possible hazards with some which we are much more familiar, or to which we are normally exposed.

The VACIS-II production units will be slightly different from the VACIS-II prototype. For example, the Co-60 source may no longer be employed. The changes in the hazards report brought on by modifications embodied in the production units will also be addressed in the body of this report.

2. DESCRIPTION OF VACIS-II AND OPERATIONAL PROTOCOL

A schematic diagram of VACIS-II is shown in Figure 1. A radiation source is shown to the right of a thick-steel-walled tanker truck. The source is moving on a trolley in synchronous motion with a detector tower, also on a trolley. The source and detector tower move along the length of the parked cargo truck (e.g., a tanker truck, in Figure 1) to generate a radiographic image of the contents, in an inspection for hidden drugs or other contraband.

A narrow, fan-shaped beam of gamma rays is directed at the detector tower when the source shutter is opened. With the source and detector trolleys moved synchronously, the fan-beam is made to fully irradiate the detector tower as both trolleys are moved along the length of the vehicle container being inspected. The following sequence of operations is designed to obtain a good radiographic image in a short time and with a minimum probability of radiation exposure or physical harm to personnel in the vicinity of the VACIS-II inspection area.

First, the vehicle to be inspected is guided forward to the point where both trolleys can cover the entire length of the truck. The truck driver is guided near the detector tower, to where the entire height of the vehicle can be inspected. Figure 1 shows this schematically for VACIS-I, which had a 12' high detector tower, just high enough to fully inspect only the tank of a tanker truck for which it was designed, whereas VACIS-II, with a 21' high detector tower, can inspect a 13-1/2' high cargo truck.

The driver then leaves the cab and walks to the end of the trolley tracks, beyond the "sweep" of the gamma-ray beam. The computer operator, seated in a camper nearby, views the entire area except where the vehicle under inspection blocks his view. The other U.S. Customs Service inspector who guided the truck into place, gives the computer operator the "go" signal when he has determined that all personnel are out of the exclusion zone, where the gamma-ray beam sweeps by.

At this point, the computer operator activates the secondary source shutter, and the motion (synchronized) of the two trolleys. A rotating (flashing) red light atop the source trolley is activated the moment the secondary source shutter is opened, warning everyone nearby that the source shutter is open and that all personnel are to stay out of the beam and off the trolley tracks. When the trolleys move, an audible alarm sounds.

With the gamma-ray source shutter open, the source and detector trolleys move along the length of the cargo vehicle, forming a gamma-radiography image in real time, one vertical line at a time, until the entire length of the vehicle has been imaged. At this point, the radiation source shutter automatically closes, and a new vehicle is brought into the VACIS-II inspection area as soon as the first pulls out. The vehicle that has been inspected is then directed to either go on with his travels or to pull into an inspection area where anything unusual in the image is checked out via a physical inspection. These suspect abnormalities in the gamma-radiography image can include unusual dark or light areas in an otherwise uniform load of produce or manufactured items; dark areas in tires, or behind, beneath or inside of the cab seats, inside the roof structure or hollow structural member; and false compartments, mostly on the front side or the bottom of the van, under the hood, in the gas tank, etc.

It should be pointed out that with VACIS-II, the source and detector trolleys can remain at the end of the trolley tracks where they have come to rest, without the need to return to the "home" position; i.e., they can inspect the next vehicle "backwards". This reduces the wear and tear on the trolleys and the time for inspecting a large number of vehicles per day. Each "trolley run" takes about 90 seconds to cover a normal cargo vehicle.

The SH-F2 source holder, manufactured by the Ohmart Corporation, is used for the Cs-137 gamma-ray source. It is licensed to hold a Cs-137 source capsule of up to 1.6 curies in source strength, and is loaded with 1.0 curies for this application. For VACIS-II, the source holder, with attached shutter-activating motor, is shown in Figure 2. Note the combination lock inserted into the lockout rod. This lock is placed on the source when it is removed from the source trolley for storage, after inspections are done for the day. Note, to the left of Figure 2, the 60° vertical span shown for the beam when the shutter is open. The "rays" of gamma radiation coverage at the center of the hemisphere at the back end of the SH-F2 source holder (shield/collimator). At this point is located a 0.25" diameter spherical bead containing 1 Ci of Cs-137. The bead is contained in stainless steel capsule, 0.5" O.D. and 0.75" long, with a 0.62-inch thick "window" heliarc welded onto the "face" of the capsule. The gamma rays pass through the "window", unimpeded, and on to the detector tower when the shutter is open and with no vehicle between source and detector trolleys.

The shutter opening and closing time is about 5 seconds. The beam emerges from the open shutter with a 60° vertical "fan" and 10° horizontal beam width. A secondary shutter, described below, restricts the beam width to 5° or less to reduce secondary scattering effects (i.e., "fogging" of the gamma-ray radiography image).

The Co-60 source holder is shown in Figure 3. This Ohmart SHLG-3 source holder weighs about 665 pounds (versus 115 pounds for the Cs-137 SH-F2 source holder, without motor activator). The plunger is pulled out (up) for the OFF position, and a padlock is inserted through the plunger shaft to keep it closed. A Co-60 source strength of 0.5 Ci was loaded into the SHLG-3 source container. It provides about the same count rate as the 1 Ci Cs-137 gamma ray source. Note: one Curie yields 3.7×10^{10} disintegrations per second. However, 100 disintegrations of Cs-137 yield only 85 gamma rays of 662 keV energy, whereas 100 disintegrations of Co-60 yield 200 gamma rays ("in cascade").

When the computer operator opens the shutter for the CS-137 or the Co-60 source, he electrically opens up only the secondary shutter, which is designed to open and close often and at a rapid rate. The primary shutter is opened at the beginning of the inspection day and remains open all day. The Cs-137 primary shutter can be opened electrically (remotely), while the Co-60 primary shutter must be opened manually. A padlock must be removed before either primary shutter can be opened (it is stored in a padlocked state because of obvious safety concerns).

Figure 4 presents a drawing of the Cs-137 secondary shutter. For the VACIS-II prototype, operating at Port of Everglades in Florida at the time of this writing, the secondary shutter has an opening speed of about 500 milliseconds. This fast shutter is "fail safe" in that it is made with a return spring so that it closes immediately upon electrical power failure.

Figure 5 presents a mechanical drawing of the Co-60 secondary shutter. It is identical to the Cs-137 secondary shutter but for a different mounting plate, one suited to the bulky Co-60 gamma-ray source holder/shield/primary collimator.

3. RADIATION HAZARDS

Both sources (1 Ci Cs-137 and 0.5 Ci Co-60) should be stored in a locked room, with a padlock that prevents the primary source shutter from being opened. The padlock remains in place until the source is moved onto the source trolley and bolted in place. The secondary shutter is automatically closed at all times of removal from the source trolley because the power is disconnected, and the return spring restores the shutter to a closed position with power off. During storage, a reading is taken outside the storage room to ensure that no reading is anywhere above the 0.5 mR/hr cabinet-radiography limit.

The radiation levels outside the SH-F2 source holder, as loaded with a 1 Curie Cs-137 source, are presented in Table 1 for front, rear, left, right, top and bottom; at contact, 1' away and 3' away. Note that at 1' from the surface, all readings are below 5 mR/hr. The estimated exposure to personnel loading the source will be at most the product of 5 minutes exposure time and the 0.5 mR/hr dose rate at 3' from the source or about 42 microroentgen, well below the permissible level of 2 mR allowed in any one hour.

Table 2 presents the radiation field mapping for the SHLG-3 source holder, as loaded with a 0.5 Ci Co-60 source. This source was primarily used as an experimental source whose role was the evaluation of the possible benefits of increased penetration of heavy cargo loads.

For the Ohmart SHLG-3 source holder loaded with a 0.5 Ci Co-60 source, the leakage radiation at the sides is 1.6 times greater than for the Cs-137 source holder. This raises the estimated exposure to the installation crew to an estimated maximum of 67 microroentgen during installation or removal of the source. Again, this is well below the allowable level of 2mR for any one hour.

After either source is installed, a sheet-metal housing surrounding the source reduces the radiation field to less than 2 mR/hr at the edge of the housing, and less than 0.5 mR/hr at the normal distance of closest approach (about 1-1/2' from the surface).

As stated in Section 2 above, the primary source shutter is opened at the beginning of the work day and left open, while the secondary shutter (designed for frequent openings and closings, without breakdown, and also designed for rapid openings and closings) is opened by the computer operator at the beginning of each scan of a cargo vehicle. The secondary shutter automatically closes at the end of each scan. Before each scan, the operator who has guided the truck into the proper location will have the truck driver leave the truck and move out of the exclusion zone described below. He then signals to the computer operator that nobody is in the exclusion zone, at which point the computer operator (who can see the entire scene except on the other side of the cargo vehicle) has the secondary source open and the source and detector trolleys move along the length of the truck. A rotating red light is turned on and stays on as long as both shutters are open. After the gamma-radiography image has been formed, the computer operator signals to the "truck dispatcher" that the area is safe and the driver is to move the truck out as soon as possible, or that suspect "hit" has been made and that the driver is to pull up to an inspection area where a physical inspection of the "hit" area is further investigated. With VACIS-II operating in the Port Everglades, Florida POE, about 400 such inspections per day are carried out (per Dr. Siraj Khan, U.S. Customs Service R&D staff, private communications).

The radiation field with the secondary shutter open is presented in Table 3 for both the 1 Ci Cs-137 source and for the 0.5 Ci Co-60 source. The fan-shaped beam is approximately 5^{o} wide. It can be reduced to any smaller width, if the beam-alignment errors allow. These include the following: the error in the synchronous motion of the source and detector trolleys (estimated to be $\pm$ 1" to 2"): in the degree of parallelism of the two tracks, when set up; in the relative "swaying" of the source and detector towers due to the degree of care or lack of care in track alignment by the installation crew; and due to swaying caused by varying wind conditions. The nominal width of the fan-beam (90% of full intensity) is about 24" at the detector tower, as determined by measurements with a gamma-ray dosimeter. This can be reduced to perhaps 18", but no more, considering the possibility of strong winds acting on the 21' tall detector tower. A narrower beam reduces "fogging" of the image due to multiple-scattered gamma rays (from the heavier portions of the cargo) reaching the gamma-ray detectors, and thus causing a reduction in the effective penetration of denser cargoes.

Table 1 DOSE RATE (Source Shielded with either shutter)
1.0 Curie Cs-137 Source (Ohmart SH-F2 Holder)

DISTANCE	FRONT (mR/hr)	REAR (mR/hr)	LEFT (mR/hr)	RIGHT (mR/hr)	TOP (mR/hr)	BOTTOM (mR/hr)
Contact	22.0	16.0	30.0	30.0	5.8	0.8
One Foot	4.0	2.4	4.2	4.2	1.7	0.3
Three Feet	0.6	0.2	0.5	0.5	0.3	0.1

Table 2 DOSE RATE (Source Shielded with either shutter)
0.5 Curie Co-60 Source (Ohmart SHLG-3 Holder)

DISTANCE	FRONT (mR/hr)	REAR (mR/hr)	LEFT (mR/hr)	RIGHT (mR/hr)	TOP (mR/hr)	BOTTOM (mR/hr)
Contact	32.0	23.0	25.0	25.0	6.0	0.0
One Foot	8.0	5.0	6.0	6.0	1.2	0.0
Three Feet	0.9	0.6	0.8	0.8	0.2	0.0

Table 3 DOSE RATE VERSUS DISTANCE (Both Shutters Open)

Source	Distance From Source				
	8mR/hr	4mR/hr	2mR/hr	0.5mR/hr	0.05mR/hr
Cs-137 (1 Curie)	20 Ft.	29 Ft.	41 Ft.	82 Ft. (calculated)	257 Ft. (calculated)
Co-60 (0.5 Curie)	28 Ft.	40 Ft.	56 Ft.	113 Ft. (calculated)	356 Ft. (calculated)

All readings in Tables 1-3 were measured using a calibrated Victoreen pressurized ion chamber (Model 450P) or a calibrated Eberline ion chamber (Model RO-2).

The fan-shaped beam, secondary source open, is moved by the trolley along the length of the cargo vehicle being inspected, and the "sweep" of this beam (about 65' for most trucks) determines the length of the exclusion zone. The breadth of the exclusion zone (the distance from the source past the detector tower) is 41' for the 2mR/hr radiation level and 82' for the 0.5

mR/hr level, for the Cs-137 source (see Table 3). For the Co-60 source, these respective distances are 56' and 113'. Since the source passes a point at about ½ mph (0.7 ft/sec), with a beam width of 24" past the detector tower, a given point just past the detector tower, for the Cs-137 source, causes an exposure of about 2 microroentgen per sweep or 777 microroentgen per day for 400 inspections. Since the "occupancy factor" for an individual who may by chance find himself standing in the beam is perhaps once per day, the most likely accidental-exposure rate is nominally 2 microroentgen per day (about 6 minutes worth of natural background radiation). At the location of the truck driver, at about 20' from the source, he would have received about 4 microroentgen (12 minutes of background radiation). It is not likely that the truck dispatcher and/or the computer operator would have allowed an accidental exposure.

Figure 6 presents the approximate radiation beam profile for the 2-, 4-, and 8-mR/hr radiation levels for the Cs-137 source, secondary shutter open. Figure 7 shows the profile for the Co-60 source.

In conclusion, it can be stated that for VACIS-II, under normal operating conditions, the radiation hazards are quite manageable. It should be pointed out that the radiation field at the location of the truck driver would be about 10,000 times greater for a 450 kV x-ray source operating with an anode current of 10mA, under the same source-collimation conditions.

4. MECHANICAL HAZARDS

Aside from the risks associated with the heavy Co-60 source holder (665# plus an additional 100# or so for the secondary shutter and mounting flanges), utilizing a fork lift and handling chains, the only recognizable mechanical hazard is that posed by the source and detector trolleys. They travel approximately 0.7 ft/sec (about ½ mph), and the trolley motors cannot handle much above a 2% grade without stopping. The trolleys have audible alarms which sound when the trolley is moving.

A dimensional drawing of the complete VACIS-II system is shown in Figure 8 (exclusive of the sheet-metal personnel-exclusion-housing around the source on the source trolley, and the power and control cables connecting mobile control center). The control center is housed in a camper with windows in the rear where the computer operator is located.

Once the system is installed, the only mechanical hazards in the normal operating protocol are associated with the truck being guided into place, the slow motions of the source and detector trolleys, and the changing out of the Co-60 and Cs-137 source holders (about 760# and 250# each, respectively, including source holder (shield), secondary shutter and mounting frame.

As stated above, the trolley movement poses no reasonable hazard, with ½ mph traveling speed and relatively weak motors. Another possible, but unlikely, hazard is posed by cables passing from the control center to the two trolley tracks. But no known incidences related to these cables have been reported in the several years of operating VACIS-I and VACIS-II.

During breakdown and shipment to another location, there are the normal hazards associated with breakdown of the system, loading, moving a camper with attached equipment trailer along public highways, and setting up the system in a new location. The detector tower is assembled by attaching one detector module at a time to the detector-tower assembly housing and raising it one module at a time by motorized winch until it is all assembled. Thus, no tall-ladder operation is required for assembling the 21' tall tower. During windstorms, this tall tower is tied down to anchor bolts with cables attached to the top of the tower.

In conclusion, the mechanical hazards are quite minimal and probably call for no further embellishment.

5. ELECTRICAL HAZARDS

During assembly and disassembly, all electrical power is off. During operation, no bare electrical wires or connecting points are exposed. Only during repairs are personnel exposed to the electrical system. But these hazards are the normal hazards associated with repairing a system with the highest voltage being 110V, 60-cycle power.

The only exception to this is the high voltage power supply that powers the photomultiplier tubes in the detector tower. This is a sealed H.V. supply that provides 18 milliampers to all the 336 photomultiplier tubes. The high voltage is set at 520 volts, a low value for photomultiplier tubes. This supply would likely provide a shock (like from an automobile spark plug) that could make the recipient jump back, with the remote possibility of injury. This has not happened to date. If the photomultiplier tube base "completes the circuit", it has a very high impedance of nominally 14 megohms, well above a value that would pose a danger. Normally, no operating personnel open the sealed detector tower for maintenance. Only trained repair personnel have access to this area.

6. SUMMARY

The radiation hazards, under normal operating conditions, are seen to be minimal. No high radiation exposures are conceivable with the well-shielded radiation sources each utilizing both a primary source shutter and a secondary shutter. The Cs-137 primary source shutter is fail-safe in that an internal backup battery automatically closes the shutter upon electrical power failure. The Co-60 primary shutter has no such fail-safe closing system. It is hand operated. However, it will not be used on future VACIS-II systems and should therefore warrant no further discussion.

The secondary shutters provide the essence of radiation-safety-protocol equipment. They were designed for SAIC to open and close hundreds of times a day with high-speed operation, with long service life expectancy, and with the ultimate in fail-safe closing. Upon loss of power, they close by means of return-spring action. No backup battery is relied on (a battery that can become non-operable with time and/or service).

In the event of someone walking past the open fan-beam (or the fan-beam sweeping past them), a total exposure of only about 4 microroentgen is received (12 minutes of natural-radiation background at Nogales, AZ).

These radiations are extremely low level, being about one part in 10,000, as high as that from a 450 kV x-ray source, at 10mA anode current, and with the same collimator system.

The mechanical hazards are minimal, what with ½ mph trolley motion and audible warning with a high detector tower that is assembled module by module with a winch-type lift: no tall ladders are needed. The greatest mechanical hazards are associated with moving the cargo trucks into location for inspection and in moving the control-station camper plus equipment trailer along public highways.

Electrical hazards are essentially non-existent, short of possible exposure to 110V power by experienced repairmen during repairs, and to 520V DC power in the sealed detector tower. The impedances are high, and only experienced repairmen will normally open up the detector-tower housing.

Registry of Radioactive Sealed Sources and Devices
Safety Evaluation of Device

Vehicle and Cargo Inspection System Product Line

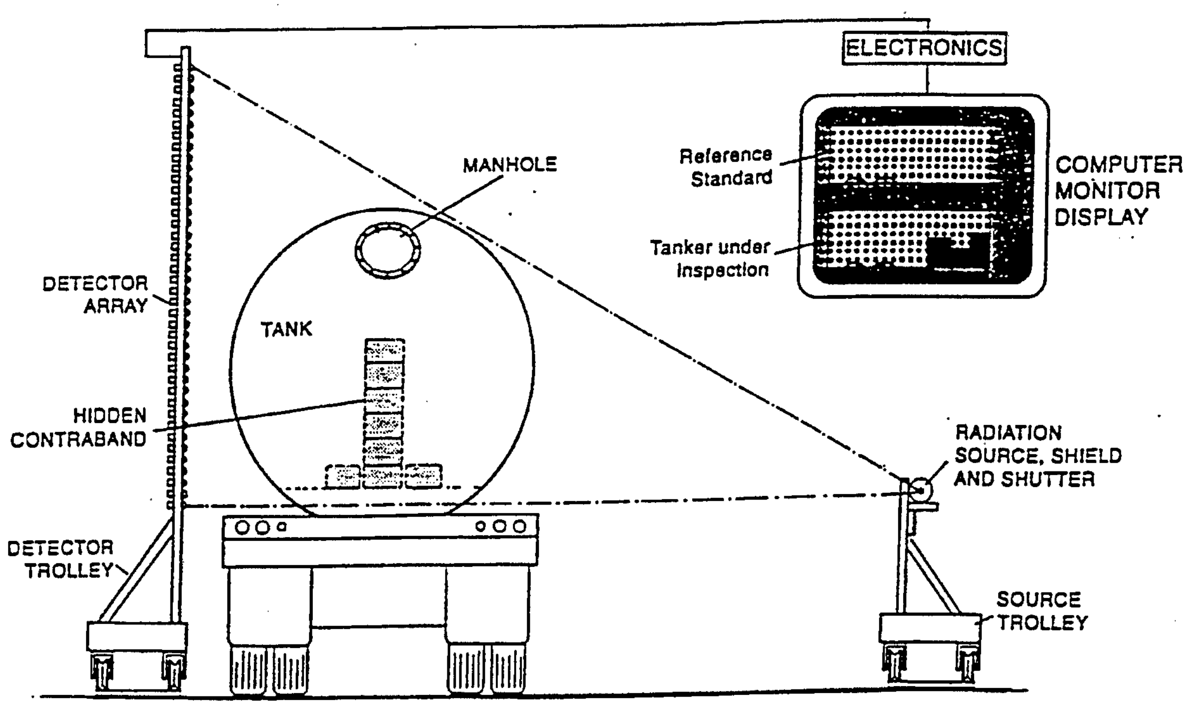

Figure 1. Schematic of Conraband Inspection System for Tanker Trucks

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Safety Evaluation of Device

Vehicle and Cargo Inspection System Product Line

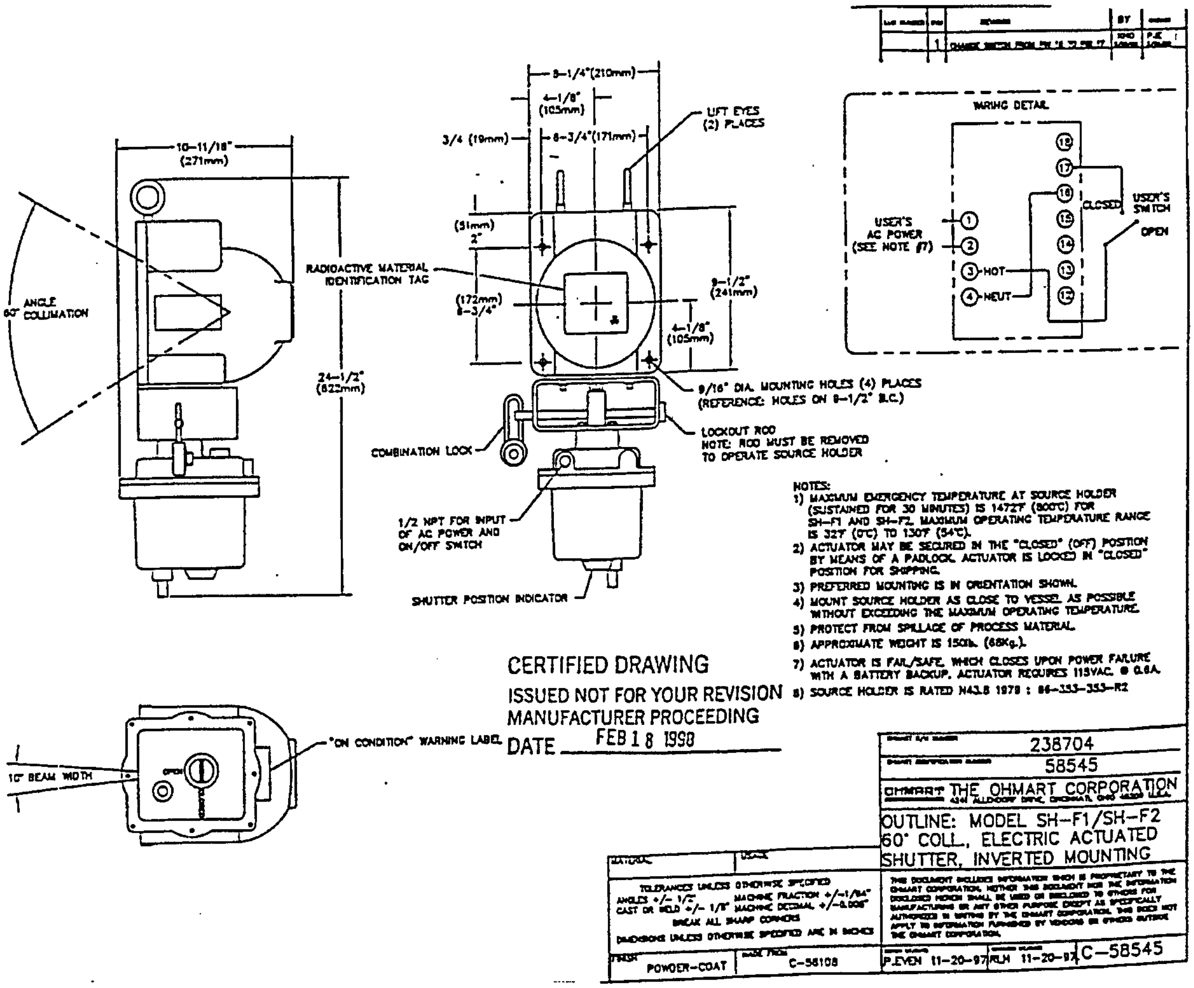

Figure 2. One Curie Cs-137 Source Shield and Shutter Mechanism

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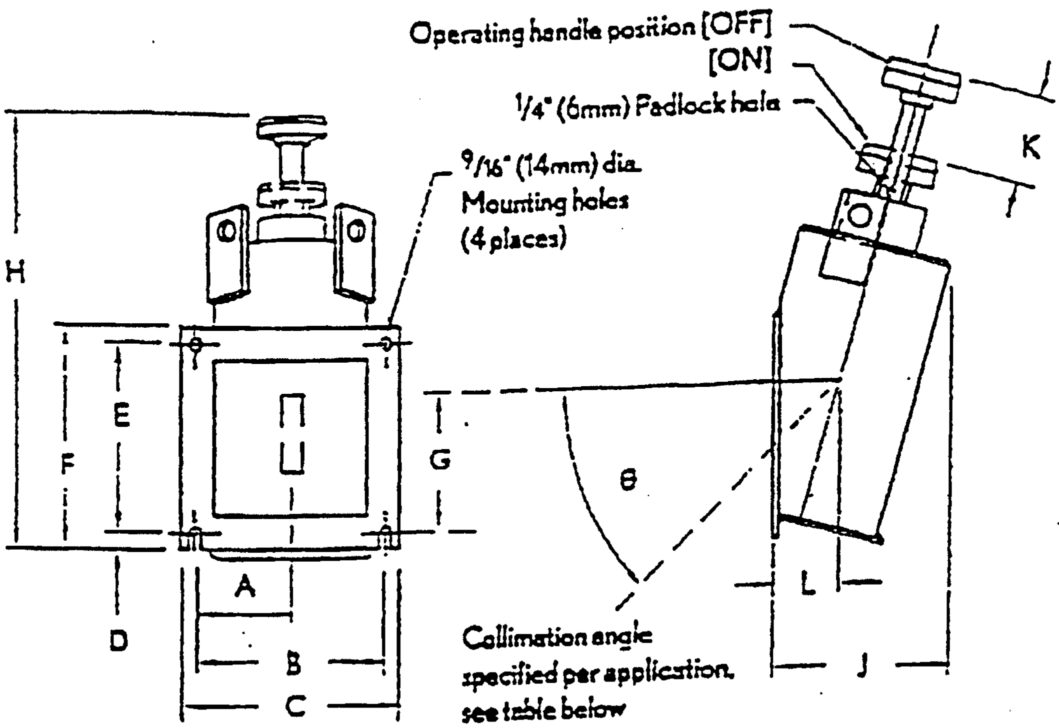

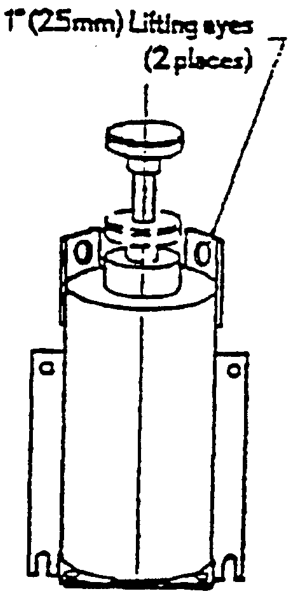

SHLG-3

A	6 1/8" (156mm)
B	12 1/4" (311mm)
C	14" (356mm)
D	1" (25mm)
E	14 1/2" (368mm)
F	16 1/2" (419mm)
G	9" (229mm)
H	24 1/4" (616mm)
J	12 1/8" (308mm)
K	5" (127mm)
L	4 1/4" (108mm)
θ	zero (±4°), 30°, 45°

Figure 3. Source Holder for 500 mCi Co-60 Gamma-ray Source

Vehicle and Cargo Inspection System Product Line

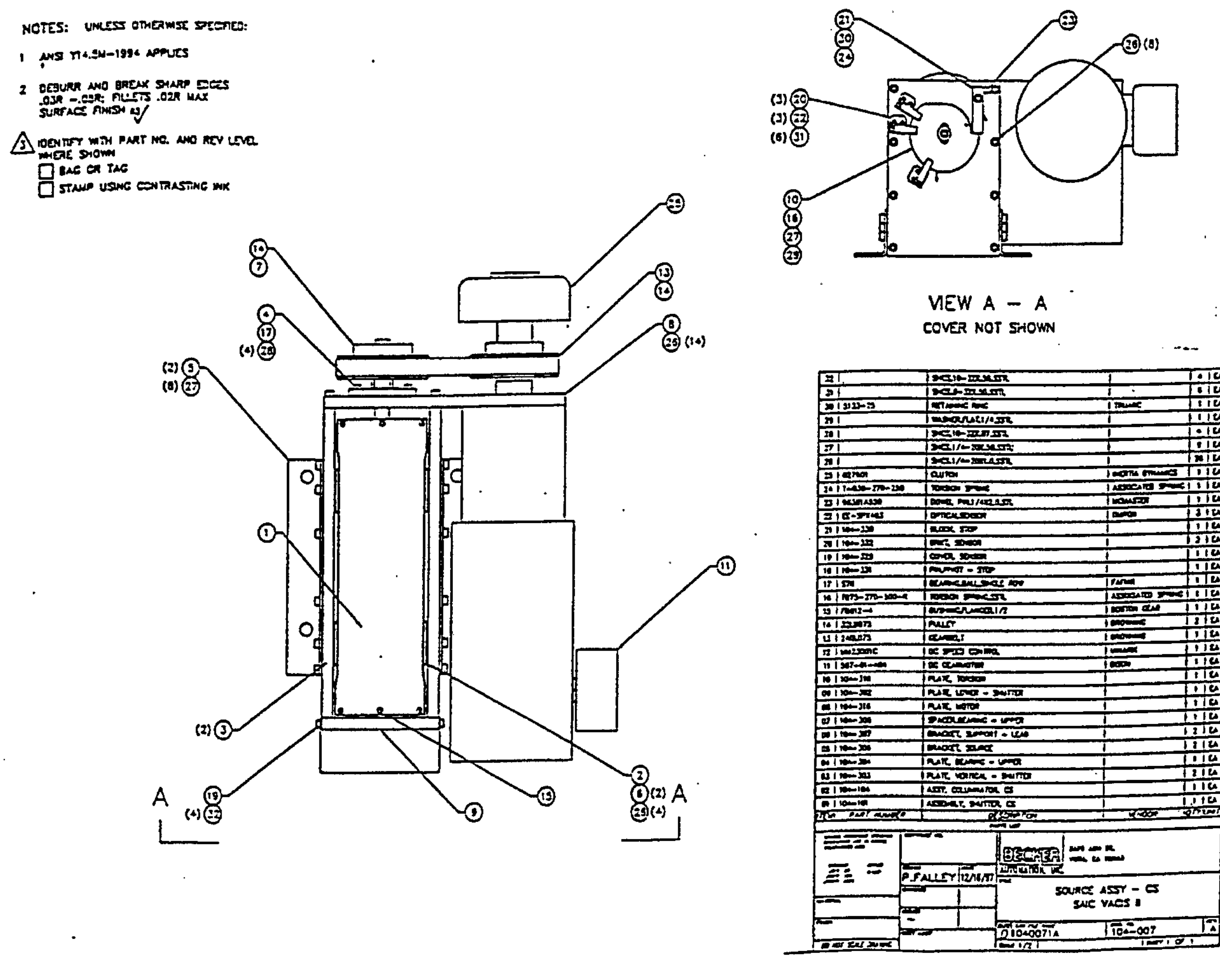

Figure 4. Fast SAIC Secondary-Shutter Mechanism

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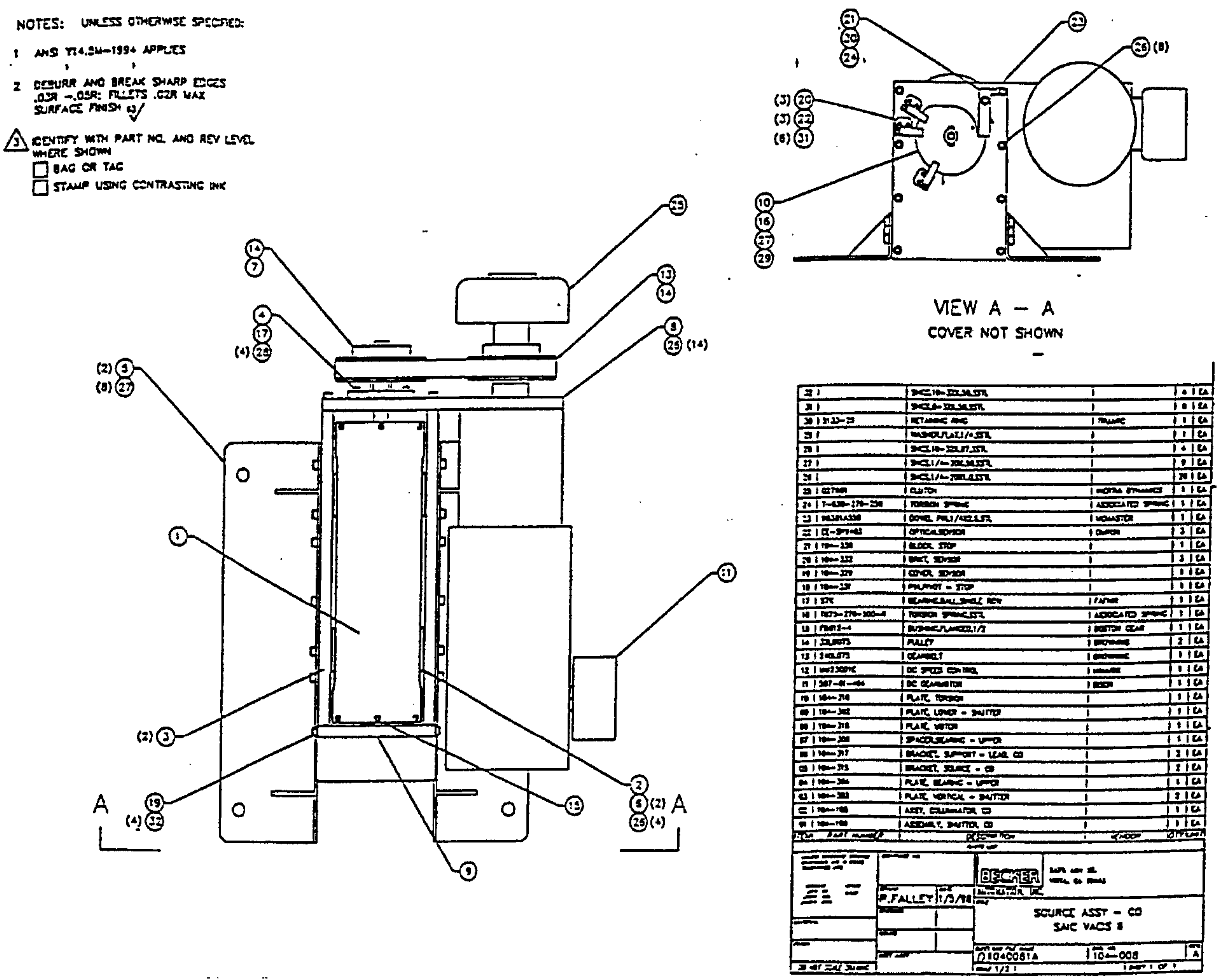

Figure 5. Fast SAIC Secondary-Shutter Mechanism

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Safety Evaluation of Device

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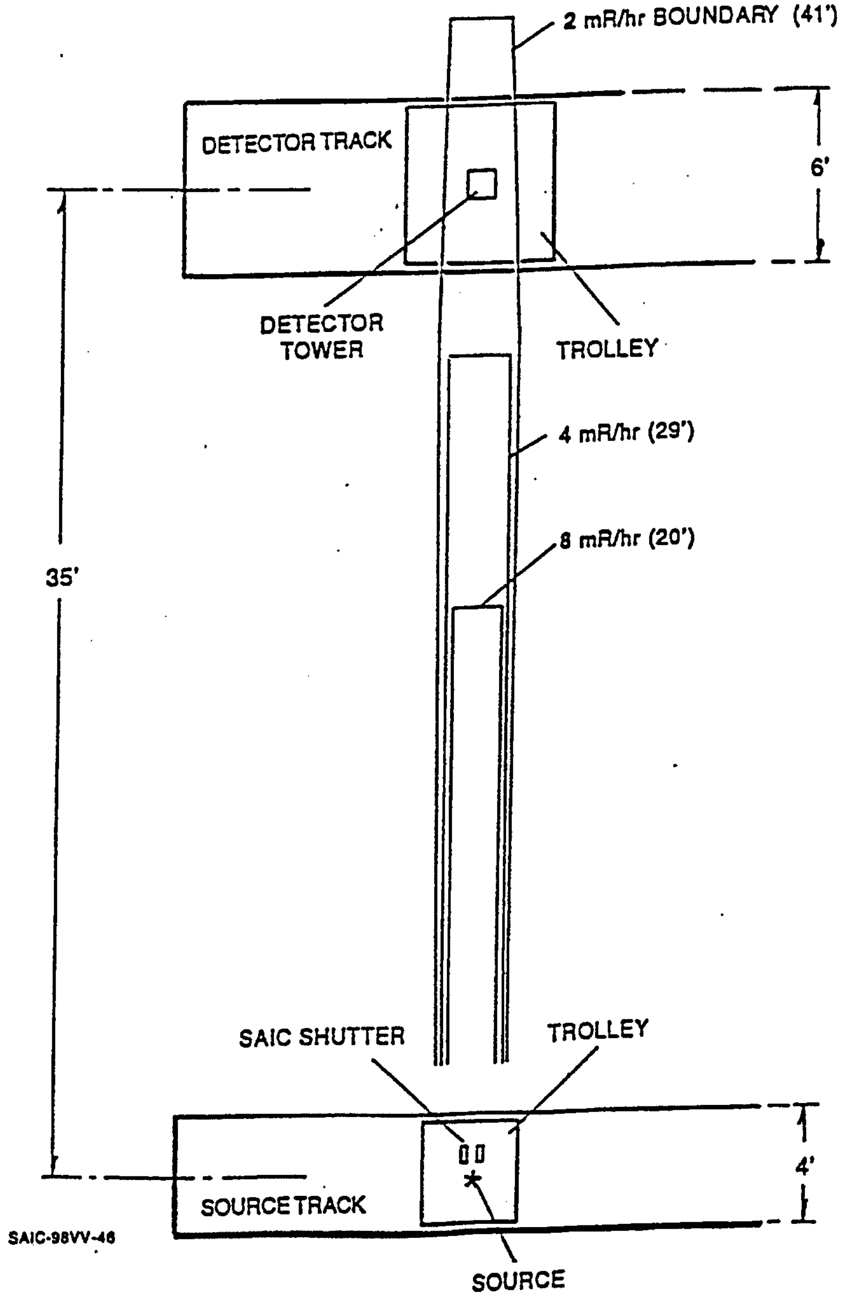

Figure 6. One Curie Cs-137 Beam Profile, Shutter Open

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Safety Evaluation of Device

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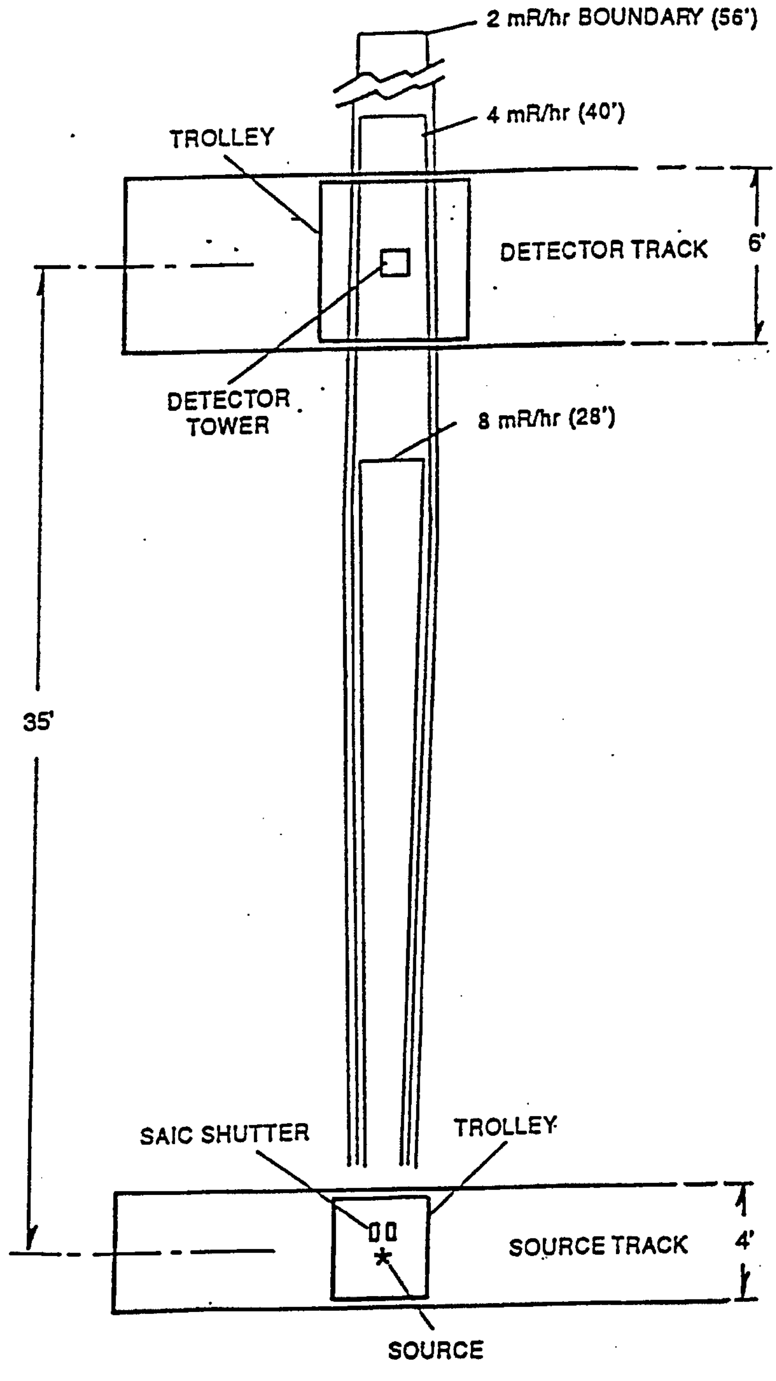

Figure 7. 0.5 Ci Co-60 Beam Profile, Shutter Open

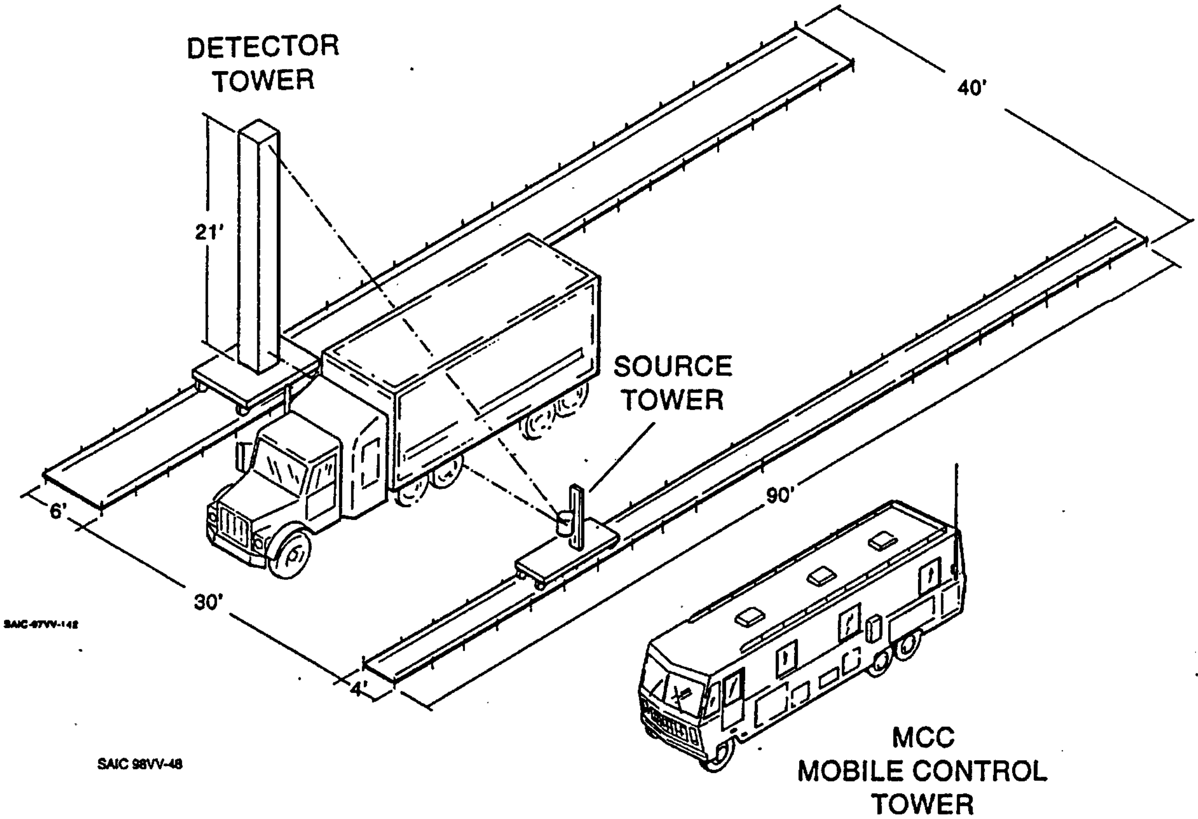

Figure 8. Dimensional Drawing of VACIS-II System

Appendix C - Radiation Safety Procedures

ADVANCED VEHICLE AND CARGO INSPECTION SYSTEM

VACIS-II

RADIATION SAFETY PROCEDURES

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Appendix C - VACIS-II Radiation Safety Procedures

1. INTRODUCTION

This report presents the rudiments of operation of the VACIS-II gamma-ray radiography system (Section 2); a description of the gamma-ray sources, source shields, and source shutters, along with the sequence of operation (Section 3); the safe operating procedures for storing, installing and using the sources, including the warning systems such as flashing lights, signs, etc. (Section 4); radiation field mapping and exclusion zones (Section 5); personal radiation dosimeter requirements (Section 6); emergency procedures in the event of source-shutter malfunction, and periodic maintenance (Section 7).

2. VACIS-II DESCRIPTION

Figure 1 presents a schematic diagram explaining the operation of the VACIS family of gamma radiography systems. A cargo vehicle under inspection is shown located between a gamma-ray radiation source and a tall linear array of gamma-ray detectors (detector tower). The source is slit-collimated so that it irradiates only the detector tower with full force.

A gamma-ray image is generated by first opening the gamma ray slit collimator, and then moving the source and detector trolleys synchronously along the length of the vehicle under the inspection. As the vehicle is being scanned, the count rate of each gamma-ray detector is recorded at predetermined intervals and transmitted to the image-generating computer. There, the count rate is converted to the density of material in that given picture element (pixel) to form a gamma-ray radiography picture that is used for hidden-drug interdiction.

After scanning the length of the truck, the gamma-ray source shutter is closed until the next cargo-vehicle is moved into place for inspection.

3. SOURCES, SHUTTERS AND OPERATION

VACIS-II is a production-prototype that is an upgrade of the VACIS-I system delivered to US Customs in 1996. Resolution has improved, the height of the detector tower and the length of trolley track have been increased. VACIS-I was designed for inspecting thick steel-walled pressurized tanker trucks. Its success motivated the potential user community to extend its use for inspecting higher and longer cargo vehicles, and with ½" pixel size instead of approximately 2" for VACIS-I.

VACIS-II is a production prototype in all but the selection of gamma-ray source type: two candidate (experimental) sources are provided; a 1Ci Cs-137 source and 0.5 Ci Co-60. The latter presents about a 33% lower gamma-ray cross section for organic materials, and structural materials that include steel. However, it concomitantly requires a much heavier shield, it has a shorter half life (about 5 years versus about 30 for Cs-137), and presents a 67% greater biological dose rate per unit photon flux.

Figure 2 shows a Cs-137 source shield complete with a slit-collimated shutter inside the housing, and a shutter actuating mechanism shown below the shield that can be remotely operated. The shutter open beam is 60º, vertically and 10º wide. This width is narrowed to about 5º with an SAIC-developed secondary shutter that follows the Ohmart Corp. primary shutter. The SAIC shutter is much faster (about 500 milliseconds versus 5000 ms for the Ohmart mechanism). Therefore, the primary shutter will be opened all day while the secondary device will flick on and off for each vehicle scan.

Figure 3 shows the much heavier Co-60 source and hand-actuated shutter. This source shield weights 665 pounds, versus 115 pounds for the 1-Ci Cs-137 source shield. The Co-60 source, like the Cs-137 source, will be un-padlocked each morning and turned on for the entire inspection day. It will also have an SAIC-developed secondary shutter. Each secondary shutter will be remotely operated from the control console where the operator is seated next to the image-generating computer. Figure 4 shows a secondary shutter, complete with fast-acting activating motor assembly.

4. SOURCE INSTALLATION, USE, REMOVAL AND STORAGE

Before removing the source from storage, verify visually that both primary and secondary source shutters are in the "shutter closed" position. Each of the secondary shutters, spring loaded in the "shutter closed" position, can be verified by looking behind the clear plastic cover in the front. The Cs-137 primary shutter will have been rotated to the "shutter-closed" position, and padlocked in this position (see Figure 2). The Co-60 primary shutter activating plunger is pulled out, and a padlock is inserted (through the plunger hole) so as to prevent the plunger from being pushed in (into the "shutter-open" position).

After a quick check around the source shield with a gamma-ray dose rate meter as a precaution, move the source with the special fork-lift provided and install it on the source trolley with the source-trolley elevator in the lowest position. Then raise it to the preselected operating height, connect the remote shutter-control cable, remove the "shutter-closed" padlock and restraining rod, and it's ready for use. It will be controlled remotely by the operator sitting at the control console next to the image-generating computer.

After installation, check that the steady yellow-warning light on the control console comes on when the primary shutter is opened, and that the flashing red light on the source cabinet is on when both are opened.

For removing and storing the source, reverse the above procedures. Lock the storage room. After locking, a redundant check of radiation dose level is required by reading the gamma-ray dose rate meter at the door and the wall nearest the source. The highest of the two readings and its location are then entered into the radiation safety logbook.

5. RADIATION FIELD MAP, EXCLUSION ZONES

Personnel operating the system are required to stay outside the 2 mR/hr exclusion zone. However, if someone walks through the beam at the average truck position, when the Cs-137 shutter is open, the radiation dose will be only about five micro roentgen: this would have to happen 400 times in an hour to receive the allowable dose of 2 milli roentgen. For the Co-60 source, the dose per "walk through" is about 10 micro roentgen (a 420 kV x-ray source yields the order of 10,000 times higher dosage in the direct beam).

A map of the 2 mR/hr exclusion zone, for the Cs-137 source shutter open, is shown in Figure 5, along with the 4 mR/hr and 8 m R/hr boundaries. These data are also shown in Table 1 along with the 0.5 mR/hr and 0.05 mR/hr boundaries.

Because of the finite size of each source (0.25" in diameter for the active region), the radiation field tapers off in the penumbra. Table 2 presents the size of the full-intensity region bordering this penumbra, the 50% intensity region of the penumbra, and the "dark border" of the penumbra. This is for both the primary shutter and secondary shutter in the open position.

The radiation mapping around the source shield, without the secondary shutter in place, is presented in Table 3 for the "source-closed" position of the primary shutter. The radiation field is well below the 2 mR/hr exclusion zone in every direction at less than 3-feet from each source.

6. PERSONAL DOSIMETER REQUIREMENTS

Since the operation of VACIS-II will be in the hands of trained personnel who will stay out of the radiation beam and who will ensure that the truck drivers are out of the beam, the operation protocol could exclude the need for the wearing of personal dosimeters (radiation badges and possibly instant reading pocket dosimeters) except for the personnel involved in source installation and storage each day.

However, because of liability considerations, the use of both radiation badges and pocket dosimeters is recommended for the entire operating crew. In the event someone does walk through the beam while the shutter is open (and both the flashing red light for the secondary shutter and the steady amber light for the primary shutter are turned on), it will be on record that the radiation dosage was almost immeasurably small.

7. EMERGENCY PROCEDURES

The Cs-137 primary shutter is motor driven and contains a trickle-charged emergency battery. The battery is not used for routine opening of the primary shutter in the morning and closing of the shutter before removal of the source for storage. For this source, routine maintenance involves replacement of the emergency-closing battery (in case of power failure) once every two years. This is well short of the expected battery life, since it is constantly trickle-charged while the VACIS-II system is in operation.

The Co-60 source has a hand-operated plunger that is engaged by pushing it in when the padlock is removed from the plunger. No routine maintenance is required for this source.
Note that each source utilizes a safety padlock which must be removed before the source can be opened.

It should be noted that the Cs-137 source shutter can be manually closed if the backup battery, the motor, or the electronic circuitry should fail. This can be done with ordinary "water-pump pliers" (adjustable pliers) which can be kept on the source trolley. The shutter is closed by rotating the shutter-control rod to the "off" position with the water-pump pliers.

7.1 Primary Shutter Failure

As mentioned above, the primary shutter for the Co-60 source is hand-operated. If somehow the plunger should get stuck in the "shutter open" position, the secondary shutter will suffice to keep it radiation safe. The source can still be used in this condition, but should be repaired by qualified SAIC and/or TMEC personnel at the earliest possible time. If the Cs-137 source shutter should fail to close, it also can be manually turned off with a pair of water pump pliers, as stated above. However, it can be safely used in this condition, because the secondary shutter will provide adequate protection. Again, the necessary repairs should take place as soon as possible. Always verify the source has been closed using a dose rate meter.

7.2 Secondary Shutter Failure

Each secondary shutter is spring loaded to close in case of power failure. If it should somehow fail to close, the primary shutter will be closed and the source will be stored until the secondary shutter is repaired. The closing of the primary shutter renders the source completely safe for each of the two source options (i.e., Co-60 or Cs-137 source).