FINAL REPORT
NEXT-GENERATION MEGA-VOLTAGE CARGO-IMAGING SYSTEM FOR CARGO CONTAINER INSPECTION

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FINAL REPORT
NEXT-GENERATION MEGA-VOLTAGE CARGO-IMAGING SYSTEM FOR CARGO CONTAINER INSPECTION

Contract Number: **DE-FG02-04ER63880**

Award Recipient: UNLV Research Foundation

Subcontractors: Varian Medical Systems-Security & Inspection Products
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Start Date: August 1, 2004

End Date: December 31, 2006

Introduction and Background

The UNLV Research Foundation (UNLVRF), as the primary award recipient, teamed with Varian Medical Systems-Security & Inspection Products (VMS-SIP) and the University of Nevada Las Vegas (UNLV) for the purpose of conducting research and engineering related to a “next-generation” mega-voltage imaging (MVCI) system for inspection of cargo in large containers.

The Department of Energy’s Office of Science has funded Phase I of the project, which began on August 1, 2004 and concluded December 31, 2007, for cumulative funding of $1,448,000. Phase II of the project is being funded by the Department of Energy’s National Nuclear Security Administration, Office of Nonproliferation Research and Engineering (NA-22).

The efficient and effective inspection of cargo at United States ports of entry has been a critical security challenge, especially since the events of September 11, 2001. The high volume of conveyances, cargo and passengers arriving in the United States each year far surpasses the capability of U.S. Customs Service to accomplish effective security screening. Over $8.8 billion worth of goods, some 1.3 million people, over 340,000 vehicles and approximately 58,000 shipments are processed daily at entry points. Of this volume, U.S. Customs is able to inspect less than two percent of all inbound shipments. This is of particular concern to security officials, recognizing that a 20'x 8'x 8' container is large enough to hold every known "weapon of mass destruction."

Of the various methods of cargo inspection, the X-ray linear accelerator (VMS' Linatron-M) is currently the "gold standard" for cargo inspection. High energy X-ray inspection is the technology of choice because it has the power to fully penetrate a container and generate a quality image of the contents within a relatively short period of time. VMS is the provider of this technology to various original equipment manufacturers (OEM's) around the world. From 1990 to 2006, more than 150 Linatrons have been used in land, sea and air cargo inspection centers throughout the world.

Despite the availability of these inspection technologies, the United States has made relatively little progress in adding non-destructive cargo inspection systems to its network of 185 deep-water ports.[1] There are very few systems deployed at land border crossings that have the capability to examine all containers.

Barriers to employing the technology include economic feasibility, the speed of the inspection process and long-term labor agreements covering cargo-handling procedures. The technology, in addition to being affordable so that wide implementation is feasible, must have the following three characteristics to be highly effective[2]:

- Safety – Ensure that operators and the general public are protected from any harm as a result of the inspection process

- High Reliability – Ensure effective inspections are performed without delay – day in and day out

- Cost-Effective Performance – Produce high-quality images that have good resolution and penetration which will allow a high probability of detecting contraband, in addition to high throughput and minimal "false positives" to avoid undue interruptions to the flow of commerce

While the current technology meets these criteria to some degree, next-generation systems must be faster and provide even higher quality imaging to assure rapid and widespread deployment throughout the major transportation entry points in the country. The "perfect system" is defined as one that provides full penetration (up to 440mm or approximately 17" of steel), high resolution (0.4 mm), high throughput (>45 containers per hour), simple design, high reliability, and low total cost of ownership. VMS-SIP's research to date has been focused upon these parameters, and the DOE Office of Science financial assistance award has been instrumental in allowing UNLVRF, in partnership with VMS-SIP and UNLV, to substantially complete the development of a "next

[1] "Cargo Inspection: Imaging Solutions Wait for Government's Call," by Winn Hardin – "Machine Vision On-Line"
[2] "A Safe, Reliable and Cost-Effective Cargo Inspection Technology," Victor J. Orphan, Rex D. Richardson & David W. Bowlin, SAIC, Port Technology International

generation" dual energy X-ray inspection solution for cargo that is suitable for use in mobile, fixed-site and other cargo screening applications.

OBJECTIVES

The primary objective of Phase I of the project has been the completion of the assembly of the K-9 linear accelerator and an optimized X-ray detection system capable of efficiently detecting X-rays emitted from the accelerator after they have passed through the device under test. The overall project objectives are to:

- Provide extremely high quality imaging capable of automatically detecting high atomic number materials;
- Improve the technology's detection accuracy to greater than 99%;
- Decrease the scanning period to maintain continuous flow of commerce (estimated to be approximately a 15-second scan for a 45-foot cargo container); and
- Enhance safety of operations to assure workers and the public are protected.

Phase II of the project is planned to validate basic performance of the accelerator component, develop a qualified data base of signatures of general materials, design and validate a system of sensors and signature processing for integration with automated decision-making software to address the most pressing containers of potential threat packages and develop an integrated test environment to address various other containers and threat packages.

UNLVRF's corollary objective focuses on providing training and academic resources to private industry to support further development of technology that is critical to the national security.

ACCOMPLISHMENTS

The primary focus of phase I has been the procurement and build-out of hardware for the MVCI project. Phase I of the project has been completed within the budget provided by DOE's Office of Science; however, there have been schedule delays, as described below. The primary deliverable, an assembled mega-voltage cargo imaging system, was completed in September 2006.

System Configuration

The system has two main parts: the first part is the K9 linear accelerator which can operate over an energy range of 5 to 20 MeV. The dual-energy portion of the system is designed to operate between 5 and 10 MeV in a mode allowing the X-ray endpoint energy and X-ray dose rate from the linear accelerator to switch between two distinct states. This dual-energy interlaced mode can be employed to search for high atomic-numbered materials (called high "Z" materials) in cargo containers, exploiting the differences between X-ray energy loss mechanisms for high and low atomic- numbered materials. There is a difference in the ratio of Compton scattering[3] and pair production[4] for various materials which can be measured by detectors that are optimized to detect high energy X-rays and process this information into an image that can provide information on the location of high "Z" materials in the container.

The second important piece of the MVCI system is an optimized X-ray detector system capable of efficiently detecting X-rays emitted from the accelerator after they have passed through the device under test. These X-rays are converted to light that is collected via a photodiode array and then digitized for display on a computer screen. This detector system has been added to the linear accelerator system and is coupled with a small computer-controlled motion system so that test objects can be moved across the X-ray beam and detector plane.

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[3] **Compton scattering or the Compton effect is the decrease in energy (increase in wave length) of an X-ray or gamma ray photon when it interacts with matter.**
[4] **Pair production refers to the creation of an elementary particle and its antiparticle, usually from a photon (or another neutral boson).**

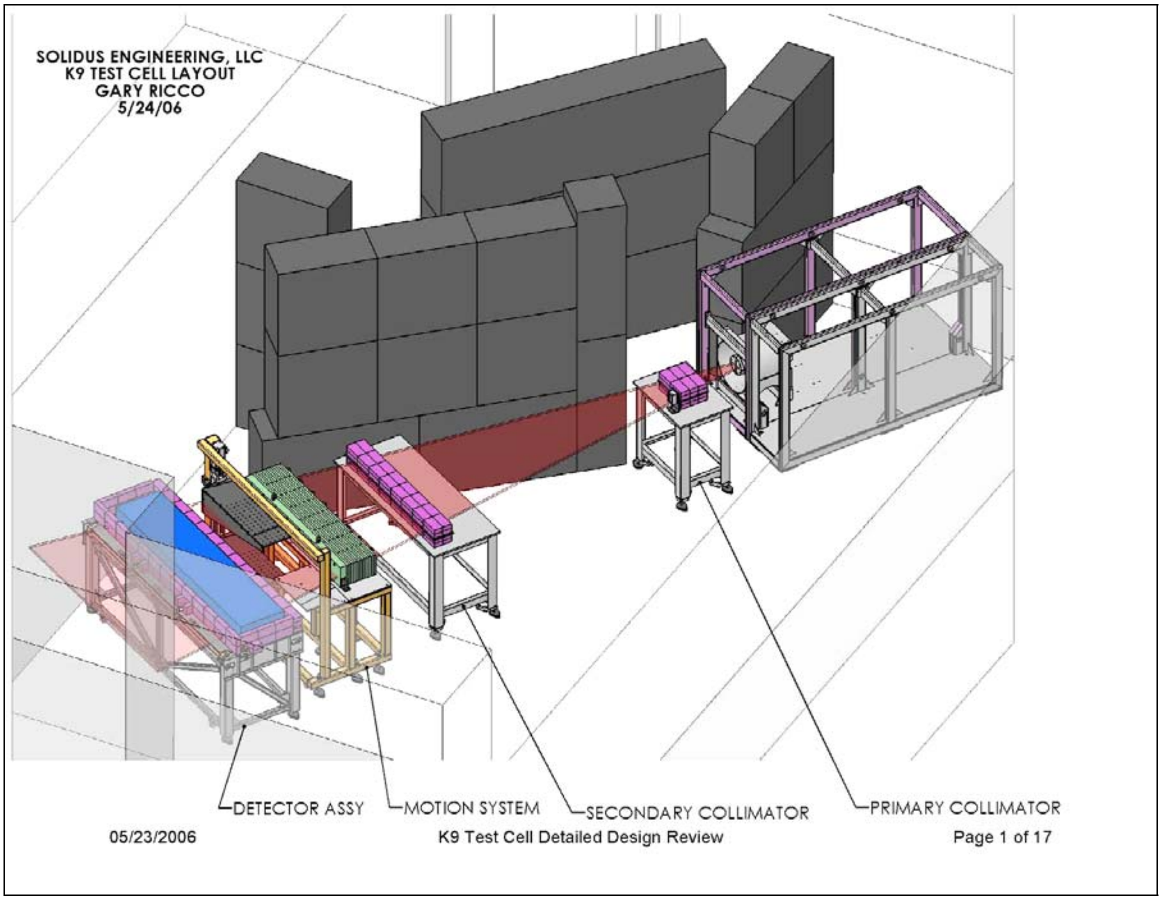

Figure 1.
Phase 1 system layout in test cell

The first part of month of October 2006 was spent putting the K9 system together. The system was then readied for shipment to the VMS/SIP testing facility in early November. When it arrived at the testing facility, the system was reassembled and moved into a rented test bunker. No serious problems were encountered during this operation.

Subsequent operational checks showed that the unit was able to achieve the objective of 30 GPM at 90 PSIG. During this period, it was discovered that VMS/SIP was not able to reach a cost effective solution for the extension on the lease for the testing facility. Due to this unforeseen circumstance, testing was halted and the remainder of December was spent disassembling the units for shipment back to the Las Vegas facility, awaiting the acquisition of another test facility.

Appendix A contains photographs of major pieces of the system hardware.

Imaging Technology Development

In an effort to provide quantitative test material to UNLV researchers who are developing digital image processing capabilities for the system, VMS/SIP supplied some crude data, including high and low energy images that were analyzed and then merged for later analysis. The UNLV researchers applied image analysis that employs discrete wavelet transformation technology for edge detection. In the image shown below, the team could easily identify edges on materials behind seven inches of steel. The results are shown below:

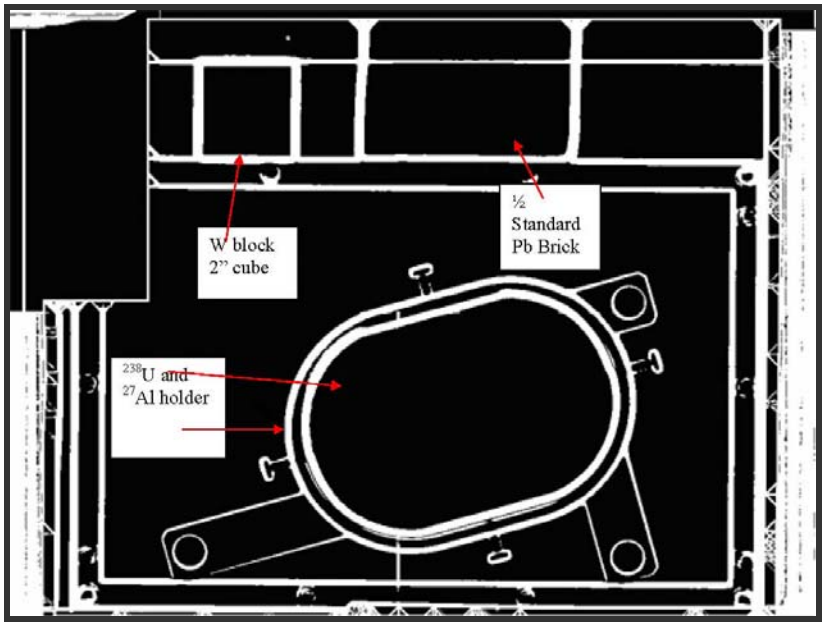

Figure 2.

Stationary wavelet transform in low contrast image at 9 MeV. This image was processed after 9 MeV X-rays passed through more than 7" of steel.

An effort to gain more information from the limited data set was undertaken and the following images show the same scenes taken with dual energy, applying a VMS threshold ratio. A threshold is set so that the ratio of iron plus two standard deviations is subtracted from the ratio images. Then a false color scheme is created. The data show that all of the high "Z" regions are displayed. The figures are for 3, 9 and 11 inches of steel that have been placed in front of the amorphous silicon (a-Si) panel. The researchers then collected 128 averaged frames and 15 frames at low and high energy. The data clearly shows that even after 11" of steel attenuation, it is possible to view the depleted uranium shielding piece. This clearly shows that the technique has merit and provides the first level of proof-of-concept. Further understanding requires many more data sets under various configurations.

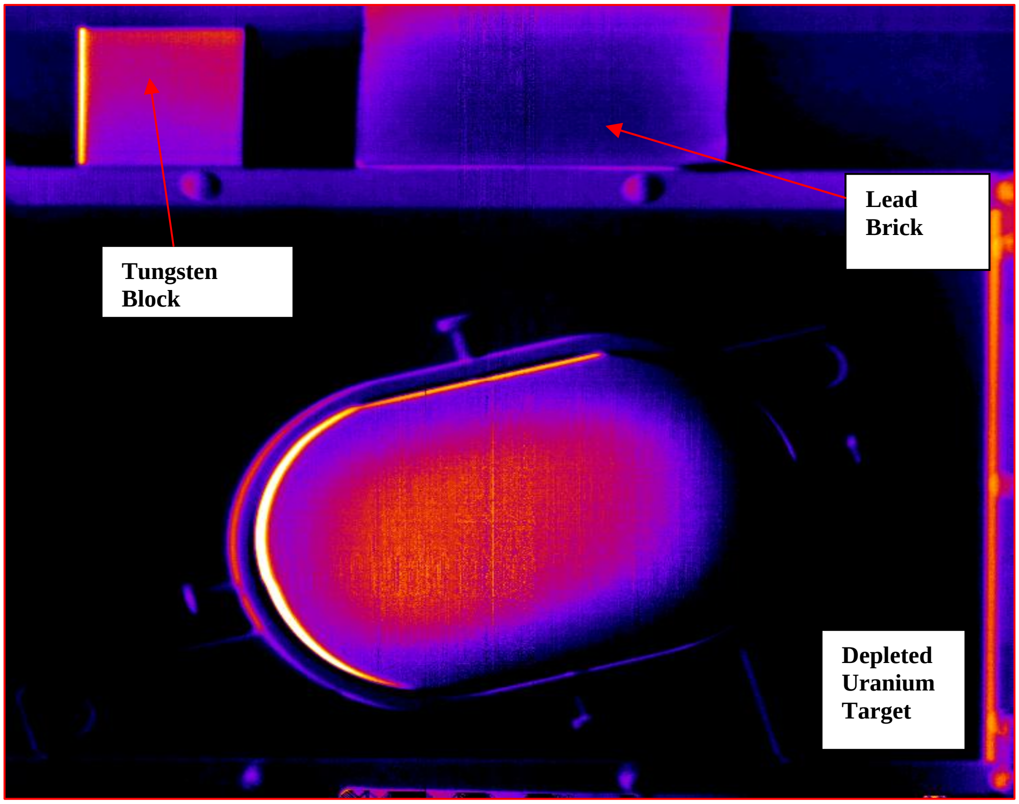

Figure 3.

Ratio Data with 3” of A36 steel in front of the a-SI Panel.

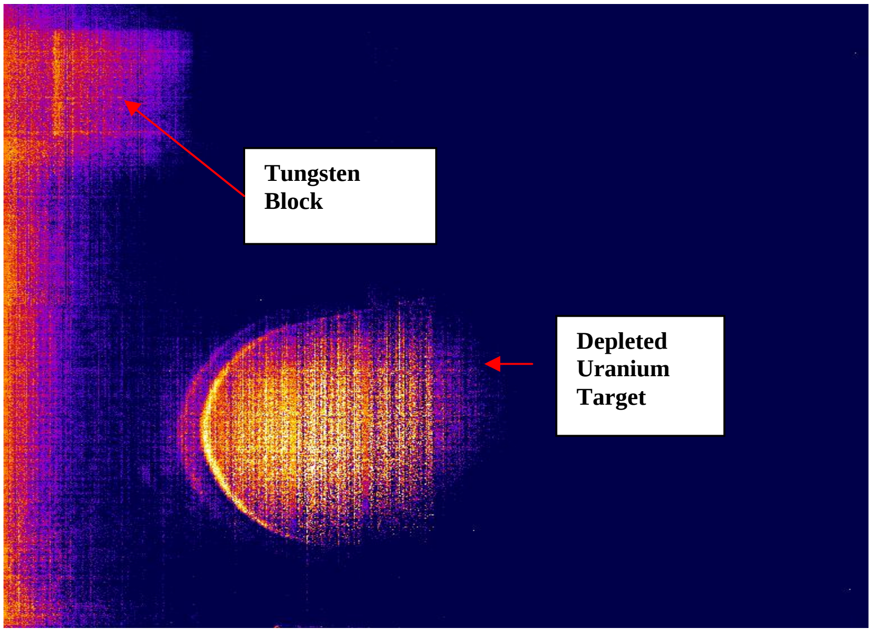

Figure 4.

Ratio data with 3” of A36 steel in front of the a-Si Panel.

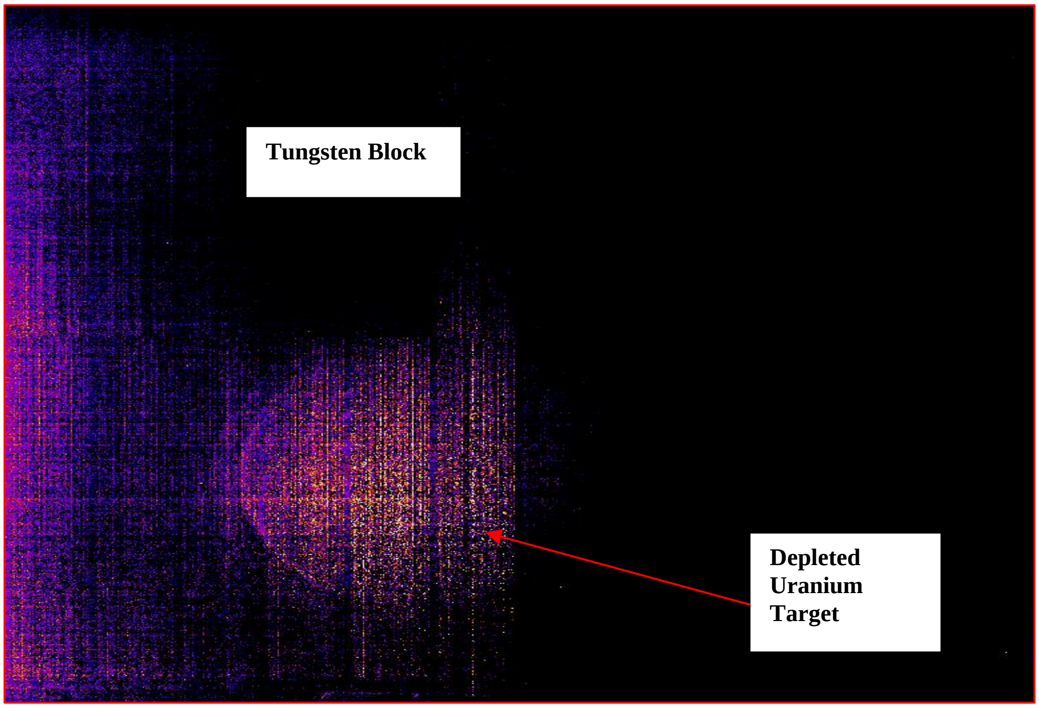

Figure 5

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Ratio data with 11” of A36 Steel in front of the a-Si Panel

Health Physics Study

UNLV, in collaboration with the MVCI research team, conducted a preliminary health physics study focused on analyzing and assessing the radiation effects of an X-ray detection system with the same parameters as the K-9 on human subjects that may be in or near the containers under evaluation. Using both EGSnrc and MCNPX Monte Carlo simulation techniques, the UNLV researchers modeled the scattered and transmitted X-ray spectrum for 6 and 9 MeV, as well as 1-10 MeV, using geometries provided by VMS/SIP. Both EGSnrc and MCNPX are Monte Carlo radiation transport codes able to measure energy deposition in various geometries and materials. In addition to energy deposition, MCNPX was utilized to determine the transmitted and scattered x-ray intensities around various exposed targets. Finally, a comparison was made between energy deposited in a simulated person located within the container for multiple geometry/energy configurations. Figure 6 below displays the photon and electron tracks generated from the MCNPX. Their report has been submitted to the Journal of Health Physics for publication.

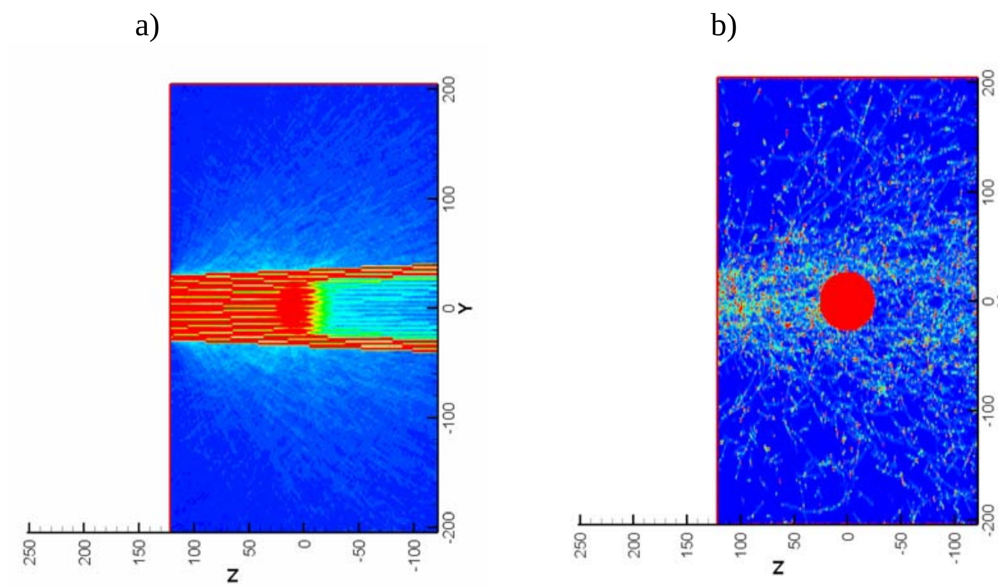


Figure 6.

Photon (a) and electron (b) tracks through the image cargo as seen from above the cargo..

Once the K-9 system is in active testing mode, additional health physics studies are planned to provide more definitive information on the health effects of the technology, both on potential stowaways and personnel who operate the equipment.

BARRIERS

The project experienced a significant delay in executing Phase I subcontracts[5] and subsequent milestone schedule adjustments caused late delivery of essential detector equipment. Another barrier which has not yet been resolved is the acquisition of a suitable testing facility for Phase II. Several options are currently being evaluated, in collaboration with the industrial partner and NNSA/NA-22.

The original milestone chart included a period of full-system testing after the MVCI system had been assembled. The milestone chart was subsequently adjusted to move the system testing into Phase II, which is now included in the scope of the NNSA/NA-22 financial assistance award.

[5] Negotiations for the VMS-SIP subcontract were complicated by intellectual property issues, delaying execution for four months.

RESULTS

The Office of Science financial assistance award has made possible the development of a system utilizing a technology which will have a profound positive impact on the security of U.S. seaports.

The proposed project will ultimately result in critical research and development advances for the "next-generation" Linatron X-ray accelerator technology, thereby providing a safe, reliable and efficient fixed and mobile cargo inspection system, which will very significantly increase the fraction of cargo containers undergoing reliable inspection as they enter U.S. ports. Both NNSA/NA-22 and the Department of Homeland Security's Domestic Nuclear Detection Office (DNDO) are collaborating with UNLV and its team to make this technology available as soon as possible.

FUTURE DIRECTIONS

The next phases of the project are focused on further development of the "next-generation" technology, including both internal and independent testing by an objective third party in order to refine the technology consistent with the project's objectives.

The approach will be to continue the testing on the K9 imaging system to allow exploration of the parameter space in energy and dose rate combinations that will optimize the overall system design. The research team, in collaboration with Department of Homeland Security, will also expand the number of materials used for attenuation to include items such as aluminum, lead, water and concrete. They will also use some agricultural goods such as rice and fruit (i.e., oranges or apples). The list of materials will represent a cross-section of materials that would be encountered in a real system.

UNLV researchers will continue to assist VMS/SIP in the development of the imaging software, including the initiation of code for basic algorithms, as well as new methodologies for automatic detection, data fusion of the images with manifests, and other pertinent information necessary for a robust cargo security system. In addition, UNLV academic staff and graduate students will assist with the development of a data display (graphic user interface) design which is a key element for the users of the system. UNLV will be involved in signal processing and noise reduction; data movements to and from main storage areas; and in detector electronics associated with the system.

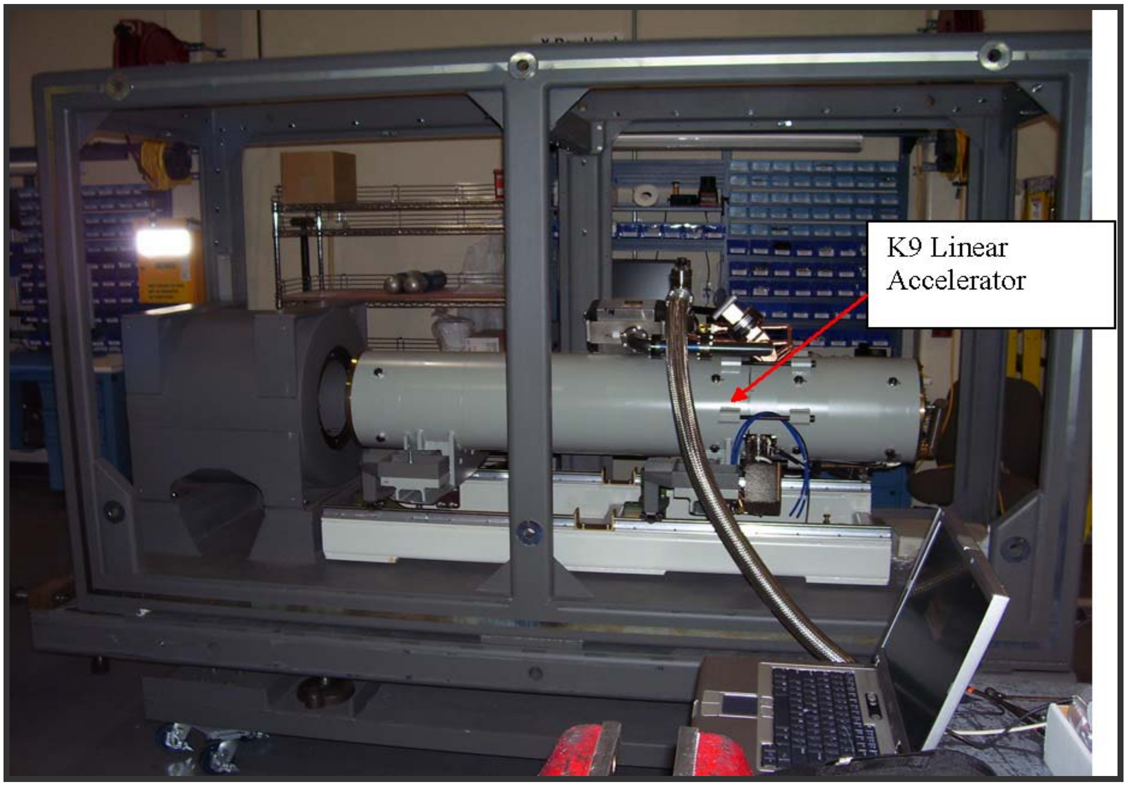
During Phase II, VMS/SIP will provide data to UNLV which will include dual-voltage imagery and complex scenes for analysis. The methods devised and tested on an experimental data set in the first round will be transferred to the new environment and extensively tested for robustness. Additionally, the conventional approach of pre-setting parameters in edge detection and image segmentation processes will be replaced by adaptive methods such as local and global adaptive threshold techniques, a change which is expected to increase the reliability of the system under conditions of variable source data. The system will be tested under more realistic conditions, as well. Object shapes will be analyzed for complex cases (e.g., partial occlusion). Additionally, the researchers will consider alternative approaches for small object detection in the image clutter. Those approaches will include the development of effective filtering techniques for small targets.

The K9 accelerator system has even more capability beyond the dual energy interlaced operation. This accelerator is based on the VMS high-energy clinical accelerator system that has an end-point energy of more than 20 MeV. The team proposes to look at the most difficult cases at photon end point energies of 15 -16 MeV. This will place the X-ray system in operational regions where the photo-fission cross-sections are maximal for all SNM materials. At these energies, any normal container should be easily penetrated by the bremsstrahlung photons. Again, looking for the delayed neutron and gamma ray signals can easily be done with the same electronics as in the 6-9 MeV state. A system that cannot be imaged by 6-9 MeV photons and showing no signature from 15-16 MeV photons would be extremely rare and should be immediately inspected and treated as suspect cargo.

The research team wants to extend the high “Z” region detection capability to be able to make an estimate of the real shape of the region of interest. This work will identify regular shapes such as parallelepipeds, cylinders and spheres as the first step. They will then extend this approach to attempt to automatically identify irregularly shaped high “Z” objects in containers. Enhancements such as this will push the state of the art in cargo screening data analysis. This data collection phase will expand the knowledge base and will provide an opportunity to bring in new ideas from academia.

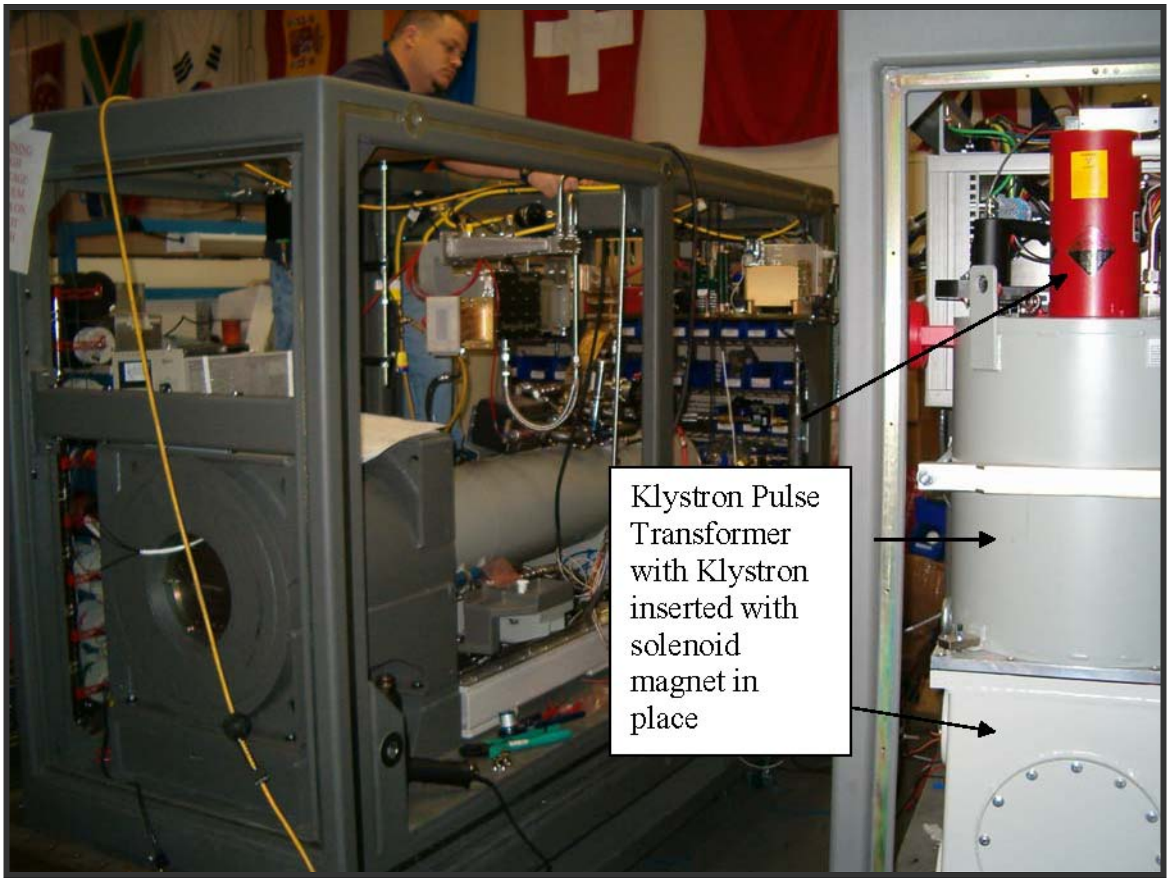
MEGA-VOLTAGE CARGO-IMAGING PROJECT
FINAL TECHNICAL ACCOMPLISHMENT REPORT
DE-FG0204ER63880

APPENDIX A
PHOTOS OF K-9 COMPONENTS

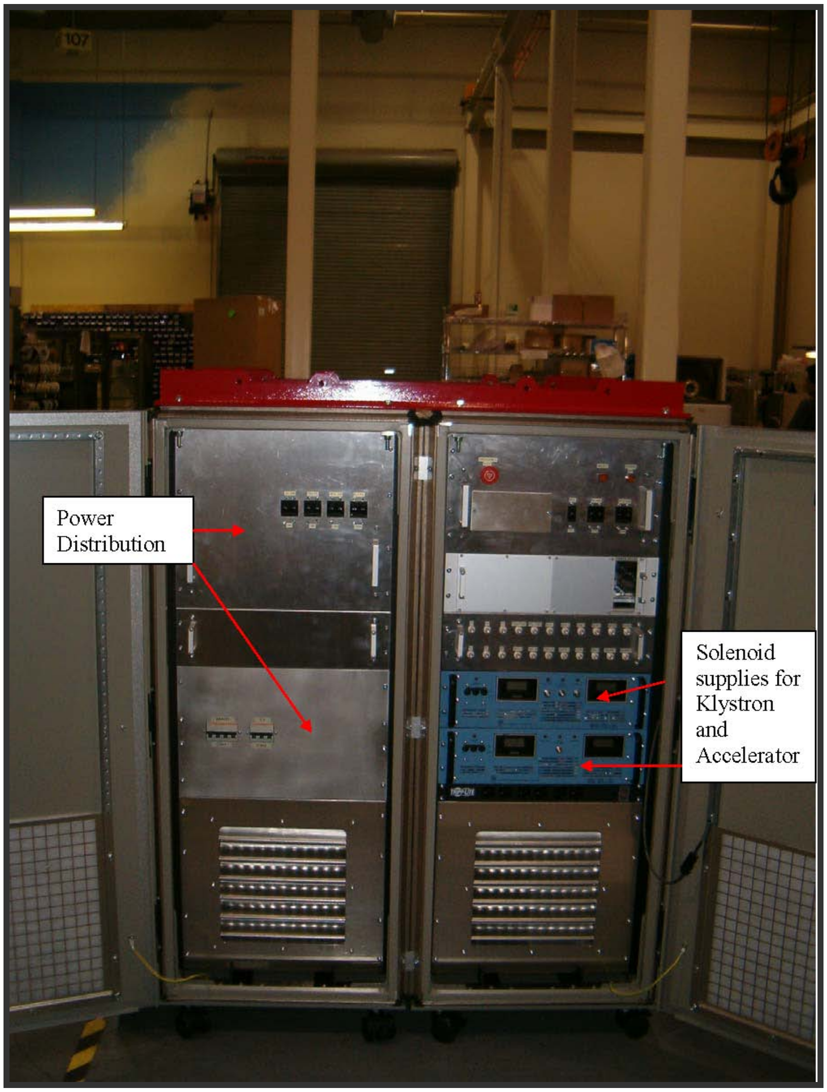


X-ray "head" which contains the accelerator. The large lead and tungsten shielding that will shape the X-ray and reduce scattered X-rays.

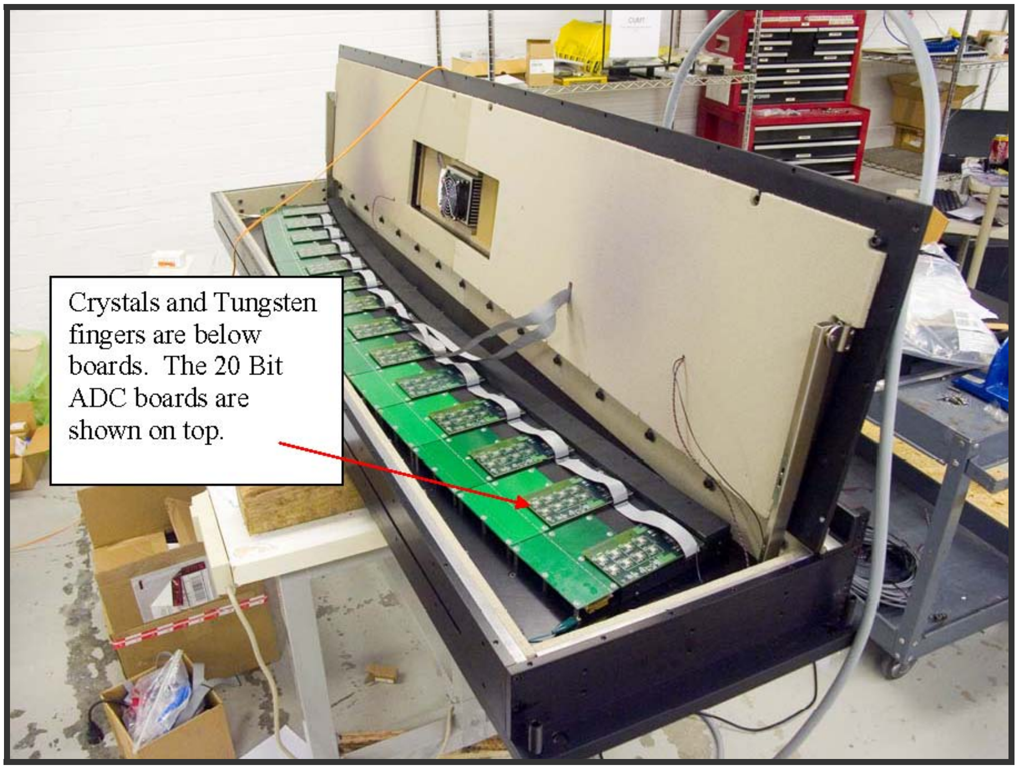
Front view of the K9 system X-ray head front view truncated from the RF unit. The klystron, klystron pulse tank and solenoid are shown rear view of the accelerator, showing the triode electron gun and the dual energy triode gun pulsar system front view of the modulator cabinet. Power distribution, the solenoid magnet power supplies for the klystron and accelerator are in this cabinet. One PLC rack is also in this cabinet.



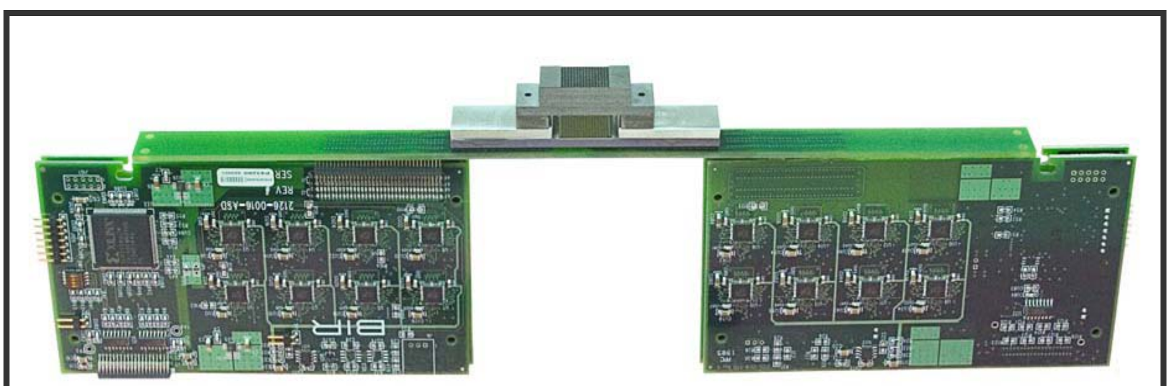
Klystron pulse transformer with klystron inserted with solenoid magnet in place.



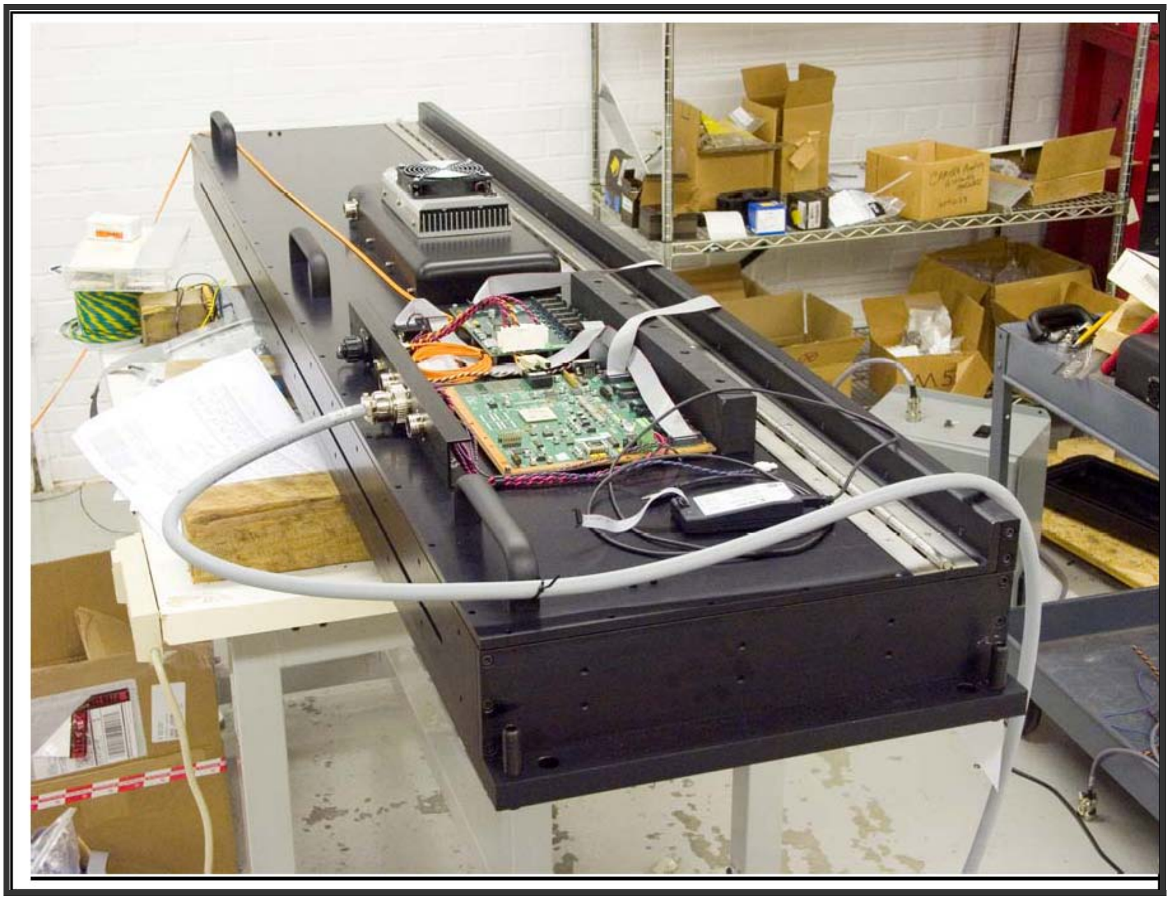
Power distribution system and solenoid supplies for klystron and accelerator.



K9 detector array shown on a 6.5 m arc. $CdWO_4$ crystals are 8 mm x 4.6 mm x 30 mm (L x W x D).



Detector 20 bit ADC Boards



K9 detector array with box lid closed with temperature controller on top of unit Front View of Sample Table 14” Steel or other material can be stacked in front of the detector array. The steel has already been ordered and delivered as part of this program.

Front view of sample table. 14” steel or other material can be stacked in front of the detector array. The steel has already been ordered and delivered as part of this program.