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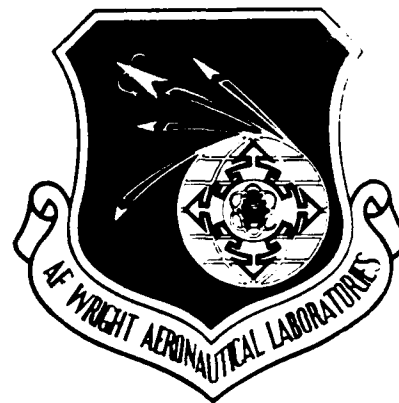
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## A NEW NDE CAPABILITY FOR THIN-SHELLED STRUCTURES

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9 December 1988

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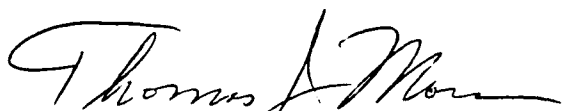
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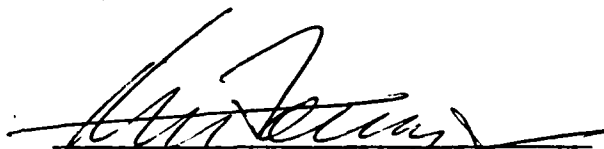
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## SUMMARY

A need currently exists within the Air Force for a more effective technique to non-destructively evaluate thin-walled structures. Such structures may be filamentary in nature, as with Kevlar motor cases, or multilayer in nature, as with carbon-carbon exit cones. A technique is required to help reduce the high rejection rate among such components and to better understand their processing environments. Defects that may occur during fabrication can compromise their structural integrity and subsequently result in unacceptable, or even catastrophic, degradation of performance. Existing radiographic NDE techniques cannot provide complete or unambiguous information regarding the integrity of many thin-walled structures presently of interest. This is because inherent structure overlying and underlying the region of interest may so confuse or obscure the resultant image that clear interpretation of the radiographic information is not always possible. A new procedure known as laminography is proposed as an NDE technique to better evaluate thin-shelled structures.

The results of a 24-month Small Business Innovative Research (SBIR) Phase II program (Contract No. F33615-85-C-5145) are documented. The program goals consisted of six technical tasks which were as follows: (1) the design of an optimized preprototype laminography system, (2) the procurement of subsystem hardware, (3) the assembly and checkout of subsystem components, (4) the integration of the subsystems into a complete preprototype laminography system also capable of accommodating a dual-energy capability, (5) the detailed evaluation of laminographic performance to determine the limits of operation, and (6) a demonstration of the capabilities of the system to a select government/industry audience.

The product of this Phase II SBIR program is a fully operational preprototype LAMinography/Dual-Energy system designated the LAM/DE System. The scope of the program was reduced to accommodate the fact that a detailed evaluation of laminography capabilities and limitations and a government/industry demonstration could not be performed within established program funding limits.

## **FOREWORD**

**This final report was prepared by Advanced Research and Applications Corporation (ARACOR), Sunnyvale, CA, and documents the work performed under Air Force Contract No. F33615-85-C-5145, "A New NDE Capability for Thin-Shelled Structures."**

**The work was conducted under the cognizance of the Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433-6533. Capt. Michael Polovino, AFWAL/MLLP, was the Air Force Program Manager for the initial part of the program and Mr. Tom Moran was the Air Force Program Manager of the later part of the program. The ARACOR Program Manager was Dr. James H. Stanley.**

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## SECTION 1

### INTRODUCTION

The rapid acceptance of computed tomography (CT) by the aerospace community as a principal inspection method for high-cost solid rocket motor components has created a demand for an X-ray imaging method which would provide essentially the same information at higher speeds and at lower costs. A highly successful Phase I SBIR program demonstrated that laminography could yield accurate X-ray images of thin slices of complex, thin structures in a fraction of the time required for CT inspection of the same structure. However, in achieving this speed of imaging, the resolution and contrast sensitivity of laminography, when compared to CT imaging, are degraded. Additionally, the absolute attenuation calibration of laminography is not possible. Therefore, any instrument based entirely on laminography alone could not provide the results which are now possible with CT in the inspection of high-value composite components. During the Phase I program it was shown that the laminographic capability could be added to an industrial CT instrument at modest cost. The inclusion of a laminographic capability in CT instrumentation, permitting the use of the excellent density and spatial capabilities of CT, offers the advantages of a fast, 100 percent inspection capability for thin composite structures, such as exit cones or aircraft structures. Since there are a number of important inspection problems which could be solved with this method, the potential of laminography to both the aerospace and civilian communities is very large indeed.

## SECTION 2

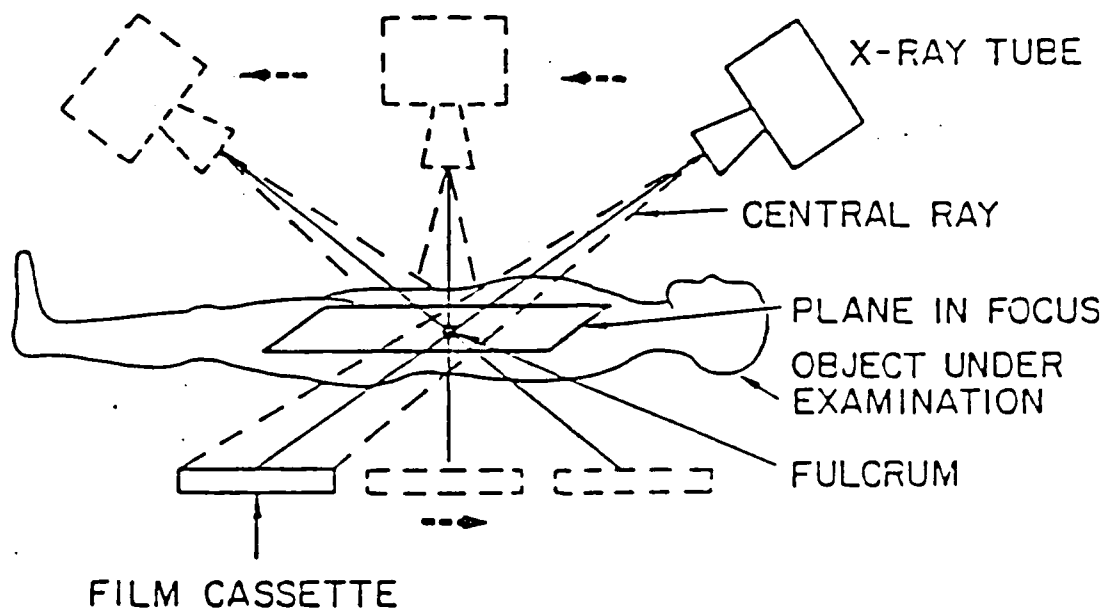
### TECHNICAL BACKGROUND

Laminography is similar to Computed Tomography (CT) in that both methods produce digital images of thin planar sections within an object and both require an X-ray source, detection system, and data acquisition and data processing capabilities. However, laminography and CT differ in the implementation of these technologies, the manner in which the data is acquired and processed, and the significance of the resulting images. The most basic difference is that CT provides information regarding the cross-sectional structure of an object whereas laminography provides information about its longitudinal structure. The images produced by the two methods are orthogonal to one another; consequently, the information provided by these two inspection modalities is complimentary but distinct. Of the two approaches, laminography appears to offer the better inspection capability for thin-walled structures. This is because laminography provides images of layers within and concentric to the natural shape of the object, a much more appropriate (and intuitive) presentation of the internal structure than the ring-like images of cylindrical or conical objects produced by CT scans. Since laminography is based upon digital radiographic and classical tomographic techniques, these techniques are briefly reviewed in the following paragraphs.

Digital Radiography is a relatively new imaging modality, directly related to classical film-based radiography, in which suitable solid-state detectors (rather than film) record the spatial intensity variations of X-rays that have traversed an object. The corresponding images are digitally prepared by the computer from the radiographic projection data and are visually presented on a video monitor or other high-resolution output device. Depending upon the dual detectors, linear arrays, area arrays, or screens; but regardless of the X-ray detection mode, the net result is a two-dimensional digital image of the object of interest. The major limitation of digital radiography, as with all standard radiography techniques, is that a two-dimensional representation of a three-dimensional object is produced and the resulting superposition of structure restricts the interpretation of the image.

Classical Tomography, on the other hand, is a well-established X-ray technique first introduced in the early 1920's. With this method, an X-ray source and film cassette move synchronously and continuously in opposite directions about a fulcrum. The image

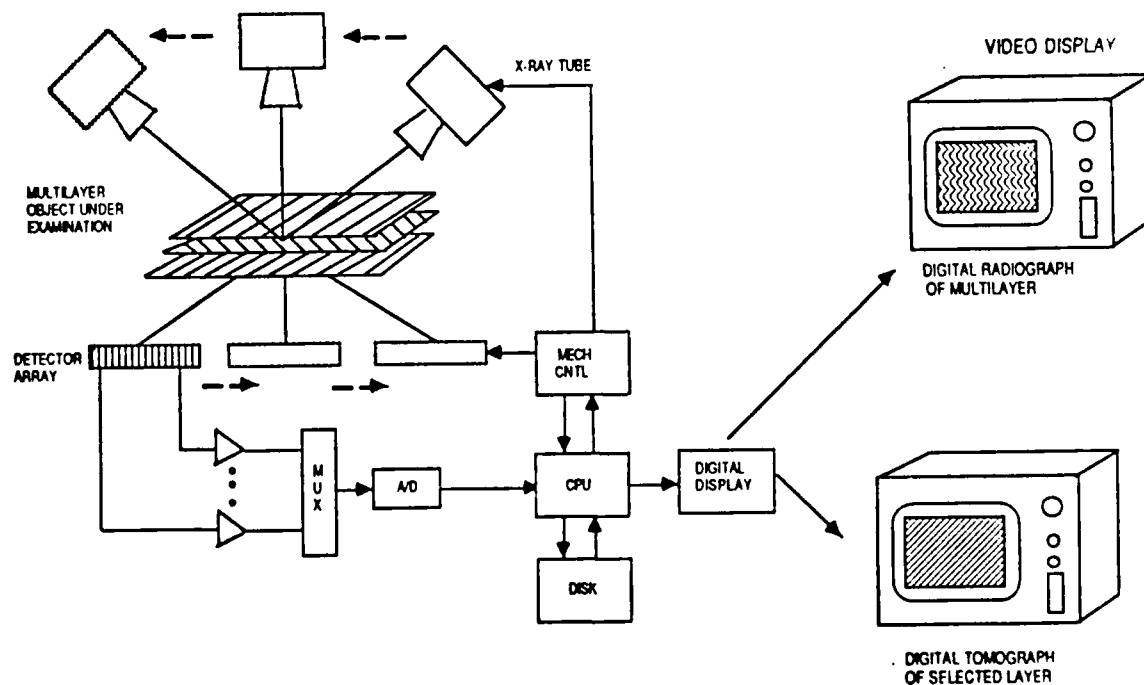
plane, called the tomographic plane, is parallel to the motion and passes through the fulcrum. An image of this plane is produced on the film because structure above or below the tomographic plane is blurred by the motion whereas structure within the tomographic plane is stationary with respect to the focal plane and thus remains in "focus" (Figure 1). By changing the level of the fulcrum, a series of parallel sections, laminograms, can be sequentially obtained. Care must be taken to ensure that each exposure is sufficiently intense to provide adequate exposure and a new film cassette must be used for each plane to be imaged.



**FIGURE 1.** Schematic of Classical Tomography Procedure

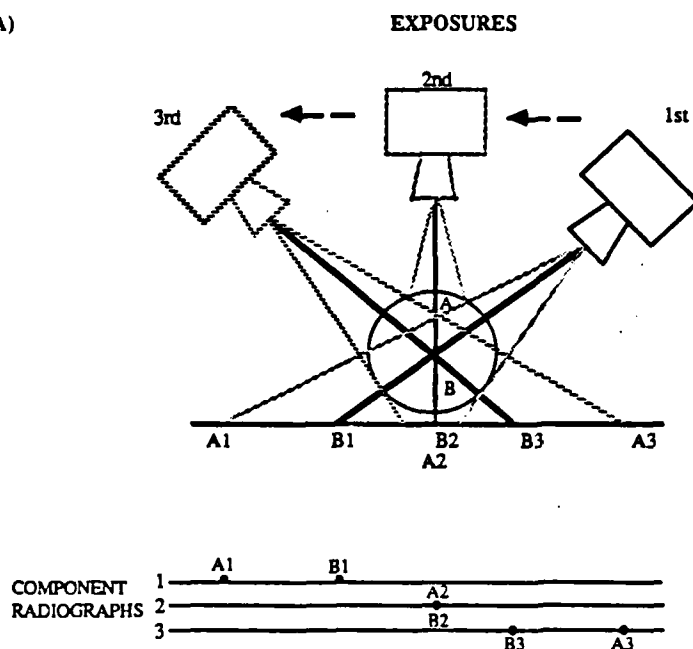
Laminography [1-9] weds classical film-base tomography and digital radiography by retaining the basic concept of focal plane imaging but replacing the film cassette with a suitable array of radiation detectors whose outputs are monitored electronically. Some type of parallax-producing motion between the object and the detector must still be maintained, but the mechanical motions demanded by classical film-based tomographic systems are greatly relaxed. This is because laminography is a two-step process: first, a complete set of digital radiographs, taken at a sequence of evenly-spaced angles of view, are measured and stored; secondly, the focal plane integration, which is performed classically by the film, is carried out after the scan by the computer from the stored, or component, radiographs.

Computer processing of these component radiographs as depicted in Figure 2 permits the reconstruction and visualization of structure in the tomographic plane. The component radiographs are processed in sequence and synthesized into a tomographic image residing in memory, which is then displayed on a video monitor. However, laminography, unlike its classical counterpart, enables arbitrarily many planes to be viewed with the data obtained from just a single exposure sequence, thereby reducing measurement time (Figure 3). This figure shows that the plane of focus is selectable, depending only on the appropriate manipulation of the recorded data. This concept can be further generalized to include the visualization not only of simple planar sections but also interior surfaces of arbitrary shape. This general ability gives laminography the ability to reconstruct arbitrary structural surfaces from a single sequence. This feature is of major significance for the examination of thin cylindrical and/or conical structures for which planar radiographic images are simply not appropriate.

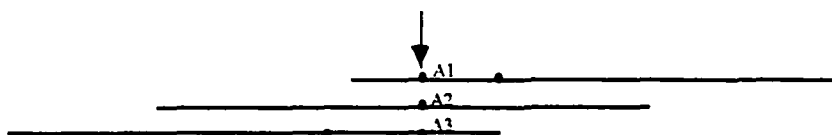


**FIGURE 2. Schematic Illustration of Laminography**

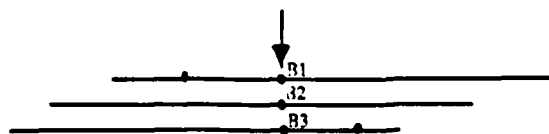
(A)



(B) RELATIVE DISPLACEMENT OF COMPONENT RADIOGRAPHS FOR POINT A TO BE IN FOCUS:



(C) RELATIVE DISPLACEMENT OF COMPONENT RADIOGRAPHS FOR POINT B TO BE IN FOCUS:



**FIGURE 3. Schematic of Data Imaging for Laminography**

## **SECTION 3**

### **PROGRAM REVIEW**

The technical objectives of this program were divided into six separate tasks set forth as follows: (1) the design of an optimized preprototype laminography system, (2) the procurement of subsystem hardware, (3) the assembly and checkout of subsystem components, (4) the integration of the subsystems into an operational preprototype laminography system also capable of accommodating a dual-energy scanning and reconstruction capability, (5) the detailed evaluation of laminographic inspections to determine limits of performance, and (6) a demonstration of capabilities to a select government/industry audience.

This program was linked to a companion program, "A New Radiographic Corrosion Inspection Capability," (Contract F33615-85-C-5151). The combined goal of both programs was to construct a fully integrated dual-energy/laminography instrument. The present program was mainly responsible for the "hardware" design and fabrication of the LAM/DE system including the detector package, the handling system, the radiation source, the radiation facility, and the facility layout. This program was responsible for the procurement of all LAM/DE equipment including the material/ODC requirements of the companion program. The other program was responsible for the design and fabrication of the detector components, the design and fabrication of the data acquisition electronics, and the design and development of the necessary software to be used on the LAM/DE system. A review of the tasks completed as a part of this program follow.

#### **3.1 PREPROTOTYPE DESIGN**

The preprototype design will be reviewed, concentrating on the design considerations peculiar to laminography and the tasks outlined for this program. This discussion will include descriptions of the detector package hardware design, the handling system design, the source design, the radiation facility design, and the overall system design.

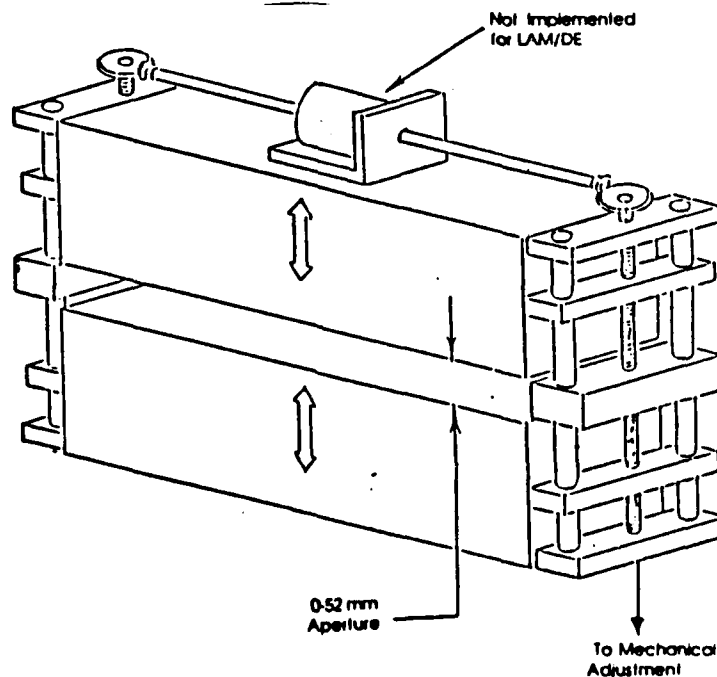
##### **3.1.1 Detector System**

To construct a laminography and dual-energy system, special attention was paid to the detector package so that the detector requirements for both capabilities could be simultaneously met with a single package. This program was responsible for the detector

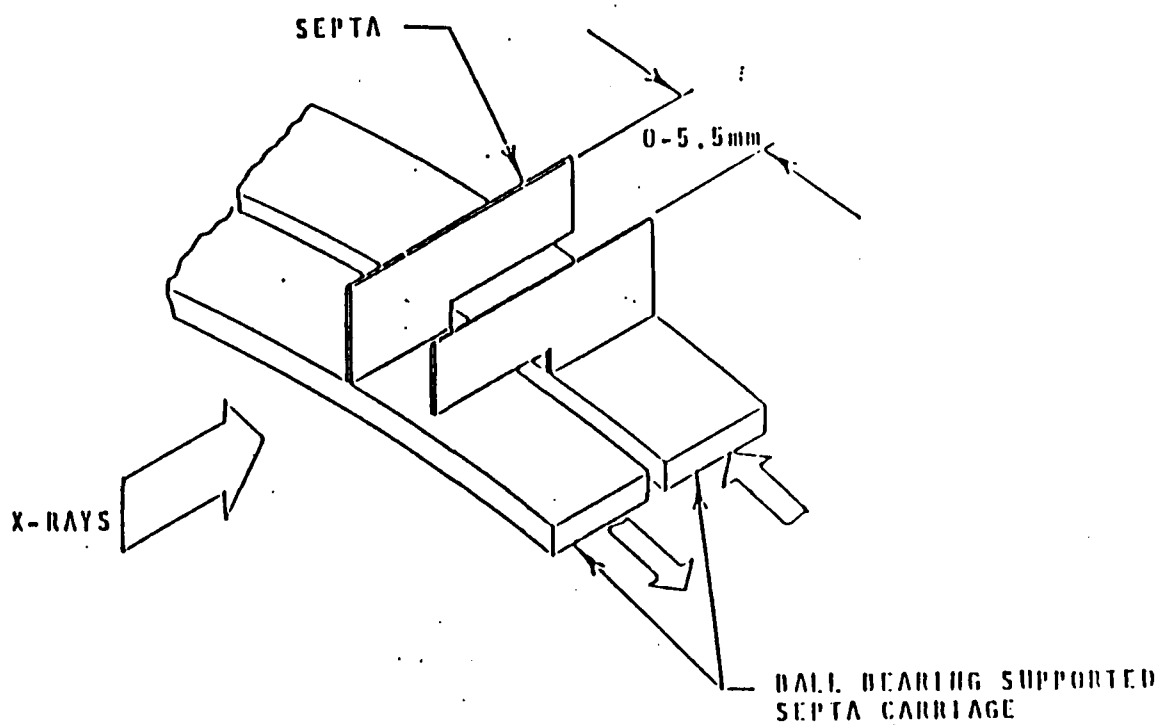
hardware design and fabrication. This task included the slice thickness and resolution collimation design, the environmental cooling system design, and the component layout within the detector package.

Initially, when the system had only to provide radiographic scans for laminography, a vertical orientation was proposed for the detector package. The design was changed to a horizontal orientation for two reasons: (1) the vertical geometry is not compatible with a dual-energy capability, and (2) further experience suggested that the laminographic reconstruction algorithm could be based on horizontal geometry. With this geometry it was possible to place the detectors in an existing ARACOR CT detector housing, significantly reducing design costs.

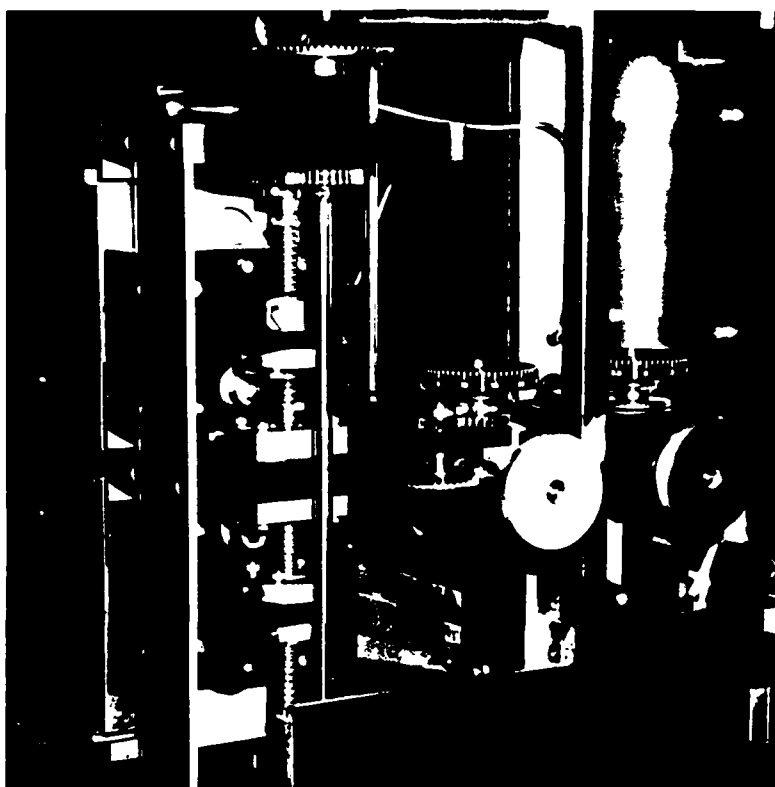
The detector collimation design consisted of height and resolution collimators. The height collimators were designed to be easily positioned vertically by use of a stepping motor and a gear design on the two collimator ends. A schematic of this which was presented at the CDR is shown in Figure 4. . The resolution collimators were designed to be positioned by a ball bearing supported septa carriage. They were designed to be capable of providing collimation from 0.5 to 5.5 mm. A schematic of this which was presented at the CDR is shown in Figure 5. Photographs of the as-built height collimation gear assembly and of the resolution collimators are shown in Figures 6 and 7.



**FIGURE 4. Slice Height Collimator Positioning Design**

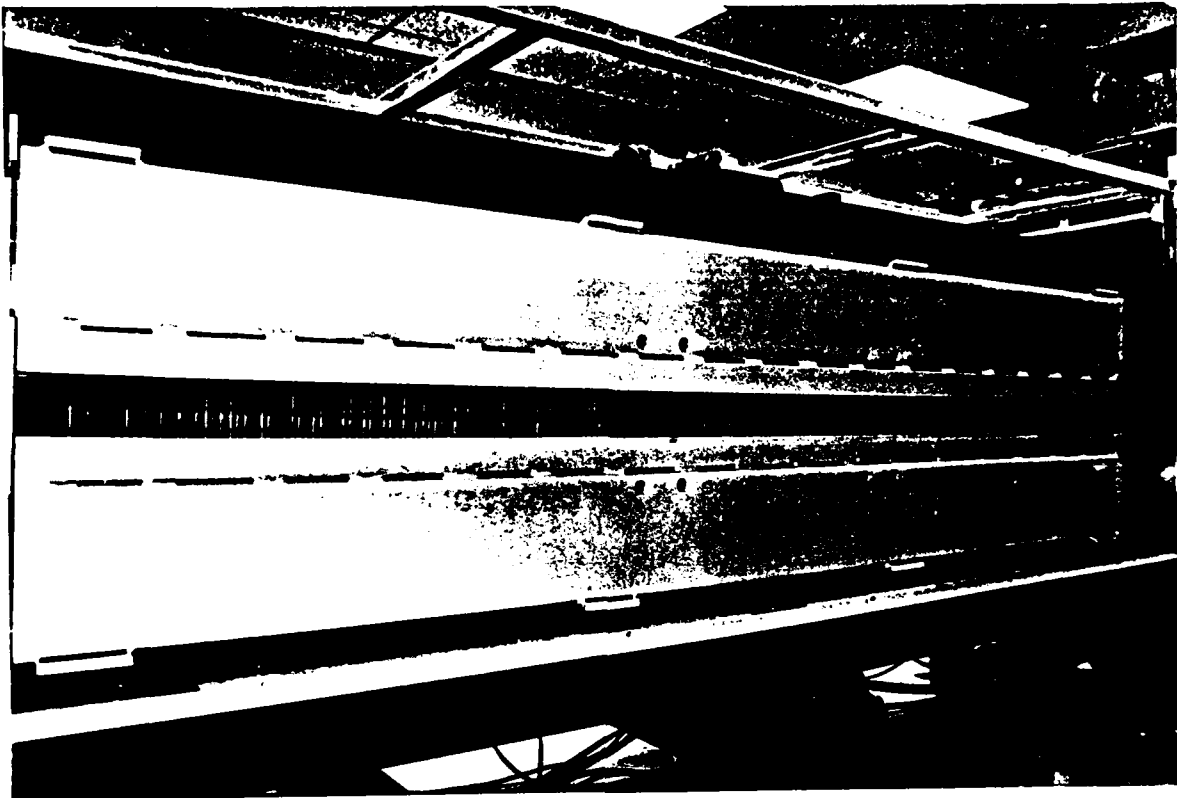


**FIGURE 5. Resolution Collimator Positioning Design**



**FIGURE 6. Photograph of Slice Height Collimator Gear Assembly**

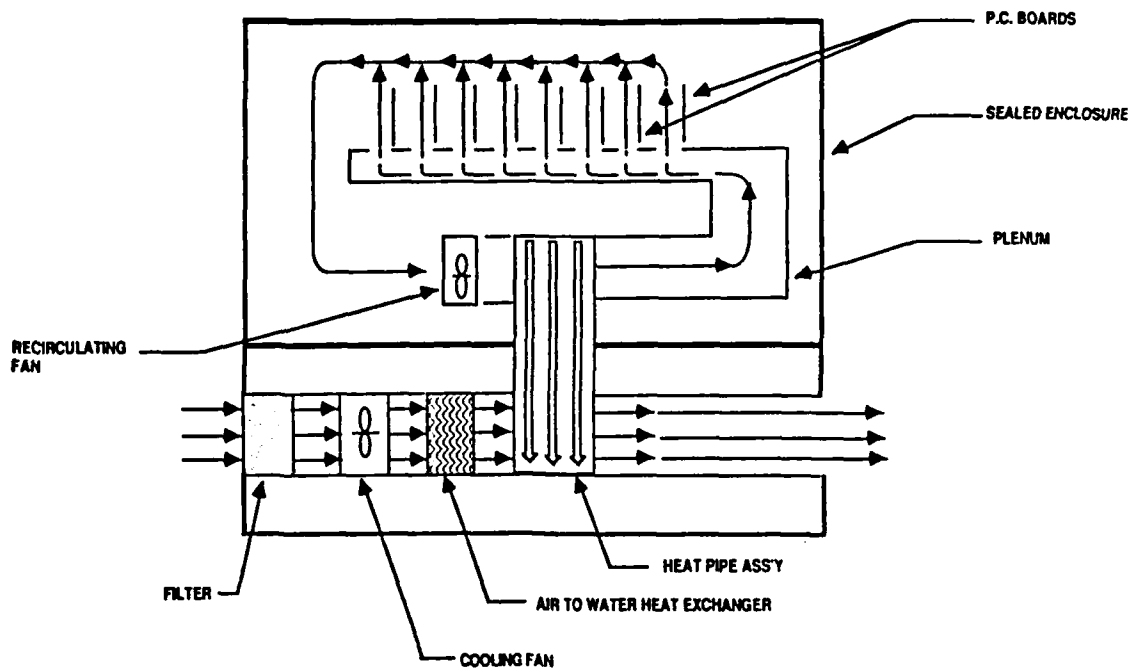




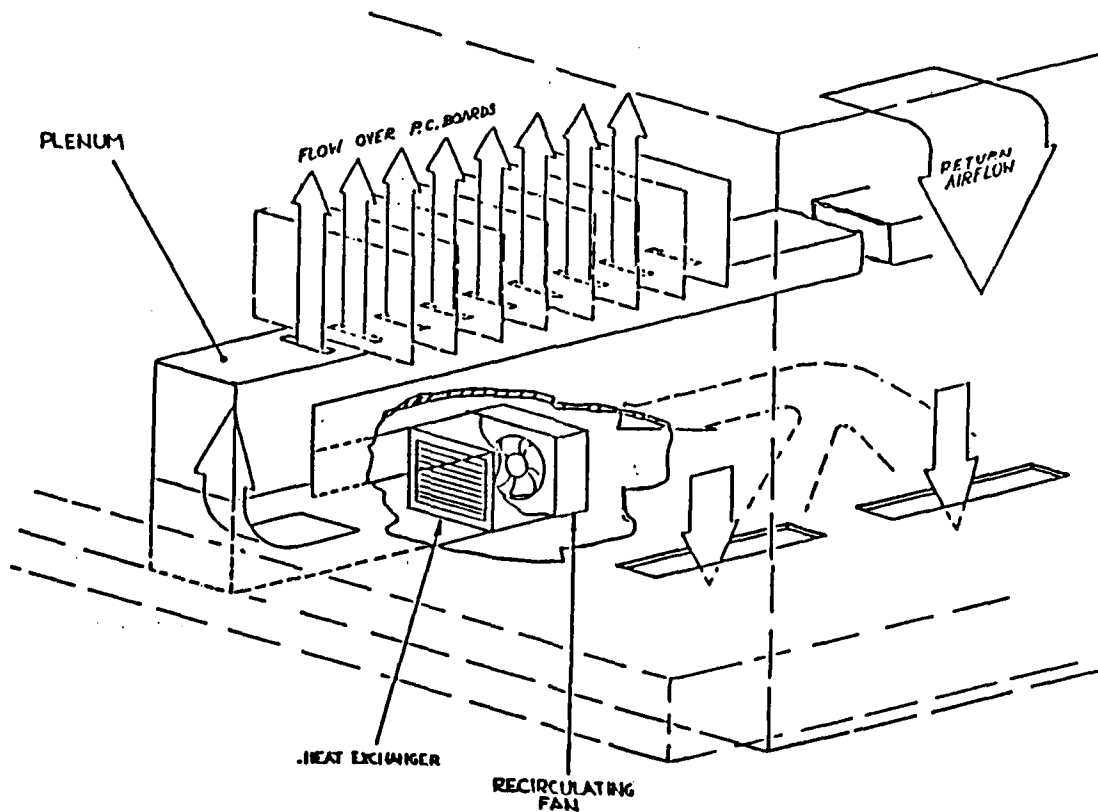
**FIGURE 7. Photograph of Resolution Collimators**

The detector system had to be designed with adequate cooling to provide a stable environment to the electronics and to insure accurate calibration of the detectors. A series of fans, heat exchangers, and heat pipes were designed into the system to provide adequate and constant cooling. A CDR schematic of the heat exchange design is shown in Figure 8. This design is intended to allow air to flow over the PC boards as shown in Figure 9.

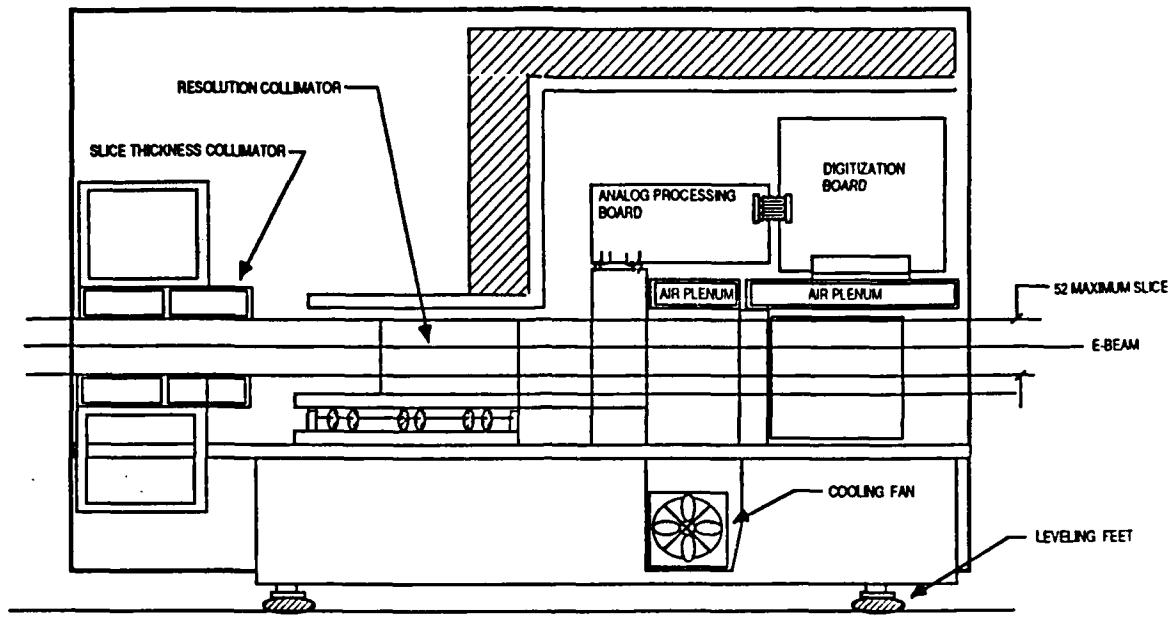
The entire detector package was enclosed with a radiation-shielded sheet-metal housing. This protected the package from ambient light, X-rays, and electro-magnetic interference. The proposed layout presented at the CDR of the various components contained in the detector package is shown in Figure 10. A CDR cutaway view of the detector package is shown in Figure 11. A photograph of the as-built outside of the detector package is shown in Figure 12. The slice thickness collimators show in the front.



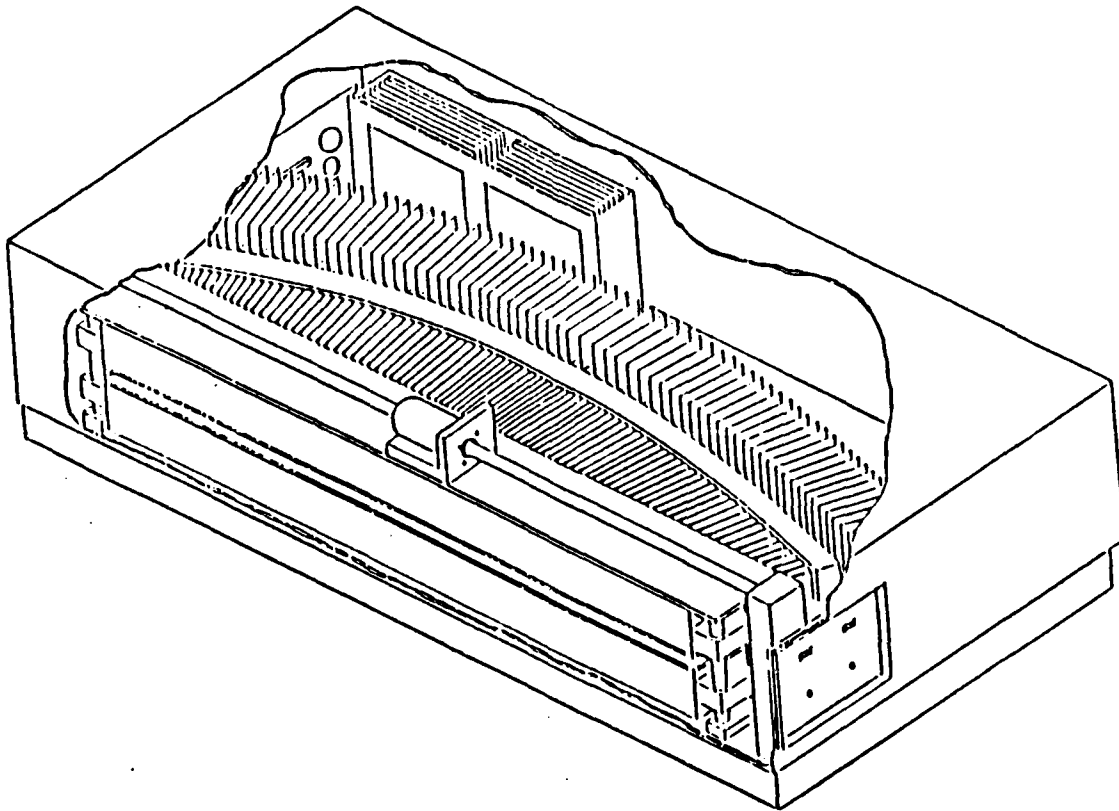
**FIGURE 8. Design of Detector Package Heat Exchange System**



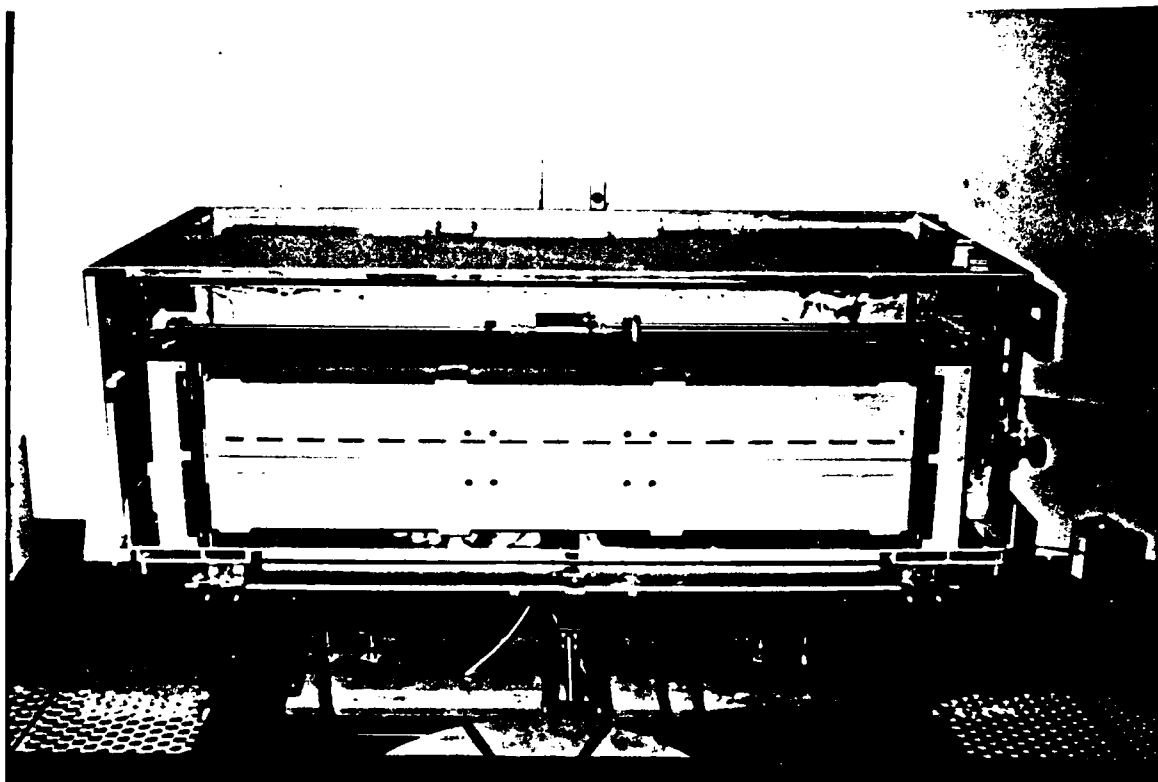
**FIGURE 9. Air-Cooling Design of Detector Package**



**FIGURE 10. Detector Package Component Layout**



**FIGURE 11. Cutaway View of Detector Package**

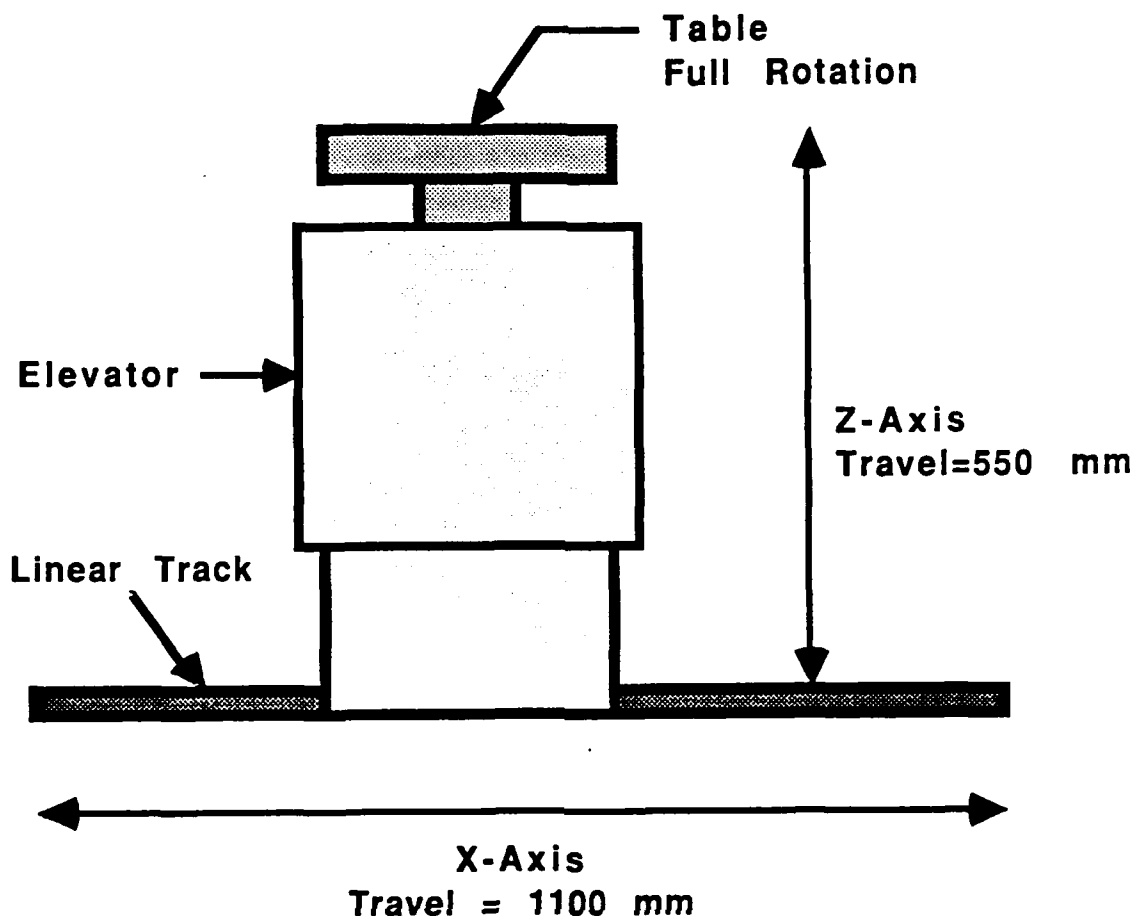


**FIGURE 12. Photograph of Detector Package**

### **3.1.2 Handling System**

For laminography, a rotate only scan geometry is in theory all that is needed to obtain the necessary radiographs to construct the laminographic images. However, to meet the dual-energy requirement, the center-to-center spacing of the detectors had to be increased. With this detector spacing, a single vertical pass is no longer sufficient and multiple passes must be interleaved to fill in the missing rays. This introduces a need for horizontal linear motion. The need for horizontal motion, however, can in principle be advantageously utilized to accommodate a CT capability.

These added requirements necessitated the need for an integrated handling system that could provide rotational, horizontal, and vertical motion. The design and fabrication of the handling system was competitively awarded to Homma of Japan. The system allowed for 1100 mm motion in the x-direction (horizontal), 550 mm motion in the z-direction (vertical), and full rotational motion. The table diameter is 820 mm. The precise handling requirements of this laminography/dual-energy system were all met or exceeded by Homma. A schematic of the Homma design is shown in Figure 13. A photograph of the actual LAM/DE handling system is shown in Figure 14.



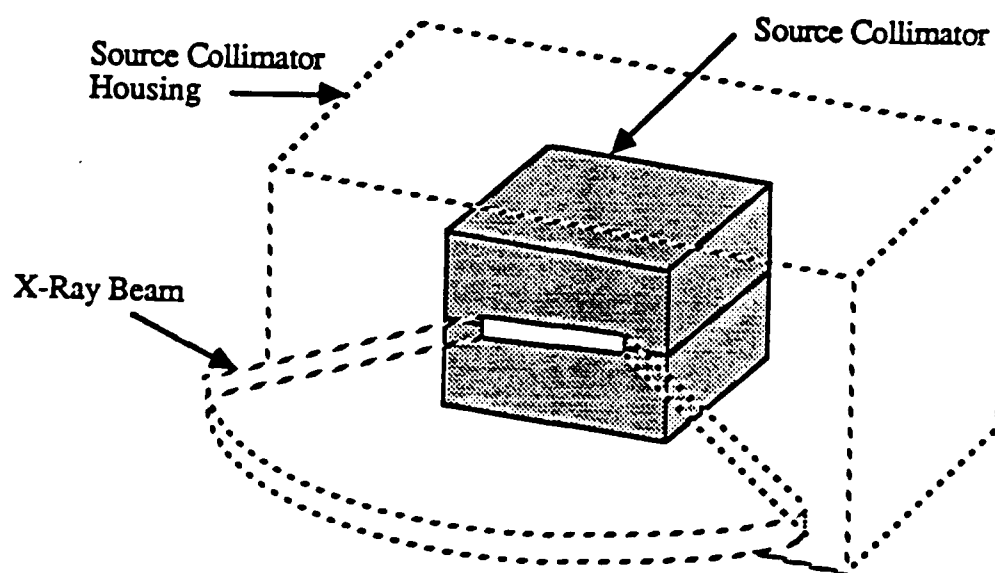
**FIGURE 13. Schematic of Handling System Design**

### 3.1.3 X-ray Source

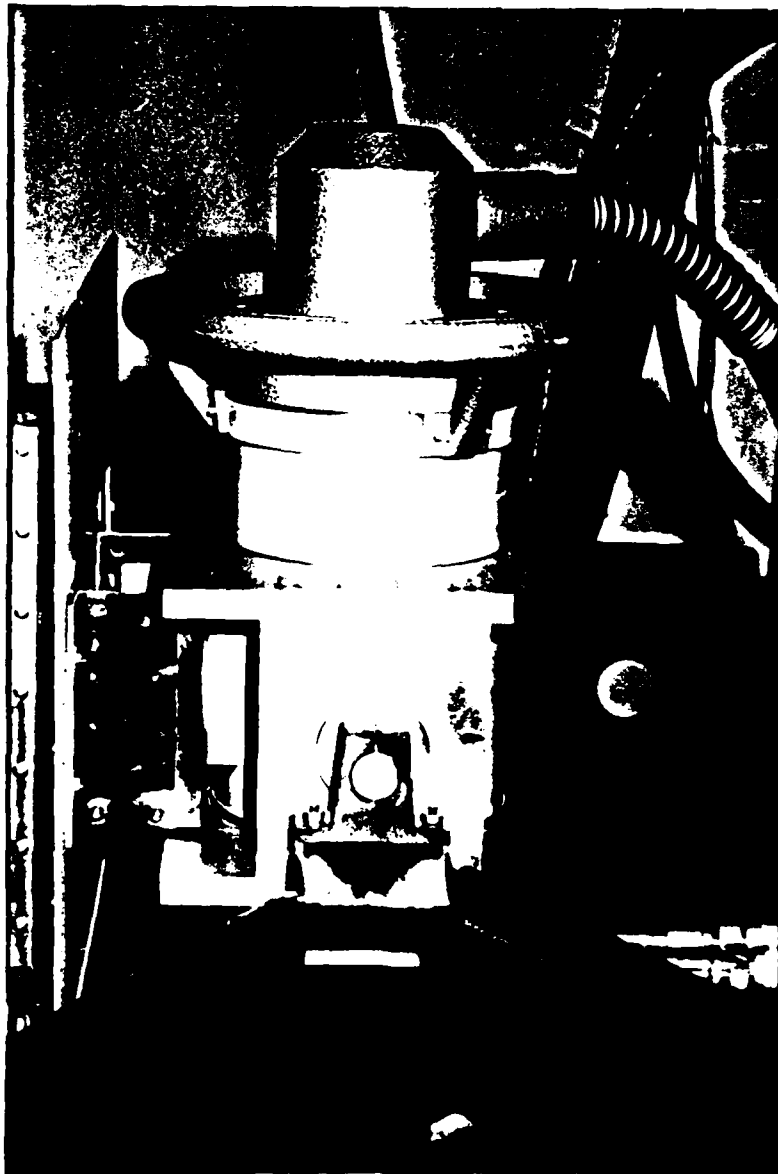
The requirements of the X-ray source are dependent on the system performance goals and specifications. The X-ray source that was decided upon was a 80 - 420 kV constant-potential industrial source with dual 1.8 mm and 4.5 mm focal spots. The source collimator was designed to provide a 36-degree fan beam. A schematic of the source collimator design is shown in Figure 15. A photograph of the X-ray source used for LAM/DE is shown in Figure 16. A photograph of the source and the as-built collimator is shown in Figure 17.



**FIGURE 14.** Photograph of LAM/DE Handling System



**FIGURE 15.** Schematic of Source Collimator Design



**FIGURE 16.** Photograph of X-Ray Source



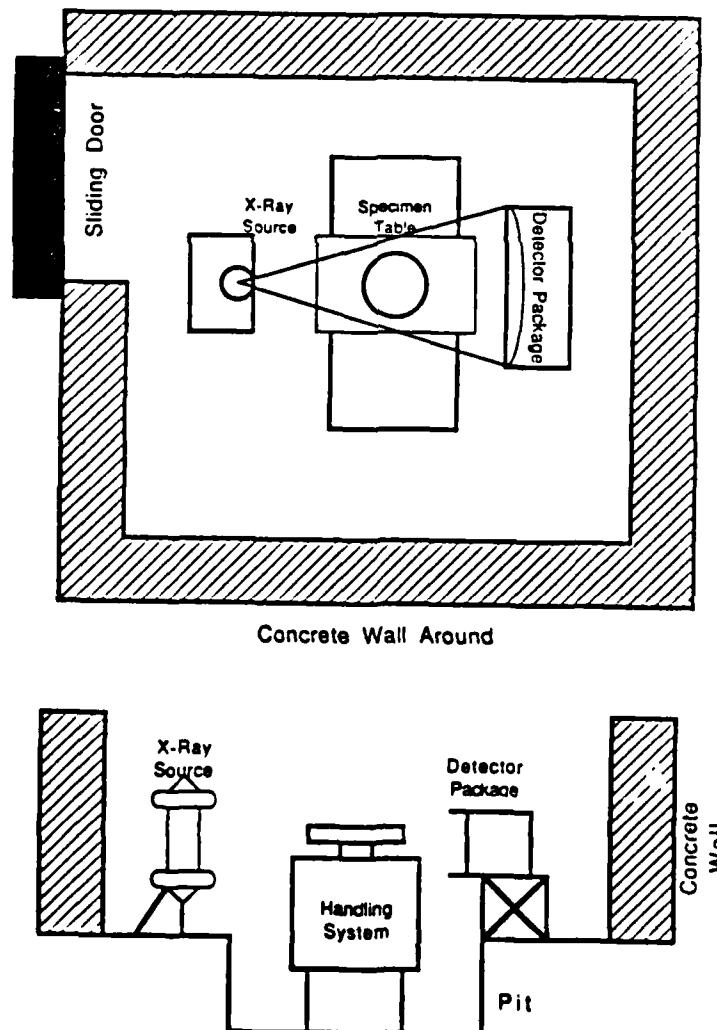
**FIGURE 17. Photograph of Source and Collimator**

#### **3.1.4 Radiation Facility**

In order to operate the LAM/DE system at ARACOR, a radiation test facility was needed that would meet the city of Sunnyvale safety code. A minimal facility was designed at ARACOR to house LAM/DE on-site during the integration and evaluation of the system. Detailed facility requirements were provided to Wright Aeronautical Laboratory, WPAFB, Ohio where the LAM/DE system will ultimately reside.

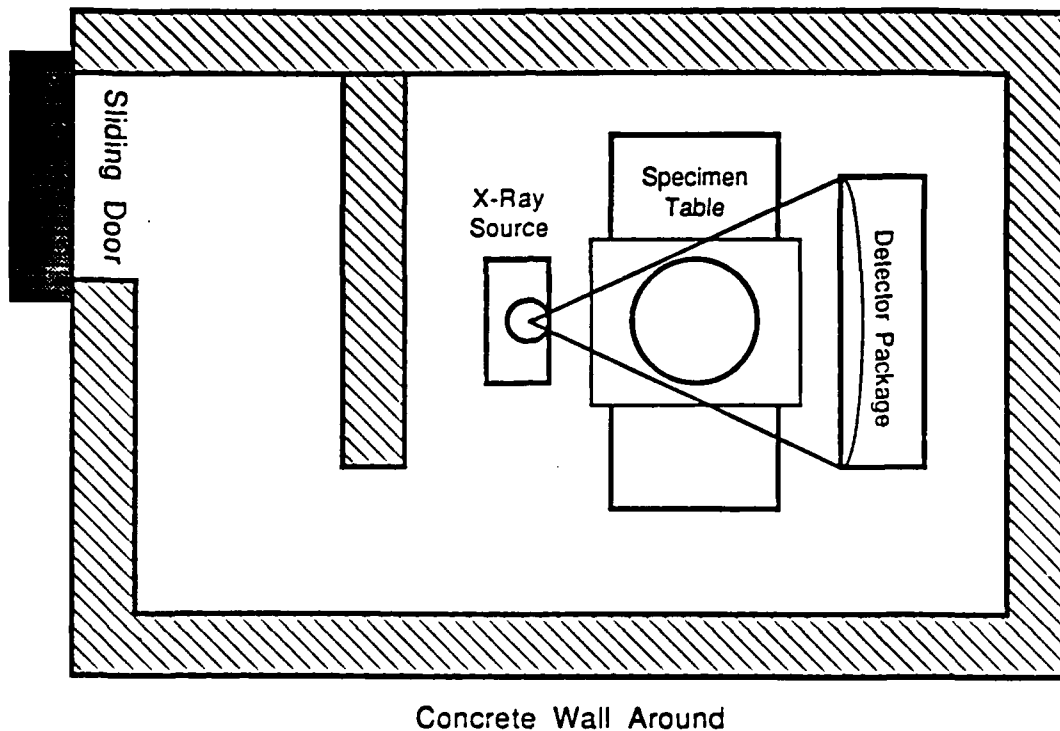


The radiation facility was designed under the constraints of adequate shielding of X rays, earthquake resistance, and sufficient room to operate the scanner. A schematic of the ARACOR facility is shown in Figure 18. The 2-foot thick concrete walls were limited to 8 feet tall; walls any taller would be deemed unsafe in case of an earthquake. Since the handling system was taller than this height when fully extended in the vertical direction, a pit was constructed so that the handling system could be set down into the pit and have full vertical motion. An advantage of placing the handling system in the pit is that it allows the operator to easily reach the specimen table while walking on steel grating placed over exposed sections of the pit. Under the original design without a pit, the operator would have had to mount a scaffolding to place specimens on the table. A switch was placed on the sliding door to the radiation facility so that if the door was opened during X-ray source operation, the source would immediately shut off to prevent unnecessary radiation exposure.



**FIGURE 18. Layout of ARACOR X-Ray Radiation Facility**

An acceptable layout for the AFWAL facility design is shown in Figure 19. This schematic, along with detailed utility and environmental needs, were provided to AFWAL. The only major difference between the two designs is the optional elimination of the pit in the AFWAL design, if desired. Earthquake resistance was less of a factor in the Materials Laboratory design.

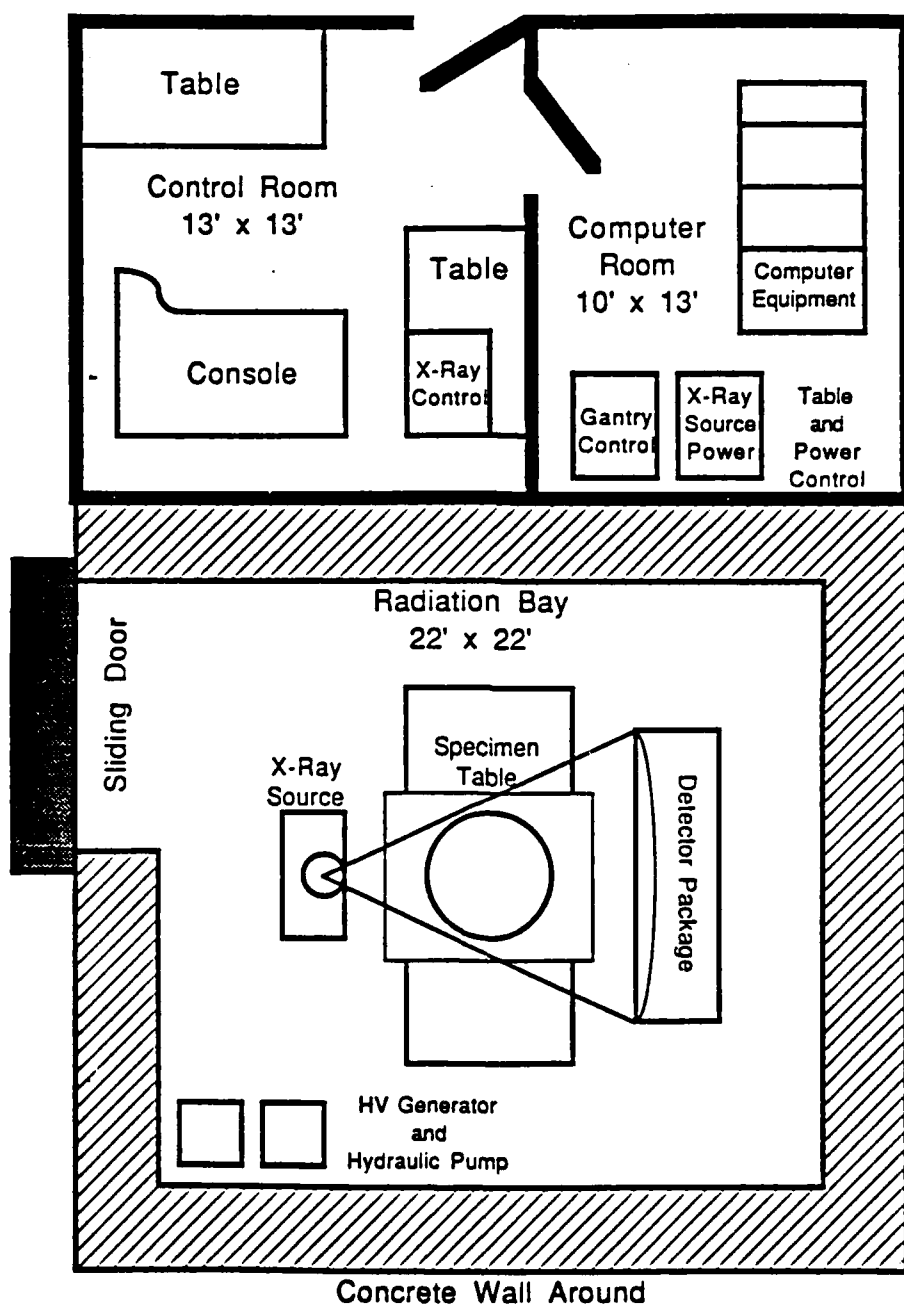


**FIGURE 19. Layout of AFWAL X-Ray Radiation Facility**

### 3.1.5 System Layout

Figure 20 shows the recommended system layout. The layout is basically divided into three separate components: the X-ray radiation facility and test bay, the computer facility, and the operator control facility. The test bay houses the LAM/DE scanner and the power supplies. The computer facility houses the scan control computer, the VAX 11/750 computer, and a magnetic tape drive. The operator control facility houses the X-ray source and handling system controls along with a CRT and display monitor to control and view the scanning data. In practice, an operator would place an object to be scanned on the specimen table of the LAM/DE scanner and close the door. The operator, after making sure the computer systems are turned on and warmed up, can then set up and

perform scans, reconstruct data, and view the results without leaving the operator control facility. This makes operation of LAM/DE very safe and convenient.



**FIGURE 20. LAM/DE System Layout**

### **3.2 PROCUREMENT**

The procurement of all materials and ODC's associated with this and the companion program were handled by this task. The X-ray source was purchased from Seifert. The handling system was procured from Homma of Japan. All other necessary components were purchased or manufactured for ARACOR by local firms. In addition, all of the electronic components necessary for the electronic and data acquisition systems were procured under this task (the design and assembly of those components were completed with funds from the companion program).

### **3.3 ASSEMBLY**

The assembly and subsystem checkout of all components was carried out by ARACOR personnel. All subsystems were successfully assembled and tested for functionality.

### **3.4 INTEGRATION**

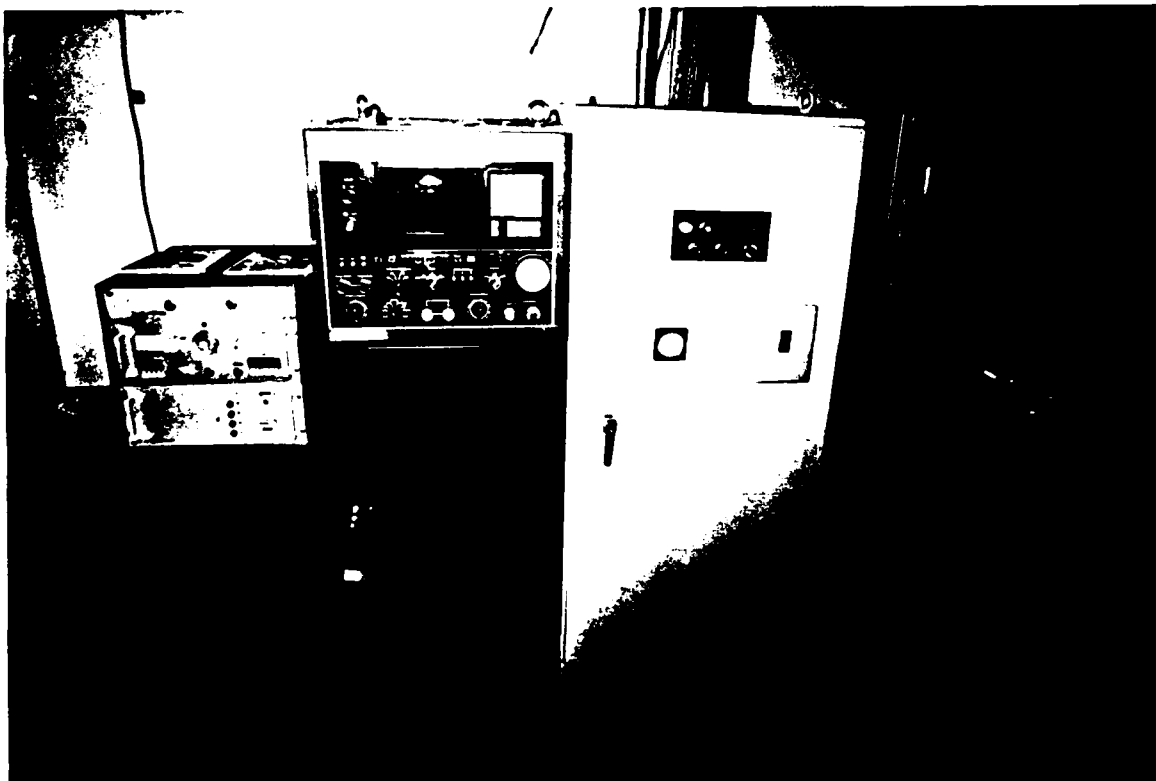
After the assembly of the various subsystems of the LAM/DE scan system was completed, they were integrated into an operational laminography/dual-energy system. A photograph of the completed LAM/DE scan system is shown in Figure 21. In this photograph, the X-ray source is on the right, the handling system is in the middle, and the detector package is on the left. The handling system is situated in a pit as described previously. Figure 22 shows a photograph of the X-ray source and handling system controls. Each time the system is powered up, the source needs to be turned on and warmed up and the handling system needs to be referenced. Once this has been done, however, the entire system can be remotely controlled at the operator control facility for as long as the system remains under power.

### **3.5 EVALUATION**

Due to funding limitations, this task was not able to be completed. A test plan document was drafted and revised. This document outlined the design of various phantoms to evaluate the parameters of the LAM/DE system and described the various tasks to be performed with the phantoms to evaluate LAM/DE operation. Funds were not sufficient, however, to fabricate these phantoms and implement the Test Plan.



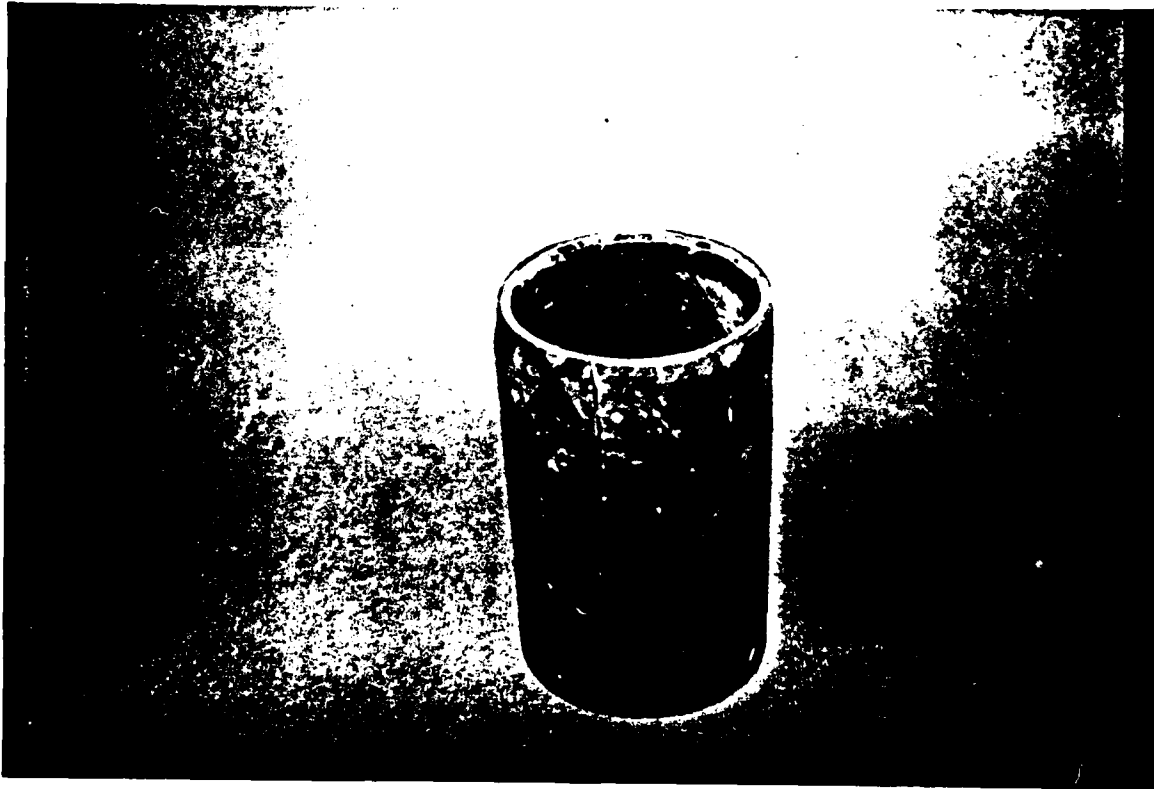
**FIGURE 21. Photograph of Fully Integrated LAM/DE System**



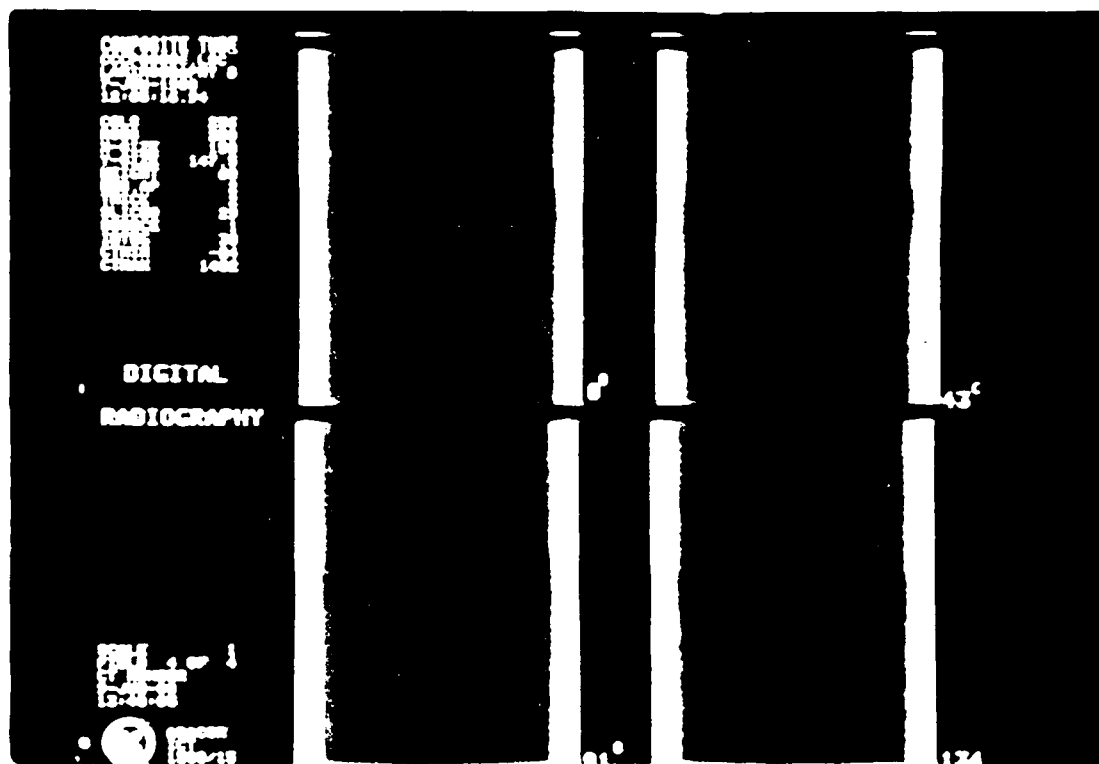
**FIGURE 22. Photograph of Source and Handling System Controls**

### **3.6 DEMONSTRATION**

To demonstrate the functionality of the LAM/DE system and its ability to perform laminographic reconstructions, a filament-wound composite cylinder was scanned. A set of 150 256 by 256 component digital radiographs over a full 360 degrees were taken of a 150-mm band around the part. A photograph of the composite cylinder is shown in Figure 23. Typical component radiographs taken of the part are shown in Figure 24.



**FIGURE 23. Filament-Wound Composite Cylinder**

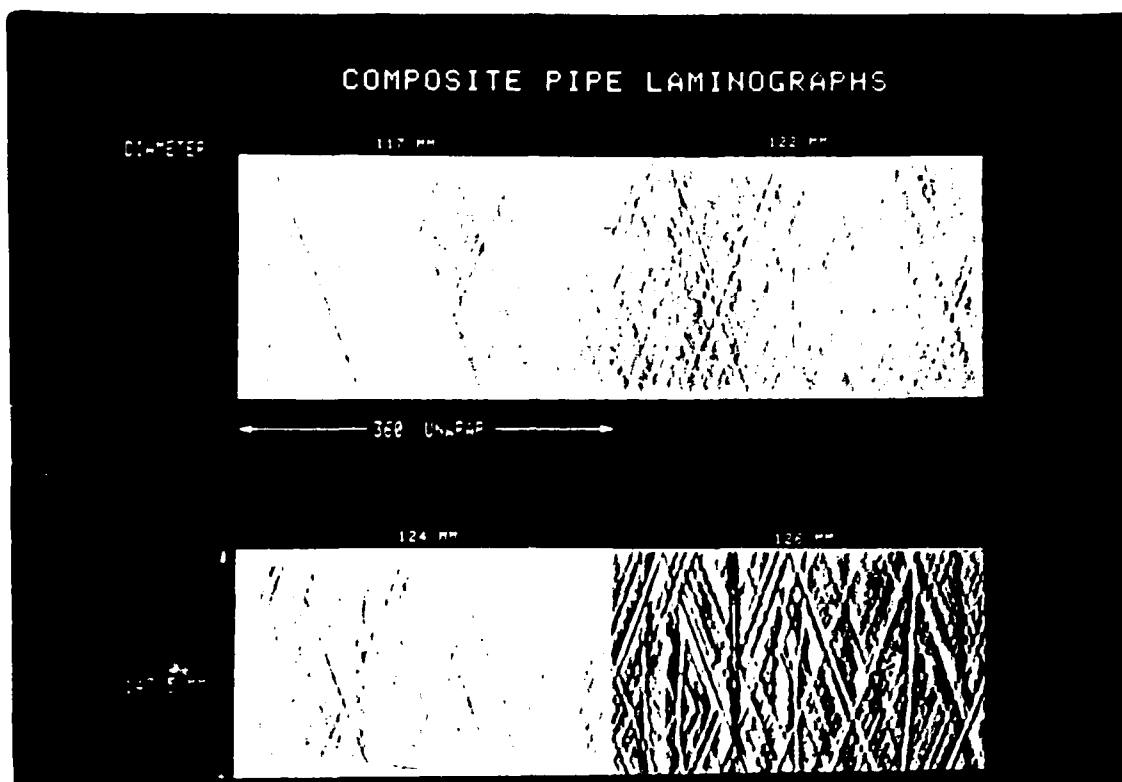


**FIGURE 24. Typical Component Digital Radiographs of Composite Cylinder**

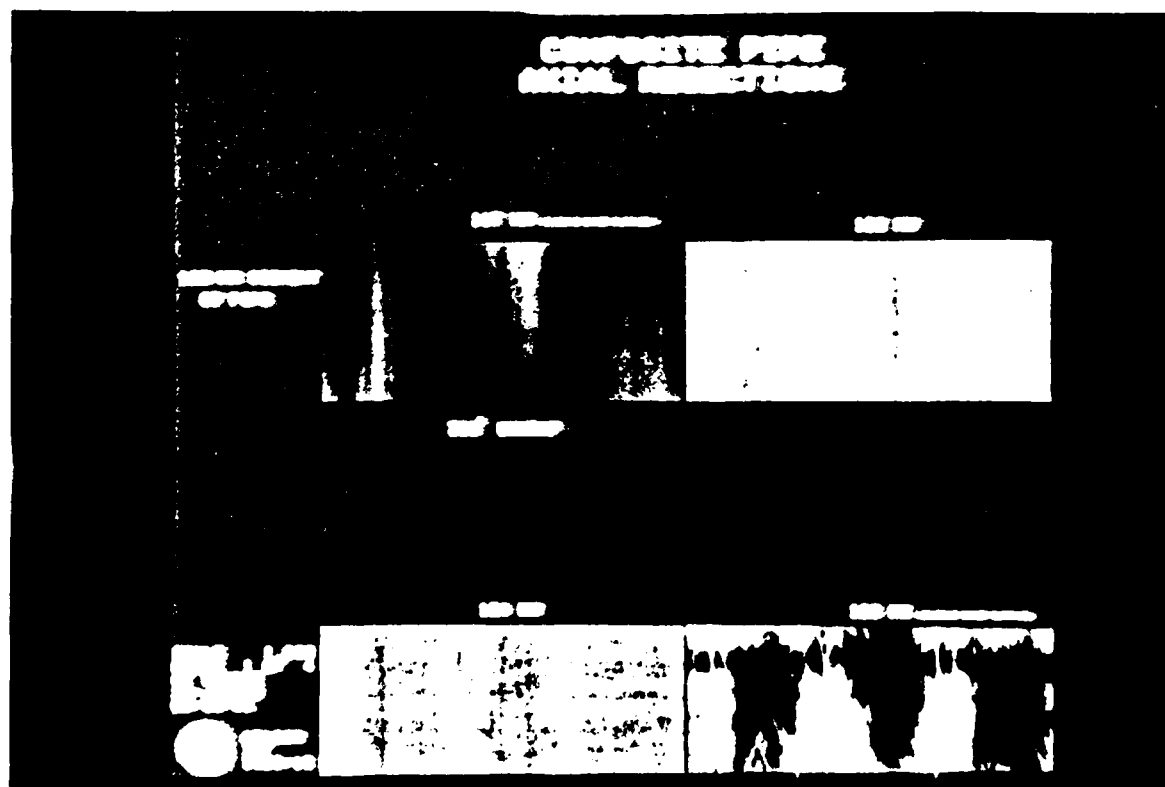
A series of concentric laminographic reconstructions were generated from the set of component radiographs. The slice thickness of each layer was measured with a special purpose slice thickness phantom and found to be approximately 1 mm. Representative reconstructions at different radii are shown in Figure 25.

To provide a point of comparison, 50 equally spaced CT scans were also taken of the same 150-mm region. The set of contiguous slices were resectioned (reformatted) to provide a comparison set of images by which to judge the quality of the laminographic reconstructions. Resectioned CT images, corresponding to the laminograms of Figure 25 are shown in Figure 26. The correlation is extremely good. While the laminograms are somewhat less quantitative than the CT images, they required considerably less time to acquire. Furthermore, the time advantage of laminography over CT increases as the size of the region of interest inspected increases.

A demonstration of the LAM/DE system to a joint government/industry audience was not performed due to insufficient funds.



**FIGURE 25. Laminographic Reconstructions of Composite Cylinder**



**FIGURE 26. Resectioned CT Images of Same Composite Cylinder**



## **SECTION 4**

### **CONCLUSIONS AND RECOMMENDATIONS**

This program has developed a fully integrated, fully operational inspection system capable of laminography and dual-energy measurements. The system provides a unique NDE tool for use in countless military/industrial applications. The limits of performance have not been fully evaluated, however, and it is recommended that further funding be used to completely evaluate and characterize the capabilities of this singular resource. The wealth of knowledge to be gained from such an endeavor can only further advance the field of NDE imaging.

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