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A NEUTRON RADIOGRAPHY SYSTEM FOR FIELD USE

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MATERIALS TESTING AND EVALUATION BRANCH

June 1989

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US ARMY
LABORATORY COMMAND
MATERIALS TECHNOLOGY LABORATORY

U.S. ARMY MATERIALS TECHNOLOGY LABORATORY
Watertown, Massachusetts 02172-0001

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER MTL TR 89-52	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A NEUTRON RADIOGRAPHY SYSTEM FOR FIELD USE		5. TYPE OF REPORT & PERIOD COVERED Final Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John J. Antal, Alfred S. Marotta, and Louis J. Farese		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Materials Technology Laboratory Watertown, Massachusetts 02172-0001 SLCMT-MRM		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS D/A Project: 1L162105AH84
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Laboratory Command 2800 Powder Mill Road Adelphi, Maryland 20783-1145		12. REPORT DATE June 1989
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Neutron radiography
Field tests
Portable equipment

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(SEE REVERSE)

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ABSTRACT

The use of neutrons as penetrating radiation expands the role of radiological nondestructive examination considerably. Radiological examination by neutrons has been limited, however, by the need to perform such radiography at the site of a nuclear reactor or a large accelerator system which can provide neutrons of an intensity equal to that of industrial X-ray sources. In 1979, the U.S. Army and the Vought Corporation demonstrated a mobile neutron radiological system designed as a prototype for the examination of lightweight aircraft structures in the field. The neutron source for this system is a very small, commercially available (d,t) accelerator which provides an on-off radiation source and a size, weight, and shielding requirement acceptable for routine neutron examination in the manner of high-energy X-ray radiological systems. Under a variety of field maintenance conditions, this system has successfully provided useful neutron radiography at reasonable exposure times and has pointed the way to a means for bringing neutron radiography to the worksite. In addition to the technological advances introduced, acceptance of this small source system as a nondestructive examination tool has required rethinking on the part of NDE professionals and reeducation of technicians regarding the goals of radiographic examinations. We shall report here our experience with this unit both in the field and in the laboratory where it serves as a resource for further neutron source developments and the exploration of new applications of on-site neutron radiological examinations.

CONTENTS

INTRODUCTION

The movement of military personnel and materiel utilizing aircraft to provide rapid deployment and the increasing concern for fuel conservation have provided an incentive to develop new lightweight structural materials. These new alloys, high performance ceramics, and composite materials have brought with them new challenges in their processing, forming, and characterization. The characterization of structural materials over their full life cycle, from the selection of raw materials to the performance of the material in the finished article in its operating environment, has become important to the production and successful application of costly, high-technology lightweight materials. Along with many new sensor systems and technical instruments, neutron radiological examination has arisen as a useful characterization tool for several new materials systems.

Neutron radiography, which uses its neutrons as a penetrating radiation to produce transmission images of material structures in a manner identical to better-known X-ray radiography techniques, was a fully developed technique by 1960's, when nuclear research reactors could readily provide convenient beams of thermal neutrons. The special characteristics of neutron radiography did not seem to be required to a great extent for many years afterward and it remained a "solution in need of a problem."[1] Even the routine application of neutron radiography to criti cal elements of space hardware by NASA and its extensive application to fuel element analysis in the nuclear industry[2,3] did not spawn a wider interest in the technique. In recent years, however, the damage to older commercial and military aircraft by hidden long-term moisture initiated corrosion combined with the need for new lightweight structural materials within the military has had a marked effect on the development of neutron radiological techniques. In 1979, the U.S. Army demonstrated a prototype mobile transportable neutron radiography system for helicopter examination developed from previous research by the Vought Corporation of Dallas, Texas.* A great deal of interest has been shown in this system and its construction has provoked a major renewal of interest in neutron radiography because it promises to bring neutron radiography to the workplace, a convenience provided by most non-destructive examination (NDE) tools, particularly X-ray radiography.[4]

ADVANTAGES OF NEUTRON RADIOGRAPHY

Neutron radiography is still a less readily available and more costly NDE technique than other radiological methods and thus is usually applied in special cases where other techniques fail. Neutron radiation is generally more penetrating than gamma-ray or X-ray radiation because these zero-charge particles do not interact with the sea of electrons present in materials. The primary neutron interaction is with the nuclei of atoms in materials, where both scattering and absorption processes play a major role in removing neutrons from a beam directed at an object. Neutrons have a very high sensitivity for interaction with hydrogen regardless of its chemical form within a material. Thus, the new lightweight structural materials formed of organic molecules (epoxy composites, plastics) and

*Presently the LTV Missiles and Electronics Group, Missiles Division, Dallas, TX

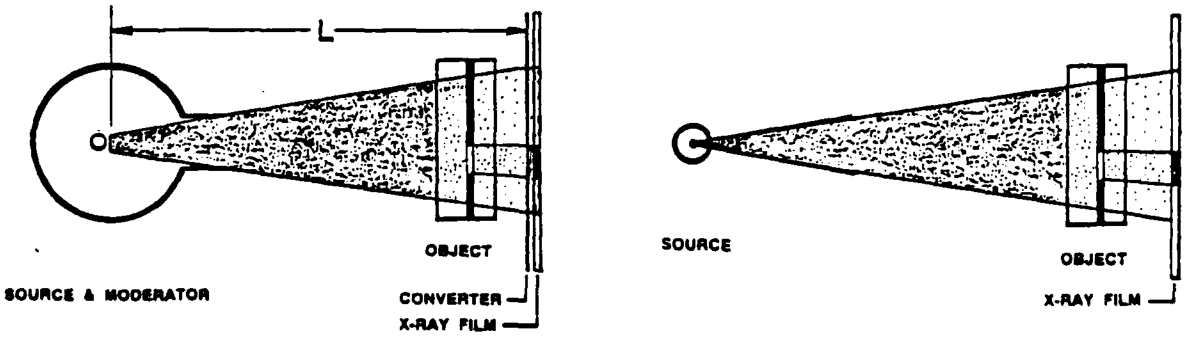
1. RAY, J. W. *Neutron Radiography, A Solution in Search of Problems,* Research/Development, v. 20, no. 7, July 1969, p. 18.
2. KOK, K. D. *Neutron Radiography of Nuclear Fuels at the Battelle Research Reactor* in Practical Applications of Neutron Radiography and Gaging, Harold Berger, ed., ASTM, Philadelphia, PA, 1976, p. 183-194.
3. ROSS, A. M. *Detecting Cladding Leaks in Irradiated Fuel Elements by Neutron Radiography and Gaging,* in Practical Applications of Neutron Radiography and Gaging, Harold Berger, ed., ASTM Philadelphia, PA 1976, p. 195-209.
4. ANTAL, J. J. *A Renaissance in Neutron Radiography via Accelerator Neutron Sources* in Materials Characterization for Systems Performance and Reliability, J. W. McCauley and V. Weiss, eds., Plenum Press, New York, N.Y., 1986, p. 385-401.

the organic adhesives with which they are bonded are susceptible to neutron examination. The detection of moisture and moisture-initiated corrosion products is a major application of neutron radiography to structures. Other light elements which are found in lightweight materials, particularly lithium and boron, are also readily imaged by neutron radiography.

NEUTRON RADIOGRAPHY LIMITATIONS

A major reason neutron radiography has yet to be applied on as large a scale as other NDE techniques is the unavailability of a small, highly efficient source system. The U.S. Army needs have demanded such a source and we review here the steps we have taken toward meeting this need.

Neutron radiographic examination has generally been applied as a supplement to X-ray radiography. By comparing the essentials of the two radiographic techniques, we can readily come to an understanding of the past and present limitations of neutron radiography. Figure 1 compares the two techniques. They differ in two essential respects, the source construction and the film recording system. The need for a moderator results in a relatively bulky source system. Neutrons, being uncharged particles, cannot be focused as is the electron beam within an X-ray source tube. This results in an effective source of extended dimensions, perhaps 100-mm in diameter, rather than the approximately 2-mm diameter point source of X-rays. The consequence of these source characteristics is that the resolution in the final neutron image is dependent upon care in the design of the collimator and often cannot be attained without placing the source at a long distance, L in Figure 1, from the film plane. In fact a commonly applied measure of resolution in neutron radiography is the "L/D ratio," where D is the diameter of the effective source, defined by the entrance aperture of the collimator. Much inefficiency is involved in the moderation and collimation processes, and consequently low beam intensity relative to X-ray sources is at times a major limitation in neutron radiography.



(a) Neutron (b) X-ray

Figure 1. A schematic representation of the neutron and X-ray radiographic techniques. Neutrons are generated with kinetic energies greater than 1 MeV as a result of nuclear reactions. To be useful for general radiological purposes, their energy must be reduced to an average of 0.025 eV. This is accomplished by random scattering of the neutrons in a hydrogen-rich moderator material such as polyethylene or water. The neutron beam is formed with a collimator, passes through the object being examined, and is recorded as an image on X-ray film. The neutrons which would fall on the film are intercepted by a "converter" screen, a plate containing elements such as gadolinium or lithium, which absorb the neutrons and emit electrons or gamma-rays to produce the latent image.

NEUTRON SOURCES

Neutrons are the product of nuclear reactions and therefore neutron sources are machines which originated in nuclear physics laboratories: nuclear reactors, particle accelerators, and radioactive materials. These represent a wide variety of sources in physical size, intensity, reliability of operation, and convenience of application.

Nuclear Reactors

The most common source for neutron radiography is the nuclear reactor. It is able to provide a well-collimated, high intensity beam so that exposure times and image quality can equal those of X-ray radiography. The nuclear reactor is a very large, complex, and expensive facility to construct and operate. In addition, its operation is highly regulated by government agencies and access to the source is limited. The objects to be examined must be transported to and from the reactor site, and this is very often a limiting constraint. These limitations notwithstanding, commercial neutron radiography services in the United States are provided reliably by vendors using nuclear reactor sources.

Particle Accelerators

In an attempt to provide a more tractable source for neutron radiography, nuclear particle accelerators have been employed as neutron sources. These range in size from a large several-room facility such as those housing linear accelerators and Van de Graff or Dynamitron accelerators to small, compact accelerators designed for use in an analytical chemistry laboratory to provide neutron activation analysis. The large accelerators are capable of producing good intensities for neutron radiography and have the advantage over reactors of requiring only moderate governmental licensing. All accelerators have the advantage of electrical beam-on and beam-off control for easy radiographic exposure. Beam intensity varies with the size of the accelerator and may be rather low for the small, compact accelerators. Accelerators are used as high-energy X-ray sources, so it is reasonable to assume that accelerators would find a place in radiological examinations as neutron sources.

Radioactive Materials

Radioactive neutron sources fall into the "small, compact" category with the practical sources providing low intensities similar to the small accelerator sources. Neutrons are produced by radioactive sources either by direct emission or by the emitted radiation striking a target material. Neutron emission is continuous and continously decreasing so that they must be renewed from time-to-time if they are to be used in a practical radiological system and exposures must be made by the mechanical interposition of shielding. The man-made isotope Californium-252 has been the most successful radioactive neutron source for radiological use to date. It has a half-life of 2.65 years which is long enough to be useful yet short enough to have a high specific activity for its direct, self-fissioning neutron emission. The advantages of all radioactive sources are their small size, their ultimately simple, reliable operation, and their low-heat generation with no input power requirement. Heat generation by Californium-252 is particularly low. A summary of neutron source characteristics is given in Table 1.

Table 1. SOME AVERAGE CHA·ACTERISTICS OF NEUTRON SOURCES SUITABLE FOR ·ADIOLOGICAL SYSTEMS

Source	Volume (cm^3)	Heat Generated (watts)	Thermal Neutron Radiography Flux ($n/cm^2/sec$)
Reactor	2×10^8	100,000	1×10^7
Van De Graaf	1×10^7	50,000	5×10^6
Kaman A-711	1.5×10^3	300	4×10^4
Pu-Be	67	200	7×10^2
Cf-252	2	1.6	2×10^4

SYSTEM DESIGN FOR ARMY NEEDS

Both the U.S. Navy[5] and the U.S. Air Force[6] with the IRT Corporation of La Jolla, California, have explored the possibilities for neutron radiography with small radioactive source systems which could be set up at a maintenance site. The exposures required were longer than maintenance personnel thought were time- and cost-effective so the development of these systems was not pursued extensively. The most desirable neutron radiography system for the U.S. Army would provide an ability to move about and survey the airfoil and skin structure of a helicopter before disassembly at a maintenance depot, and would provide neutron radiography side-by-side with X-ray radiography in laboratory and proving ground nondestructive testing facilities. The system would also have a simple beam on-off control to meet safety and mobility regulations. To meet these requirements, one would like to combine the high intensity of reactor sources with the on-off beam convenience of accelerators with the portability, efficiency, and reliability of radioactive sources. Clearly, some engineering compromises have to be made in taking even the first steps toward this goal. Based on earlier studies by the Vought Corporation which provided a concept of a transportable neutron radiography system providing on-off beam convenience, the U.S. Army entered into an agreement with that firm to produce an engineering model of such a system suited to Army needs.

The Neutron Head Assembly

The neutron source employed in the system is the small, compact A-711 accelerator manufactured by Kaman Instrumentation Corporation of Colorado Springs, Colorado. It produces 14 MeV neutrons by accelerating deuterium ions at 180 keV into a tritium gas-filled target and is designed and packaged for routine laboratory operation. The decision to use this accelerator was based on extensive experience with its reliability and operating characteristics in both Army and Vought laboratories and its availability as an off-the-shelf item. The accelerator system consists of a power supply unit, a cooling unit, a control console, and the accelerator head which might be arranged, as shown in Figure 2 in an analytical chemistry laboratory. As a radiography source, the accelerator head was enclosed in a 0.91 meter (36 in.) iron sphere containing transformer oil for neutron moderation and shielding. Additional oil shielding was introduced into the accelerator tube housing which effectively eliminated the leakage of high energy neutrons through the cable end of the tube housing. The water-cooled accelerator target is located

5. JOHN, J., ORPHAN, V. J., RUNDQUIST, D. E., and SHARP, R. *Application of Neutron Radiography Techniques for Nondestructive Detection of Corrosion in Naval Aircraft & Aircraft Components.* IRT Corporation Report No. INTEL-RT 6044-002, March 1974.
6. LARSON, J. E., PARKS, R., BALTGALVIS, J., and JOHN, J. *Investigation of Neutron Radiographic Techniques for Maintenance Inspection of Air Force Aircraft.* IRT Corporation Report No. INTEL-RT-6081-001, March 1975.

about 40 mm (1.6 in.) from the center of the sphere where it is out of direct sight of the collimator port and where it provides improved moderation through convection cooling of the surrounding oil. The use of a liquid reduces considerably concerns of radiation damage to the moderator.

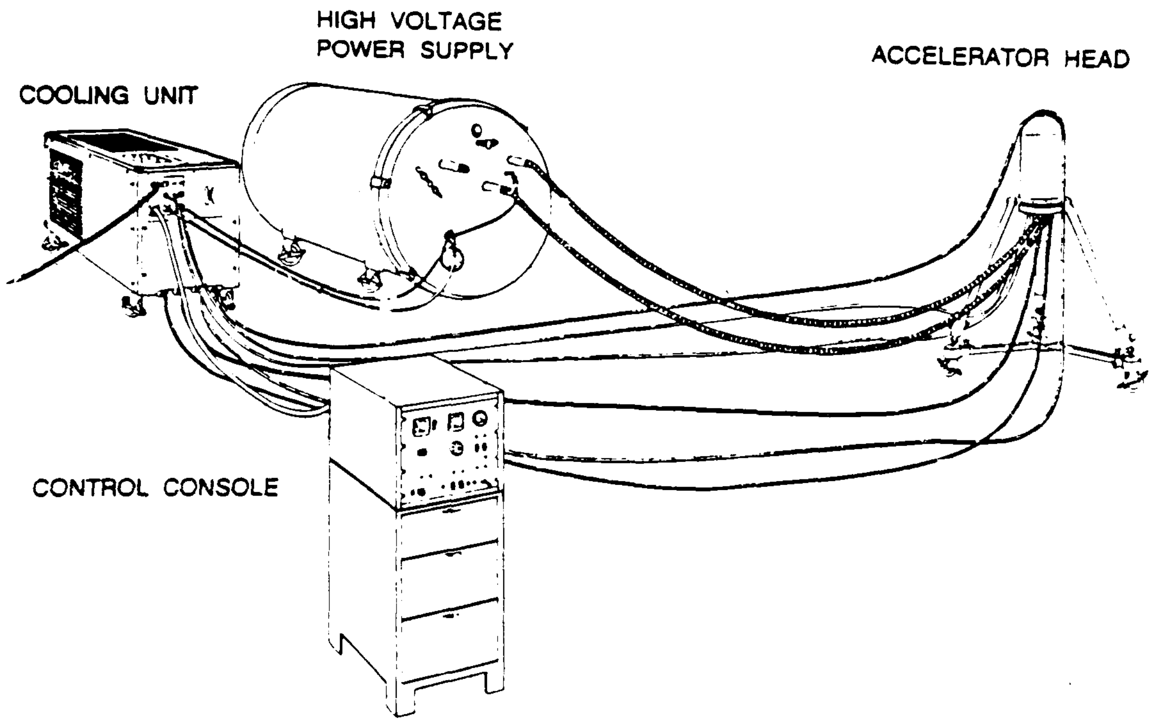


Figure 2. The neutron accelerator as delivered by the manufacturer for laboratory use. The accelerator head, shown on a tripod support, is 0.25 m in diameter and 0.55 m high. The power supply tank is 1.0 m in diameter and 1.8 m long. The cooling unit size is 0.45 m x 0.55 m x 0.43 m.

Thermalized neutrons are formed into a beam by a divergent collimator, which is an integral part of the spherical head. It is constructed of neutron and gamma-ray absorbing materials and provides for a minimum image size of 200 mm x 250 mm (8 in. x 10 in.).

The Positioning Carriage

The neutron source system was completed by mounting the head on a specially designed carriage which provides rotational, lifting, and lowering motions for the head and mobility for the complete source. A sketch of the source system is shown in Figure 3. The power supply tank, batteries, a battery charger, and oil handling utilities provide ballast to the carriage in addition to their normal functions. The orientation of the collimator and the location of the carriage is accomplished using a single operator pendant through battery-operated electrical drives and wheels. The collimator port may be positioned from ground level to a height of 2 meters (6.6 feet) and may be rotated over a 200-degree range, passing through straight-up and straight-down positions. The cooling unit was not made a part of the carriage assemblage because of a local need for the system to move through a restricted passageway. It rests on wheels on the floor nearby and its attached hoses are equipped with quick disconnect couplings. The control console is placed at a location remote from the radiation area during operation. Power for the accelerator and cooling unit is supplied by a line cord (approx. 8.5 kW).

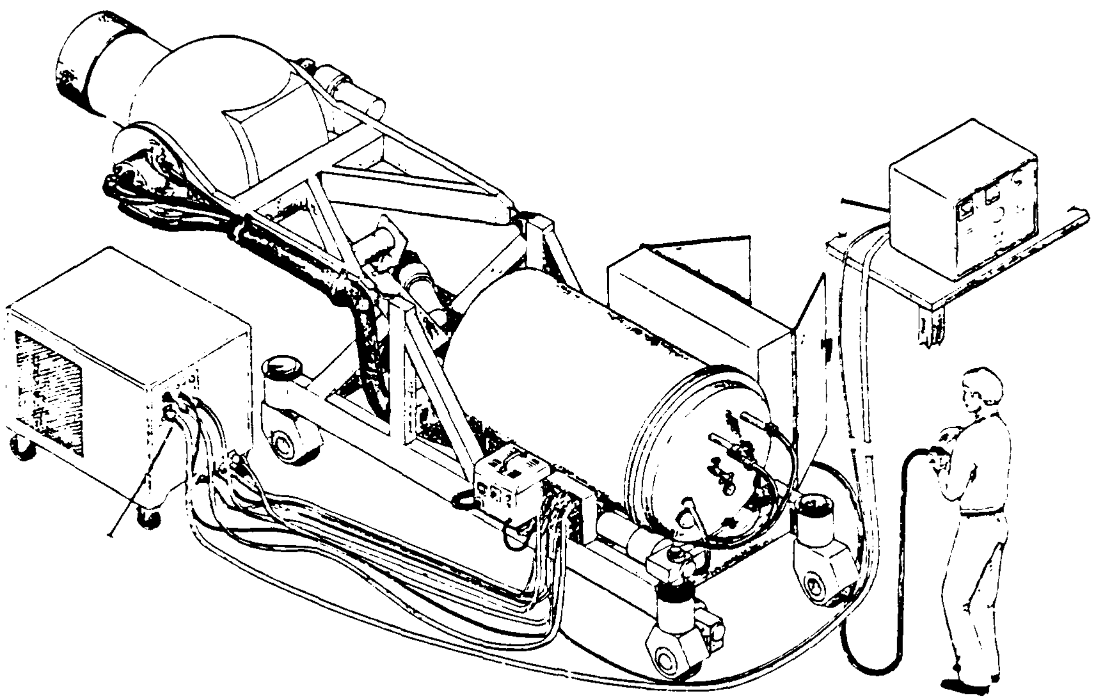


Figure 3. The sketch of the U.S. Army's mobile neutron radiography system. The carriage is 4.6 m long x 1.3 m wide x 1.3 m high (15 ft x 4.3 ft x 4.3 ft) and weighs 2205 kg (4860 lb).

The Complete System

The system was demonstrated to officials of the Department of Defense and its contractors and was subsequently field tested at an air force maintenance depot and an Army proving ground to collect data on its performance and adaptability to field use. From the beginning, the system produced useful radiographs and proved itself to be a very successful implementation of a mobile neutron radiography system. In fact, it behaved more like a finished product than an engineering model. A more complete description of the neutron radiography system is given in References 7 and 8.

EXPERIENCE WITH SYSTEM TESTING

Experience with the system was gained through testing programs carried out at Defense Department locations having extensive experience with X-ray radiography and where it was thought neutron radiography might be useful to on-going operations. Our aim in this testing was to evaluate its operation further and to evaluate its acceptance as a nondestructive testing tool in a realistic workplace setting. The system was first tested in the environment of a development laboratory in Dallas, Texas, to determine its operational characteristics. It was taken next to a U.S. Air Force aircraft maintenance center in Sacramento, California.[9] At this center,

7. ANTAL, J. J., DANCE, W. E., CAROLLO, S. F., and MORAVEC, J. D. *Experience with an On-Off Mobile Neutron Radiography System* in Neutron Radiography, Proceedings of the Second World Conference, Barton, Farney, Person, and Rottger, eds., D. Reidel Publishing, Dordrecht, Holland, 1987, p. 407-414.
8. DANCE, W. E., CAROLLO, S. F., and BUMGARDNER, H. *Mobile Accelerator Neutron Radiography System.* LTV Aerosace and Defense Company, Contract DAAG46-78-C-0007, Final Report, AMMRC TR 84-39, October 1984.
9. DANCE, W. E., AND CAROLLO, S. F. *Demonstration and Evaluation of Mobile Accelerator Neutron Radiography for Inspection of Aircraft Structures at SM-ALC/McClellan AFB.* Vought Advanced Technology Center Report No. R-92200/2CR-4, January 1982.

it was operated jointly with the X-ray radiography staff in their daily workplace after the last shift of the day. Figure 4 shows the system in use at this site radiographing an aircraft which was scheduled for a major overhaul. At a later date, the system was transported to an Army desert test site where again the X-ray radiography staff operated the system, radiographing a variety of items common to their daily activities as an X-ray facility.[10] Figure 5 shows the system in use at the U.S. Army Yuma Proving Ground in Arizona. Finally, it was transported to the U.S. Army Materials Technology Laboratory where it now serves as a test-bed for further developments of small systems and provides radiography for materials studies on a routine basis.

The system was transported between field stations by ordinary truck with the carriage supported upon and restrained by a wooden skid. The system has sustained over 12,000 km (7770 mi) of travel in this manner with only minor damage and very little lost time attributable to the rigors of shipping. Overall, downtime has been about 1% of operating time, including the time spent in field operations. Over 700 film radiographs were taken during this testing period which we considered to be very successful in all respects.

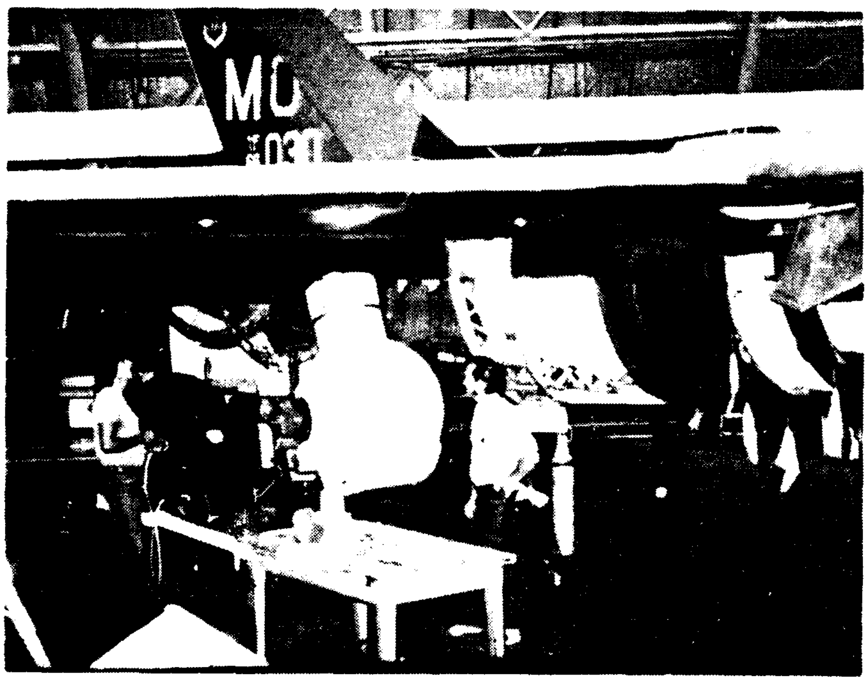


Figure 4. The mobile neutron radiography system examining the leading edge wing section of an aircraft undergoing scheduled maintenance. Personnel were not allowed in the area during an exposure period.

10. DANCE, W. E., AND CAROLLO, S. F. *AMMRC Mobile Accelerator Neutron Radiography System Operations at U.S. Army Yuma Proving Ground.* LTV Aerospace and Defense Company Report No. 3-41000/4R-110, April 1984.

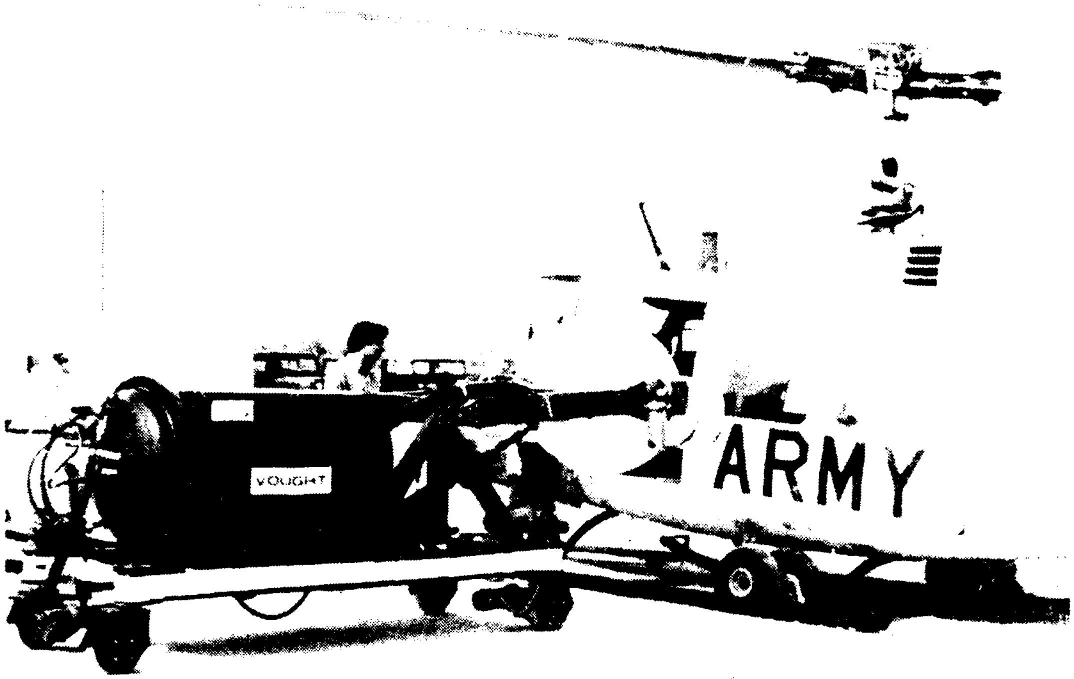


Figure 5. Operational demonstration at Yuma, Arizona. Radiation protection for operators was provided by an exclusion area in this temporary situation.

SYSTEM LIMITATIONS AND IMPROVEMENTS

Although success with the system went beyond normal expectations, it was limited. Users of the system were pleased with what the system could do for them, but it always left them witn a thirst for something better. Something better was primarily shorter exposure times. For radiographs to be of an acceptable quality to users in the field, exposure times of a minimum of 30 to 45 minutes were required. However, to keep up with the pace of X-ray radiography, exposure times under 5 minutes are desired. To reach such a goal, one can either strive to increase the source intensity by a factor of ten or increase the sensitivity of the image detector by a factor of ten. Several industrial programs are attempting to design a small accelerator with increased output, but increasing the source intensity of an accelerator without the physical size and weight of the system becoming unmanageable is proving to be very difficult.

Increasing the sensitivity of the image detection system is proving to be more rewarding. During the past few years, including during the field tests, we have been exploring combinations of film types from various manufacturers and several convertor screen materials in search of useful improvements in sensitivity with some success. More recently, we have been using an electronic imaging system of the type described by Dance and Carollo[11] which is specifically optimized for low neutron flux imaging. This electronic system is more sensitive than any of our film systems and has the added advantage of immediate viewing (no film processing time is required). The resolution of the images is limited by the line scan of the

11. DANCE, W. E., and CAROLLO, S. F. *High Sensitivity Electronic Imaging System for Reactor or Non-Reactor Neutron Radiography* in Neutron Radiography, Proceedings of the Second World Conference, Barton, Farney, Person, and Rottger, eds., D. Reidel Publishing, Dordrecht, Holland, 1987, p 415-422.

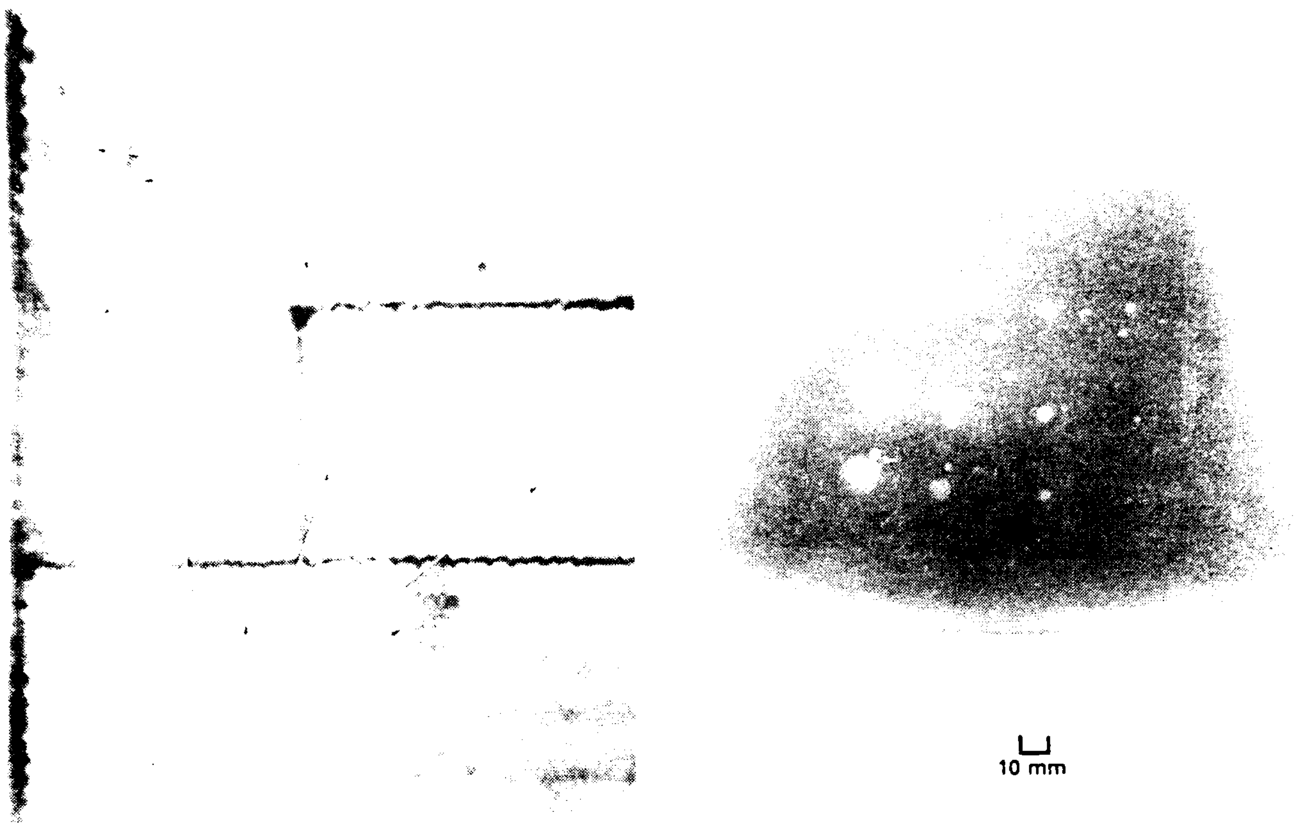
CRT screen, however. Reductions in exposure and processing times have thus been achieved with careful selection of working parameters. The data in Table 2 describes our present working environment.

The data in Table 2 represent radiological work in a developmental laboratory where each radiological examination may be very different from the next, rather than a repetitive inspection for quality control of specific items or processes in a manufacturing environment. However, it shows that a trade-off is possible between the resolution in the recorded image and the exposure time. The excercise of this trade-off has been one of the most important lessons learned from the development of this small source neutron radiographic system. We have learned that many practical problems can be effectively attacked with low-resolution radiography. This is particularly true in the aircraft maintenance area where the location of regions of corrosion and moisture entrapment in airfoil structures are the "defects" sought. Figure 6a is a reproduction of a neutron radiograph which illustrates this case. If the smallest dimension which the radiograph must reveal is the order of 0.1 mm (0.004 in.), then an exposure time of about 60 minutes may be necessary (medium resolution attained) with a small source. If the smallest dimension which the radiograph must reveal is the order of 0.2 mm (0.008 in.), then the exposure time may readily be reduced to below 30 minutes (low-resolution attained). If this latter dimension can be seen readily (very often the case) on a 525-line raster video screen, few-minute exposure times, comparable to those usual for X-rays, can be utilized.

Table 2. NEUTRON IMAGING SYSTEMS IN USE WITH SMALL SOURCES AT THE U.S. ARMY MATERIALS TECHNOLOGY LABORATORY

Image Resolution	L/D Ratio	Avg. Exposure Time	Converter Material	Image Recorder
High	35:1	6 hr	Evaporated Gadolinium Film	Kodak AA Film
Medium	25:1	1 hr	Evaporated Gadolinium Film	DuPont NDT 75 Film
Low	18:1	30 min	Gadolinium Oxysulphide	Kodak T-MatG Film
Low	15:1	3-5 min	Lithium-Loaded Plastic	LTV NRTV-2 CRT Image

The maximum film density, found in areas where the incident radiation has not intercepted the object, is another parameter which can be adjusted to shorten exposure times. In our small source radiography, we try to be satisfied with a maximum density of 2.0 density units rather than 4.0 density units radiographers generally wish to attain. Figure 6 illustrates two cases where high resolution was not required to locate the defects sought. An exposure of 30 minutes was more than adequate to show all of the details in Figure 6a; the regions of corrosion and trapped moisture were well defined with even a 3-minute exposure time. Figure 6b was a coating application problem where it was necessary to eliminate air bubbles of a diameter greater than 3 mm. A low-resolution image taken rapidly would suffice to monitor this coating process.



(a) (b)

Figure 6. Typical neutron radiographs taken with the Army's mobile neutron radiography system. (a) Radiograph showing the location of moisture and corroded aluminum honeycomb in an airfoil. (b) The boron-containing, 1.3 mm-thick coating on a metal structure. The seven well-defined bright spots are holes in the coating. The remaining spots are undesirable air bubbles within the thick coating.

One might assume that a technical person with radiographic experience would have chosen the radiographic route just described some time ago. But we found that the high state-of-the-art which X-ray radiography has reached has worked against the acceptance of the less well developed neutron technology. X-ray radiography is standardized and equipment producing excellent image quality economically is readily available. Radiographers are trained to suspect radiographs showing a poor overall quality, including poor resolution and low density in areas where the direct beam is imaged. This is as it should be for industrial X-ray radiography where the equipment and training are readily available to meet exacting standards. To apply the same standards to neutron radiography requires that a source such as a nuclear reactor be employed. Relaxing these standards to accept near the minimum required to solve the problem at hand often allows one to find small neutron sources quite suitable for particular nondestructive evaluations.

On the other hand, we found that those who work daily with radiography readily accepted the Army's machine since its size, weight, and safety requirements were not too far different from MeV X-ray units within their experience. The presence of a familiar kilovoltmeter and millimeter on a fairly simple control panel also played a role in this acceptance.

THE FUTURE FOR NEUTRON RADIOGRAPHY

During the past eight years of development and use of the Army's small accelerator source neutron radiography system, there has been a growing interest in providing industrial neutron radiology in the workplace. The reliable operation and surprisingly wide applicability of the Army's system had encouraged many to consider anew small source neutron radiological systems for in-house use. The U.S. Navy has sponsored the construction of a unit similar to that described here but configured to suit their need for examining aircraft which stand much higher off the ground than do helicopters.[12] The U.S. Air Force is establishing a facility for automated neutron radiological scanning of complete aircraft prior to scheduling maintenance work.[13] New small neutron sources, such as compact cyclotrons, are being developed or proposed.[14]

At the same time, we are currently expanding the use of neutron radiography in our Neutron Analysis Laboratory in large part because of the convenience offered by small, easy to manage source systems. We have moved beyond traditional NDT examinations to supplement research and developmental activities with materials characterization and process monitoring using neutron radiological methods. Studies of high performance structural ceramics have been a particularly fertile area for neutron radiological analyses.[15,16] The development and successful fielding of this small accelerator source unit seems to have provoked a rethinking of the role neutron radiology can play in the nondestructive examination world.

12. ORPHAN, V. J., KEDEM, D., and JOHANSEN, F. *Mobile Neutron Radiography System for Aircraft Inspection* in Neutron Radiography, Proceedings of the Second World Conference, Barton, Farney, Person, and Rottger, eds., D. Reidel Publishing, Dordrecht, Holland, 1987, p. 447-454.
13. FROOM, D. A., and BARTON, J. P. *Plans for Aircraft Maintenance Neutron Radiography Systems* in Neutron Radiography, Proceedings of the Second World Conference, Barton, Farney, Person, and Rottger, eds., D. Reidel Publishing, Dordrecht, Holland, 1987, p. 431-438.
14. HAWKESWORTH, M. R. *Reactor-Quality Neutron Radiographs with a New Mobile Machine - A Superconducting Magnet Cyclotron* in Neutron Radiography, Proceedings of the Second World Conference, Barton, Farney, Person, and Rottger, eds., D. Reidel Publishing, Dordrecht, Holland, 1987, p. 183-190.
15. ANTAL, J. J., MAROTTA, A. S., CORBIN, N. D., and PUJARI, V. K. *NDE of Structural Ceramics Using Neutron Radiography* in 16th Symposium on Nondestructive Evaluation, C. D. Gray and G. A. Matzkanin, eds., Southwest Research Institute, San Antonio, TX, 1987, p. 241-251.
16. CORBIN, N. D., PUJARI, V. K., ANTAL, J. J., and MAROTTA, A. S. *A Preliminary Assessment of Neutron Radiography for Detecting Inhomogeneities in Ceramics* in Nondestructive Testing of High-Performance Ceramics, A. Vary and J. Snyder, eds., The American Ceramic Society, Westerville, Ohio, 1987, p. 114-127.

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A NEUTRON RADIOGRAPHY SYSTEM FOR FIELD USE -
John J. Antal, Alfred S. Marotta, and
Louis J. Farese

Technical Report MTL TR 89-52, June 1989, 14 pp -
Illus-tables, D/A Project 1L162105AH84

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Neutron radiography
Field tests
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The use of neutrons as penetrating radiation expands the role of radiological nondestructive examination considerably. Radiological examination by neutrons has been limited, however, by the need to perform such radiography at the site of a nuclear reactor or a large accelerator system which can provide neutrons of an intensity equal to that of industrial X-ray sources. In 1979, the U.S. Army and the Vought Corporation demonstrated a mobile neutron radiological system designed as a prototype for the examination of lightweight aircraft structures in the field. The neutron source for this system is a very small, commercially available (d,t) accelerator which provides an on-off radiation source and a size, weight, and shielding requirement acceptable for routine neutron examination in the manner of high-energy X-ray radiological systems. Under a variety of field maintenance conditions, this system has successfully provided useful neutron radiography at reasonable exposure times and has pointed the way to a means for bringing neutron radiography to the worksite. In addition to the technological advances introduced, acceptance of this small source system as a nondestructive examination tool has required rethinking on the part of NDE professionals and reeducation of technicians regarding the goals of radiographic examinations. We shall report here our experience with this unit both in the field and in the laboratory where it serves as a resource for further neutron source developments and the exploration of new applications of on-site neutron radiological examinations.

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