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**NEUTRON RADIOGRAPHY OF
AEROSPACE STRUCTURE
HIDDEN CORROSION**

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by

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ABSTRACT

The detection of corrosion in operational aircraft is vital for an effective repair and maintenance program intended to extend the service lifetimes of these aircraft. Neutron radiography is an established non-destructive inspection technique that can detect early-stage corrosion, even within relatively thick aluminum structures. This report presents the results of a study to measure experimentally the detection sensitivity of neutron radiography to aircraft corrosion, using both laboratory-prepared and environmentally produced aircraft corrosion specimens. Thermal neutrons were obtained from the medical research reactor at the DOE's Brookhaven National Laboratory (BNL) as part of a Cooperative Research and Development Agreement (CRADA) between Northrop Grumman Corporation and BNL. Initial work at the reactor consisted of enhancing the beam collimation for high-resolution radiography. The neutron beam conditions were then measured using activation foils and several commercial beam-quality indicators. Radiography of the corrosion specimens was carried out with a vacuum cassette employing a gadolinium converter screen and fine-grain X-ray film. Measurement of the optical film density of the corrosion images allowed an evaluation of the effective thermal neutron attenuation coefficient for corrosion products. This evaluation was facilitated by the use of water specimens to calibrate the measurement procedure, since water has a known thermal neutron attenuation coefficient. An assessment of the thickness threshold for visually distinguishing corrosion by-products in neutron radiographs indicated a threshold of about 2 mils (0.002 in.) for the laboratory-prepared corrosion and less than that for the aircraft corrosion samples examined. The experimental results obtained with the BNL reactor thermal-neutron beam were used to help predict the potential capability of an accelerator-based neutron radiography system that could be deployed in a hangar type of environment to inspect either intact aircraft or subassemblies from such aircraft.

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1. INTRODUCTION

Hidden corrosion in both Department of Defense and civilian aircraft is a major factor affecting the service lifetime of these aircraft; it also is a serious concern for continued flight safety (Ref 1). Such corrosion is very difficult to detect with traditional inspection methods such as X-rays, ultrasonics, eddy currents, etc., unless significant corrosion damage is already present or the corrosion is located close to the surface. Radiographic inspection with a collimated beam of thermal neutrons has been demonstrated to be very sensitive to early-stage corrosion, even within thick metallic components (Ref 2, 3, 4, and 5). This high corrosion detection sensitivity can be compromised if the corrosion is located behind strong neutron-absorbing materials such as boron-epoxy composites, fuel, or thick sealants and plastics. In spite of this, neutron radiography is a powerful non-destructive evaluation (NDE) corrosion detection technique for a wide range of inspection situations and is an extremely valuable asset for a general aviation inspection and repair facility. Neutron radiography is routinely used for aircraft engine turbine blade quality assurance for cooling-channel inspection (Ref 6). Other unique inspection applications include water or moisture accumulations, sealant or adhesive flaws, fuel or oil accumulations, composite material flaws, plastic materials (tubing, hoses, plastic-coated electrical wires, etc.), and rubber materials (O-rings, shims, etc.), even within several inches of surrounding aluminum structure. Such inspection/repair-related applications are difficult, or impossible, with X-ray or other traditional NDE techniques.

In the past, a number of "portable" neutron radiography systems were built to exploit this corrosion detection sensitivity for inspecting aircraft and their subsystems in a repair environment (Ref 7, 8, 9, and 10). These portable systems, using relatively low-yield particle accelerators or radioactive sources, were not capable of supplying high-spatial-resolution radiography with acceptably short exposure times. High-resolution neutron radiography at short exposure times currently requires a nuclear

reactor to supply the radiographic beam. Reactor-based neutron radiography allows excellent resolution of spatial details and sufficient beam intensity to radiograph through thick aerospace structures, even with some amount of neutron-absorbing materials in the beam path. The recent development of compact, high-current accelerators (Ref 11, 12, and 13), however, now offers the exciting possibility of developing powerful neutron radiography inspection systems with beam intensities approaching those of nuclear reactors, but at much lower cost and with greatly reduced radiological hazard and improved radiographic flexibility. While such a system would be considerably more expensive than inspection systems using more "traditional" techniques such as X-rays and ultrasonics, for example, this must be balanced against the unique inspection information obtained and the cost of the premature replacement of flight-worthy aircraft.

A vital first step before developing this type of novel inspection system, however, is to verify that neutron radiography is capable of detecting low levels of aircraft corrosion. While some experimental studies have been published (for example, Ref 4 and 5), these studies have been relatively few in number and additional data are required to justify future design efforts. This report presents the results of a program conducted by the Northrop Grumman Advanced Technology & Development Center to obtain the experimental data needed to develop an accelerator-based neutron radiography inspection system. This study was conducted under a Cooperative Research and Development Agreement (CRADA) between Northrop Grumman Corporation and the DOE's Brookhaven National Laboratory (BNL). The CRADA was formally approved in September 1993 as CRADA No. BNL-C-93-06.

The present work started with enhancing the neutron collimation at the reactor beam port to allow radiography with high spatial resolution. This was followed by measuring the resultant beam flux with gold foils and then imaging a number of laboratory-prepared and environmentally produced aircraft corrosion specimens. Measurement of the optical film densities in the radiographic images was used to

obtain the effective neutron attenuation coefficient for corrosion products. This report presents the test results and their extrapolation to a potential accelerator-based inspection system.

2. EXPERIMENTAL PROCEDURE

The experimental procedure consisted of using the thermal neutron beam from the BNL Medical Research Reactor (BMRR) to radiograph laboratory-prepared as well as actual aircraft corrosion specimens. Optical density measurements of the radiographic images then supplied data for determining the effective neutron attenuation coefficient for corrosion products. In addition, inspections of the radiographs on a standard X-ray film viewer were used to determine the threshold for visual detection of corrosion directly from the radiographs.

The prepared corrosion material was obtained by exposing 3 in. x 6 in. x 0.060 in. type 7075-T6 aircraft aluminum panels to a salt spray environment in a corrosion production chamber for periods ranging up to four weeks and then scraping off the resultant surface corrosion deposits. This laboratory-generated corrosion material was then packed into a series of flat-bottomed, 1/4-in.-diameter holes counterbored in an aluminum plate. A 1/8-in.-thick aluminum plate was secured on top of the counterbored plate, encapsulating the specimens. In this way, the thickness of the prepared corrosion would have fixed, well-established values for the study. This method of presenting laboratory-prepared corrosion products follows that employed in Ref 2 and 4. The counterbored holes varied from 0.002 to 0.030 in. (2-30 mils) in depth. As a means of investigating the effect of enclosing aluminum structures on the detectability of internal corrosion, the test specimens were radiographed through a number of aluminum covering panels, ranging up to one inch in thickness.

The aircraft corrosion specimens used for this study were three skin panels from an E-2B aircraft. These specimens had mottled patches of corrosion with a range of corrosion thickness, including areas of exfoliation that are typical of environmentally produced aircraft corrosion. The aircraft specimens were 2024-T4 aluminum panels that had been located near the wing root of the aircraft and varied in size from 2 in. x

2.5 in. to 8 in. x 10 in. in area. The thickness increase of the aircraft panels at the corroded areas was measured to estimate the depth of the internal corrosion products by assuming that the internal corrosion products are three times thicker than the original metal lost (Ref 4).

Neutron radiography of the corrosion samples was carried out in the Patient Treatment Room No. 1 of the BMRR. The standard nuclear reactor beam port for this room is a 10 in. x 10 in. opening. This beam port opening is too big for radiography with good spatial resolution and thus was reduced to a 1-15/16-in.-diameter circular opening by using various neutron-absorbing materials. The thermal neutron flux from this collimator was measured by activating bare and cadmium-covered gold foils at a reactor power level of 3 MW. The degree of activation of the exposed foils was subsequently measured in a nuclear counting laboratory near the reactor facility, and the thermal flux at the exposure plane was computed from the counting data. Knowledge of the thermal neutron flux was needed initially to estimate exposure times, and later to extrapolate the test results obtained with this reactor beam to an accelerator-based system. In addition to measuring the thermal neutron flux at the exposure plane, beam-quality indicators ("Image Quality Indicator System," ASTM standard E 545-91, obtained from Aerotest Operations, Inc.) were used to estimate the effective thermal neutron content, the scattered neutron content, and the gamma-ray content of the beam relative to the film images.

Radiographs were obtained by recording the thermal neutron beam image after its passage through the specimens using an Aerotest Operations, Inc., 14 in. x 17 in. neutron radiography vacuum cassette. This cassette contains a gadolinium screen that converts thermal neutrons into low-energy beta particles (internal-conversion electrons) that expose an adjacent sheet of Kodak, type SR-5, X-ray film. After development of the film in a Kodak X-Omat-B automatic processor, a Macbeth TD502 optical densitometer was used to measure the film-density change between corroded and adjacent non-corroded areas. The measured image densities and the contrast were then correlated with the depth of corrosion in the specimens. These data

allowed an evaluation of the thermal neutron attenuation coefficient of the corrosion products. Finally, the neutron fluence needed for adequate film density in the radiographs was used to predict the exposure times expected for accelerator-based radiography systems.

3. NUCLEAR REACTOR FACILITY

3.1 DESCRIPTION OF BNL MEDICAL RESEARCH REACTOR (BMRR)

The BMRR, which operates on demand up to 3 MW, is a tank-type, light-water moderated and cooled thermal reactor with a graphite reflector. It is housed in a 60-ft-diameter, controlled-access, dome-shaped building. The reactor and its biological shield are located in the center of this air-lock-entry building, with an open area encircling the reactor within the outer walls. The reactor control room is located up a flight of stairs on an upper level between the reactor and the outer building. There are two shielded treatment rooms, thermal and epithermal, on the west and east sides, respectively, of the BMRR. These treatment rooms have double-door access, viewing windows, and controlled interlocks. The current CRADA experimentation was carried out in the west patient treatment room.

Each patient treatment room measures 11 ft x 21 ft within its shielding walls, and each has a window for viewing conditions during exposures. Neutrons are admitted into a treatment room through a beam port in the reactor's biological shield that is located 36 in. above the treatment room floor. This neutron beam port from the reactor core has an internal bismuth filter and an outer shutter that serve as part of the reactor's biological shield between exposures. The beam shutter was used to time the duration of the current radiographic exposures, after the BMRR had stabilized at the desired operating power level.

Under standard exposure conditions, the thermal neutron beam enters the patient treatment room through a square opening, measuring 10 in. by 10 in., with a thermal-neutron-flux density of 6×10^{10} n/(cm²-sec), at a reactor power level of 3 MW. However, because the current CRADA effort required a thermal neutron beam with much tighter beam collimation in order to obtain "crisp" neutron radiographs, this full

beam output could not be utilized. Instead, only a relatively small spatial area of the beam output could enter the treatment room. This was accomplished by using a boral sheet to cover all of the beam port, except for an opening with a diameter of 1-15/16 in. This neutron "focal spot" allowed about 3% of the available beam area to be used for the current radiography. This method of beam collimation is described in more detail in the next section.

3.2 COLLIMATION OF NEUTRON BEAM

The overall layout of the radiography beamline is shown in Fig. 1. As a means of reducing the exposure room radiation background, a structure immediately outside the reactor beam port serves as a partial radiation shield for the exposure area. This enclosure has thick (lithium carbonate and resin) neutron shielding walls and is entered through a shielding door on rollers located on the side of the structure. The enclosure has a square 10 in. x10 in. opening that lines up with the reactor beam port, which has a similar shape and size. After leaving the shielding enclosure, the radiography beam crosses a 6-ft-wide exposure area and is finally stopped by a boron-loaded polyethylene absorber layer. Figure 1 shows the neutron radiography cassette placed 4 ft from the enclosure's outlet. This location was used for most of the current radiography. Without additional collimation, this geometry has a distance-to-opening ratio ("L/D") of about 10:1 which provides inadequate radiographic spatial resolution.

The boral plate shown in Fig. 1 was introduced to improve beam collimation by reducing the effective "focal spot" of the emerging radiography beam. Figure 2 is a sketch of the collimation geometry employed. An aperture that is 1-15/16 in. in diameter punched in a 0.265-in.-thick, large-area, boral plate (Reactor Experiments, Inc., material type 291) was aligned with the center of the reactor beam port. In

Figure 1 - Sketch of the overall beamline geometry, starting with the reactor beam port to the left and the neutron beam stop to the right. The shielding enclosure is composed of thick neutron shielding walls with a 10" by 10" opening to allow the neutron beam to enter the exposure area. The radiography cassette is supported by an adjustable table. A large plate of boral with a 1-15/16" aperture serves to improve collimation of the thermal neutron beam. With this aperture diameter, a maximum (L/D) of about 60 can be obtained with the cassette placed close to the right beam stop.

Figure 2 - Sketch of the collimation geometry used for this study. The two sheets of lead are to help reduce low-energy gamma rays, to which the X-ray film used is sensitive. A distance of about 8" between the reactor beam port exit and the boral plate is for a peripheral structure supporting the plate.

addition to the boral neutron shielding, 1/4-in.-thick lead was placed within the beam port, and 1/8-in.-thick lead was placed on the outer surface of the boral. The lead shielding was used to help reduce the low-energy gamma-ray content of the beam, the energy range to which the radiography film is most sensitive. Most of the current radiography was carried out at an (L/D) of about 50. Measurement of center-to-corner film density variations yielded about 5% for the 14 in. x 17 in. film format employed. Variation in beam intensity can be reduced by moving the cassette farther away from the aperture.

3.3 NEUTRON FLUX MEASUREMENTS

Neutron flux measurements were carried out at several locations in the exposure room, using bare and cadmium-covered gold activation foils. The activation runs were conducted at a reactor power level of 3 MW. Subsequent counting of the foil activities provided a measurement of the neutron flux intensities at several (L/D) positions for both beam axis and off-axis points. Figure 3 shows two of the measured axial flux values plotted as functions of their (L/D) locations. The dashed line in that figure represents an inverse square relationship in (L/D), which is expected to be obeyed by neutrons leaving the collimator aperture. The agreement of the data points with the dashed line indicates that the thermal neutron beam emerging from the collimator predominates over room-scattered neutrons. Use of an ASTM E545 "beam purity indicator" (see Section 3.4), which measures both an "effective thermal neutron content" and an "effective scattered neutron content" in the radiographs, helps to confirm this conclusion.

The location used for most of the corrosion testing was at an (L/D) of about 50 at a reactor power level of 3 MW. Thermal neutron flux at this radiography location was estimated using the dashed curve in Fig. 3, which extrapolated to a value of $7.0\text{E}+06$ n/(cm²-sec). A 3-min. exposure under these conditions produced a film density of 2.0 (transmission densitometer) using the cassette and the film type described in

Figure 3 - Plot of thermal neutron flux as a function of (L/D) ratio showing two measured data points. Bare and cadmium-covered gold activation foils were used to measure the thermal flux. The dashed line represents an inverse square dependence on (L/D). Agreement of the measured flux to this dependence indicates that the direct beam is dominant over room-scattered flux.

Section 2. The ASTM E545 beam purity indicator, described in more detail in the next section, furnished a value of 62% for the "effective thermal neutron content" in the radiographs (see Table 1). These results imply that a thermal-neutron-related film density of 1.24 (obtained from $2.0 \times 62\%$) was produced by a neutron fluence of $1.3\text{E}+09$ neutrons per square centimeter ($7.0\text{E}+06 \times 3 \text{ min} \times 60 \text{ sec/min}$). It must be stressed that this result is based on the present experimental conditions, since film density is dependent on the details of the film processing employed (developer, time, temperature, agitation, etc.). For this work, we used an automated processor (a Kodak X-Omat [M64N] at 31.6°C) at the Calverton QC X-ray inspection facility. Use of faster X-ray film or electronic imaging systems would allow shorter exposure times or greater image detail resolution, i.e., increased (L/D) values.

3.4 IMAGE QUALITY MEASUREMENTS

As a means of assessing the radiographic effect of different beam constituents (such as thermal neutrons, scattered neutrons, gamma rays, etc.), the Aerotest Operations, Inc., type ASTM E545 Image Quality Indicator (IQI) system was mounted on the film cassette for all test radiographs taken. Measurement of the film density at selected portions of the images of these indicators then allowed calculation (following instructions in ASTM Bulletin E545-91) of the density contribution due to the different beam components in the exposure. For example, two boron nitride disks (2-mm-thick) -- one close to the film and one raised about 1/4 in. -- help determine the fraction of the total exposure due to collimated thermal neutrons and the fraction due to room-scattered thermal neutrons (which "undercut" the raised disk). It is important to note that the exposure contributions obtained here relate to their effect only in the specific radiographs measured and not to the real, or actual, abundance of these quantities in the radiography beam. Their value resides in assessing the relative importance of the different beam components in the resulting neutron radiograph. Such measurements allow a comparison of different reactor facilities for neutron radiography using identical imaging methods.

Table 1 summarizes the percentages obtained for the main exposure contributions in the current corrosion testing study. The first column is for direct exposure of the IQI, and the second is for the IQI placed behind a large slab of 1/2-in.-thick aluminum.

Table 1 Test Study Exposure Contributions

Quantity	Direct	Thru 1/2-in. Alum.
Eff. thermal neutron content	62.0%	58.0 %
" scattered " "	4.4 %	5.7 %
" gamma-ray "	3.4 %	2.1 %
" pair production "	2.4 %	1.5 %

These data indicate that the aluminum placed in the neutron beam is not a significant source of secondary gamma rays. The aluminum lowers the effective gamma-ray content and behaves like a filter for the gamma rays in the radiography beam. Some additional scattered neutrons are generated by interactions in the aluminum.

4. CORROSION SPECIMEN TESTING

4.1 OPTICAL DENSITY MEASUREMENTS

The test specimens and their preparation prior to radiography are described in Section 2, Experimental Procedure. The exposure conditions are described in Section 3, Nuclear Reactor Facility. After development of the exposed film, the resultant film densities at selected points in the images were measured using an industrial X-ray film transmission densitometer. This densitometer was a digital-readout Macbeth model TD502. The ambient, or background, density at the specimens was estimated from density values measured at close adjacent points, and the departure from background for the specimens was then calculated. Figure 4 shows these density differences plotted as a function of the test specimen thickness. The error bars shown in Fig. 4 (generally, plus and minus 0.010 density) were estimated by noting the repeatability of the measurements.

Since *optical density* is defined as the log (to the base 10) of the film darkening, or film "*opacity*," a straight line in Fig. 4 implies a logarithmic, or exponential, reduction of thermal neutron intensity with specimen thickness. This type of thickness dependence is expected for the neutron attenuation by the specimens. One objective of this study was to determine the thermal neutron linear attenuation coefficient for both prepared and aircraft corrosion. This requires density measurements using a material with a known attenuation coefficient in order to help calibrate the measurement system and to compensate for a variety of experimental factors.

A number of experimental conditions modify the relationship of film density and the thermal neutron attenuation coefficient of a test specimen. One of these is the "in-scattering" of neutrons when a relatively wide test specimen is near the film, that is, the specimen subtends a large solid angle from the film. This is the present test situation.

Figure 4 - Plots of the film optical density decrease for water, laboratory-prepared corrosion products, and aircraft corrosion specimens as a function of specimen thickness. The straight-line dependence observed here implies an exponential attenuation of thermal neutrons with specimen thickness. The water specimens were used to help calibrate the test system for determining the attenuation coefficient of corrosion products.

Another is the amount of light scattering in the relatively "thick" X-ray film used, which is different from that occurring in the "thin" emulsion density-strip used to calibrate the measuring densitometer. At the same time, the spectral distribution of the radiography beam is not a pure "thermal" distribution, but rather has epithermal and higher neutron energies. To compensate for these experimental conditions, water specimens were used to calibrate the measurement system. Water has a known linear attenuation coefficient of 2.51 cm^{-1} (Ref 14).

We will briefly derive the relationship used here to calculate the thermal neutron attenuation coefficient from the measured density data. The following definitions are used for the experimental parameters:

t = thickness of specimen (cm)

μ = linear attenuation coefficient of specimen (cm^{-1})

D = density change observed with specimen

ϕ = thermal neutron flux incident on specimen.

The exposure of the film to thermal neutrons is assumed to be modified by exponential attenuation of neutrons in the specimen. Neutron flux reaching the film cassette will be given by $[\phi * \text{EXP}(-\mu t)]$, where $\text{EXP}(-\mu t)$ is the flux fraction emerging from the specimen. Film "*density*" is defined as the log (to the base 10) of the film darkening, or "*opacity*." Film darkening due to neutrons is proportional to the incident neutron flux. Thus, the density decrease produced by the specimen will be given by:

$$D = k * [\log_{10}(\phi) - \log_{10}(\phi * \text{EXP}(-\mu t))],$$

where k is a constant proportionality factor, and

$$D = k * \log_{10} [\phi / (\phi * \text{EXP}(-\mu t))] = k * \log_{10} [\text{EXP}(\mu t)].$$

Solving for the proportionality constant, k , and using a density difference of 0.25 for 30 mils of water ($\mu = 2.51 \text{ cm}^{-1}$) from the upper curve in Fig. 4 yields:

$$k = D/\log_{10} [\text{EXP}(\mu \cdot t)] = 0.25/\log_{10} [\text{EXP}(2.51 \cdot 0.030 \cdot 2.54)],$$

$$= 3.0097.$$

This then furnishes the following equation:

$$\mu = \ln(10^{D/3.0097})/t = \text{linear attenuation coefficient of unknown specimen,}$$

$$= \mu(D,t).$$

4.2 PREPARED SPECIMENS

The density differences measured for the prepared corrosion products are shown in Fig. 4 as square data points. See Sections 2 and 3 for a description of sample preparation and exposure conditions. The density measurements yielded a density reduction of about 0.08 for a specimen depth of 30 mils. Using the formula derived in the previous section yields a linear attenuation coefficient of 0.803 (cm⁻¹) for the present salt-fog-produced corrosion products. The water specimens used for calibration purposes were placed in identical specimen holders as those used for the prepared corrosion products to maintain consistent scattering geometries for the two types of specimen. The results obtained here indicate that (dry) laboratory-produced aircraft aluminum corrosion products have a thermal neutron attenuation coefficient about one-third that of water. If this attenuation is due to hydrogen contained in the corrosion products, then this would indicate that these laboratory-produced corrosion products have a hydrogen density of about 2.23E+22 atoms per cubic centimeter.

Visual inspection of the radiographs on a standard X-ray film viewer allowed relatively easy identification of the 4-mil-deep prepared corrosion as well as positive identification of the 2-mil-deep corrosion. This indicates a detection threshold of better than 2 mils for (dry) laboratory-produced corrosion products, using standard film-based neutron radiography. This visual detection threshold was not noticeably

changed when as much as one inch of covering aluminum, the maximum used, was placed over the specimens. This corrosion detection threshold confirms measurements performed by other investigators (Ref 2 and 4). The measurements carried out here were under "ideal" conditions, without neutron scattering from complex peripheral aircraft structures or other hydrogenous materials present. Various image-enhancement techniques could be used to increase image contrast, such as digitizing the film image or using one of several electronic imaging systems currently available to obtain even greater corrosion-detection sensitivity.

4.3 AIRCRAFT SPECIMENS

The aircraft specimens produced radiographs with clearly observable patterns that corresponded to the visual corrosion details on the aircraft panels, even through as much as a 1-in. thickness of covering aluminum. The corrosion on these aircraft samples is mottled, uneven, and difficult to measure accurately. However, the largest density changes observed in the aircraft-panel images were about 0.08, with micrometer readings in these areas yielding panel thickness increases of 8-13 mils. This result, for the most easily quantified, environmentally produced corrosion areas on the aircraft panels, is shown as a single, triangular data point in Fig. 4, along with the estimated experimental error. We have assumed a corrosion thickness to metal loss ratio of 3:1 (Ref 4). This data point falls between the prepared-corrosion and the water curves, and implies that the present environmentally produced aircraft corrosion specimens have neutron attenuation coefficients between those of the salt-fog corrosion products and water. Operational aircraft may have additional water of hydration and free water present at the corrosion sites, thus improving detection sensitivity.

5. TEST RESULTS

The test results obtained here include both the thermal neutron fluence required to obtain adequate film exposure levels for neutron radiographic inspections as well as the detection sensitivity to aircraft corrosion. The details of the experimental procedures employed and the data obtained have been described in preceding sections. In this section, we present the main results of the experimental testing.

5.1 EXPOSURE REQUIREMENTS & CONDITIONS

- A thermal neutron fluence of $1.3\text{E}+09$ (n/cm²) produced a total film density of 2.0, using a Gd screen with SR-5 film and an automated X-ray film processor
- About 60% of the film exposure is due to collimated thermal neutrons, and about 10% is divided between scattered neutrons, gammas, and pair production
- Exposure results were relatively unchanged by interposing as much as one inch of aluminum in front of the imaging cassette requiring, however, about 20% more exposure time.

5.2 AIRCRAFT CORROSION DETECTION

- Laboratory-produced (salt-fog method) packed aluminum corrosion products yielded a linear thermal-neutron attenuation coefficient of 0.803 cm^{-1}
- Environmentally produced aircraft corrosion samples from a E-2B aged aircraft produced thermal-neutron attenuation exceeding that of the salt-fog corrosion
- The threshold for visually distinguishing a corrosion/non-corrosion boundary with this type of radiography is better than 2 mils (0.002 in.) of corrosion-product

thickness for the laboratory-produced corrosion and less than that for the aircraft samples

- These visual-thickness thresholds were relatively unchanged with a one-inch-thick panel of aluminum covering the corrosion.

6. EXTRAPOLATION TO ACCELERATOR-BASED RADIOGRAPHY

Accelerator-based neutron radiography requires moderation of the fast neutrons produced at the accelerator target to produce neutrons having thermal energies. The thermalized neutrons are then "collimated" to achieve the spatial resolution [(L/D) ratio, discussed above] needed for specific inspection problems. Moderation and collimation are accomplished by placing moderating and shielding materials around the accelerator target assembly. Northrop Grumman Corporation has conducted computer modeling and design of such accelerator hardware for specialized applications. Use was made of this available modeling technology to predict the thermal neutron output of an accelerator-driven radiography system and to compare it to the beam parameters used for this CRADA on the BNL nuclear reactor.

Figure 5 shows the predictions obtained for placing an optimized moderating and collimating system around a beryllium accelerator target receiving a deuteron beam from a low-voltage, high-current accelerator. Figure 5 plots radiography beam intensity (thermal neutron flux) as a function of radiographic spatial resolution (L/D) for a given thermal-neutron source. By moving away from the neutron source to increase radiographic sharpness, the beam intensity decreases (as the inverse square of distance), and longer exposure times are required. Also shown in this figure are the curves for a General Atomics TRIGA reactor (designed for neutron radiography) along with two low-power systems: a californium-252 isotopic system and a sealed-tube neutron generator system. The beam parameters for the present CRADA experimental testing are indicated by the circle in Fig. 5. Note that the present CRADA testing beam could be obtained from the TRIGA reactor by operating at a power level of about 50 kW or from a 2.0-MeV accelerator operating at a beam current of about 10.0 mA (20 kW of beam power). These high beam currents are now achievable due to recent advances in accelerator technology, as illustrated by the Continuous Wave Deuteron

Figure 5 - Thermal neutron flux at the radiography cassette as a function of the ratio of length, L , away from a neutron-emitting circular aperture of diameter, D , for different thermal neutron sources. The (L/D) ratio determines the spatial resolution capability of a radiography system. The two upper dashed curves are for a General Atomics TRIGA reactor optimized for neutron radiography operating at two different power levels. The two upper solid curves are theoretical predictions for an accelerator-driven radiography system operating at two different beam currents. Also shown are two low-power sources, a Cf-252 (30 mg) isotopic source and a 14-MeV sealed-tube-type system. The testing parameters used for this CRADA are depicted in the circle near the top.

Demonstrator (CWDD) accelerator designed by Northrop Grumman at Argonne National Laboratory. (It should be noted that the TRIGA reactor discussed above can reach peak power levels in the megawatt region for extremely high (L/D)'s, well above those needed for aircraft inspection.)

The significance of the current CRADA experimental work is that an accelerator-driven neutron radiography system should be capable of detecting relatively low levels of corrosion, above about a mil (0.001 in.) in thickness, within the aluminum structural elements of an intact aircraft under ideal inspection conditions. Our calculations indicate that an accelerator, supplying a 10-mA deuteron beam at 2.0 MeV, could furnish the thermal neutron flux levels used for this CRADA, allowing 3-min exposures with slow, fine-grain film. At the (L/D) ratio used here, the radiographic inspection could resolve corrosion details greater than about 1/8 in. in diameter throughout a 6-in.-thick wing section. The use of higher speed X-ray film or electronic imaging (40-200 times faster than film imaging) would allow shorter exposure times, higher detail resolution, or reduced accelerator beam current. Such an accelerator-driven system is capable of generating the thermal neutron beam near the aircraft, allowing the radiographer to obtain good inspection angles during exposure. Facility requirements, such as radiation shielding and beam transport to the moderator/ collimator assembly, remain unresolved issues for a real working system.

7. ACKNOWLEDGMENTS

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