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DEVELOPMENT OF A CORROSION DETECTION EXPERIMENT TO EVALUATE CONVENTIONAL AND ADVANCED NDI TECHNIQUES

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ABSTRACT

The Aging Aircraft NDI Validation Center (AANC) was established by the Federal Aviation Administration Technical Center (FAATC) at Sandia National Laboratories in August of 1991. The goal of the AANC is to provide independent validation of technologies intended to enhance the structural inspection of aging commuter and transport aircraft. The deliverables from the AANC's validation activities are assessments of the reliability of existing and emerging inspection technologies as well as analyses of the cost benefits to be derived from their implementation. This paper describes the methodology developed by the AANC to assess the performance of NDI techniques. In particular, an experiment being developed to evaluate corrosion detection devices will be presented. The experiment uses engineered test specimens, as well as complete aircraft test beds to provide metrics for NDI validation.

KEY WORDS : Nondestructive Inspection, Corrosion, Evaluation

EXPERIMENT PURPOSE AND BACKGROUND

It has been recognized by both the FAATC and the aviation industry that the National Aging Aircraft Research Program (NAARP) has produced a number of potentially beneficial NDI techniques. It has also been acknowledged that these new techniques should be evaluated and ranked in order to expedite their integration into aircraft maintenance hangars. The following passage from a recent program review conducted by the Technical Oversight Group for Airworthiness Assurance (TOGAA) describes the need to quickly validate advanced NDI: "The Aging Aircraft Program is reaching a level of maturity that is akin to a mid-life crisis. All of the investigators have produced useful results; in many instances equipment and techniques are on the shelf, so to speak, ready to be exploited by the industry. Many of the research and developments have reached the plateau of feasibility from which they can be competed against alternatives. Some culling has been done but more is appropriate. For example, the Program should evaluate the many skin corrosion detection systems and only fund those with promise for the early detection of corrosion resident in multiple skin layers and other complex structural elements throughout the airframe. TOGAA believes the R&D program is at a mid-life point where many projects can be terminated without jeopardy. Others should be pushed to fruition."

With these ideas in mind, the AANC is developing a formal NDI Validation Experiment to assess the ability of conventional and emerging NDI techniques to inspect for hidden corrosion in faying surfaces. The main goal is to assess various equipment's ability to detect and quantify corrosion (thinning) with an emphasis on percent thinning in the 5-10% region.

Inspection validation involves the independent, quantitative and systematic evaluation of both the reliability and implementation costs of an NDI process. The objective of any inspection validation exercise is to provide quantifiable evidence that a particular inspection methodology is capable of achieving a satisfactory inspection result. The validation process considers the numerous factors which affect the reliability of an inspection methodology including the individual inspector, his equipment, his procedures and the environment in which he is working.

This experiment will use blind flaw samples, current aircraft inspection Job Cards, and specific protocols in a controlled manner to arrive at uniform, comprehensive NDI assessments. A series of representative test specimens containing known flaw profiles will be submitted to nondestructive examination. Each NDI technique will analyze the data it generates and produce projected flaw maps for each test specimen. Reference [2], which details the necessary protocols for NDI validation experiments, will be used to guide the experiment design. A series of metrics will be used to evaluate the various NDI techniques. Final assessments will be made in light of the criteria described in Reference [3] and summarized later in this paper.

The modular approach shown in the Figure 1 flowchart will be used to guide the experimentation process. Participants will be given a briefing. They will then set up their equipment using a series of reference standards as well as select specimens which are representative of the blind specimens used for the actual evaluation. During this set up time, experimenters will be provided with drawings showing the flaw profiles of the specimens. In this manner, they can calibrate their equipment with full knowledge of the flaws they are inspecting. After completing the set up or calibration phase, the experimenters will move on to the blind specimens while test monitors provide oversight and record qualitative information about each test method.

The ultimate goal of this experiment is to establish an inspection assurance baseline (i.e. how well are we doing now) and to transfer improved NDI techniques to aircraft maintenance hangars. Near-term benefits include: 1) aiding NDI development activities, 2) directing NDI technology to appropriate inspection applications, and 3) providing guidance to the FAATC in funding NDI methods for development and/or validation activities as appropriate. It should be noted that Tinker Air Force Base has conducted a series of experiments aimed at evaluating corrosion detection devices [1]. The effort discussed in this paper will build upon the lessons learned in the Tinker AFB experiments so that the resulting data compliments the findings obtained in the completed Tinker studies.

TEST SPECIMEN DESIGN

In order to determine the ability of a specific technique to locate and measure corrosion depth, well characterized samples are required. These can be provided in a number of ways:

- Locate corroded areas on existing aircraft. In this case, it is often difficult to characterize the samples prior to the evaluation. They can be cut open after testing, but one runs the risk of having inadequate corrosion profiles.

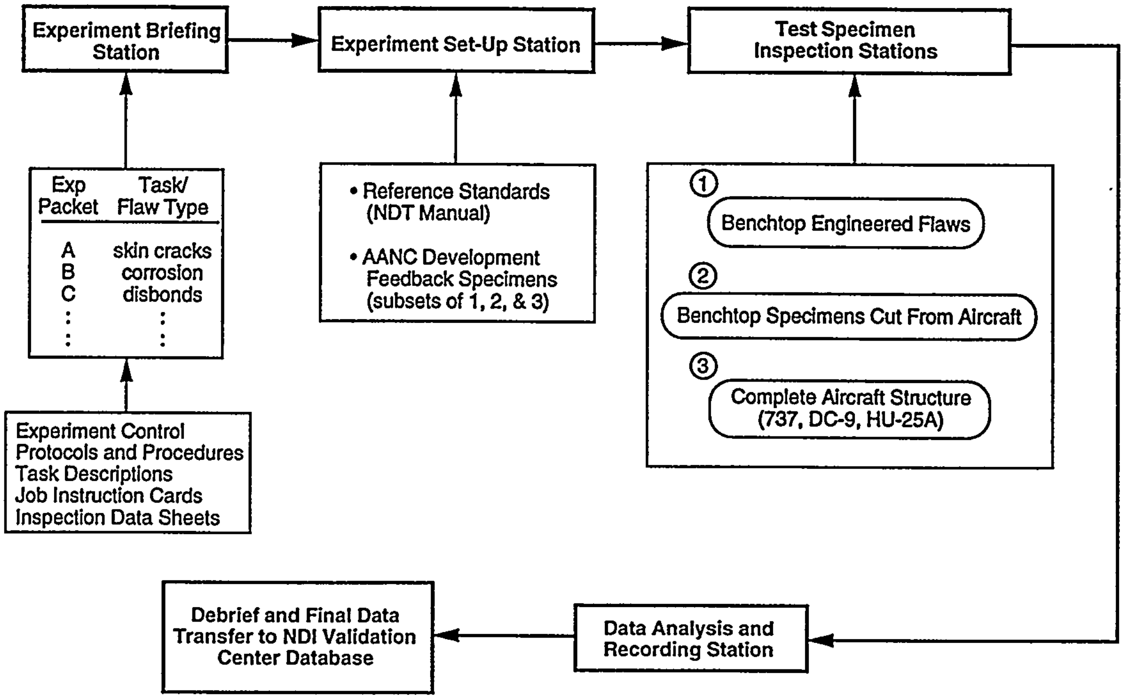


FIGURE 1: Flowchart for Conducting Structured NDI Evaluation Experiments

- Corrode aluminum skin material in the laboratory prior to assembly. This technique provides accurate information about the extent of corrosion, but it lacks some of the features, such as pillowing, which are often present in severely corroded aircraft.

- Force corrosion in structural sections cut from aircraft. This requires disassembly of the structures to introduce corrosion and it has been shown that the extent of corrosion continues to change over time [4].

This latter process has been used by the National Research Council of Canada to produce corroded samples [4]. The samples were prepared by removing the rivets, heating the panels to soften the adhesive, and opening the joints. Any protective layer or sealant was then removed from the joint surface, and the panels were re-assembled. The panels were then exposed to acidified salt fog in a Singleton Corrosion Chamber. The main advantage of this technique is that because the corrosion products are formed *in-situ,* external evidence of corrosion (pillowing) is created. The primary drawback is that the accumulation of salts, corrosion products, and electrolytes in the joint results in a continuing corrosion reaction which is difficult, if not impossible, to arrest. Thus, an ever-changing flaw profile is generated.

One of the keys to a successful validation experiment is the utilization and/or production of relevant and realistic flaw specimens. In order to avoid a complete dependence on any one of the above approaches, the AANC experiment design philosophy is to utilize specimens from each of the four categories listed below:

1. NDI reference standards
2. manufactured specimens with engineered flaws
3. sections cut from aircraft
4. complete aircraft test beds.

With the exception of the reference standards which are described in the aircraft manufacturers' NDI Manuals, the use of specimen types 2, 3, and 4 will now be outlined. A series of corrosion specimen design scenarios which are being proposed for this experiment will now be presented along with a description of alternative fabrication processes.

Basic Test Specimen Design Considerations

In order to develop a suitable suite of test specimens, whether they contain natural or engineered flaws, the following design variables must be addressed.

1. Shape/Geometry - The test specimens should represent the shape and geometry of the structures of interest. Damage Tolerance considerations may be used to select those specimens with the smallest critical size (area and depth). Worst case conditions can also be generated by selecting specimens with geometries that pose special manipulation problems or produce NDI responses that obscure flaw signals.

2. Flaw Types - Specimens cut from aircraft (or complete aircraft) should be used to include naturally occurring flaws. The artificial or engineered flaws should be designed to produce realistic responses for the parameter or inspection method(s) being assessed.

3. Flaw Sizes and Numbers - Quantitative assessments require that a statistically relevant number of flaw sites and detection opportunities exist in the test specimens. Flaw sizes should not be so large that they are always found or so small that they are always missed - the flaw sizes should cover the expected range of increasing reliability. The human vigilance factor can only be assessed if there are sufficient unflawed inspection sites in the test specimens. A specimen design goal will be to make the number of unflawed sites large enough to permit some estimate of false call rate.

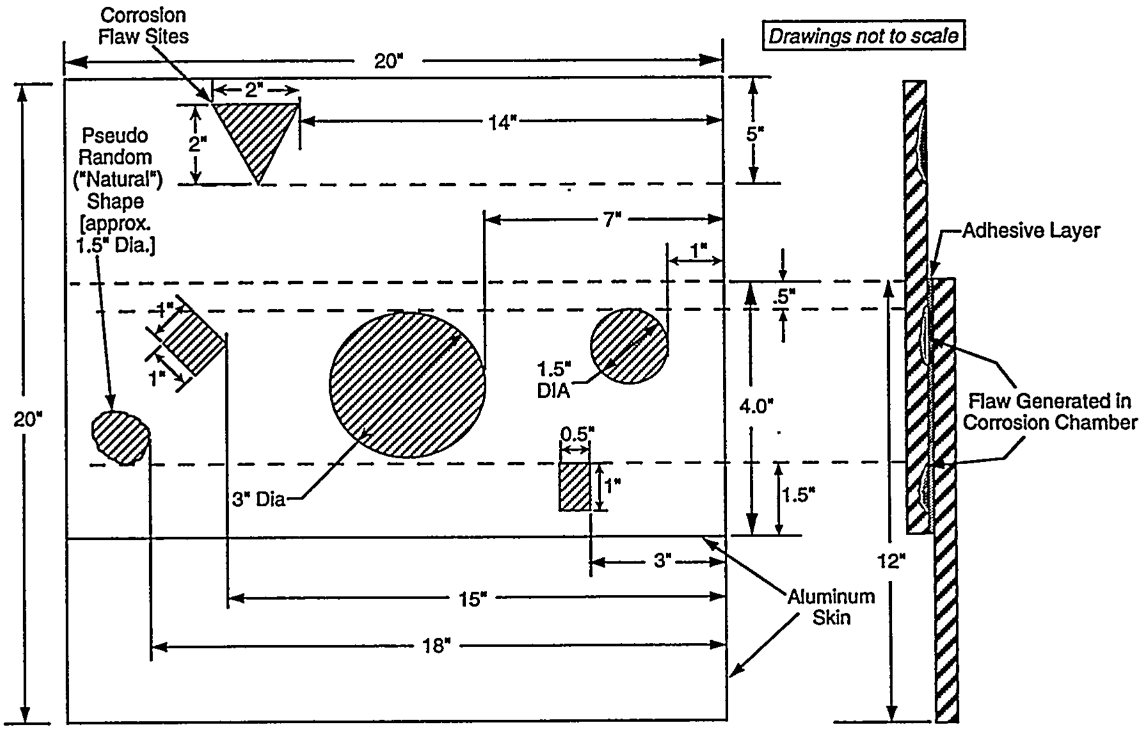
4. Characterizing Flaw Profiles - The flaw profiles in specimens manufactured with engineered flaws should be measured prior to final assembly. The samples cut from aircraft may also be disassembled after testing in order to definitively determine the flaw profiles.

When one considers final assembly of the test specimens, the following additional design options arise.

- flaw proximity to edge
- use of different corrosion depths on a single specimen
- use of different parent material thicknesses
- assemble the panels with both countersunk and buttonhead rivets
- add non-corroded substructure elements in some specimens to assess any masking effects (e.g. tear straps and stringers)
- include both painted and unpainted panels.

Figure 2 shows one of the preliminary specimen designs. Different geometric shapes and corrosion depths were generated in 2024-T3 aluminum material. The following specimen features were included in six proof-of-concept panels to serve as NDI performance metrics:

1. The specimens contain an assortment of flaw sizes, shapes, depths, and flaw proximities.
2. Each flawed specimen has the same five basic flaws. Shapes (specific geometric shapes and quasi-random shapes) and surface areas are held constant to provide equal opportunities for flaw findings on each specimen.
3. The flaw surface areas range from 3.23 cm^2 to 45.8 cm^2 and the flaw depths range from 0.005 cm (5%) to 0.046 cm (30%) in order to assess equipment sensitivity.
4. Flaws are located as close as 0.635 cm from an edge to assess edge effects.
5. Flaws are completely outside of the lap joint to assess corrosion detection in areas without second layers or substructure elements.
6. The presence of air gaps, collocated with corrosion or alone, can be incorporated into the specimen design. The use of air gaps in the corrosion experiment is discussed below.
7. The final overall specimen dimensions are 50.8 cm X 50.8 cm (20" X 20") with a 10.2 cm (4") lap joint. This design allows the specimens to be mounted, side-by-side, on existing AANC test frames [2]. The total assembly mimics a fuselage and allows for a more realistic experiment. Figure 3 is a schematic of the test set-up with the corrosion panels mounted in the test stand.



Specimen No.: ISU-6
Material: 2024-T3
Plate Thickness: 0.06" (0.15 cm)
Corrosion Depth: 20% to 30% (.012" - .018"; 0.030 - 0.046 cm)

FIGURE 2: Lap Splice Joint With Engineered Corrosion Produced in a Singleton Corrosion Chamber

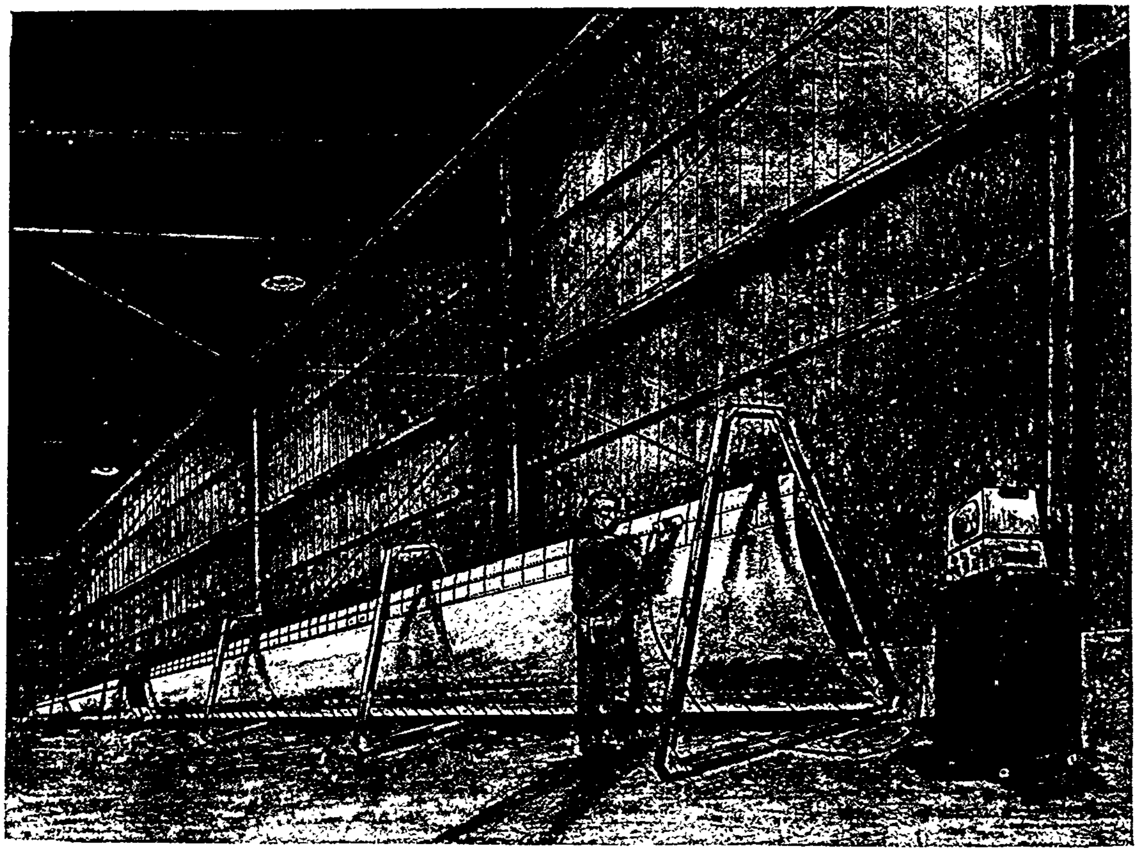


FIGURE 3: Series of Corrosion Specimens Mounted in Test Stand to Simulate Fuselage Geometry and Inspection Orientations

Sections Cut From Aircraft

The use of naturally occurring flaws is a necessary element of the structured experiments. The AANC will use a series of sections cut from aircraft to provide this realism. The AANC Test Specimen Library currently contains a number of 737 and L-1011 fuselage sections and we are in the process of determining what our experiment needs are with regards to sections cut from aircraft (Boeing, Douglas, and Lockheed). The sections cut from aircraft provide the most realistic flaw specimens, however, since the degree of corrosion will not be known until post-experiment disassembly, the engineered specimens provide a necessary element of experimental control.

Complete Aircraft Test Beds

One of the most important and widely used specimens in the Test Specimen Library is the "FAA/AANC Transport Aircraft Test Bed." This specimen, shown in Figure 4, is a 25 year old Boeing 737 aircraft which possesses key aging aircraft features: subjected to numerous cycles (46,000 cycles; 38,000 flight hours), cold bond lap splice joint, no lap splice modifications (terminating actions), and extensive corrosion.

Because of its ability to provide all of the 737 inspection requirements, the FAA/AANC Transport Aircraft Test Bed (B737-200) permits the assessment of the technical merits (reliability and sensitivity) of various NDI techniques. It also allows the AANC to evaluate human factors issues (e.g. environment, protocols), accessibility concerns (e.g. deployment, portability, need to remove peripheral items), and cost benefit data (e.g. inspection times, versatility).

Two other large aircraft test structures housed in the hangar are fuselage sections from a DC-9 aircraft. This particular DC-9 is a former Eastern Airlines airplane which was based in Miami and flew in the Caribbean (Mfg. Date - 1973, Hours - 56520, Cycles - 64,360). The forward fuselage section (radar bulkhead back to station 280) and the aft pressure bulkhead (fuselage station 924 to 1032) may also be designated for use in the corrosion experiment.

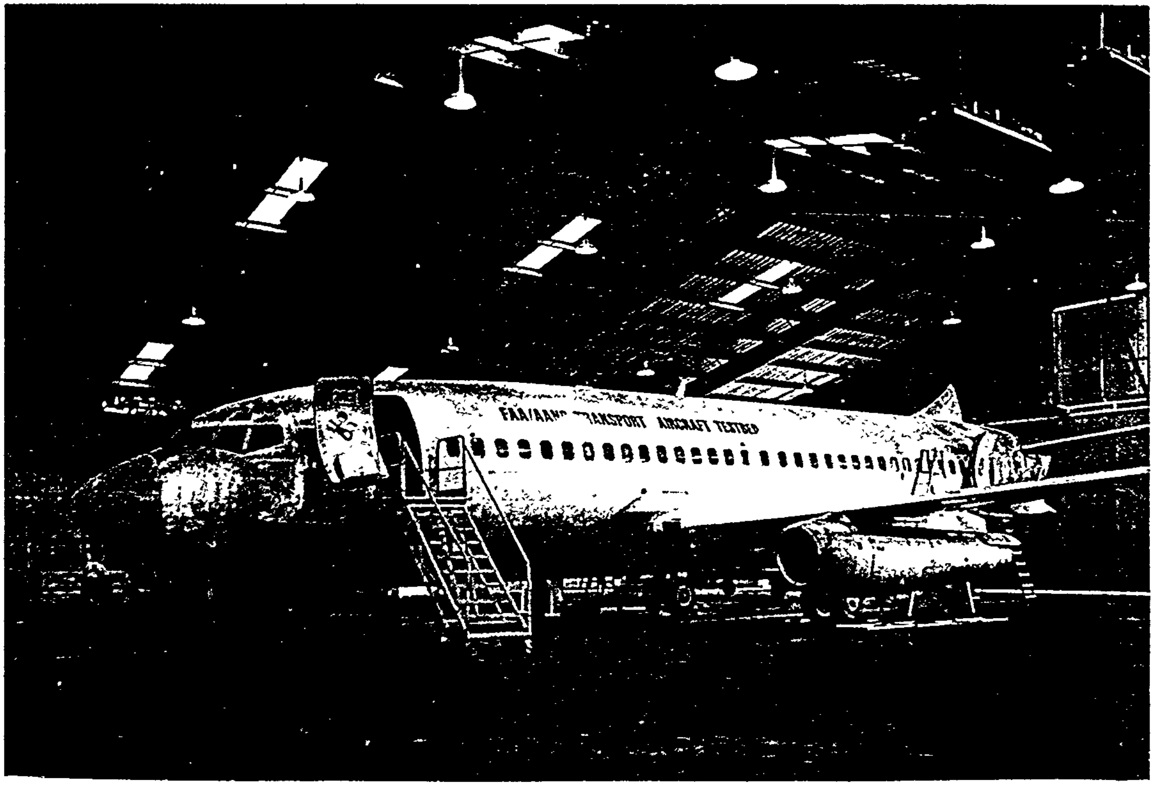


FIGURE 4: **FAA/AANC 737-200 Transport Aircraft Test Bed**

ENGINEERED TEST SPECIMENS - FABRICATION OPTIONS

Corrosion can be engineered into test specimens using several different processes. It is believed that the use of engineered blind samples with well-known flaw profiles is essential to achieving proper experimental control. These samples also assure a suitable statistical distribution of corrosion flaws. The key issue is whether or not the specimens adequately represent corrosion commonly found on aircraft structure.

Following is a discussion introducing the different engineered corrosion specimen designs and fabrication options: 1) panels with machined material removal, 2) panels corroded using a Singleton Corrosion Chamber, and 3) panels corroded using a sodium hydroxide (NaOH) chemical solution. The specimen design features, used to provide NDI performance metrics, will also be presented. At this time, the AANC has completed a study into each of these methods, however, final specimen configurations and corrosion generation schemes will be determined in collaboration with a panel from the aviation industry.

1. Panels With Machined Material Removal

The corrosion test specimens with machined material removal were designed to simulate joint geometries found in both Boeing and McDonnell Douglas aircraft. Simulated corrosion loss of material was represented by machined domes of varying diameters and maximum depths. Domes, with gradual transitions to maximum material loss, provide a better test of material thinning detection. Flat-bottomed holes contain an instantaneous transition from complete plate thickness to "fully corroded" area and are easier to detect. The plates can be arranged to simulate the Boeing lap splice or the Douglas butt joint including the finger doubler. The range of corrosion "domes" is from 5% to 25% of the 0.2 cm thick aluminum plate.

2. Panels Corroded Using a Singleton Corrosion Chamber

The Singleton Corrosion Chamber offers a means of producing specimens with corrosion damage similar to that occurring naturally, but at a much accelerated rate. The corrosion chamber is operated per the requirements of ASTM B117, Standard Test Method of Salt Spray (Fog) Testing. This neutral salt spray test is the most common and widely used corrosion test for comparing the corrosion performance of materials. This test method is used by most aircraft manufacturers and their suppliers to evaluate the corrosion resistance performance of various aluminum alloys and protective coatings.

Using this chamber, specimens were produced with pitting and thinning which closely resemble actual damage found on aircraft. Surface roughness, which is considered a key feature for specimens used for NDI method evaluations, has been measured to be 350 to 400 microinches RMS on several sections of corroded aircraft skin. Specimens produced in the corrosion chamber exhibit corrosion damage with a surface roughness also in this range. Figure 5 shows a photo of a specimen produced in the Singleton Corrosion Chamber (reference Fig. 2 design drawing) while Figure 6 shows the corresponding flaw map produced by an ultrasonic scanner inspection system.

3. Panels Corroded Using Sodium Hydroxide Chemical Solution

In order to produce controlled corrosion flaws in aluminum, the use of a sodium hydroxide (NaOH) chemical solution method was also studied. The area of corrosion was defined by a glass cell attached to the surface with RTV silicone. The solution was in contact with the surface for several hours while the corrosion reaction proceeded. The solution was then removed from the cell, the sample was rinsed in deionized water, and the degree of attack was measured. The NaOH solution was effective in producing the desired corrosion morphology. It produced the same corrosion products as those found in aircraft (mostly aluminum hydroxide).

In the course of producing proof-of-concept corrosion coupons, calibration curves (corrosion depth vs. exposure time) for this process were generated. Figure 7 is a plot of these data for NaOH. The corrosion rate increases in a linear fashion initially, but reaches a plateau after about 10 hours. For this experiment, the target for the extent of corrosion was 10% thinning, which was easily achieved by exposure for less than 1 day. It is clear that the corrosion process is quite predictable. The extent of corrosion can be controlled and the corrosion products remain intact on the surface.

It is clear that a perfect method for sample production does not exist. The relative advantages and disadvantages of any given method must be weighed, along with the required application of the samples, to determine the appropriate fabrication method.

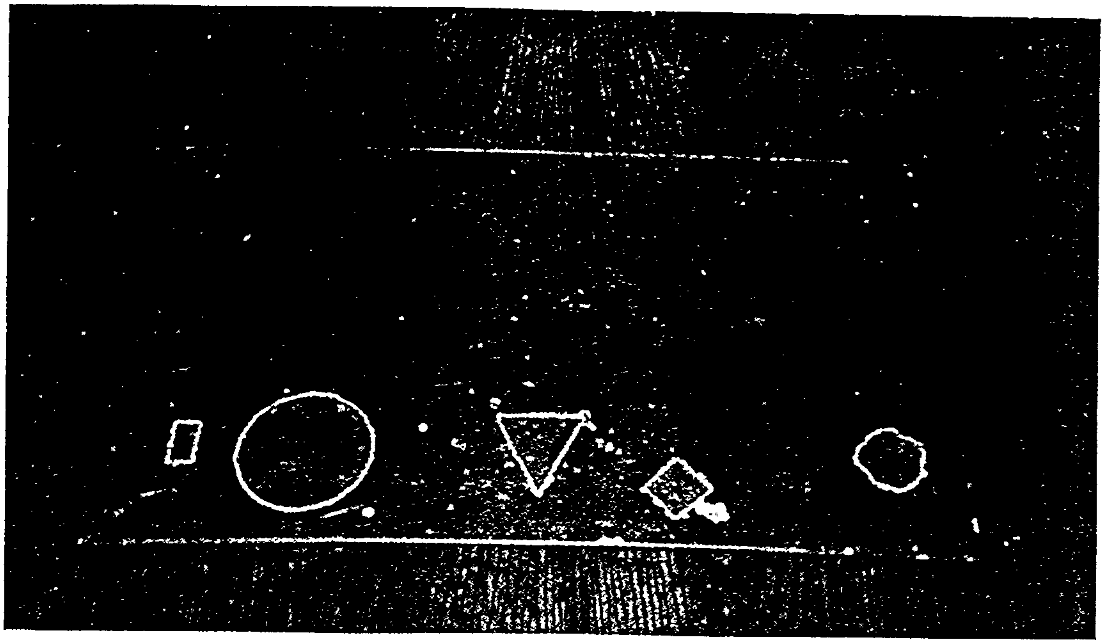


FIGURE 5: Photograph of Corrosion Specimen With Engineered Flaws Produced in the Singleton Corrosion Chamber

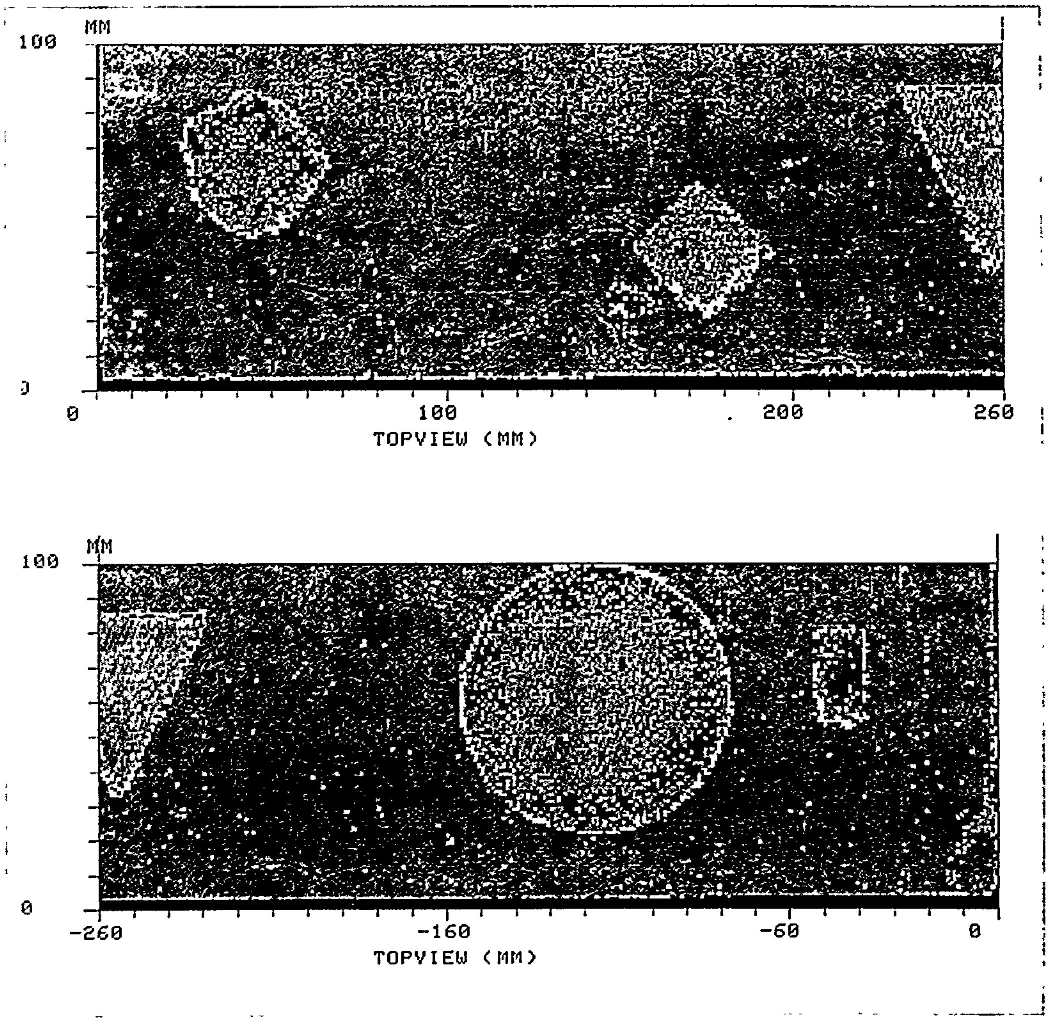


FIGURE 6: C-Scan Ultrasonic Image of Corrosion Specimen

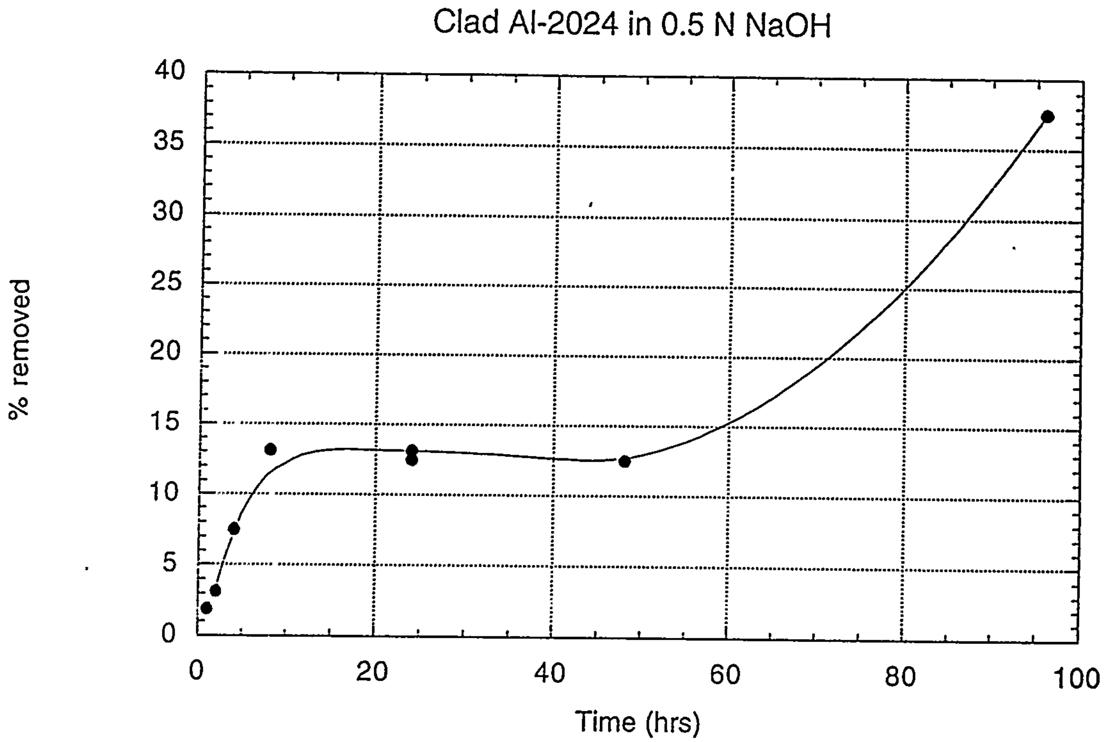


FIGURE 7: **Corrosion Rate for Clad Al-2024 in NaOH Solution**

STRUCTURAL ASSEMBLIES TO IMPLEMENT CORROSION EXPERIMENT

Structural assemblies beyond flat corroded plates must be used to provide realistic vehicles for assessing corrosion inspection equipment. The AANC, in conjunction with an industry review team, is considering two primary structural assemblies. One of the assemblies is a Boeing lap splice joint; Figure 2 shows how the corroded plates may be bonded to create a lap splice configuration. The second assembly has not been determined at this time, however, it will probably be representative of a Douglas configuration.

Since corrosion is usually accompanied by a loss of sealant, the preliminary design plan includes collocated air gaps which simulate sealant loss. It was decided that these air gaps should be larger and/or a different shape than the collocated corrosion so that the scoring metrics could differentiate between the two flaw types. The flaw distribution will also include corrosion areas without sealant loss and sealant loss areas without corrosion. The most straightforward way to create controlled areas of sealant loss is to replace select areas of the sealant layer with Teflon pull tabs or inserts. These inserts seal off the geometry of interest and eliminate migration of the sealant into the designed "air gap" areas. After the sealant has cured, the Teflon sheets are removed and air gaps are left in their place.

EXPERIMENT CONTROL THROUGH THE USE OF PROTOCOLS

The purpose of using protocols in the execution of the structured experiments is to ensure consistency and repeatability among successive iterations of the same experiment. More specifically, protocols will ensure that:

1. Objectives of the experiment are reached

2. The experiments are carried out consistently and according to the plan
3. Recorded data are defined and gathered consistently
4. Consistent information is given to participants
5. Deviations from the plan are dealt with effectively
6. Subsequent experiments are conducted under the same conditions.

The AANC has demonstrated the value of well constructed experiments through its Eddy Current Inspection Reliability Experiment [2]. The protocol contents include:

1) Inspector Supervision Procedure (for facilitators and monitors)
2) Initial Contacts & Scheduling (outline experiments, specimens, request written procedures from participants)
3) Experiment Set-Up (hangar support, site preparation, data acquisition)
4) Experiment Checklist (readiness, how to handle situations)
5) Test Specimen Layout (order of flawed specimens, order of inspections)
6) Experimenter Briefing
7) Experiment Packets -
    a. step-by-step instructions for participants
    b. list of calibration specimens; set-up feedback areas
    c. list of blind test specimens
    d. engineering drawings of test specimens
    e. NDI evaluation criteria document
8) Data Recording and Transfer (database entry)
9) End of Trial Debriefing and Experimenter Questionnaire
10) Close Down

EVALUATION OF NDI TECHNIQUES

NDI Evaluation Criteria

A key element in evaluating NDI methods is a criteria with which to "score" systems and compare them with competing NDI techniques. While specific systems and inspections will have their own individual features of interest, there are some basic evaluation criteria which are of fundamental importance for any NDI system. The evaluation criteria used to assess NDI techniques can be broken down into the following eight basic categories: 1) accuracy, 2) sensitivity, 3) analysis capability, 4) human factors, 5) versatility, 6) portability, 7) availability, and 8) cost. A complete description of both the technical and economic evaluation criteria for NDI techniques can be found in Reference [3]. The eight evaluation criteria categories are outlined below and summarized in Table I.

1. **Accuracy and Sensitivity** - The equipment must be able to locate, quantify, and characterize hidden flaws. As a minimum, the equipment should be able to detect flaws that would require a repair effort such as replacement of portions of the aircraft skin. Specific reliability figures of merit related to probability of detection (PoD) and probability of false alarms (PoFA) will be quantified to the extent possible for an NDI system. These figures of merit may be determined as a function of a flaw characteristic, such as crack length.

2. **Analysis Capability** - Factors such as clarity of display modes and ease of identifying flaw locations will be considered. Other factors may be: 1) compatibility with other equipment in the maintenance hangar, 2) degree of automation, 3) data storage and retrieval.

TABLE I: SUMMARY OF NDI EVALUATION CRITERIA

RANK	CRITERIA	DESCRIPTION	MEASURE
*	Accuracy	Correct flaw locating/ High probability of detection Low probability of false indications	$\frac{\text{no. of flaws detections}}{\text{no. of actual flaws}} > X\ \%$ $\frac{\text{no. of false calls}}{\text{no. of total calls}} < Y\ \%$
*	Sensitivity	Capability to detect small flaws and provide location, type, and degree of damage	Types or severity of corrosion/ debonds detected Length of cracks detected Detect 10% reduction in skin thickness due to corrosion
*	Analysis Capability	Clarity of results and time required to obtain them	Real-time presentation Provides rework decision Ease of flaw location ID Measures peripheral factors and removes subjectivity
*	Human Factors	Ease of use	Evaluation of man-machine interface (MIL-STD-1472) Compatible with existing equipment and current inspection demands
*	Versatility	Detect flaws in a variety of locations on the aircraft, under different circumstances and structural configurations	Number of recalibrations required for different circumstances Capability to inspect through paint Detect flaws at different levels of various multi-layered structures
*	Portability	Ease of shipping and handling	Can be moved around hangar to meet inspection demands
*	Scan Rate	Rapid and precise set-up	Area inspected per unit of time
*	Availability	Off-the-shelf or available to meet near-term inspection requirements	Lead time for vendor to produce operational system
*	Cost	Cost-benefit analysis	Operational and fixed costs vs. other NDI methods

* Determine a suitable rating system (e.g. High, Med, Low; assign numeric values from 1 to 10)

3. **Human Factors** - The equipment should be capable of being used by experienced inspectors in an efficient manner that minimizes errors induced by operator fatigue. The equipment should be user friendly; the amount of operator training required should be considered.

4. **Versatility** - A versatility assessment may include how much recalibration is required for different skin thicknesses or for different fastener or skin materials, whether the system can inspect structures in different orientations, or whether the system can inspect through paint.

5. **Portability** - The equipment should be of suitable configuration, size and weight for its intended use in aircraft maintenance. Are their power, tethering or remote control issues or other aspects which may restrict the use of the equipment?

6. **Availability** - Will the equipment be readily available for purchase and use in the near future?

7. **Cost** - The equipment cost should not be greater than the long-term savings obtained through its lifetime of use. These economic issues should be considered in a detailed cost-benefit analysis. In this approach, the benefits to be derived from the application of a particular NDI technique must be translated into cost savings which can then be entered into the overall analysis. These benefits must be weighed against the economics associated with the NDI method(s) which the new technique is replacing or improving. A detailed treatment of the cost-benefit analysis of aircraft NDI is provided in Reference [5].

Experiment control requires the use of written NDI procedures which address issues such as: set-up, calibration, training required, interpretation of results, and specifics about the inspection task. By formulating a checklist and accumulating similar information on each experimenter, it will be possible to make straightforward intercomparisons.

CONCLUSIONS

Numerous private and federally-funded research programs have produced advanced NDI equipment and techniques which may be applicable to aircraft inspections. Similarly, improvements have been made to conventional NDI equipment in order to make them more cost effective, sensitive, or have a broader range of applications. Some of the techniques are developed for specific inspection tasks while most are simply aimed at detecting the two basic flaw types: cracks and corrosion. Due to financial, personnel training, and equipment constraints, only a few of the techniques will be accepted for wide scale use in aircraft maintenance depots. Thus, it is imperative that these new or improved NDI techniques be evaluated so that inspection alternatives can be assessed and approved for use. The Sandia Labs' AANC program is developing an experiment to assess the ability of conventional and emerging NDI techniques to inspect for hidden corrosion in faying surfaces. The main goal is to measure various equipment's ability to detect and quantify corrosion (thinning) with an emphasis on percent thinning in the 5-10% region. The two key elements in developing such an experiment are: 1) use of a structured approach to achieve proper experiment control and quantitative assessments, and 2) production of realistic flaw specimens which have well characterized corrosion profiles. Through these experiments, the AANC hopes to help develop and direct NDI technology and facilitate the transfer of improved NDI to aircraft maintenance hangars.

ACKNOWLEDGMENTS

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BIOGRAPHY

Dennis Roach is a Senior Member of Technical Staff in the Airworthiness Assurance Department at Sandia National Labs. Most of his work has been in the area of experimental and analytical response and nondestructive inspection of structures. Before joining Sandia, Mr. Roach worked on the Space Shuttle program at McDonnell Douglas Corp. and was a research fellow at the National Aerospace Laboratory in the Netherlands.

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