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ADVANCED NONDESTRUCTIVE EVALUATION (NDE) FOR RETIREMENT FOR CAUSE/ENGINE STRUCTURAL INTEGRITY PROGRAM (RFC/ENSIP)

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The Eddy Current Inspection System (ECIS) is an automated aircraft engine part inspection system that uses eddy current technology to inspect aircraft engine parts for small flaws and cracks (5 to 10 mils.) created by engine wear and fatigue. This technology was used in the Retirement for Cause/Non-Destructive Evaluation (RFC/NDE) portion of the Engine Structural Integrity Program (ENSIP). The ECIS is comprised of three primary modules, the Signal Generation/Detection Module, the System Control Module, and the Robotics Module. Presently, there are 41 ECIS systems in operation and these systems have successfully performed to specification since their implementation to conduct RFC/ENSIP life management and safety inspection functions. The USAF intends to continue using the ECIS systems for many more years; however, the state-of-the-art of various areas of the supporting technology of the individual modules has advanced since the initial ECIS system design. Many other components have become obsolete increasing maintenance costs. The ECIS systems deliberate modular design makes allowances for the upgrade of the system to incorporate many of these state-of-the-art technology improvements.

14. SUBJECT TERMS
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DISCLAIMER

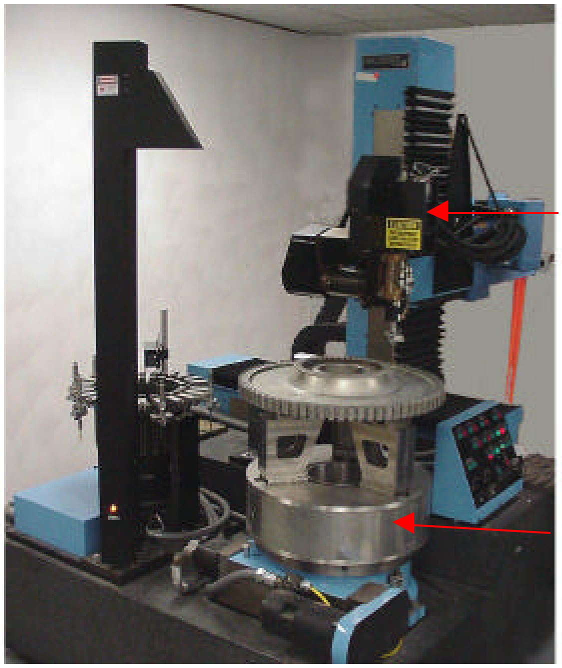
The information contained in this document is neither an endorsement nor criticism of any software applications, computer hardware, eddy current inspection equipment, or other equipment used in this effort.

1.0 Introduction

In the early 1980's Veridian Engineering, formerly Systems Research Laboratories, Inc., developed the Eddy Current Inspection Station (ECIS) for the United States Air Force (USAF) Research Laboratory (AFRL) Materials and Manufacturing Directorate, under the Retirement for Cause/Nondestructive Evaluation (RFC/NDE) portion of the Engine Structural Integrity Program (ENSIP). The ECIS is an automated aircraft engine part inspection system that uses eddy current technology to inspect aircraft engine parts for small flaws and cracks (5 to 10 mils.) created by engine wear and fatigue.

The ECIS is comprised of three primary modules, the Signal Generation/Detection Module, the System Control Module, and the Robotics Module. These three modules are all contained in two assemblies, the Mechanical Manipulator Assembly and the Instrumentation Console Assembly (see Figure 1). The Signal Generation/Detection Module consists of the Inspection Probe, Scanner, Eddy Current Instrument (ECI), and a pair of External Filters. The Signal Generation/Detection Module generates the probe drive signal, which induces the eddy current into the part being inspected, detects any flaw indications, and prepares the flaw signal for processing by the System Control Module. The System Control Module consists of the System Computer, Cathode Ray Tube (CRT) Display, and Operator Console. The System Control Module controls all communications between modules, performs signal processing to separate the flaw signal from associated part anomalies, determines the flaw size and acceptability status, records the flaw size and position, and sends all pertinent flaw data to the Information/Data Base Archival system for storage. The Robotics Module consists of the Mechanical Manipulator, Robot Control Panel, Robot Controller, and Robot Drive Assemblies. The Robotics Module controls the part rotation, moves the Inspection Probe over the part during inspection, and sends positioning data to the System Control Module. There is also a fourth component, the Information/Data Base Archival system, which connects to multiple ECIS systems. The Information/Data Base Archival system consists of a Digital Equipment Corporation (DEC) Virtual Address Extension (VAX) Computer that is centrally located in an aircraft engine inspection laboratory. The Information/Data Base Archival system stores all engine part data associated with the inspection of the engine part.

Presently, there are 41 ECIS systems in operation and these systems have successfully performed to specification since their implementation to conduct RFC/ENSIP life management and safety inspection functions. The USAF intends to continue using the ECIS systems for many more years, however the state-of-the-art of various areas of the supporting technology of the individual modules has advanced since the initial ECIS system design. Many other components have become obsolete increasing maintenance costs. The ECIS systems deliberate modular design makes allowances for the upgrade of the system to incorporate many of these state-of-the-art technology improvements.



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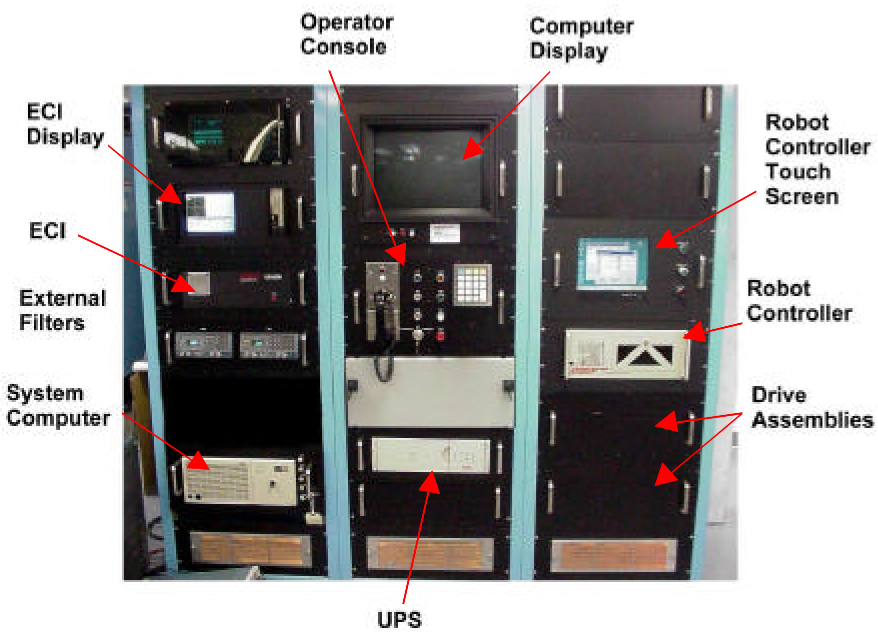

INSTRUMENTATION CONSOLE

Figure 1. ECIS System Assemblies

In 1995 the AFRL Materials and Manufacturing Directorate announced in the Commerce Business Daily (CBD), January 31, 1995, their Program Research and Development Announcement (PRDA) entitled Advanced Nondestructive Evaluation (NDE) for Retirement For Cause/Engine Structural Integrity Program (RFC/ENSIP) for contract opportunities to address nine identified areas of improvements to the ECIS system. These nine areas were Eddy Current Probes, Signal Generation and Detection, Signal Processing, Display/Recorder, Mechanical Positioning, Calibration Process, System Computer, Information/Data Base Archive, and Specialized System/Technology Issues. Veridian Engineering formed a team of companies and submitted a proposal, which addressed all nine areas set forth in the CBD Advanced NDE RFC/ENSIP Contract announcement. The companies that formed the Veridian Engineering Team were Veridian Engineering, United Western Technologies (UniWest), Southwest Research Institute (SWRI), TechnoSoft, and D&W Enterprises Limited.

Three of the nine areas originally mentioned in the CBD announcement were not funded. These three areas were Signal Processing, Display/Recorder, and the Information/Database Archive. The Veridian Engineering Team was funded to investigate four of the remaining six areas. These four areas were the Eddy Current Probes, Signal Generation and Detection, System Computer, and Specialized System/Technology Issues. The remaining two areas, Mechanical Positioning and Calibration Process, were awarded to American Robot Corporation (ARC) and University of Dayton Research Institute (UDRI), respectfully. The Veridian Engineering Team, ARC, and UDRI, along with representatives from two of USAF Air Logistic Centers (ALC); Jet Engine Overhaul Facilities at Oklahoma City, Oklahoma (OC-ALC) and San Antonio, Texas (SA-ALC) formed the Advanced NDE RFC/ENSIP Project team, which was lead by Mr. Charles Buynak of the USAF, AFRL Materials and Manufacturing Directorate. The basic approach to all of the project tasks was to first study the assigned problem area, determine a recommended course of action, and then orally submit this course of action to the overall project team at a quarterly meeting and in writing in a concept report. Based on the discussion of the recommended course of action, and the data supplied in the concept report, the government entities of the Project team would decide whether or not to pursue the recommended course of action. If the government decided to proceed with the task, the work would begin and be monitored through briefings given at the quarterly meetings. At the completion of each task, a final report noting the degree of success, associated data, and any problems encountered was generated and delivered to the government.

This team approach was adapted for three primary reasons:

- The ALC's are the primary end users and their input ensured that the hardware/software being produced would provide a satisfactory end product for their use.
- The overall team included a wide variety of expertise with both the ECIS system and the RFC program in general to ensure that the newly developed hardware/software would integrate into the ECIS system correctly to update the system and open opportunities for future system growth.
- The team expertise would also ensure that the changes to the ECIS system would not inversely affect the critical Probability of Detection (POD) or Reliability of the overall ECIS system.

The Veridian Engineering Team incorporated its four assigned areas into three tasks: Signal Generation/Detection (includes probe improvements), System Computer, and Specialized System/Technology Issues. Each of these tasks is discussed in the next three sections of this report.

2.0 Signal Generation/Detection

In the Advanced NDE RFC/ENSIP contract announcement, probe improvements were specified separately from the signal generation and detection areas. The Veridian Engineering Team combined these two areas into one task because they both related to the Signal Generation/Detection Module of the ECIS system as described in Section 1.0, Introduction. The Signal Generation/Detection task therefore focused on three component areas within the ECIS Signal Generation/Detection Module. These three areas were the Stavely NDT25L Eddy Current Instrument (ECI), the Veridian Engineering ECIS scanner, and eddy current probe improvements. Each of these areas is discussed in the following three subsections.

2.1 Eddy Current Instrument Replacement

The Stavely NDT25L ECI is an obsolete piece of equipment that requires a 6-month calibration cycle, which is an expensive process. There was a definite need to replace this piece of equipment, but because of the ever-increasing demand to find smaller flaws and to inspect more difficult geometries, there was also a need for greater capabilities. These greater capabilities included a larger bandwidth, processing of multiple channels and multi-frequency. This subtask and associated work was assigned to UniWest with assistance from Veridian Engineering. UniWest had already developed several ECI of their own, but none of them were exact drop-in replacements for the NDT25L. An overview of the work performed is given in the following subsections.

2.1.1 Project Scope

The project scope was to design, develop, test and implement a drop-in replacement for the obsolete Stavely NDT25L ECI with a bandwidth of 100KHz to 10MHz. Investigate the advantages and disadvantages of incorporating multi-channel and multi-frequency capabilities into the ECIS system.

2.1.2 Work Performed

Development of the ECI replacement was broken down into two phases. Phase 1 involved developing a fully functional drop-in replacement for the existing NDT25L with the wider bandwidth. Phase 2 involved investigating the additional multi-channel and multi-frequency capabilities. The two phases were required because the additional multi-channel and multi-frequency capabilities would require modifications to the scanner plus a scanner characterization/design, both of which would be accomplished in Phase 1.

For Phase 1 the NDT25L was characterized by Veridian Engineering to determine its exact functionality within the ECIS system. Once the characterization of the NDT25L was completed, the information was provided to UniWest in order to develop their preliminary design. As stated earlier, UniWest had already developed several ECI units, all of which were computer controlled, using a UniWest developed program called ELAB. The NDT25L replacement developed by UniWest was based on one of their existing ECI units, the US-450, and used a modified version of the ELAB software. The new ECI design by UniWest was designated the US-500 and it is comprised of two boxes, the ECI box and the Computer Control/ Display box. This mirrored the old design well since the NDT25L was also comprised of two boxes, the ECI box and the Display. The US-500 ECI box was designed to directly connect to the ECIS system using the same connections as the NDT25L. The US-500 Computer Control uses a new version of the UniWest ELAB software program with an NDT25L emulation module. This emulation module allowed the ECIS system to communicate with the US-500 using the same protocol as the NDT25L so that modifications to the ECIS software were not required. Once the preliminary design for the US-500 was complete, it was presented to the Project team for review and approval. The Project team approved the new design and UniWest built the US-500 prototype. The US-500 prototype was sent to Veridian Engineering, Dayton, Ohio for testing.

In-depth testing was performed on the replacement ECI to verify that it was an acceptable drop-in replacement for the NDT25L. Testing was performed in three steps: bench test, in-system test, and site acceptance test. The bench test was performed with the US-500 out of the ECIS system to isolate the system and all signal responses. The bench test involved comparing the amplifier and filter responses of the US-500 to those of the NDT25L. For the amplifier response testing, the six performance areas that best measured the amplifier characteristics were evaluated. These six areas were the output compression point, the input compression point, absolute gain, relative gain, sensitivity, and dynamic range. A brief description of each of these performance areas is provided below:

- **Output Compression Point** – The peak-to-peak voltage amplitude level at which the output signal of the ECI begins to distort or clip.
- **Input Compression Point** – The peak-to-peak voltage amplitude level of the input signal when the output signal of the ECI reaches the output compression point.
- **Absolute Gain** – The actual signal gain measured through the ECI at a given gain setting (i.e., if the ECI is set for a gain of 15dB which is the measured gain?).
- **Relative Gain** – The measurement of the difference between incremental gain changes (i.e., if the gain is changed from 25db to 30dB, which was the measured gain change?).
- **Sensitivity** – Also referred to as minimum detectable signal, and is the measurement of the smallest detectable input signal that the ECI can detect.
- **Dynamic Range** – The measurement of the range of input signal amplitudes levels that the ECI can detect and tolerate.

Data associated with the 6 performance areas shown above was collected at 11 different gain settings of the ECI. An average of the results for each of the 6 performance areas is given in Table 1. More in-depth information is presented in the Eddy Current Instrument Replacement Final Report.[1]

Table 1. US-500/NDT25L Amplifier Response

Parameter	NDT25L	US500
Output Compression Point	26.31 Vp-p	24.78 Vp-p
Input Compression Point	292.4mVp-p	223.7mV
Absolute Gain	Within 1.35%	Within 6.18%
Relative Gain	Within 7.08%	Within 3.02%
Sensitivity	54.55mVp-p	43.45mVp-p
Dynamic Range	55.26dB	56.53dB
Bandwidth	6MHz	10MHz

For the output compression point, the NDT25L specification sheet states that this will be 24Vp-p. The test results show the NDT25L to actually be 26.31Vp-p and the US-500 to be 24.78Vp-p. For this particular test, the higher the value the better, but since the US-500 falls within the NDT25L specification it is acceptable. The input compression point is not given in the NDT25L specification sheet and the US-500's measured value is a little lower than that of the NDT25L. This basically shows that the NDT25L can tolerate a slightly higher input signal, but since the ECIS's system inputs to the ECI are in the high microvolt to low milli-volt range, this is not a problem. The NDT25L tracks the absolute gain a little closer than the US-500, but the US-500 has a better relative gain variance. Therefore, the US-500 has a slightly higher gain, but tracks the gain changes better for small incremental gain changes. Since the ECIS system makes small incremental changes (+/- 5dB) during its gain calibration procedure, it should perform slightly well than the NDT25L. The US-500 has a slightly higher dynamic range and a much larger bandwidth. Higher frequencies are required to find the smaller cracks, so the larger bandwidth should prove useful in future crack-detection requirements.

For the filter response testing, the US-500 was connected to a Hewlett-Packard HP3577A Network Analyzer and the flaw signal frequency was swept over varying ranges as the filter settings were adjusted on the NDT25L and US-500. From the characterization of the NDT25L, it was found that many of the NDT25L filter settings were not accurate. Since the US-500 was to be a drop-in replacement for the NDT25L, and the scan plans had been developed with the NDT25L filter values, the US-500 filter settings in the NDT25L emulation mode had to be modified to match the NDT25L. Table 2 below shows a comparison of the US-500 filter response to the NDT25L filter response.

Table 2. US-500/NDT25L Filter Response Comparison

High Pass Filters			Low Pass Filters		
Filter Setting	NDT25L Response	US500 NDT25L Emulation Mode Response	Filter Setting	NDT25L Response	US500 NDT25L Emulation Mode Response
0	1.4Hz	1.4Hz	10	9.4Hz	9.3Hz
2	2.3Hz	2.2Hz	30	10.6Hz	10.2Hz
5	5.5Hz	5.3Hz	100	101Hz	99Hz
10	11.5Hz	10.6Hz	300	312Hz	296Hz
20	21Hz	21Hz	1000	732Hz	750Hz
50	47Hz	52Hz	3000	2264Hz	2310Hz
100	92Hz	99Hz	10000	5530Hz	5900Hz
250	237Hz	248Hz			
500	484Hz	500Hz			
1000	885Hz	950Hz			
2500	1850Hz	2175Hz			

Table 2 shows the NDT25L Emulation Mode of the US-500 tracks the filter response of the NDT25L very well, with all but one of the values (2500Hz high pass) being within 10 percent of the NDT25L values. The last item that was checked during the bench test was the amplitude levels of the probe drive signal output at various frequencies and at no load and 50-ohm termination (see Table 3).

Table 3. US-500/NDT25L Probe Drive Signal Amplitudes

FREQUENCY	NDT25L		US500		PERCENT DIFFERENCE	
	OPEN Volts	50 OHM Volts	OPEN Volts	50 OHM Volts	OPEN Volts	50 OHM Volts
200KHz	6.78	5.73	7.95	6.20	17.26%	8.20%
500KHz	-	-	7.95	6.20		
2MHz	7.75	5.98	7.95	6.20	2.58%	3.68%
3MHz	-	-	8.15	6.25		
6MHz	9.50	6.28	7.95	6.05	16.32%	3.66%
10MHz	-	-	7.35	5.30		

Table 3 shows the probe drive signal amplitudes with the 50-ohm termination, which is the typical operating load for the ECI in the ECIS system. All are within 10 percent of the NDT25L values. All of the bench test results showed that the US-500 accurately emulated the NDT25L within tolerance and testing proceeded to the in-system test.

In-system testing involved installing the US-500 into an ECIS system and performing communications protocol analysis, reliability tests, and parts tests. The communications protocol analysis verified that the ECIS system was able to correctly communicate with and control the US-500 as it did the NDT25L. A special scan plan was written to allow an ECIS operator to test all of the NDT25L control commands and verify that the US-500 functioned the same.

For the reliability tests, data was collected from IN718 bolt hole and Waspoly flat plate reliability specimens at both 2MHz and 6MHz. The reliability data was collected with both the NDT25L and the US-500 and then compared. Table 4 provides a brief summation of the results of the in-system reliability testing as analyzed by Veridian Engineering.

Table 4. US-500/NDT25L In-System Reliability Test Results

Reliability Ran	Threshold	NDT25L A90/A95 Values	US500 A90/A95 Values
TI6246 2MHz Bolt Hole	120	5.74 mils.	5.77 mils.
TI6246 6MHz Bolt Hole	120	9.1 mils.	8.28 mils
2MHz Waspoly Flat Plat	100	5.74 mils.	5.98 mils
6MHz Waspoly Flat Plat	100	5.16 mils	4.98 mils.

As the data shows the NDT25L and US-500 results are all well within 1 mil of each other. Typically, 1 mil is the maximum difference allowed for acceptability and since the US-500 is within 1 mil of the NDT25L, it is acceptable as far as the reliability testing. The reliability data was also sent to Dr. Al Berens of UDRI for an independent analysis of the data. Dr. Berens' analysis showed similar results to the Veridian analysis. The results of Dr. Berens' analysis are available in Section 4.0 of his final Advanced NDE RFC/ENSIP report. [2]

The parts test initially involved running a total of six parts plus the San Antonio Eddy Current Calibration (SA_EC_CAL) verification kit. Three of the parts, (F110 3RD Stage Fan Disk, P/N 1359M73P02-110, F110 HPT Disk, P/N 1359M33P01-110, and F110 4-9 Spool, P/N 1359M16G05-110) were selected by the OC-ALC. The remaining three parts (F100 8TH Stage HPC Disk (P/N 4040108), the F100 13TH Stage HPC Disk (P/N 4041013), and the F220 1ST Stage Fan Disk (P/N 4071701)), as well as the SA_EC_CAL verification kit, were selected by the SA-ALC. During the in-system test, four of the parts and the SA_EC_CAL verification kit could not be ran, because of nonavailability of either parts, jaws, or calibration standards at the time of testing. Although these parts were not ran during the in-system test, they were part of the site acceptance test and were ran during that phase of testing. The two parts that were available and could be run were notched parts, and were run with both the US-500 and NDT25L for comparison. Table 5 shows the results of this testing.

Table 5. US-500/NDT25L In-System Part Test Results

Part Number	Number of Geometries Inspected	Number of Notches	Number of Hits		Number of Notches Found	
			NDT25L	US500	NDT25L	US500
1359M33P01-110	8	11	63	54	11	11
1359M16G05-110	2	1	1	1	1	1

As the data in Table 5 shows, the US-500 performed as well if not better than the NDT25L. They both found all the notches and they both had some false calls. The US-500 had fewer false calls then the NDT25L, but to evaluate whether one was actually better than the other in this respect would require multiple runs for comparison. It should be noted that there are many reasons for false calls, one of which is whether the part is clean. We did not clean or polish these parts prior to testing. These are test parts and are generally fairly clean, but they do tend to collect scratches, dings, and dirt over time. All of the data collected during the in-system test showed that the US-500 met the minimum specified requirements, or higher, to satisfy as a drop in replacement for the NDT25L. The only remaining test was the site acceptance test.

The site acceptance test was performed at both ALCs and involved the same parts listed for the in-system test including the parts that were not available during in-system testing. The F110 3RD Stage Fan Disk (P/N 1359M73P02-110, un-notched), the F110 HPT Disk (P/N 1359M33P01-110), and the F110 4-9 Spool (P/N1359M16G05-110) were ran at the OC-ALC while the F100 8TH Stage HPC Disk (P/N 4040108), the F100 13TH Stage HPC Disk (P/N 4041013), the F220 1ST Stage Fan (P/N 4041701) and the SA_EC_CAL Verification Kit were ran at the SA-ALC. Testing at both sites involved running a baseline test of the notched parts using the NDT25L to compare results with the US-500 site test inspections. At each site, the same ECIS was used for testing the ECIs with the only variables being the ECI. Table 6 shows the part inspection results of the site acceptance testing. As Table 6 shows, both units found all the notches on the notched parts. The NDT25L and the US-500 basically had the same number of hits except with the P/N 4071701 inspection at the Kelly ALC. In this inspection, the US-500 had almost double the amount of hits. These extra hits occurred in the Web_8.Fwd inspection and are believed to be caused by the probe. The Web_8.Fwd was run with the NDT25L late in the day, and the inspection with the US-500 was performed the next day. When it came time to run the Web_8.Fwd with the US-500, the probe that was used the previous day could not be located and a different probe was used. It is believed that the second probe was noisier than the first. Since the US-500 did find all the notches, it did pass the part test.

Table 6. US-500/NDT25L Site Acceptance Part Test Results

Part Number	Number of Geometries Inspected	Number of Notches	Number of Hits NDT25L	Number of Hits US500	Number of Notches Found NDT25L	Number of Notches Found US500
TINKER ALC						
1359M73P02-110	2	Un-Notched	0	0	-	-
1359M33P01-110	8	Un-Notched	37	44	-	-
1359M16G05-110	2	1	20	1	1	1
KELLY ALC						
4040108	7	12	12	12	12	12
4041013	13	7	20	22	7	7
4071701	5	18	25	50	18	18

Table 7 shows the results of the SA_EC_CAL reliability test ran at the Kelly ALC. The reliability data in Table 7 again shows that the US-500 and NDT25L results are within 1 mil of each other; the US-500 SA_EC_CAL results were therefore acceptable.

Table 7. US-500/NDT25L SA_EC_CAL Reliability Results

SA_EC_CAL RELIABILITY	Threshold	NDT25L A90/A95 Values	US500 A90/A95 Values
Waspoly Bolt Hole	120	10.7 mils.	10.8 mils.
IN100 Bolt Hole	120	14 mils.	13.6 mils.

All three phases of testing were successful; see the Eddy Current Instrument Replacement Final Report [1] for more details. A redline of the Technical Orders (T.O.) was also completed and submitted to show the installation and removal procedures for the new ECI.

Following the completion of the Phase 1 portion of the ECI replacement, Phase 2 began and was completed. Phase 2 addressed the design concepts associated with providing both multi-channel and multi-frequency capabilities in the replacement ECI. The replacement ECI multi-channel and multi-frequency design concepts were developed along with the replacement scanner design concept and are presented in the Improved ECIS Scanner and US-500 Eddy Current Instrument Advanced Features Design Concept report. [3] To add the multi-frequency capability to the US-500 required the redesign of the frequency card, plus an additional analog card, and an additional digital signal processing (DSP) card. The US-500 ELAB software would also have to be modified to allow the display of the multi-frequency data. No additional design requirements were needed for the scanner, but extensive software modifications to the ECIS system software would be required to interface with the ECI for multi-frequency operation. To implement multi-channel capabilities in the replacement ECI, would require another analog card and another Digital Signal Processing (DSP) card. The US-500 ELAB software would also have to be modified to display the multi-channel data. Due to the limited number of rotary transformer taps available in the new scanner design, the system would be limited to only two additional channels, one horizontal and one vertical. The cost associated with providing the multi-channel and multi-frequency capability was in excess of $180K. This information was presented to the Project team for review. The Project team decided not to pursue the multi-channel or multi-frequency option for the replacement ECI at this time because the initial return did not outweigh the cost.

2.1.3 Acceptance

With successful site test completions at both ALC sites and acceptable results from the independent analysis of the reliability data, the US-500 was officially accepted as a drop-in replacement for the NDT25L ECI. To date, the majority of the NDT25L ECI have been replaced with the new US-500 ECI following this successful demonstration of the prototype ECI.

2.1.4 Benefits

There are four benefits with the US-500 ECI. First, the US-500 is less expensive than the NDT25L. The current cost of purchasing an NDT25L is $45,000 (if one can be located since they are obsolete), and the US-500 sells for $17,500, making a cost difference of $27,500. Secondly, the NDT25L requires a calibration twice a year at a cost of $2000 per calibration. The Tinker ALC alone has 25 NDT25L units, not counting spares. The elimination of the NDT25L calibration will save at least $100,000 per year, meaning that the elimination of the calibration cycle will pay for the new US-500 upgrades within 5 years. The US-500 does not have a return-to-factory calibration cycle because, basically, it self-calibrates during use. However, it is recommended that it be checked once a year to verify that there is no problems. This check can be done by on-site maintenance technicians following UniWest's QSP-6295 calibration procedure using calibrated oscilloscopes and multi-meters. Third, the US-500 has an extended bandwidth. The bandwidth of the NDT25L was 100KHz to 6MHz where the bandwidth of the US-500 is 100KHz to 10MHz. This extended feature will become useful as demands occur for smaller flaw detections in the future. Fourth, the US-500 has several future enhancement options allowing for growth to the ECIS stations. It has an extended filter range, in both the low-pass and the high-pass filters, and has a digital output option. Both of these added features will assist in eliminating components and reduce the cost of the ECIS system. However, modifications to the ECIS system, both hardware and software, are required to take advantage of these options.

2.1.5 Lessons Learned

The US-500 ECI is controlled by UniWest's proprietary ELAB software, which is used in the majority of the ECI units that UniWest makes. The US-500 version was created by modifying the existing US-450 ELAB software. This approach was taken in an effort to save both time and money during the development of the US-500. Once development started, there were several unexpected problems that had to be overcome to make the US-500 ELAB software emulate the NDT25L so that the US-500 would be a drop-in replacement for the NDT25L. Hindsight indicates that it would have been better to create a new version of the US-500 software specifically for ECIS. This mostly likely would have lead to an ECIS specific US500 ELAB software package for the ECIS stations, which would not have met the present USAF goal of commercial off-the-shelf (COTS) products. However, it would have provided a cleaner software package and would have allowed for easier modification of the software in the future to allow the ECIS to take advantage of many of the US-500's advanced features.

A second lesson learned is that since the US-500 is composed of two components: an Eddy Current Unit and a separate Computer Unit; the Computer Unit can be replaced in the future by the ECIS System computer. Therefore, the ELAB software will have to be ported over from the Windows 95 operating system to the Windows NT operating system, and will have to be developed to reside and operate from the ECIS System Computer. This will allow the elimination of the US-500 computer, reducing cost and complexity of the ECIS System. This approach was not done under the Advanced NDE RFC/ENSIP contract because the new ECIS computer was being developed at the same time, and was not available. It would also have a direct effect on the drop-in replacement requirement.

2.2 Scanner Replacement

There are several areas of the scanner that need to be investigated and improved. First, the ECIS scanner is composed of several obsolete components, which is making it increasingly difficult and expensive to repair and maintain. Second, the overall design of the scanner requires that it be removed from the ECIS system for repairs. This is a time-consuming process that adds to the downtime of the stations. A third area concerns the scanners limited bandwidth of 100KHz to 6MHz. This limited bandwidth makes it difficult to meet the ever-increasing demand of smaller flaw requirements. This subtask and associated work was assigned to Veridian Engineering. An overview of the work performed is given in the following subsections.

2.2.1 Project Scope

The project scope was to design, develop, test, and implement a drop-in replacement for the ECIS scanner to improve the signal response, signal integrity, and repair/maintainability of the scanner. Every effort to utilize newer electronic technologies will be made. Investigate the advantages and disadvantages of incorporating multi-channel and multi-frequency capabilities into the ECIS system.

2.2.2 Work Performed

The scanner was characterized to determine areas for improvement and to develop the design concept and associated design goals as shown below:

- The new scanner must be a drop-in replacement for the existing scanner as far as mounting, interconnection and signal integrity.
- An increase of the scanners signal bandwidth from approximately 6MHz to at least 10MHz.
- A flat signal response (+/- 1dB or less) across the signal bandwidth of 100KHz to 10MHz.
- Decrease signal noise through the scanner.
- Update circuit components to eliminate obsolete components.
- Improve and simplify scanner maintainability and repair.

The existing scanner was characterized and a new scanner design concept was developed with the goals stated above. The design concept also included the requirements and costs associated with adding multi-channel and multi-frequency capabilities to the overall ECIS system (US-500 and scanner). The design concept was presented to the Project Team for approval (see the Improved ECIS Scanner and US-500 Eddy Current Instrument Advanced Features Design Concept report [3] for details).

The Project Team approved the new scanner design without the multi-channel and multi-frequency capabilities. It was decided not to include the multi-channel and multi-frequency capabilities at this time, because the initial return did not outweigh the cost. Following the Project team's approval, the design was finalized and the prototype development began. Schematics and printed circuit card layouts were created. The printed circuit cards were manufactured, assembled, and tested. In an effort to save funds, an older style surplus scanner was transferred to the contract and upgraded to the present ECIS Version 3 level. The scanner was further upgraded with the new wiring and electronics required for the Advanced NDE RFC/ENSIP project improvements. Some mechanical modifications were required to achieve the repair/maintainability improvements of the new design. Following the completion of the prototype scanner, testing was performed to verify that the design goals were met. Three levels of testing were performed: bench test, in-system test, and site acceptance test.

The bench testing included testing the bandwidth and gains of the probe drive, received 0 and received 180 signal paths, checking the micro-manipulator control circuitry, testing the regulation of the power supplies, checking system noise, running the existing scanners acceptance test on the new scanner, and performing an endurance test. Table 8 shows the results of the bandwidth and gain tests of the signal paths mentioned.

Table 8. Scanner Signal Path Bandwidth and Gain Results

Signal Path	OLD SCANNER		NEW SCANNER	
	Bandwidth	Gain (dB)	Bandwidth	Gain (dB)
Probe Drive	8.95MHz	0.73 +0.0/-0.6	11.6MHz	1.0 +0.07/-0.02
Rec. 0	9.7MHz	2.52 +2.58/-0.0	13.6MHz	2.90 +0.36/-0.0
Rec. 180	9.7MHz	2.52 +2.58/-0.0	13.6MHz	2.90 +0.36/-0.0
Absolute	7.07 MHz	0.046 +0.07/-0.0	12.4MHz	0.041 +0.03/-0.0

The bandwidth points shown in Table 8 were taken at the –3.0dB point or the 70 per cent point, which is the typical point where bandwidth is measured. The new scanner values are all above the 10MHz goal and the old scanner values are all below 10MHz. The gain data shows that the new scanner design has a much more stable gain that varies only about 0.36dB or about 1.04 linear gain. The old scanners received 0 and received 180 signal paths show a variance of 2.58dB or 1.34 linear gain. This gain variance of the old scanner occurs at the 6MHz-frequency range and is due to the parasitic nature of the rotary transformer, which are compensated for in the new scanner design. The probe drive signal path of the old scanner would show the same gain variance except that the power supplies on the rotary card go out of regulation, reducing the supply voltages which has the effect of reducing the gain. The reason the probe drive signal supplies go out of regulation and the receive signals do not is because the probe drive signal is at +/-6Vp-p and the receive signals are only about +/-100mVp-p. The probe drive signal pulls more current in the 6MHz range, thus causing the supplies to become unregulated.

The micromanipulator motors are controlled by the Galil card, which resides in the station computer. Without the controls of the Galil card, only limited bench testing could be performed on the motor control circuitry within the new scanner. A motor was connected to the scanner and the motor control circuitry was told to move the motor forward and reverse, which it did. While moving the motor in the forward and reverse directions, the encoder outputs were checked to verify that the correct encoder pulse sequence was present. The complete bench test of the micromanipulator control circuitry was completed and worked as intended. Additional testing of the micromanipulator motor control was performed during in-system testing.

The power supplies of the old and new scanners were measured with a 6Vp-p probe drive signal at various frequencies and a 50-ohm termination at both the probe drive output as well as the two receive signal outputs. Measurements of the rotary motor control cards of both units were also taken with motors attached and being driven. Table 9 shows the results of these measurements.

Table 9. Scanner Power Supply Regulation Results

Scanner	6Vp-p Measurement Point	No Input	200KHz Volts	2MHz Volts	6MHz Volts	10MHz Volts
Old	Stationary Card +12V	+11.22	+11.21	+11.22	+11.21	+11.22
	Stationary Card -12V	-11.13	-11.12	-11.13	-11.12	-11.13
	Probe Rotary Card +7V	+7.07	+4.82	+5.04	+4.6	+5.9
	Probe Rotary Card -7V	-7.07	-4.88	-5.11	-5.08	-6
	Rec/Motor Rotary Card +7V	+6.91	+6.92	+6.92	+6.92	+6.92
	Rec/Motor Rotary Card -7V	-6.94	-6.95	-6.95	-6.95	-6.95
	Rec/Motor Rotary Card +7V Motor Active	+4.80	+4.80	+4.80	+4.80	+4.80
	Rec/Motor Rotary Card -7V Motor Active	-4.65	-4.65	-4.65	-4.65	-4.65
New	Stationary Card +12V	+11.52	+11.52	+11.52	+11.52	+11.52
	Stationary Card -12V	-11.41	-11.41	-11.41	-11.41	-11.41
	Probe Rotary Card +5V	+5.05V	+5.05V	+5.05V	+5.05V	+5.05V
	Probe Rotary Card -5V	-4.99V	-4.99V	-4.99V	-4.99V	-4.99V
	Motor Rotary Card +4V	+4.01V	+4.01V	+4.01V	+4.01V	+4.01V
	Motor Rotary Card -4V	-3.98V	-3.98V	-3.98V	-3.98V	-3.98V
	Motor Rotary Card +4V Motor Active	+4.01V	+4.01V	+4.01V	+4.01V	+4.01V
	Motor Rotary Card -4V Motor Active	-3.98V	-3.98V	-3.98V	-3.98V	-3.98V

Table 9 shows that the voltages on the stationary cards of both units remain stable across the various probe drive frequencies. The power supply outputs on the rotary cards of the old scanner are not as stable across this same range of frequencies. Keep in mind that the ECIS system was originally designed for 2MHz operation, the 6MHz requirements came after the initial design and the system has had to function in the 6MHz range. The old scanner's rotary power supplies are unregulated supplies, and because the supplies are unregulated the outputs were adjusted to their maximum value of +/-7V to compensate for any heavy current draws. The old scanner design also uses older designed components, which have minimum supply voltages of +/- 5V. As Table 9 shows, under heavy current loads the unregulated supplies often fall at or below this minimum +/- 5V level. The new scanner design uses regulated power supplies and uses components that operate at +/- 3V minimum levels whenever possible. The new scanner's Probe Rotary card uses +/- 5V supplies and the motor control card uses +/-4V supplies. Table 9 shows that the new scanner power supplies remain stable across the various frequency ranges and with the load of the motor. The new scanner's power supplies prove to be an improvement over those of the old scanner.

The system noise of the two scanners was the next test run. The noise measurements were made under two conditions: no input and a 6Vp-p 6MHz probe drive input. All unused inputs and outputs were terminated with 50-ohms. Table 10 shows the results.

Table 10. Scanner Noise Comparison Results

Rotary Side									
	Input	Probe Drive Input	Outputs				Supply Voltages	
			Probe Drive	Rec. 0	Rec. 180	Abs.	+7V/+5V	-7V/-5V
Old Scanner	No Input	22mVpp @ 20KHz	18.5mVpp @ 20KHz	8.5mVpp @ 20KHz	6mVpp @ 20KHz	6.5mVpp @ 20KHz	7mVpp @ 20KHz	7.5mVpp @ 20KHz
	6Vpp @ 6MHz Input	N/A	N/A	206mVpp @ 6MHz	157mVpp @ 6MHz	66mVpp @ 6MHz	99mVpp @ 6MHz	91mVpp @ 6MHz
New Scanner	No Input	35mVpp @ 113KHz	3mVpp @ 170MHz	8.5mVpp @ 200MHz	13mVpp @ 200MHz	22mVpp @ 113KHz	5mVpp @ 113KHz	4.5mVpp @ 113KHz
	6Vpp @ 6MHz Input	N/A	N/A	300mVpp @ 6MHz	285mVpp @ 6MHz	440mVpp @ 6MHz	11.5mVpp @ 6MHz	22.5mVpp @ 6MHz

The new scanner design had considerably less noise on the power supplies, but did have more 6MHz crossover on the receive signal output. The additional 6MHz crossover noise is due to the probe drive and receives circuits being on the same rotary card in the new design. Since the 6MHz will be demodulated out in the ECI, this added crossover is not a problem. Overall, the two designs are about equal in noise levels.

The next test performed on the bench was to run the old scanner Acceptance Test Procedure (ATP) on the new scanner. Table 11 shows the acceptable values and the values measured on the new scanner. All of the new scanner values measured were within the tolerances of the ATP.

Table 11. New Scanner ATP Measurements

Scanner Acceptance Test					
	Receive 0		Receive 180		Absolute
	Large Signal	Small Signal	Large Signal	Small Signal	
Acceptable Value	20mV +/- 20%	Less Than 15mV	20mV +/- 20%	Less Than 15mV	35mV +/-20%
Measured New Scanner Value	19mV	3mV	20mV	3mV	34.6mV

The last bench test performed was an endurance test. The new scanner was run for 100 hours straight with a Rotating Eddy Current Hole Inspection Instrument (RECHII) probe rotating in the collet, and a 6Vp-p 6MHz probe drive signal applied. All unused inputs and outputs were terminated with 50-ohms. The RECHII spinning was stopped periodically to take measurements to ensure that the scanner was still operating correctly. During the measurement periods the following measurements were made and recorded:

- Internal scanner temperature.
- Power supply voltages of all scanner circuit cards.
- Noise levels.
- Frequency response plots.
- Motors were installed and the motor circuit tested.
- Old scanner ATP.

The new scanner passed the endurance test without problems and without any unacceptable measurement drifts. This concluded the bench test phase of the scanner testing, the next set of tests to be performed were the in-system tests.

The in-system testing involved installing the new scanner into an ECIS system and performing a more in-depth micromanipulator motor control test, parts tests, and reliability tests. For the in-depth micromanipulator motor control test, a number 971-micromanipulator probe was inserted into the scanner. The probe was initialized and sent to the 0-degree position. A dial indicator was used to verify that the probe was at the 0-degree position. The probe tip was then moved to the 90 degree position and again checked with the dial indicator. The probe tip was moved from 90 degrees to 0 degrees and back to 90 degrees 10 times. After each move the position was verified with the dial indicator. Each time the probe tip was within the allowable 5mil tolerance of the position, it was commanded.

The next in-system test was the parts test which included inspecting various geometries of the F229 1ST Stage Fan Disk (P/N 4071223), the F129 1ST Stage Fan Disk (P/N 1359M73P01-129), the F220 1ST Stage Fan Disk (P/N 4071701), and the F110 HPT Disk (P/N 1359M33P01-110). All of these were notched parts, and were run with both the old and new scanner for comparison. Table 12 shows the results of the in-system parts test.

Table 12. Scanner In-System Part Test Results

Part Number	Number of Geometries Inspected	Number of Notches	Number of Hits		Number of Notches Found	
			Old Scanner	New Scanner	Old Scanner	New Scanner
4071223	6	11	19	23	10	11
1359M73P01-129	2	14	25	15	14	13
4071701	1	8	14	14	8	8
1359M33P01-110	5	14	41	43	14	13

For the P/N 4071223 F229 1ST Stage Fan Disk, the new scanner found all 11 notches and the old scanner found all but 1. On the P/N 1359M73P01 F129 1ST Stage Fan Disk, the old scanner found all the notches and the new scanner found all but one. Both the new scanner and the old scanner found all the notches on the P/N 4071701 F220 1ST Stage Fan Disk. On the last part inspected, the old scanner found all the notches and the new scanner missed one notch. In all three cases where either the old or the new scanner missed a notch, the notches were in the wrong locations. They were just outside the area of inspection. With each inspection, the probe may start at a slightly different position and depending on the start position the notch may be found or it may be missed. The new scanner's part inspection results were acceptable and the last in-system test, reliability was begun.

The in-system reliability test included the 6MHz IN718 bolt hole, 6MHz Waspoly flat plate, 2MHz Waspoly flat plate and 6MHz TI6246 broach slot reliability specimens. The 6MHz IN718 bolt hole, 2MHz Waspoly flat plate, and the 6MHz Waspoly flat plate data were collected. It was decided to collect the 6MHz TI6246 broach slot reliability data at the Tinker ALC because of problems with collecting the 6MHz TI6246 broach slot reliability data with both the old scanner and the new scanner, and station availability problems. The reliability data collected with the new scanner at Veridian, Dayton, Ohio was compared with existing old scanner data or recently collected old scanner data. Table 13 shows the results. The 6MHz IN718 bolt hole and the 2MHz Waspoly flat plate results were both within the 1mil acceptability range for the reliability data, but the 6MHz Waspoly flat plate data was out by as

Table 13. Scanner In-System Reliability Test Results

Reliability Ran	Threshold	NDT25L A90/A95 Values	US500 A90/A95 Values
IN718 6MHz Bolt Hole	50	9.63 mils.	9.52 mils.
2MHz Waspoly Flat Plat	50	6.77 mils.	5.78 mils.
6MHz Waspoly Flat Plat	250	8.75 mils.	1.87 mils.

much as 7 mils. Veridian felt that an error in either collecting the data or in analyzing the data had occurred. Time was running short on the contract and since the bench test, part test, and two-thirds of the reliability data was acceptable, it was decided to send the reliability data to Dr. Al Berens of UDRI for an independent analysis of the data and proceed with the site acceptance testing.

The site test involved running the same parts used in the in-system test at the OC-ALC plus the TI6246 broach slot reliability that was not run during in-system test.

A baseline of the notched parts was run using the old scanner as a comparison for the new scanner site test results. The same ECIS was used with the old and new scanner; the scanners themselves were the only variables. Table 14 below shows the results of the site test at the Tinker ALC.

Table 14 shows that the new scanner had as good, if not better results than the old scanner. The new scanner found all but one of the notches, on the F110 HPT Disk, P/N 1359M33P01-110, and the old scanner missed that same notch. The old scanner missed two notches on the F229 1ST Stage Fan Disk P/N 4071223, but these notches were in

Table 14. Scanner Site Part Test Results

Part Number	Number of Geometries Inspected	Number of Notches	Number of Hits		Number of Notches Found	
			Old Scanner	New Scanner	Old Scanner	New Scanner
4071223	6	11	77	58	9	11
1359M73P01-129	2	14	185	236	14	14
4071701	1	8	62	20	8	8
1359M33P01-110	5	8	30	32	7	7

the dove tail inspection and are just outside of the inspected area. These are the same notches that were missed during in-system testing, and they might be found or might be missed depending on the starting position of the inspection.

The TI6246 broach slot reliability data was run and returned to Veridian for analysis. Table 15 shows the results.

Table 15. Scanner Ti6246 Broach Slot Reliability Results

Reliability Ran	Threshold	NDT25L A90/A95 Values	US500 A90/A95 Values
TI6246 Broach Slot Reliabilty	150	4.43 mils	5.70 mils.

The TI6246 broach slot data for the new scanner was out from the old scanner data by 1.27 mils. This is sometimes acceptable depending on other parameters of the analysis, but in this case Dr. Berens of UDRI felt that the scatter was too large and therefore the results were unacceptable. The results of Dr. Berens analysis are available in Section 4.0 of his final report.[2]

After testing was completed, the Scanner Replacement Final Report [4] was submitted, which provided complete details of the task.

2.2.3 Acceptance

All of the new scanner design goals were accomplished; however, to date the new scanner has not officially been accepted for production. All of the bench tests showed positive results while the in-system test showed mixed results. The 6MHz bolt hole and 2MHz Waspoly flat plate reliability results were good and accepted by Dr. Al Berens of UDRI as part of his independent analysis. However, the 6MHz Waspoly flat plate and 6MHz TI6246 broach slot data comparisons showed disparities and were not approved by Dr. Berens. The parts tested for both the in-system and site testing showed that the new scanner could find the notches as well or better than the old scanner. Due to some concerns associated with the amplitudes of the notches, the new scanner was not accepted by the OC-ALC at the site test. With the present data, Veridian Engineering believes that the cause of the concerns with the notch amplitudes and 6MHz flat plate and broach slot reliability is associated with the probe drive signal amplitude. In order to maintain a constant gain through the scanner, the probe drive signal at the scanner's output is equal to the 6Vp-p probe drive signal input. This is higher than the probe drive signal of the old scanner. This can be easily adjusted, but will require additional testing both at Veridian Engineering and at the OC-ALC site.

2.2.4 Benefits

The benefits of the Advanced NDE RFC/ENSIP project scanner cannot be realized until it is officially accepted. They are basically the same as the design goals and are provided below:

- The new scanner is a drop-in replacement for the existing scanner as far as mounting, interconnection and signal integrity.
- The new scanner has a wider signal bandwidth of 100KHz to 10MHz.
- The signal response is flat to less than +/- 3dB across the signal bandwidth of 100KHz to 10MHz.
- Signal noise through the scanner is as good or better than the existing scanner.
- Updated circuit components were added to eliminate obsolete components.
- The new scanner's maintainability and repair has been simplified.

Of the benefits listed the extended bandwidth, the updated components, and the improved maintainability are the most useful benefits. The extended bandwidth will assist in more accurately finding smaller flaws as future requirements to find smaller flaws are investigated. Many of the out of date components are getting harder to find and more expensive to purchase. The obsolete LH0002 and LM733 devices are presently selling for $28 and $55 each, respectfully. These costs will continue to rise until these components can no longer be found. The devices that replace these components in the new scanner sell for $2.60 and $11.90, respectfully. The improved maintainability will be the most recognized benefit. The printed circuit cards in the new scanner have been relocated for easy access and removal of the scanner from the station will no longer be required for scanner repair. This will cut the scanner repair time down by 10 to 12 hours and will decrease station downtime by as much as 4 hours. The actual cost savings associated with these reduced labor hours are difficult to estimate since we presently do not have sufficient cost and labor data concerning scanner repair and related station downtime. However, qualitatively the primary benefits are that the uptime has been increased and the scanner maintenance time has been decreased.

2.2.5 Lessons Learned

Over the last 10 to 15 years, military electronics has shifted away from the Military Specification (MILSPEC) requirements and shifted more to off-the-shelf components (COTS). Cost and availability have primarily driven this effort. Components tested to MILSPEC requirements must go through much more intensive testing and the cost is considerably higher. Although COTS components are lower in cost and generally easier to obtain, they do have a down side. Electronic component manufacturers are in business to make a profit. If a commercial component does not have a high enough demand to maintain a reasonable profit ratio, the manufacturer discontinues the component. With the present rate that technology is advancing, the product end of life of these components will generally occur within 2 years. This means that a circuit design must be reviewed under a sustaining engineering process at least every 2 years.

Lessons learned in regards to the scanner data variances associated with the 6MHz bolt hole and broach slot reliability is still being determined. There are several areas where the problem could lie and until the problem is solved no lessons have actually been learned. Further testing associated with probe drive amplitudes and associated notch responses are still being investigated. Veridian Engineering is committed to completing the new scanner development and will continue working on the solution to the reliability data variances seen with the new scanner.

2.3 Eddy Current Probes

Several goals for improvement of the eddy current probes were established. These goals included improving sensitivity, stability, noise reduction, and probe tip wear as well as investigating higher compliance and wide-scan area probes. The investigation into wide-scan area probes and associated funds were later removed from the contract because this same investigation was being done on some of the F100-PW-220 Component Improvement Programs (CIP), and it was felt that this would be an inefficient use of funds. The remaining five areas of improvement were further broken down into three subtasks. These three subtasks were Improved Probe Internal Wiring, Shoe Wear, and High Compression Probes. Each of these subtasks is discussed in the following subsections.

2.3.1 Improved Probe Internal Wiring

The improved probe internal wiring task involved studying the present probe wiring and determining what enhancements, if any, could be made to improve the sensitivity, stability, and noise reduction aspects of the eddy current probe. This subtask and associated work were assigned to Veridian Engineering. An overview of this work is given in the following subsections.

2.3.1.1 Project Scope

The intent of the project scope was to analyze the present internal wiring system of the eddy current probes, with emphasis on enhancing the design using advanced signal distribution and shielding techniques. The goal of this task was to baseline the present wiring techniques used and enhance the present design to improve eddy current probe sensitivity, stability, and noise reduction.

2.3.1.2 Work Performe d

The coils typically used in the eddy current probes are differential reflection coils, which have one drive coil and two receive coils (see Figure 2). When the probes are inserted into the ECIS scanner for an inspection, the outputs of the two receive coils travel through the probe and are applied to the two inputs of a dual output differential amplifier located in the scanner.

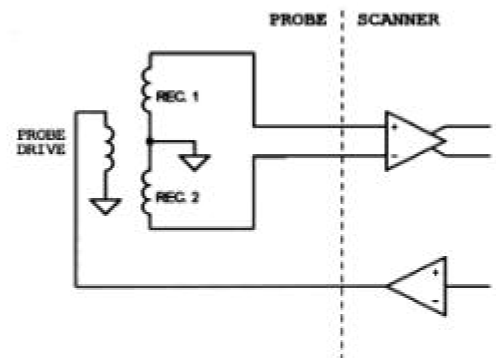

Figure 2. Probe/Scanner Interface

The movement of the coils across a flaw produces two similar signals slightly delayed from each other. The delay is due to the fact that the coils are constructed such that one coil follows the other across the flaw (see Figure 3). These two signals are applied to the two inputs, Input A and Input B, of the differential amplifier. The differential amplifier subtracts the signal at Input B from the signal at Input A, applying the difference of the two signals to Output A, and subtracts the signal at Input A from the signal at Input B, applying this signal difference to Output B. It is this action by the differential amplifier that produces the 180-degree phase difference of the two signals and it is

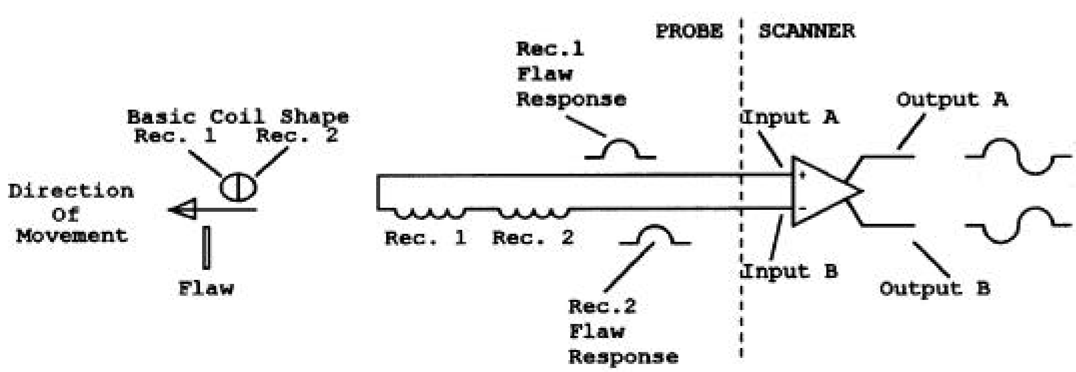

Figure 3. Probe Signal

also this action that provides the major noise reduction on the incoming probe signals. Any like signals, same phase and amplitude, on the two inputs of the differential amplifier, such as noise, are subtracted out or canceled at this point. The closer the balance, both phase and amplitude, of the two receive signals at the output of the probe, the better the system sensitivity to flaw indications and the better the noise reduction.

The basic design of the existing eddy current probe was analyzed and tested with emphasis on the probe wiring and its effect on the coil balance, both phase and amplitude. The differential reflection coil imbalances associated with the manufacturing limitations of the coils were also investigated.

The probe types used on the ECIS system are categorized into five categories, dimensioning, RECHII (bolt holes), surface, variable axis (micromanipulator or variable tip angle), and contour following (scallops). The variable axis probes are further subcategorized into surface and sewing stitch probes. The dimensioning probes use either an absolute coil (number 91 probe) or a linear variable displacement transducer (number 92 probe). Only the differential reflection coils used for flaw inspections in the other four probe categories were of interest for this analysis, so the dimensioning probes are excluded. The remaining probe categories all use the same basic type of differential reflection coils, varying only in coil size, inductance, and frequency range of operation.

The internal wiring of all four probe categories of interest is basically the same. The coil assembly consists of three separately wound coils, the probe drive coil, receive 1 coil and receive 2 coil. The two receive coils are manufactured by wrapping magnet wire around a "D" shaped ferrite resulting in a "D" shaped receive coil. The two "D" shaped receive coils are then placed back-to-back and wrapped together with another magnet wire. This outer wrapping creates the probe drive coil and works to contain the two receive coils. The result is a slightly oval shaped coil assembly with six leads (see Figure 3). The six leads of the coil assembly are then attached to four hookup wires through either direct wiring, a jumper block, or a small connector. This wiring format is dependent on the category of probe RECHII, surface, or variable angle/contour following. This is done by tying one end of each coil to a common wire or point (ground) and each of the three remaining coil wires to one of the remaining hookup wire/points (see Figure 4 below).

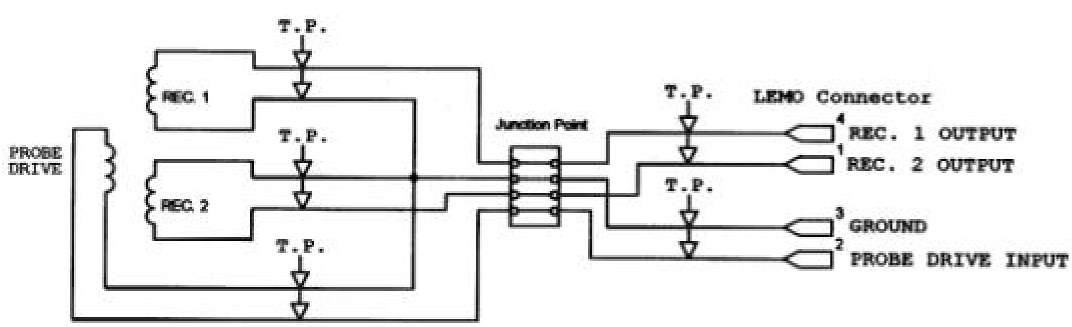

Figure 4. Internal Probe Wiring

The other end of the hook-up wires connects to the LEMO connector, which in turn will form the interconnection to the scanner.

The first step of the analysis was to look at only the coil assembly and its associated wiring. A 6MHz coil was connected to an HP3577A Network Analyzer and the balance of the coil, both phase and amplitude, was measured with three different twisting configurations of the wire, no twist, light twist (1 to 2 twists per inch) and a tight twist (4 to 6 twists per inch). In both of the twist configurations, each of the three coils received 1, received 2 and probe drive were twisted with the associated return wire. The results of these measurements are shown in Table 16.

Table 16. Coil Assembly Balance

Wire Configuration	Balance	Sensitivity To Wire Position
No Twist	Poor	Very Sensitive
Light Twist (1-2/In.)	Good	Very Insensitive
Tight Twist (4-6/In.)	Excellent	Very Insensitive

As Table 16 shows, the best results were obtained by using the tight twist; the balance was excellent and was very insensitive to wire position. Having determined the best wiring configuration for the coil assembly, the interconnection, from the coil assembly wires to the LEMO connector, was added using hookup wire. Ideally, we would have continued the six-wire approach all the way through the probe to the LEMO connector. However, the number of pins in the LEMO connector was a limiting factor, so we had to proceed with the original approach of transferring from the six-wire coil assembly to a four-wire system. A similar testing approach like the coil assembly testing was used, although now, we were testing the complete wiring through the probe and varying the

Table 17. Complete Probe Wiring Balance Results

Wire Configuration	Balance		Sensitivity To Wire Position
	Phase	Amplitude	
No Twist	-0.224 Deg	0.606 dB	Sensitive
No Twist with Foil	-0.224 Deg	0.08 dB	Very Insensitive
Light Twist (1-2/In.)	-0.224 Deg	0.290 dB	Very Insensitive
Light Twist with Foil	-0.224 Deg	0.08 dB	Very Insensitive
Tight Twist (4-6/In.)	-0.089 Deg	-0.069 dB	Very Insensitive
Tight Twist with Foil	-0.089 Deg	-0.069 dB	Very Insensitive

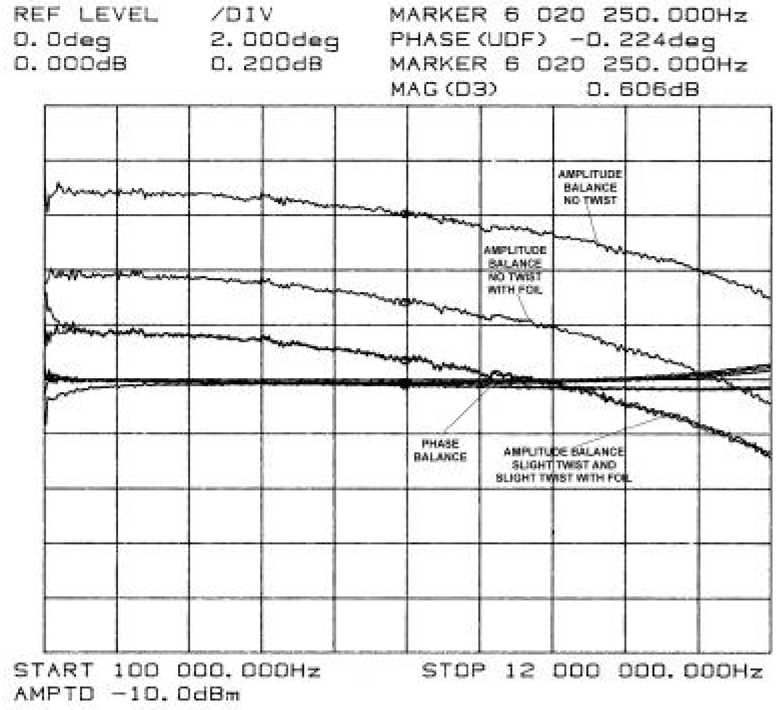

Figure 5a. Improperly Twisted Wiring Response

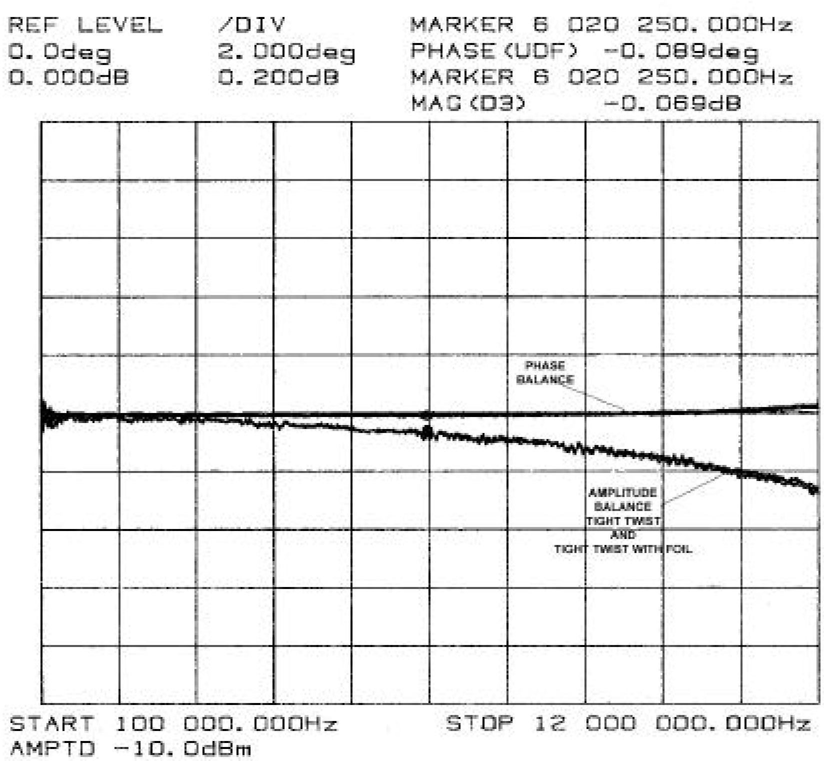

Figure 5b. Properly Twisted Wiring Response

Figure 5. Twisted Wire Phase and Amplitude Plots

twist configuration of the four hookup wires. For this test, the receive 0 and receive 180 wires formed one twisted pair, and the probe drive and ground wires formed the other. The same three-twist configurations were used as for the coil assembly testing; no twist, light twists (1 to 2 twists per inch) and a tight twist (4 to 6 twists per inch). In addition to the three-twist configurations, foil shielding was used over both the six-wire and the four-wire areas to see what effect the additional shielding would have (see Table 17). Figures 5A and 5B show the Network Analyzer Plots of the various configurations tested. The center horizontal line of both plots of Figure 5 is the 0dB point for the amplitude balance and 0-degree point for phase balance, while the center vertical line is the 6MHz point. The coil used in these tests was a 6MHz coil, so the point of interest is the intersection point of the 0dB/0-degree and 6MHz lines. Ideally, both the phase balance and the amplitude balance would be 0 at the 6MHz-intersection point. From Table 17 and the plots in Figure 5, it is clear that the proper twisting of the wires is essential for maintaining a good coil balance. The additional foil shielding seems to help with wiring that is improperly twisted, but has little effect on properly twisted wiring. The results of this testing shows that to achieve the best coil balance without adding components is to twist both the coil assembly wires and the coil hookup wires with four to six twists per inch. It also shows that going with the added cost of additional shielding will result in little improvement, which means that simple twisting of the wires, is sufficient.

Having determined that the four to six twists per inch is the best approach for the internal probe wiring without adding components, testing was done to see if additional components could enhance the coil balancing. The prime objective was to overcome the inherent differential coil imbalances associated with the manufacturing limitations of the coils as well as any imbalances induced by the probe wiring itself. The goal was to have an adjustment range that would allow for perfect phase (0 +/- 0.1 degree at frequency of operation) and amplitude balancing (0 +/- 0.1dB at frequency of operation) of the probes. The resistor/potentiometer circuit shown in Figure 6 was developed and installed in two 0.143 diameter experimental RECHII probes (S/N 12276 and 12279) for testing purposes. A photo

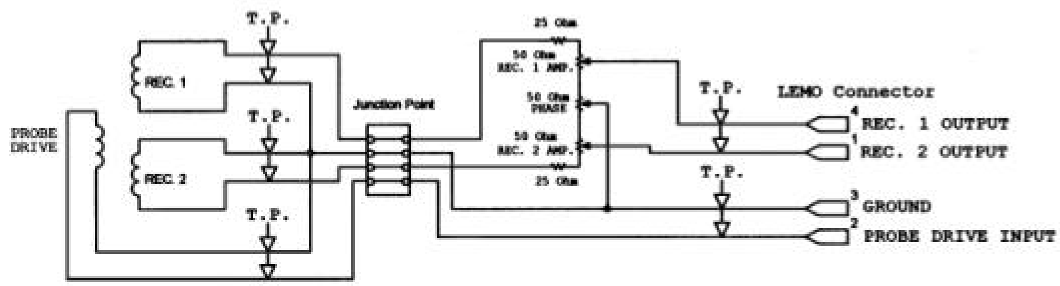

Figure 6. Resistor/Potentiometer Circuit

of one of the experimental RECHII probes is shown in Figure 7. RECHII probes were selected because of concerns of whether the potentiometer adjustments would change during operation. Under typical operation, a RECHII is spun at a maximum velocity of 1500 RPM. This spinning would put the most amount of strain,

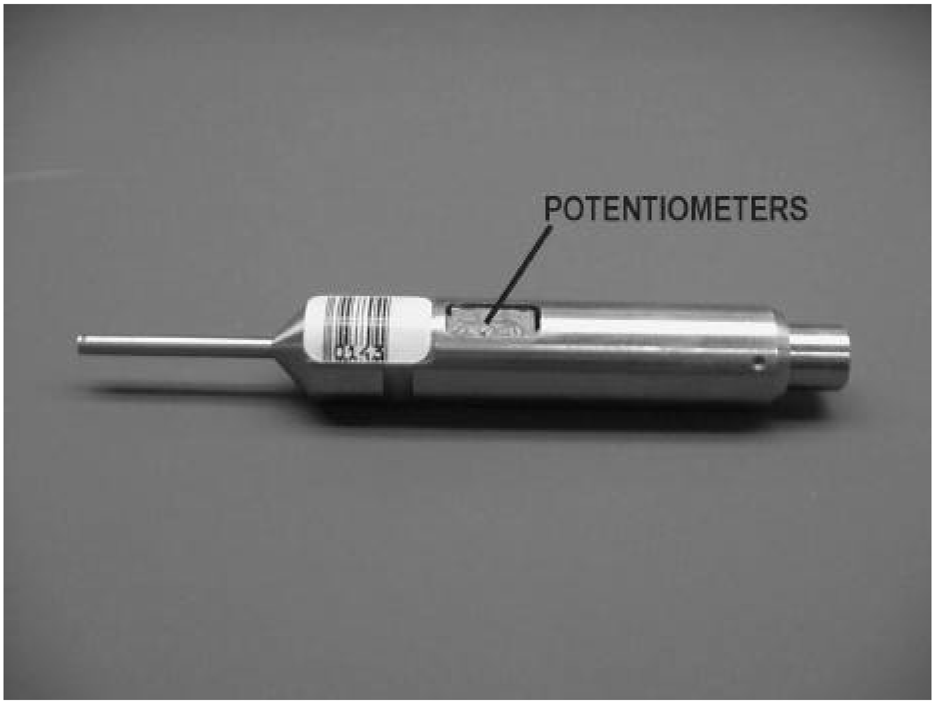

Figure 7. 0.143 RECHII Probe With Potentiometers

due to the angular velocity and acceleration, on the resistor/potentiometer circuitry and would determine the stability of the installed circuit and its adjustments. The RECHII probe was balanced using an HP3577A Network Analyzer by adjusting the three potentiometers, shown in Figure 7, for the optimum balance. After adjustment the potentiometer adjustment screws were secured with an anti-tamper paste to help enhance the stability of the adjustment screws and to ensure that the screws were not tampered with during testing. Table 18 shows the balances obtained for the two probes and Figure 8 shows the typical phase and amplitude balanced frequency response plots. As both Table 18 and Figure 8 show, the goal of 0 +/- 0.1 degree and 0 +/- 0.1dB balance was achieved.

Table 18. 0.143 RECHII Probe Balance Results

0.143 Probe Serial Number	Phase 0 +/- 0.1 Deg	Amplitude 0 +/- 0.1dB
12276	0.000 Deg	-0.001dB
12279	0.006 Deg	-0.013dB

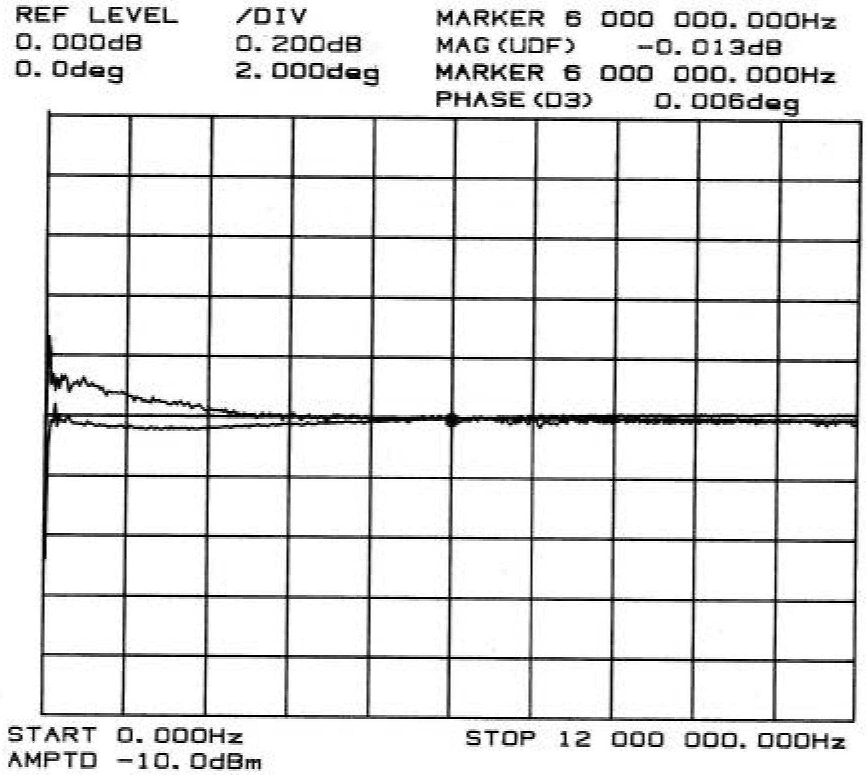

Figure 8. Potentiometer Circuit Phase and Amplitude Balance Plots

The 0.143 RECHII serial number 12279 was spun for 20 minutes with periodic starting and stopping of the spin, to evaluate the stability of the potentiometer adjustment screws. At the end of the 20 minutes the phase and amplitude balance was rechecked to see if it had changed. The phase balance at recheck was 0.007 degrees and the amplitude balance was –0.006dB, which indicated that the potentiometer circuitry and adjustments were stable. The results of the evaluation and testing showed that the phase and amplitude balance of the probes and their associated coils could be controlled with proper wiring techniques and could be improved with additional circuitry.

2.3.1.3 Acceptance

The results of the probe wiring evaluation and testing were presented to the Project Team and accepted by the Government Team. Veridian Engineering had already specified the 4 to 6 twists per inch specification in all of our internal probe drawings and is presently adding this specification to all of our vendor and source control drawings.

The resistor/potentiometer balance circuitry has shown the greatest improvement in the 6MHz probes. It has been implemented in several 6MHz probes, the number 928, number 929, and number 930 probes to mention a few. These are the sewing stitch probes, and because of their design they have additional wiring length and interconnections, which have a greater effect on the probes phase and amplitude balance.

2.3.1.4 Benefits

Several benefits are realized by the improved probe wiring and probe balance circuitry, which are listed below:

- Reduction of noise associated with wiring cross talk.
- Better stability due to reduced susceptibility of receives signals to wire movement.
- Higher Common Mode Rejection (CMR) due to improved phase and amplitude balance.
- Better sensitivity due to a higher Signal-to-Noise Ratio (SNR).

In the field, these benefits equate to fewer false calls and an improved ability to more consistently recognize small flaws. Overall, this means a higher throughput of engine parts through the inspection process and less downtime associated with noisy probe problems. The actual cost savings is difficult to estimate since we presently do not have sufficient cost data associated with the hours spent in analyzing false calls and noise problems associated with the probe wiring. A conservative estimate of labor savings during the inspection process would be 20 to 25 percent. These labor savings would primarily be in the areas of repolishing and reinspection.

2.3.1.5 Lessons Learned

The primary lesson learned is that the phase and amplitude balance of the probe and its associated coil is crucial in eliminating noise and improving both the CMR of the system and the stability of the probes receive signals. Although there are inherent probe/probe coil imbalances induced due to manufacturing limits and the wiring itself, these imbalances can be compensated with additional circuitry. Presently, this circuitry is installed in the probe itself and has to be periodically checked and adjusted, which adds maintenance cost and additional manufacturing costs to the probe. For future consideration, it may be possible to place this balancing circuitry into the scanner and eliminate it from the probes, thus eliminating the additional probe manufacturing and maintenance costs. This balancing circuit in the scanner would be self-adjusting using a software algorithm and the probe balance could be checked and adjusted prior to each inspection.

2.3.2 Shoe Wear

The original probe tips (shoes) developed for the ECIS system were cast with epoxy and filled with aluminum oxide. The shoes were placed on the part to be inspected and compressed sufficiently to take up the expected +/-0.005-inch part deviation. During the first years of inspection, this shoe material allowed probe shoes to be used for several hundred hours before it was necessary to replace the shoes. This was due to the parts being relatively smooth, but as parts began to age, and mean time for inspection increased, the parts surface became rougher and probe shoes began to wear more rapidly. A number of quick fixes to remedy the problem were tried, different spring tension, teflon tape, etc., but a thorough investigation into the wear phenomena was never conducted. This investigation was conducted under the Advanced NDE RFC/ENSIP contract. This subtask and associated work was assigned to

SWRI. An overview of the work performed is given in the following subsections. Note: A large portion of the text in this section of this final report, some of it verbatim, came from the SWRI final study report [5], which was generated as part of the Advanced NDE RFC/ENSIP shoe wear study.

2.3.2.1 Project Scope

The project scope was to conduct an investigation into the shoe wear phenomena by selecting various shoe materials to be tested, test and evaluate these shoe materials, analyze the associated probe wear, and submit a report on the investigations and any conclusions/recommendations.

2.3.2.2 Work Performed

Two basic tests were performed, the first was a test to determine the Coefficient of Friction (COF) of 11 different shoe materials with the results of this test determining which materials would be used for the actual shoe wear evaluation test. These 11 different materials along with their determined COF are listed in Table 19. For the COF test, a disk of each material was placed on a test jig and attached to an Implant Science Corporation ISC-200 Tribometer and rotated at approximately 100rpm. A stylus was placed on the rotating disk and the friction between the stylus and the test material was determined by the drag on the stylus, which was monitored by a load cell. Table 19 shows the results of the first eight materials. The last three materials : aluminum oxide, silicon nitride, and aluminum oxide with a Diamond-Like Coating (DLC) all had very large COF and quickly wore down the stylus. From the first eight materials the Delrin AF had the lowest COF at 0.26. The Delrin AF with the DLC started with a COF of 0.32, which then rose to 0.50 and fell to approximately 0.26 as the DLC was worn away. The Vespel with a DLC had the next lowest COF at 0.30 and the remaining five materials had COF ranging from 0.46 to 0.80. Based on the COF results, it would appear that the Delrin AF with its low COF would wear the best, but to be sure a second test was performed.

The second test was to actually evaluate the shoe materials chosen to determine which materials wore the best and would make the longest lasting probe shoes. Based on the results of the COF test, three materials with different added properties were selected for the wear test. These materials were machined into the shape of a number 8 probe shoe because of its minimal surface area. A total of 12 shoes were made and tested. These 12 shoes, the materials, or materials plus properties they were made from, and the results of the wear test, are listed in Table 20 below. The shoe wear test was performed on a test fixture, which consisted primarily of a lathe.   A Third Stage Fan Disk, P/N 4057703 was mounted to the spindle of a lathe. The lathe spun the engine disk at approximately 36.4rpm.   All 12

Table 19. Coefficients of Friction

Item	Material	Coefficiant of Friction (u)
1	Delrin AF	0.26
2	Delrin AF with a DLC	0.5 - 0.26
3	Vespel	0.46
4	Vespel with a DLC	0.30
5	Ceramic Filled Araldite GY 509 with HY956 Hardner	0.62
6	Ceramic Filled Araldite GY 509 with HY956 Hardner and a DLC	0.50 - 0.60
7	Unfilled Araldite GY 509 with HY956 Hardner	0.50 - 0.80
8	Unfilled Araldite GY 509 with HY956 Hardner and a DLC	0.70
9	Aluminum Oxide (Al_2O_3) plates on Shoe Surface	See Text
10	Silicon Nitride plates on Shoe Surface	See Text
11	Aluminum Oxide (Al_2O_3) plates on Shoe Surface with a DLC	See Text

shoe specimens were mounted to a plate, which in turn was mounted to the lathe in a stationary position. The specimen mounting plate compressed the shoe specimens against the engine disk with a spring force of 41 grams and a compression of 0.040-inches. The shoe mount located the shoes so that all 12 specimens would travel along

Table 20. Probe Shoe Wear Test Results

Item	Material	Shoe Wear After 20 Hours (inch, +/- 0.0005 inch)	Wear (micro-inch/inch)
1	Unfilled Vespel	0.003	150
2	Delrin AF	0.001	50
3	Araldite Filled with Al_2O_3	0.004	200
4	Unfilled Araldite	0.0185	925
5	Vespel with a DLC*	0.004	200
6	Araldite with Al_2O_3 a DLC	0.0075	375
7	Unfilled Araldite with a DLC	0.0015	75
8	Unfilled Araldite with II**	0.0075	375
9	Unfilled Vespel with II	0.02	1000
10	Araldite with Al_2O_3 and II	0.0025	125
11	Delrin AF with II	0.015	750
12	Araldite with Al_2O_3 and Air	0.005	250

* = Diamond-Like Coating
** = Ion Implantation

the, same groove of the engine disk. Air was supplied to the shoe specimen to simulate the RFC inspection process. From this data, it appeared that Delrin; Unfilled Araldite with a DLC, Ceramic-filled Araldite with Ion Implantation and Vespel had the least wear. However, a large amount of material transfer was observed from the shoes to the part and also from the part to the shoes. The effects from this transfer could be twofold. First, the softer shoe material that was transferred to the engine part helped lubricate some of the shoes. Second, the harder shoes removed material from the disk, and this material became embedded in other shoes. Since the probe never travels over the identical same path during an RFC inspection, both of these effects could lead to a false interpretation of the wear data. Also, it became clear that a major part of the probe wear was abrasion because both the DLC and the Ion Implantation surface modifications, which have a thickness of less than 10 to 20 microns, were worn off very quickly.

The probe wear test was changed to better simulate the RFC scanning process. First, instead of testing multiple shoes at one time, which lead to a contamination of the probe shoe (and part) and to a false data interpretation, it was decided to test only one shoe at a time. Second, the probe was not scanned continuously for long periods; rather, it was decided that the probe would be allowed to rotate in contact with the part for a period of time not to exceed 4 hours before it was cleaned to remove any transferred material. Then, the test would be continued with the periodic part cleaning and shoe wear measurement.

Using this testing procedure, additional wear test were conducted on Vespel, Vespel with a DLC, Delrin AF, Araldite epoxy filled with aluminum oxide, aluminum oxide plate, and silicon nitride blocks. It was noticed that the hard materials, such as aluminum oxide and silicon nitride, showed very little wear, but they also began to wear a groove in the disk material after long periods of testing. This says that the hard probe material actually wore the part instead of the probe being worn by the part under inspection. The goal of the project was to develop material or material processes that would provide minimum probe wear, but at the same time not induce wear damage to the engine disk.

The probe wear test was taken one step further by rerunning the wear test on a subset of the materials and spraying the part with a teflon spray. The results of the test of the subset of materials are provided in Table 21 below. For this test the materials were ran for over 300 hours.

Table 21. Probe Shoe Wear Test Results with Teflon Spray

Item	Material	Wear Without Teflon Spray (micro-inch/inch)	Wear WithTeflon Spray (micro-inch/inch)
1	Vespel	1100	-
2	Unfilled Epoxy with a DLC*	250	-
3	Aluminum Filled Epoxy	900	-
4	Delrin AF	363	-
5	Aluminum Wear Plate	57	25
6	Silicon Nitride	73	29
7	Silicon Nitride with a DLC*	-	25

* = Diamond-Like Coating

The subset test results show that out of the materials tested in the initial evaluation, Delrin AF was the best material with respect to lubrication. Tests using the Implant Science Corporation's Tribometer confirmed this. However, the mechanism for this performance is the transfer of Delrin to the test object being rotated under the Delrin probe, which does the lubricating but also produces wear in the shoe.

The harder materials, such as the aluminum oxide and the silicon nitride plates, epoxied onto the cast shoe showed the least amount of wear; and, when used in conjunction with the teflon lubrication spray on the part, exhibited even lower wear.

2.3.2.3 Conclusions/Recommendations

The following four conclusions were drawn from the shoe wear testing:

1) DLC did not significantly improve the wearability of the probe shoes.
2) Silicon nitride and aluminum oxide ceramic blocks bonded on the tip of the probe shoe (cast from epoxy) provided an order of magnitude for better wear resistance than the original aluminum oxide filled shoes. This means that the low-cost process of casting epoxy shoes (versus the more expensive process of machining Delrin) can be used for probe fabrication, thus keeping the cost of probe shoes to a minimum. (NOTE: It is understood that Pratt & Whitney do not allow silicon nitride to come in contact with their titanium disks. Therefore, if a probe is to be used on titanium and other nickel-based alloys, aluminum oxide would be the shoe material of choice).
3) When a teflon lubricating spray such as Elmer's Slide All was applied to the disk prior to using the probes, the wearability of the probe shoes improved.
4) The Delrin material recently used in some probes offered better wearability than the aluminum oxide filled epoxy, but it is more expensive and does not wear as well as either the Silicon Nitride or the aluminum oxide plates with the teflon spray.

Based upon the conclusions obtained it is recommended that the RFC probes be fitted with cast epoxy probe shoes, which have either a silicon nitride contact surface (for non-titanium disks) or an aluminum oxide surface (which can be used for all disk materials). It is also recommended that each part be sprayed with a teflon lubricant prior to inspection. An equivalent approach would be to coat the tip of the probe with a teflon tape, but it is believed that this process would be much more labor intensive than the spray.

2.3.2.4 Benefits

The probes and their associated shoes are the highest maintenance item in the engine kits because they are in constant contact with the parts, wear the most, and therefore have the shortest life expectancy of any of the components used during inspection. The benefit from this study was to identify the materials and material processes that will wear the best and extend the life of the probe shoes, thereby saving repair and maintenance costs associated with the probe shoes. In considering the 4 major engine kits F110, F129, F220, and F229, available for the ECIS System, with an average of 31 surface probes per engine kit. The Tinker ALC has approximately 25 ECIS systems and if you consider spare probes, their surface probe inventory is in the range of 500 probes. Assuming 2 production shifts are ran and assuming that with dimensioning, bolt hole, broach slot, and scallop inspections also being ran, we will estimate that surface inspections are ran 25 percent of the time. Also assuming that the 500 surface probes are equally ran over the 2 shifts, the probes run an average of 0.008 ((.25 x 16 Hours)/500 probes) hours per probe per day. Assuming these inspections run 260 days per year, the probes are run 2.08 hours per year on the average. This means that if the probes are not protected with some sort of lubrication (i.e., teflon tape or spray) the probe shoes will need to be replaced at least four times a year. Given the average cost for shoe replacements is approximately $450 times 500 shoes, times 4 times per year the cost for shoe replacements is approximately $900,000 per year (keep in mind that this cost is based on several assumptions). The study shows that by simply lubricating the shoes during inspection the cost would be reduced by at least 50 percent, which is a cost saving of $450,000. It should be noted again that teflon tape has been used in the production facilities since the mid 1990's so some of the probe shoe repair costs associated with the lubrication have already been realized. The study also shows that these costs can be further reduced by as much as another 50 percent by using an aluminum oxide plate shoe with the teflon lubricant.

2.3.2.5 Lessons Learned

The primary lesson learned from this study is that lubrication of the probe tip approximately doubles the life of the probe tip. This lubrication can be in the form of spray, gel, or tape. Both the spray and the gel would have to be cleaned after each inspection, where as the tape is applied to the probe shoe and is easily removed. The tape may take more time to apply, but that time is made up by not having to reclean the part. Since the early to mid 1990's the ALCs have been adding teflon and kapton tape to the probe tips in an effort to keep the probe tip from wearing and extending the life of the probes. Periodic points have also been added to the scan plans to change the tape.

The original probes used in inspections on the ECIS used aluminum oxide filled epoxy. In the Mid 1990's the shoe material was changed to machine formed Delrin in an effort to reduce shoe wear. This study supports this material change along with the addition of the teflon/kapton tape as one of the two best approaches. The best approach would be to use an aluminum oxide or silicon nitride plate bonded to an epoxy molded shoe. The silicon nitride plates should probably be avoided since it can not be used with titanium, and in the production atmosphere could easily be used by mistake, thus damaging the part. The aluminum oxide plate along with the teflon/kapton tape would increase the shoe life even longer then the Delrin and could most likely reduce the cost of the shoes. Further investigation into the cost savings of using the aluminum oxide plates is warranted.

2.3.3 High Compression Probes

Present eddy current surface probes have a typical compression of 0.025 inches. Depending on the part being inspected and its associated deviation, a 0.025-inch compression is not always enough to keep the probe from lifting off the part. An investigation into whether or not existing probes could be retrofitted with higher compression capability was required. This subtask and associated work was assigned to Veridian Engineering. An overview of the work performed is given in the following subsections.

2.3.3.1 Project Scope

The project scope was to investigate design alternatives for retrofitting existing probes with higher compression capabilities. The goal was to determine effects that the higher compression will have on existing scan plans and suggest possible modifications to the scan plans.

2.3.3.2 Work Performed

Three existing surface probes were modified for high compression; these three probes were the number 8, number 71, and number 971 probes. The high compression version of the number 8 probe was assigned a new probe number 873. The high compression versions of the number 71 and number 971 probes were given an "A" designator (i.e., 71A and 971A). Table 22 below shows the old and new compression points of these three probes.

Table 22. Probe Compression Point Comparison

Probe Number	Old Compression	New Compression
8/873	0.025 Inches	0.125 Inches
71/71A	0.025 Inches	0.06 Inches
971/971A	0.025 Inches	0.04 Inches

The high compression capability on all three probes was accomplished by replacing the existing cantilever springs with a ball bearing slide mechanism held in tension with a coiled spring (see Figure 9).

Veridian Engineering provided three each of the three different high compression probes along with associated drawings. The probes with their extended compression were tested at Veridian Engineering and also sent to the OC-ALC for further testing. Testing of the high compression probes at Veridian Engineering was done on the more open geometries of the F110 HPT Disk (P/N 1359M33P01-110) and on the F220 1ST Stage Fan Disk (P/N 4071701). On the F110 HPT disk the Web_71.Fwd and the Bore_8.Fwd geometries were run and on the F220 1ST Stage Fan Disk the Web_971.Fwd geometry was ran. Modification to the probe length in the Common_Subs library was

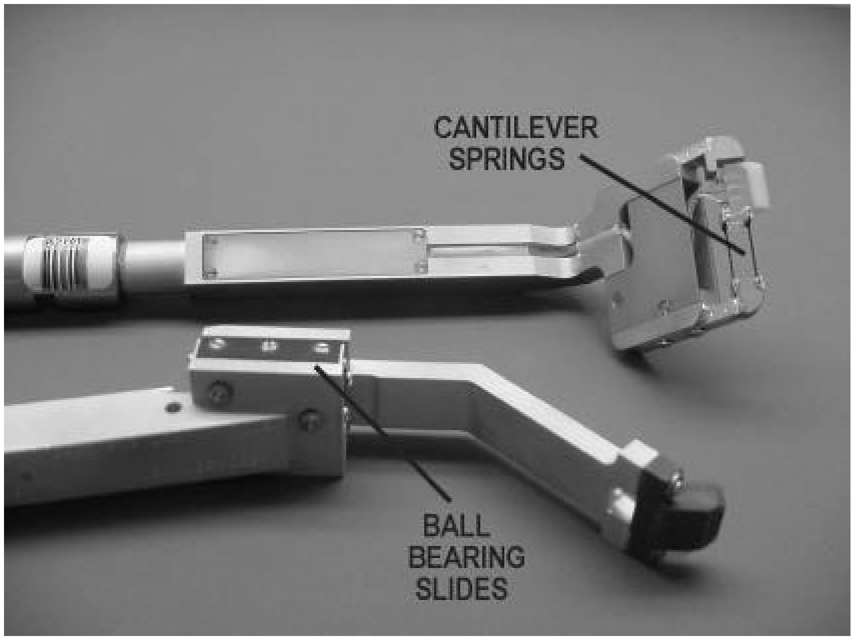

Figure 9. High Compression Probes

required for the number 873 and number 71A probes in order to pass the Get_Probe_Length part of the inspection and to keep the probe from crashing into the part. To get the high compression capability, the probes must be slightly longer than the original probes. Because the number 971A probe has only an additional 0.015-inches of compression, it is only 0.0075-inches (0.015/2) longer than the original number 971 probe. This means that it will generally be within the probe length tolerance and we did not have to modify the probe F220 Common_Subs library or 1ST Stage Fan Disk's Web_971.Fwd geometry scan plan for testing. The number971A probe for our testing and other site tests done to date have not required scan plan modifications, but this may not always be true. There is still the possibility that the number 971A probe could crash into the part in tight areas. It is recommended that before the number 873, number 71A, and number 971A probes are put into old scan plans, an in-depth analysis of the dimensions of the part and the inspection area should be done to ensure the probe does not crash into the part. It is also recommended that the probe length in the Common_Subs library be corrected for the new probe length. This will ensure that problems with dimensioning will not occur. It is Veridian Engineering's belief, based on testing, that the high compression probes will have to be phased into the older inspections and the older low compression probes phased out.

2.3.3.3 Acceptance

All three high compression probes were accepted with the understanding that they were not necessarily drop-in replacements for the older version of the probes. The fact that these are high compression probes means that they must be a little longer than the original probes, which means that they will generally require scan plan modifications to safely inspect a part.

2.3.3.4 Benefits

There are two primary benefits with the high compression probes. The first is that they are more robust. The old cantilever springs were easily bent or deformed by over-compression or by mishandling. The ball bearing design has a more solid shoe design with all the movement being at the bearings. In going from the old cantilever spring design to the ball bearing slide design will extend the life of the probe shoes by ensuring that the shoe wears more uniformly. The second benefit is that the high-compression probes are more tolerant to part deviations and will not lift off the part during inspection. This will reduce the number of false calls and inspection errors due to liftoff and will increase engine part throughput in the production inspection facilities at the ALCs. The actual cost savings is again difficult to estimate since we presently do not have sufficient cost data associated with the hours spent in analyzing false calls associated with the probe lift-off. A conservative estimate of labor savings during the inspection process would be 20 to 25 percent.

2.3.3.5 Lessons Learned

The original goal was to make the high compression probes drop-in replacements for the lower-compression probes, but it was quickly learned that this was not possible. The whole concept of the high-compression probe was to compensate for larger deviations in the parts being inspected. It was the larger deviations that were causing the periodic probe lift-off during the inspections. In order to compensate for positive as well as negative deviations, the probe tips had to have the capability to extend as well as compress. This meant that the overall probe length had to be longer by at least half the new compression length minus half the old compression length. As an example, for the number 873 probe this is an additional 0.05 inches in length (0.125/2 – 0.025/2). This additional length causes the number 873 probe to fail probe length tolerance when it is directly substituted for the number 8 probe. This means that to use the number 873 probe in place of the number 8 probe, some scan plan software changes are required.

3.0 System Computer

The System Computer task involved the upgrade of the existing System Computer, based on the Intel Multibus I and II chassis, to a more state-of-the-art computer system. The Intel Multibus II system was designed in 1989 and did not become as widely used as expected. New technology available for the Intel Multibus II system is either nonexistent or lags behind the state-of-the-art. Since the introduction of the Personal Computer (PC), Intel Multibus II system components have become obsolete and the systems have become expensive to maintain. A new state-of-the-art computer system is required to reduce maintenance/repair costs and to increase throughput of the system. Increasing the system throughput will decrease inspection time and its associated cost. This subtask and associated work was assigned to Veridian Engineering. An overview of the work performed is given in the following subsections.

3.1 Project Scope

The scope of this project was to design, develop, test, and implement a new drop-in replacement for the existing RFC Eddy Current Station computer that utilizes state-of-the-art technology. All existing scan plan software will execute on this new system without modification. The new system computer will use COTS components wherever possible. Every effort will be made to ensure that the new system will support future technological improvements. Repair/maintainability will be a key design goal.

3.2 Work Performed

The overall task was divided into three phases: concept development, prototype development, and acceptance.

3.2.1 Concept Development Phase

A Critical Risk Analysis was performed during the concept development phase of this task. The purpose of this analysis was to study/evaluate the characteristics of candidate operating systems that would be implemented within the new system. Critical operating system characteristics were identified and candidate operating systems including Windows NT and Real-Time UNIX were evaluated. Critical characteristics evaluated included basic operating system capabilities, real-time performance, and graphics interface. Also, a PLM-to-C translator was required to convert the 80,000 lines of existing PLM code to the Visual C++ language. Since the translator was critical to the success of this program, it was also evaluated as part of this analysis. The result of this analysis was documented within the “Application of Windows NT to the Retirement For Cause PC-Based Eddy Current Inspection Station Critical Risk Analysis Report. [7] In summary, Windows NT was selected as the Operating System for the drop-in replacement. The PLM-to-C translator appeared adequate to translate existing PLM software.

3.2.2 Prototype Development Phase

The goal of the prototype development phase was to design and build the new computer system and convert all existing application software from PLM to Visual C++ running under Windows NT. Extensive testing was necessary to ensure compatibility with the existing ECIS computer system. The new computer system also required a new keyboard and monitor, which were selected and integrated into the ECIS.

Several COTS computers were evaluated as the best candidate for the drop-in replacement. Several criteria, which included cost, future expansion, and maintainability, were considered. A Texas MicroComputer running the Windows NT operating system was finally selected. The new computer utilizes a passive backplane and contains a 300MHz Pentium II processor, 128Mbytes of memory, a 4 Gigabyte hard drive, 3 available PCI and 5 available ISA expansion slots. A block diagram of the computer system is given below.

As shown in the block diagram, Figure 10, special purpose I/O cards were added to the computer system to provide additional I/O capability. Parallel I/O cards provide control of the ECIS power sequencer and perform I/O to the existing ECIS version 3 keypad and lights. A PC-based Galil motion control card was selected which is functionally compatible with the Multibus version and used for micromanipulator probe tip position control. An IEEE488 interface card from National Instruments was selected for communications with the oscilloscope and filters. A 4-port PCI-type Rocketport serial card was used for all RS-232 communications required. The majority of I/O cards are available COTS items.

The only proprietary component in the new system is the Veridian Engineering Digitizer Card, which was redesigned for the new system. It was decided to design this special purpose card only after an exhaustive search for a COTS card was performed. The new Digitizer Card was designed to be installed into the PCI bus of the new PC. The new design took advantage of newer electronic technology, such as Complex Programmable Logic Devices (CPLD) which feature the ability to be programmed while remaining in the circuit. Other technologies used include Surface Mounted Devices. These devices use a smaller footprint and therefore take up less space than their through-hole counterparts. By utilizing state-of-the-art technologies, the digitizer maintained the same functionality as the old Multibus-based digitizer card in less than half the card space. Several new features added to the digitizer include: selectable word size (12, 13, and 16), 4 probe inputs, and 2 selectable input gains.

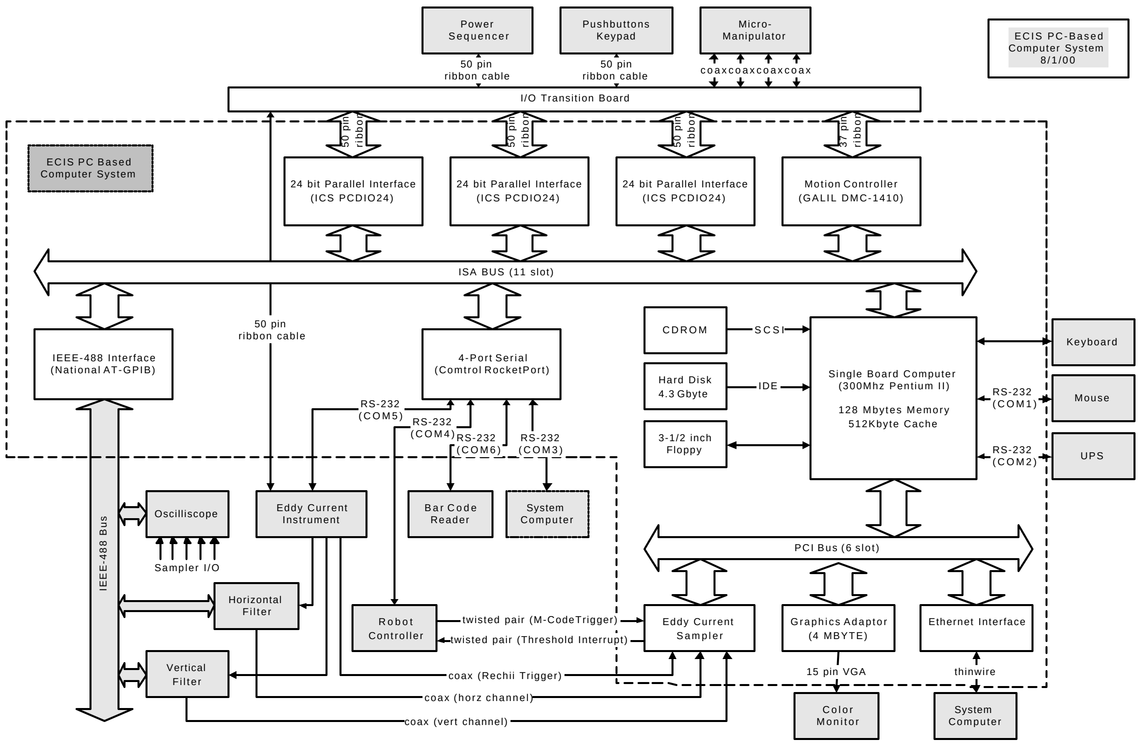

Figure 10. Computer System Block Diagram

The new computer system is relatively simple to assemble and resulted in a significant reduction in components as compared to the old Multibus-based computer system. A new drawer was also designed to hold the new computer chassis. Although the computer chassis was rack mountable, the ECIS system utilizes 24-inch racks whereas the chassis fits into a 19-inch rack. Several additional interface cards were required to ensure plug-in compatibility between the old and new computer systems. In fact, two additional PC cards were designed and built. These cards were mounted in the new computer drawer and were required for compatibility between the computer drawer and existing ECIS cabling. Drawings for the new computer system and drawer, and keyboard drawer are given in the final report New ‘OPEN’ Inspection Station Computer [6], Appendix B and D, respectively.

Computer application software for the ECIS version 3 computer system was originally developed using the PLM386 language and the RMX386 operating system. The RFC ECIS application source code contained over 80,000 lines of code. This software was converted to the Visual C++ language and modified to operate under the Window NT operating system. Much of the source code was converted using a PLM-to-C translator. However, because of errors within the translator the code required modification and thorough testing after translation. Some of the code could not be translated because of differences between the Windows NT and RMX 386 operating systems and was rewritten.

A block diagram illustrating the processes resulting from the conversion is shown in Figure 11 below.

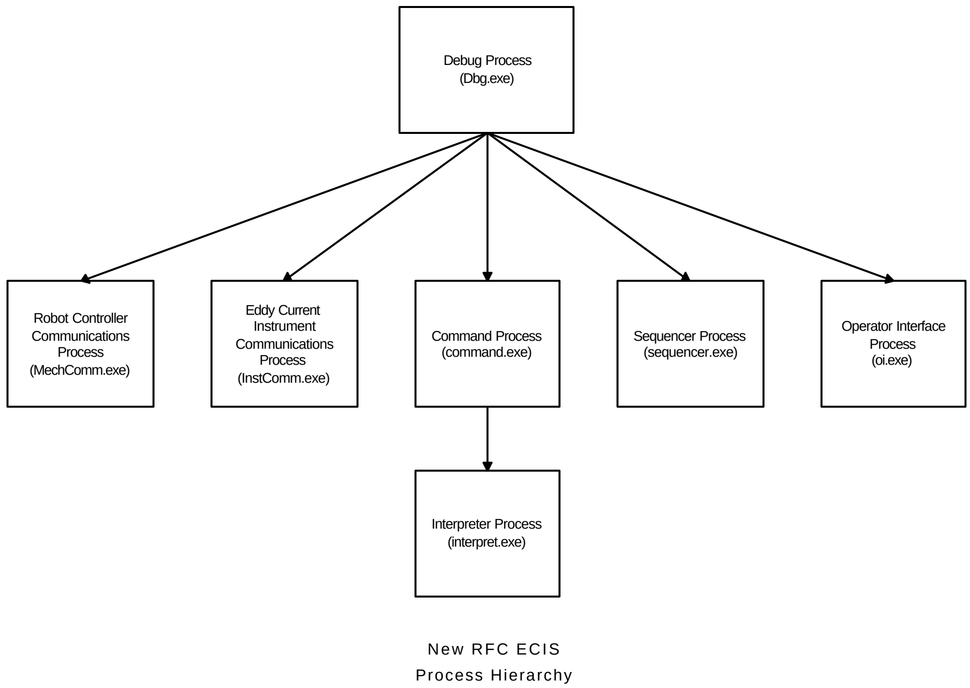

Figure 11. Process Hierarchy

As shown, the ECIS application software consists of seven processes. This is a significant reduction from the 13 processes required in the old Multibus-based computer. The reduction in the number of processes mainly results from the simplification of the computer architecture. The old computer system required two chassis: a Multibus I and Multibus II chassis, and two single board computers. The simplification of the computer system is possible because of increased processor and memory capabilities as well as reduced size of the peripherals and add-on I/O cards.

Toward the end of the prototype development phase a battery of tests were performed to ensure that the new computer system and software maintained equivalent reliability and flaw detection capability with the old Multibus computer. Two types of testing were performed: first, notched engine parts were inspected to ensure the software/hardware was able to execute the scan plan software without error; secondly, reliability tests were ran to ensure the system maintained equivalent flaw detection capability. The ECIS system performs 45 complicated inspection processes. All the tests performed, including Reliability and Notched Parts, were selected specifically to ensure that all 45 different types of inspection processes were tested. Fourteen different reliability tests and geometries from 10 different engine parts were run. The reliability data collected with the new System Computer was compared to existing reliability data. The collected reliability data was also sent to Dr. Al Berens of UDRI for an independent analysis of the data. The results of Dr. Berens analysis are available in Section 4.0 of his final report.[2] These results are also presented within the final report, New 'OPEN' Inspection Station Computer Appendix E.[6]

3.2.3 Acceptance

The purpose of acceptance testing was to validate/verify that the new computer system was a drop-in replacement for the old Multibus computer system. The new system would be installed in an ECIS version 3 and a set of engine parts inspected. Originally, the site acceptance tests were going to be run at both of the ALCs, but with the SA-ALC in the process of closing down it was decided to do the SA-ALC site test at Veridian Engineering, Dayton, Ohio. The OC-ALC site test included testing of four General Electric (GE) engine parts the F110-129 Stage 1-2 Spool, the F110-100 3RD Stage Fan Disk, the F100-100 4-9 Spool, and the F110-100 HPT Disk. The SA-ALC site test at Veridian Engineering, Dayton, Ohio included two Pratt & Whitney (PW) F229 engine parts, the 2ND Stage Turbine Disk, and the 2ND Stage Retaining Plate. All testing was completed successfully. Integration test results can be found in the final report, New 'OPEN' Inspection Station Computer, Appendix F. [6]

With the successful completion of the site acceptance test at OC-ALC and Veridian Engineering, Dayton, Ohio plus Dr. Al Berens independent approval of the of the reliability data, the new System Computer was accepted as a drop-in replacement for the older System Computer. To date, approximately 10 new System Computers have been installed at the OC-ALC.

3.3 Benefits

There are several benefits resulting from the development of the new PC computer system. The first and most important is faster inspection times. This speed-up of part inspection occurs because of the faster processor available within the new computer. A slight improvement was noticed throughout the inspection. A significant improvement in inspection time was noticed within the dovetail inspection where intensive signal processing is performed. The dovetail inspection was reduced from 53 to 17 minutes per slot.

There was also a significant reduction in the overall cost of the computer system. The old computer system cost over $60,000, and the new computer is around $25,000. This is a cost saving of $35,000.

The old computer system contained many obsolete components. The PLM386/RMX386 software was difficult to maintain because of the antiquated editors and compilers used. Moving to a PC-based platform under Windows NT/ Visual C++ greatly improved maintainability/supportability. The state-of-the-art software development tools greatly increase programmer productivity and provide new capabilities not offered with the old operating system/compiler. This is especially true in the area of networking. Since the acceptance of the new Windows NT-based computer system within the ECIS, the RFC System computer has also been converted to a PC platform and Ethernet communications to the ECIS has been developed.

More future improvements are now possible. The new computer system has card slots available for future expansion. An additional Pentium processor can be added and memory easily expanded. Windows NT and Visual C++ allow improvements to be implemented including better utilization of the network capabilities now available and improving the operator interface by using the many Windows-based Graphical User Interface (GUI) capabilities.

3.4 Lessons Learned

Overall, the System Computer task went well and resulted in a drop-in replacement for the ECIS computer system. That is not to say, however, that there were not a few bumps in the road along the way.

One problem that impacted the program was the PLM-to-C translator. The translator introduced bugs into the software during translation that had to be manually found and corrected. The list of known bugs is given below:

- Pointers were not translated correctly.
- The DO LOOPs with negative increment were incorrect.
- The SIZEOF function was not compatible from PLM-to-C.
- All pointers were translated using the #define statement, which disables the Debugger variable watch capability.
- The SWITCH statements were not translated correctly.
- Variables within structures having the same name as a variable declared outside of the structure caused a compiler error since the #define was used for both variables.

Because of the bugs listed above, after a file was translated, a programmer had to examine the resulting Visual C++ code one line at a time and fix any errors introduced by the translator. This greatly increased the amount of labor necessary to perform code conversion and adversely affected schedule. The translator was evaluated during the Critical Risk Analysis of Phase I of the program. Several bugs were found during that analysis which the manufacturer of the translator fixed. A more thorough analysis should have been performed at that time. Then perhaps these other bugs would have been found and the conversion process would have proceeded much smoother.

Another problem area was the testing of the new computer system, especially in the area of reliability data collection. Reliability data collection was originally estimated to take approximately 6 weeks, but the testing actually took 6 months. This dramatic increase resulted from difficulty acquiring the reliability specimens, probes and calibrations blocks. Because the reliability scan plans were not deliverable items, the reliability procedures were somewhat lacking, which caused some difficulties in the setup and running of some of the reliability scan plans. Veridian is in the process of updating the reliability procedures in an effort to ensure that these same types of problems do not reoccur in the future. Although the testing was difficult, it proved to be crucial to validating the flaw detection capability of the new computer system.

4.0 Specialized System/Integration Features

The only item covered in the Specialized System/Integration Features task was the Automatic Scan Plan Generator (ASPG). Current scan plan development is extremely time consuming and at the present time can only be performed by Veridian Engineering. In addition, it is very difficult for the users to make even minor changes to the existing scan plans. The ALCs have expressed the need to be able to respond to changes in part specifications (e.g., dimensions, material, tolerances) and inspection criteria (e.g., inspection area, rejection criteria). Automation of the scan plan development process would offer the users the capability to respond more quickly to changes in inspection requirements and hardware changes. It would also allow the users to more quickly develop/acquire scan plans for new parts. This subtask and associated work was assigned to TechnoSoft Inc., of Cincinnati OH., with assistance from Veridian Engineering. An overview of the work performed is given in the following subsections.

4.1 Project Scope

The scope of the project scope was to design, develop, and test an ASPG to allow quick easy development of and modifications to software scan plans used for engine inspections on the ECIS system. The ASPG should be user friendly and allow the user to easily select a probe, model a new probe, import an engine International Graphics Exchange Specification (IGES) file, and create a scan plan associated with the selected probe and engine part.

4.2 Work Performed

Using TechnoSoft's proprietary Adaptive Modeling Language (AML) and the ECIS system model supplied by Veridian Engineering; TechnoSoft designed and developed a prototype ASPG. Veridian Engineering completed testing by creating a scan plan for the Pratt & Whitney P/N 4080102 Rear Rear Drum Rotor engine part. The P/N 4080102 Rear Rear Drum Rotor engine part was selected because of the complex movements required to inspect the internal geometries of the part. The ASPG successfully generated the scan plan for the engine part with some minor difficulties. These difficulties were primarily related to the direction of the seven machine axis and their associated signs (+ or -). These errors were easily identified and corrected. The major problem with the ASPG developed by TechnoSoft was that it required a highly skilled operator. Results of the test scan plan, recommendations for improvements, and the associated cost and schedule were submitted to the Project team. The Project team decided not to continue with the development of the ASPG due to the cost and schedule. It was felt that at that point in time it was not an efficient use of funds.

4.3 Benefits

There are two basic benefits associated with the ASPG. The first is that it would reduce scan plan development time by as much as 50 percent depending on the scan plan requirements. Its primary use would be in creating scan plans of parts with typical geometries such as bolt holes, surface, scallop, and broach slot inspections as long as the inspection does not require a new technique. The ASPG as it was developed would have minimum effect on reducing time for developing new inspection techniques.

The second benefit would be for analyzing inspection problems using an inspection modeling capability. The ASPG could allow the inspection to be observed on a computer screen and allow the analyst to zoom in and out of inspection areas and see what is happening during the inspection, specifically with probe contact and movement. The ASPG concept has many possibilities for assisting in improving and developing scan plans. With enhancements in software technology and capabilities it is possible that the ASPG could also become a useful tool for technique development.

4.4 Lessons Learned

Any ASPG must be designed with the concept of creating a user-friendly system. To get the maximum benefit from the investment, the software must be easily used by both scan plan writers, engineers, and technicians, both in the development laboratory and in the field. The ASPG should operate with a minimum set of buttons, screens, and set-up criteria. The system must be able to easily import the part manufacturers IGES files and be able to quickly create or import probe characteristics used in the inspection.

5.0 Summary

All of the areas assigned to the Veridian Engineering Team were completed and overall the Advanced NDE RFC/ENSIP contract was successful. All three phases of the Eddy Current Probe investigations were completed and much of the improvements developed are presently in use. The replacement US-500 ECI and the new System Computer are being installed in the OC-ALC and at the Pratt & Whitney Alamo Downs inspection facility, with notable improvements associated with inspections and inspection times. These improvements should easily generate a minimum cost savings of $200,000 per year, considering reduced calibration, labor, materials and repair costs.

The scanner replacement, although not officially accepted, did reach all of its design goals and shows considerable promise. It is presently believed that with some minor adjustments and retesting, the new scanner will be accepted. The ASPG successfully generated the F229 Rear Rear Drum Rotor (P/N 4080102) scan plan showing that the concept works. The software needs to be made more user friendly and would be a useful tool in the ECIS eddy current inspection world.

For information regarding the two areas not assigned to the Veridian Engineering Team, Mechanical Positioning, and Calibration Process, refer to “Advanced Capability Motion Controller”[8], and “Retirement for Cause (RFC) Eddy Current Inspection System Calibration Improvement”[9], respectfully.

6.0 Reference

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9. D. Stubbs, “Retirement for Cause (RFC) Eddy Current Inspection System Calibration Improvement,” University of Dayton Research Institute Contract Number F33615-95-C-5241, Report Number UDRI-TR-2000-00057, AFRL Report Number AFRL-ML-WP-TR-2000-4035, February 2000.

7.0 Abbreviations

LIST OF ABBREVIATIONS

ALC	Air Logistics Commands
AML	Adaptive Modeling Language
ARC	American Robot Corporation
ASPG	Automatic Scan Plan Generator
ATP	Acceptance Test Procedure
CBD	Commerce Business Daily
CIP	Component Improvement Program
CMR	Common Mode Rejection
COF	Coefficient of Friction
COTS	Commercial Off-The-Shelf
CPLD	Complex Programmable Logic Devices
CRT	Cathode Ray Tube
DEC	Digital Equipment Corporation
DLC	Diamond-Like Coating
DSP	Digital Signal Processing
ECI	Eddy Current Instrument
ECIS	Eddy Current Inspection Station
ENSIP	Engine Structural Integrity Program
GE	General Electric
GUI	Graphical Users Interface
IGES	International Graphics Exchange Specification
ISC	Implant Science Corporation
MILSPEC	Mil Specification
NDE	Nondestructive Evaluation
No.	Number
OC-ALC	Oklahoma City-Air Logistics Center
P/N	Part Number
PC	Personal Computer
PRDA	Program Research and Development Announcement
PW	Pratt & Whitney
RECHII	Rotating Eddy Current Hole Inspection Instrument
RFC/ENSIP	Retirement for Cause/Engine Structural Integrity Program
SA-ALC	San Antonio - Air Logistics Command
SNR	Signal-to-Noise Ratio
SWRI	Southwest Research Institute
T.O.	Technical Order
UDRI	University of Dayton Research Institute
USAF	United States Air Force
UniWest	United Western Technologies
VAX	Virtual Address Extension