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TRW

CR- 171 865
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FINAL REPORT

NONDESTRUCTIVE EQUIPMENT STUDY

25 JANUARY 1985

DRL NO. RA 509T
CONTRACT NO. NAS9-17101

PREPARED BY

FEDERAL SYSTEMS DIVISION
SPACE & TECHNOLOGY GROUP
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PREPARED FOR

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24 January 1985

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, TX   77058

Attention: Herbert H. Baker, Jr.
             Contracting Officer

Subject: Final Report Upon Completion
                     Of the Contract

Reference: Contract NAS9-17101
             Non Destructive Equipment Study

Submitted herewith, in accordance with Article 10 of the
reference contract, is your copy of the subject report.

Additional copies are to be distributed as shown below.

If you should have any questions or comments please contact
either Martin S. Toll at (213) 535-0214 or myself at
(213) 535-5503.

TRW Inc.

Jay R. Fisgus

Jay R. Fisgus
Contract Administrator

JRF:lg
Enclosure

cc: NASA/Lyndon B. Johnson Space Center
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.85.P780-MST-001
25 January 1985

National Aeronautics & Space Administration
Lyndon B. Johnson Space Center
Houston, Texas   77058

Attention: Mr. Stacy Nakamura/ND56
              Technical Monitor

Subject: Submission of Final Report pursuant to
              DRL T-1830, Line Item #2

Reference: Contract Number NAS9-17101

Dear Mr. Nakamura:

The submission of the Final Report enclosed herewith, completes
performance of the referenced contract. All of the objectives
defined in the Statement of Work have been met.

This enclosed Final Report encompasses the material presented at
the 60-day Technical Interchange Meeting of 18 April 1984 and in
the Interim Report dated 9 July 1984.

It covers many types of Non-Destructive Evaluation (NDE) methods
considered for use in a low-earth-orbit environment, and
emphasizes those showing the most promise for application to
pressure vessels. The results of our review and evaluation of
state of the art NDE capabilities are reported, together with the
results of our experimental work on advanced NDE techniques. The
most promising methods are summarized and recommendations are
made regarding additional studies that would be useful in
developing NDE methods to be used in space.

The principal tasks accomplished in the study include the
following: 1) identification of existing Non-Destructive
Evaluation (NDE) methods that could be used in a low earth orbit
environment; 2) evaluation of each method with respect to the set
of criteria called out in the statement of work; 3) selection of
the most promising NDE methods for further evaluation; 4) use of
selected NDE methods to test samples of pressure vessel materials
in a vacuum; 5) pressure testing of a complete monolythic
pressure vessel with known flaws using acoustic emissions in a
vacuum; and 6) recommendations for further studies based on
analysis and testing.

If you have any questions about any of the material in the
attached Final Report, please let me know.

Sincerely,
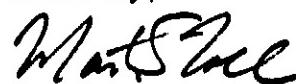
Martin S. Toll
Project Engineer

FOREWORD

This final report describes work done under Contract No. NAS9-17101 from NASA/Lyndon B. Johnson Space Center (JSC), Houston, Texas. The technical officer for NASA was Mr. Stacy Nakamura. Mr. Nakamura's guidance and support has been invaluable and is gratefully acknowledged. The study manager for TRW was Mr. Martin S. Toll.

Prepared By:

Dr. Thomas Chung
Dr. May Kwan
Mr. Joseph C. Lewis
Mr. Martin S. Toll

i

CONTENTS

R5-010-85

ILLUSTRATIONS

TABLES

R5-010-85

1. INTRODUCTION AND SUMMARY

This document presents the results of a study of nondestructive evaluation (NDE) methods that could be used for frequent monitoring in space of the integrity of pressure vessels used on long-life spacecraft. In-space monitoring is an attractive alternative to the approach of simply making the pressure vessel heavy enough to sustain the expected number of pressure cycles over the planned lifetime of the spacecraft, even if the vessel has some initial flaws. In the case of the space station or other more or less permanent facilities in space, this approach would: 1) result in extremely heavy pressure vessels that would still have finite lifetimes, and 2) fail to take advantage of the replacement possibilities offered by space servicing.

What is needed, therefore, is a technique for either continuously or at frequent intervals monitoring the integrity of the pressure vessels so that incipient flaws could be detected well before catastrophic failure. Only NDE methods are appropriate for such monitoring, and it is important to identify those that would be best suited to this application.

For these reasons, NASA funded the present study of NDE methods for use in space. Our approacn was to begin with an identification of existing NDE methods and then evaluate them with respect to their suitability for use in a space environment. This evaluation resulted in the elimination of all but eight of the original 40 methods identified. Further analysis of these methods resulted in the selection of the two most promising for further study and laboratory testing: these are ultrasonic inspection and acoustic emission monitoring.

1.1 CONCLUSIONS

Although there is abundant data on NDE methods, there is very little on their application in a space environment. Our investigations showed that the selected NDE methods can be applied in the hard vacuum of space without loss of sensitivity. Our conclusions can be summarized as follows:

   a) <u>Determining the location and size of flaws in pressure vessels by NDE methods is a feasible task in a space environment.</u>

   Although the space environment has introduced a variable in the realm of NDE methods, this environment does not present

1

formidable and uncontrollable conditions. For example, ultrasonics can be used effectively in space with suitable couplants, as shown by testing.

b) NDE methodology must be tailored to suit the particular application in a space environment as it must under ambient conditions.

As described in Section 2, seven NDE methods were identified as feasible for use in space (leak detection is not included in this group). The method selected depends on the exact conditions of the material, configuration, surroundings, and accessibility.

c) Acoustic emissions and ultrasonics are the most valuable methods for detecting flaws in pressure vessels.

Acoustic emission proved to be the most useful method for locating, monitoring, and assessing damage because of its ability to track sound from a remote stress region. Ultrasonic inspection provided better local flaw size definition. During pressure vessel testing it was shown that acoustic emission can effectively locate a flawed region, a fact which was then confirmed by ultrasonic testing.

1.2 RECOMMENDATIONS

This study, with its emphasis on flaw detection of pressure vessels, revealed that few new developments in the field of nondestructive evaluations are anticipated. Instead, the refinement of existing technologies and their application is where greater future effort should be expended. The following recommendations are made for future study:

a) Perform an NDE study for composite structures in a space environment.

Fiber-reinforced composite material has been extensively utilized in modern spacecraft as a primary structural element. Continued study on such material with ultrasonics, acoustic emission, X-ray, and infrared methods in space will be fruitful in developing a data base.

b) Initiate an in-flight structural monitoring study.

Tailor an NDE in-space integral module of the space station to continually monitor the well-being of the space station.

c) Use of an extra-vehicular-activity-related NDE.

On the forthcoming satellite servicing technology program supported by the space station, there may be abundant extra-vehicular NDE-related tasks. A robotic arm may be utilized to

2

position sensors and perform scanning of satellite components. The methods of scanning, the design of the search units, the methods of recording their data, and their trade-offs need further development.

d) <u>Initiate a partial fracture mechanics study.</u>

Although space station endeavors are radically different from traditional satellite technology, the majority of basic structures, materials, and processes are similar. Fracture (or partial fracture) mechanics studies should be conducted on pressure vessels to render some insight into the sensitivity required for NDE methods.

e) <u>Define potential cost swings.</u>

For monolithic metallic pressure vessels, the next phase of the study should include detailed trade studies to precisely define the potential swings in life-cycle costs available by periodic nondestructive inspection on-orbit.

f) <u>Establish equipment requirements and inspection procedures.</u>

Any equipment modifications necessary for use of the NDE methods on-orbit in vacuum and zero gravity should be identified. Furthermore, ground demonstration must be conducted to determine the ability of a fully suited astronaut to operate the NDE equipment.

g) <u>Initiate studies for detection of micrometeoroid impacts.</u>

There is a need for automatic sensing, remote sensing, and measurement of flaws caused by impacts with micrometeoroids and space debris.

3

2. NDE TECHNOLOGIES IN SPACE

The purpose of performing NDE in a space environment is to establish an accept/reject decision concerning pressure vessels on the basis of non-destructive measurements. Application of NDE methodologies follows three historic phases: zero defects, deterministic, and probabilistic. In the zero defect phase, rejection of hardware is automatic whenever a defect is found. In the deterministic phase, the use of fracture mechanics with a worst-case model of stress environment allows certain flaws to be acceptable in the hardware. In the probabilistic phase, knowledge of probability of failure, flaw distribution, and cost of false rejection will all be sought as determining factors. Therefore, no straightforward accept/reject criteria can be given.

For NDE application in a space environment, a deterministic phase can be directly entered. One can then proceed to develop a set of basic requirements for nondestructive methods based on the knowledge of ambient conditions. Preliminary NDE requirements are as follows:

- Operable in hard vacuum of space

- Operable in zero gravity

- Operable by fully-suited crew person

- Equipment must be portable and transportable by resupply vehicle

- Equipment must represent minimum risk to crew

- Material used must be nonflammable and nontoxic

- Material used should meet outgassing requirement

- Method should be capable of evaluation without removal of thermal coating

- Method should be capable of remote, in-situ automatic sensing

- Method should be operable without access to inside of tanks or pipes.

2.1 SCREENING NDE METHODS FOR SPACE APPLICATIONS

Early in the program, we started conceptual screening of 40 NDE methods. These NDE methods were considered valuable by the American

4

Society of Quality Control (ASQC) and the American Society of Nondestructive
Testing (ASNT) for locating flaws and discontinuities. The 40 methods were
classified into seven categories: mechanical-optical, penetrating, radia-
tion, electromagnetic, sonic-ultrasonic, thermal, chemical-analytic, and
special imaging techniques. Some of these methods were not applicable to
the inspection of large structures. These methods have a very small field
of view and are typically utilized for failure analysis. Examples include
Auger spectroscopy, X-ray fluorescence, etc. The defects of interest are
limited to a few microns. Other methods that depend on material stability
are also not suitable for space applications. These include radioactive
gas penetrant, corona discharge, and electrothermal methods, etc. Certain
novel methods were not recommended because of a lack of data base for eval-
uation; these included nuclear magnetic resonance (NMR). Twenty methods
were screened and weighted based on flaw sensitivity, worst environment,
ease of operation, crew safety, outgassing problems, equipment weight, and
remote sensing potential. The results of this evaluation are summarized in
Table 1.

2.2 EFFECT OF VACUUM ENVIRONMENT ON NDE METHODS

NDE methodologies are affected by two factors of the space environ-
ment: material properties and electronic instrumentation. Hard vacuum
(less than 10^{-5} torrs) has been the most demanding factor. Penetrant and
magnetic particle methods, in the most advanced stage, can only operate
down to 10^{-2} torrs and could not be utilized in a space environment.

Because certain liquids are stable in vacuum and can transmit sound
favorably, NDE methods employing sound waves (acoustic emission, ultra-
sonic) are only moderately affected. Temperature extremes (0 to 100
degrees Celsius) have a more profound effect on these liquids since the
vapor pressure and viscosity of liquid are strongly temperature dependent.
Zero gravity did not turn out to be of great concern; surface tension of
the liquid serves as an attractive force for keeping the transducer and
part surface together.

The influence of vacuum on electronic instrumentation is a well
studied subject. Electronic instrumentation for space application has to
be specially designed and manufactured for high reliability.

5

Table 1. Nondestructive Methods Evaluation

NDE Method	Flaw Sensitivity	Worst Environment	Ease of Operation	Crew Safety	Out-gas	Equipment Height	Sensing	Points
Acoustic Emission	G	G	G	G	G	G	G	11
Ultrasonics (Pulse Echo)	G	G	G	G	M	G	G	10
Surface Wave Ultrasonics	G	G	G	G	M	G	G	10
Eddy Current	M	G	G	G	G	G	G	7
Holography	G	G	B	M	G	B	G	6
Infrared Thermography	M	G	M	G	G	M	G	5
X-Ray Radiography	M	G	B	M	G	B	B	0
Acoustic Holography	G	G	M	G	B	G	G	8
Exo-Electron Emission	B	G	G	G	G	G	G	1
Leak Detection	M	G	G	G	G	M	G	6
Strain Gage	B	G	G	G	B	G	G	-1
Gamma Radiography	M	G	B	B	G	B	B	-1
Neutron Radiography	M	G	B	B	G	B	B	-1
Ultrasonics Spectroscopy	G	G	G	G	M	G	G	10
X-Ray Diffraction	M	G	B	B	G	B	G	1
X-Ray Tomography	G	G	B	B	G	B	G	5
Liquid Penetrant	G	B						--
Liquid Crystal	G	B						--
Magnetic Particle	G	B		Dropped From Further Investigation				--
Visual	B	B						--

G = Good sensitivity
M = Medium sensitivity
B = Bad sensitivity

6

R5-010-85

2.3 NDE METHODS EVALUATION

The following describes the screening criteria used to evaluate 20 NDE candidates. Flaw sensitivity was given a larger and wider range of weighing factors than other requirements. For example, we assigned +5 for good sensitivity, -1 for medium sensitivity and -5 for poor sensitivity. We assigned +1 for good operator ease and operation safety, -1 for poor operating ease and safety, etc. The eight best NDE methods are summarized in Table 2.

Table 2. Rating of Eight Best NDE Candidates

NDE Method	Merits (Based on Sensitivity in Air)
Acoustic Emission	11
Ultrasonics (Pulse Echo, Surface Wave Spectroscopy, Holography)	10
Eddy Current	7
Leak Detection	6
Infrared Thermography	5
Holography	6
X-Ray Tomography	5
X-Ray Radiograph	0

2.4 RECOMMENDED NDE METHODS FOR EARLY DETECTION OF POTENTIAL FAILURE

The eight NDE methods presented herein are considered most promising in early detection of potential structural defects that may lead to failure in pressure vessels. These are the methods presently utilized in field services on the ground.

Our investigation revealed that sensitivities of these NDE methods were not greatly reduced in vacuum compared to those on earth. However, there are other limitations associated with their use. Except for leak detection, all methods are sensitive to part geometry. X-ray radiography

7

is particularly sensitive to crack orientation; thus, it will probably be utilized for internal examination rather than monitoring service-induced cracks. Eddy current, on the other hand, is not sensitive to deep cracks. X-ray tomography utilizes the penetrating radiation and presents the digitized data through computer software. As such, it offers certain advantages in examining structure with axial and radial symmetry. However, the method is relatively new and lacks a sufficient data base for monitoring pressure vessels. Acoustic emission, eddy current, and ultrasonic methods have a long history of successful application. New advancement in transducer design and computer automation constantly pushes the state of the art forward for these methods.

2.5 DISCUSSION

The criteria and selection of satellite servicing technology for the early space station has been studied by TRW for NASA, and three categories of tasks are defined*. NDE technologies could be utilized for Category III tasks (future satellite servicing, refurbishment, and repair programs). Both routine service and nonroutine service can be carried out with NDE technologies. Routine service includes periodic maintenance of structural components, remote fluid transfer, and preparation for satellite to return to ground. Nonroutine service includes replacement of failed units, repair/service of the satellite in the space station, and emergency incidents. One example of an emergency incident is meteoroid impact. By employing acoustic emission sensors, the arrival and location of the incident can be traced and the proper decision of replace/ repair/use can be made.

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*"Definition of Satellite Servicing Technology, Development Missions for Early Space Stations," TRW report for NASA/Marshall Space Flight Center.

3. SUMMARY OF TEST RESULTS

The overall approach of this contract is to provide an overview of promising NDE technologies, followed by an evaluation of the two most promising NDE methods for space application, ultrasonics and acoustic emission methods. In addition, X-ray radiographs were stored in vacuum to examine outgassing characteristics of X-ray film.

3.1 ULTRASONIC TESTING FOR WELD DEFECT

Conventional ultrasonic inspection utilizes an angled transducer arrangement with a 60 to 70 degree angle plastic wedge, shown in Figure 1. The typical frequency range is 5 to 10 MHz. The time gate on the ultrasonic A-scan scope identifies the distance of the flaw from the transducer. Until recently, defect sizing was estimated by comparing pulse amplitude against a known standard. Newer techniques can extract defect information from the waveform reflected from the defect.
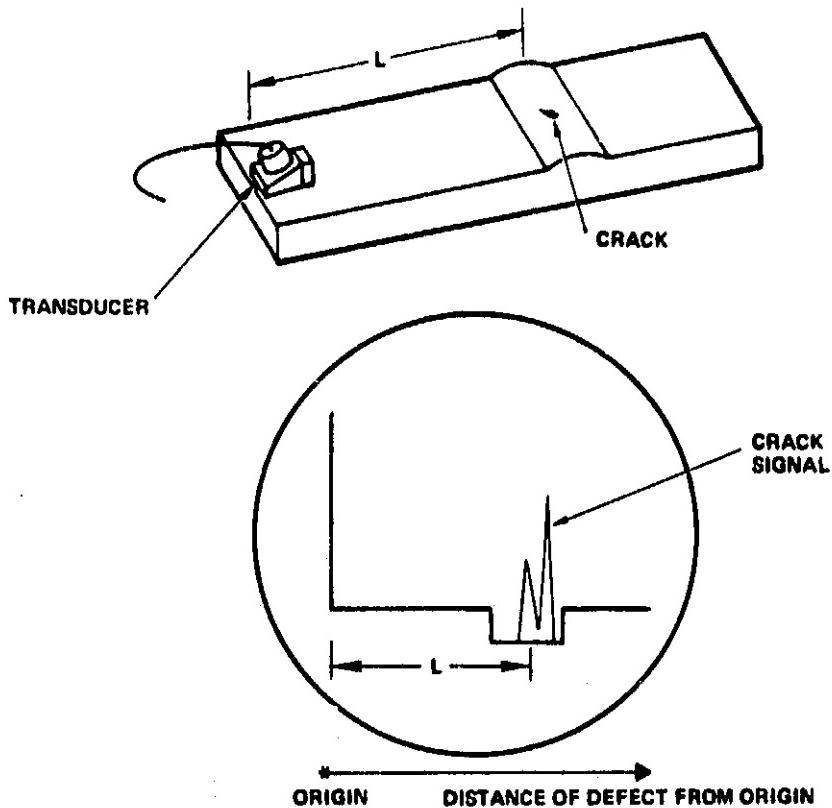
Figure 1. Ultrasonic Angle Beam Scanning for Weld Defect

9

A 1/8-inch thick titanium plate with center region thinned to 0.060 inch, and containing two longitudinal cracks was tested. X-ray radiography revealed only the larger crack. Both cracks were easily detected by ultrasonic inspection. Figure 2 displays the ultrasonic equipment setup. Ultrasonic signal from the crack was monitored both in ambient and in vacuum. A 60 to 70 percent reduction, or 3 to 4 dB, was detected in vacuum. This is believed to be due to trapped air in the transducer. The pulse height was easily observable on an oscilloscope (see Figure 3). Satellite signals originating from sound diffraction at the crack tip were also visible. The distance between the main and the satellite pulses is related to the crack depth.

Six couplants were evaluated and the results showed that they can all be good sound transmitting mediums. The data for couplants are displayed in Table 3.

Figure 2. Ultrasonic Equipment (Pulse echo equipment in foreground and C-scan station in background)

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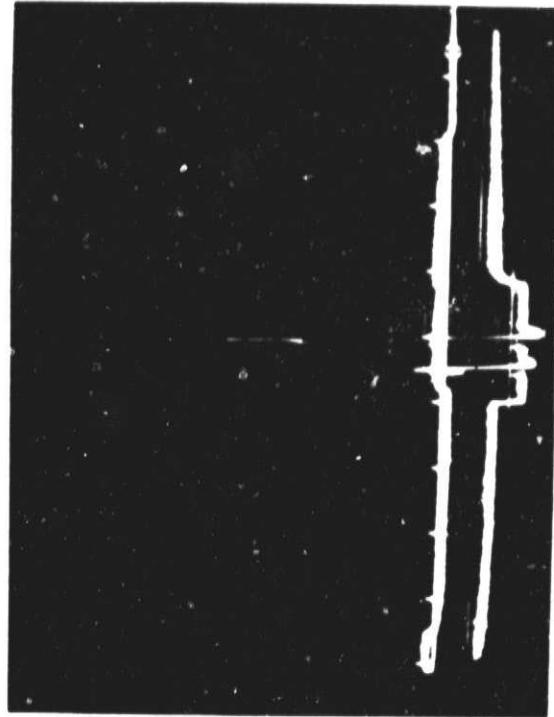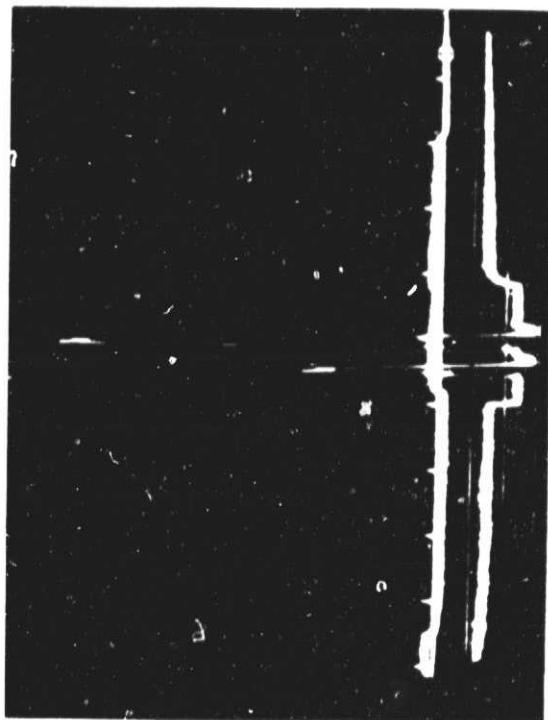
IN VACUUM

AMBIENT

Figure 3. Crack Detection on Aluminum Plate

11

R5-010-85

Table 3. Vacuum Effects on Couplants

| Name	Type	Gravity	Ultrasonic Pulse Height (-dB)		
			Ambient	Low Vacuum	High Vacuum
Apiezon L	Silicone Grease	0.90	28	32	32
Apiezon N	Silicone Grease	0.91	31	33	33
FS1265	Fluoro-Silicone Fluid	1.28	32	35	34
Braycote 3L-38RP	Fluorinated Hydrocarbon Fluid	1.87	31	35	35
Krytox 143AC	Fluorinated Oil	1.90	33	33	33
Viscail 5000	Silicone Fluid	1.93	34	38	35

3.2 LIQUID COUPLANT IN VACUUM

The six couplants selected for this study were space-graded compounds commonly used as lubricants. Typically, the vacuum weight loss is less than 0.06 percent and the volatile condensible material is less than 0.02 percent, making them suitable for long-term utilization in a space environment. The greases and oils listed here are used extensively for lubricating aircraft components, missiles, satellites, and attendant ground support equipment.

As the density of the couplants increases, there is slight reduction in reflected pulse height, both in air and in vacuum. This is due to increase in sound impedence in these liquids as density increases. There seems to be no further change in sound impedence from low vacuum to high vacuum. There is an increase in signal from low to high vacuum in silicone fluid. There is no change of sound impedence from ambient to vacuum in fluorinated oil.

3.3 ADVANCED ULTRASONIC METHOD FOR WELD

After it has been shown that one can perform ultrasonic testing (UT) in a vacuum environment with confidence, one may want to utilize the most advanced UT method to facilitate an inspection service. One of the advanced ultrasonic methods TRW has studied is the scanning laser acoustic microscopy technique. A 2 inch by 3 inch area can be almost instantly viewed on a video screen. Ultrasonic sound is sent by one transducer and the area is viewed with laser optics. In the welded solar cell sample of Figure 4, light regions indicate good sound transmission. The larger the light area within a weld zone, the better the welded contact between the cell and the stress-relieved interconnect.

3.4 X-RAY TESTING IN VACUUM

It is interesting to note that as early as 1973, an advisory circular published by the U.S. Federal Aviation Administration stated that sensitivity of radiographic techniques for small cracks is inferior to other (ultrasonic and eddy current) methods. In addition to viewing internal structure of components, X-ray testing has limited usefulness to thick materials. For instance, a through-thickness crack can be detected in 0.080-inch thick titanium tank when the crack depth is more than 0.050 inch.

There are no anticipated vacuum effects on the electronics of X-ray Equipment. However, isotope sources commonly used on the ground, such as cobalt, are not recommended for space usage because of radiation hazard and lack of sensitivity.

In utilizing X-ray equipment in a space environment, the image may be detected by a sensor and stored on computer or stored on radiographic film. Radiographic film may be in a vacuum environment for a prolonged period before the image is developed. Two films were exposed to X-ray at the same time. One was stored in vacuum for eight hours before both were developed. There is no apparent difference between them, indicating that radiographic film is stable in a space environment, as displayed by the two prints from the radiograph in Figure 5.

13

14

WELD ZONE 1: PARTIAL LIGHT AREA
INDICATES POOR WELD JOINT

WELD ZONE 2: FULL LIGHT AREA
INDICATES EXCELLENT WELD JOINT

INTERCONNECT TAB A

BACK SURFACE OF
SOLAR CELL

INTERCONNECT TAB B

SILICON
SOLAR CELL

WELD ZONE 4: FULL DARK AREA
INDICATES BAD WELD JOINT

WELD ZONE 3: FULL DARK AREA
INDICATES BAD WELD JOINT
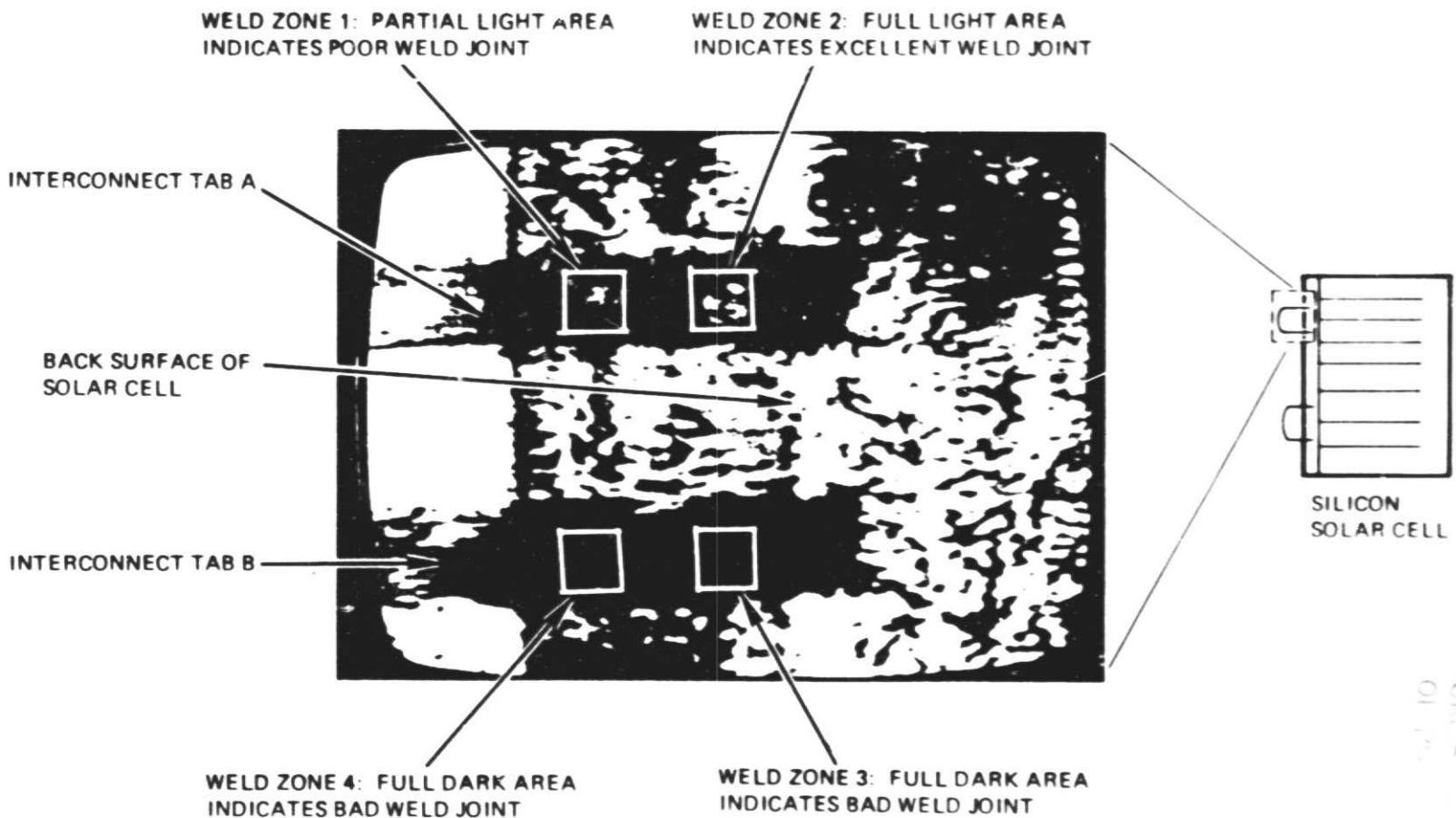
Figure 4. Advanced Ultrasonic Methods for Welds
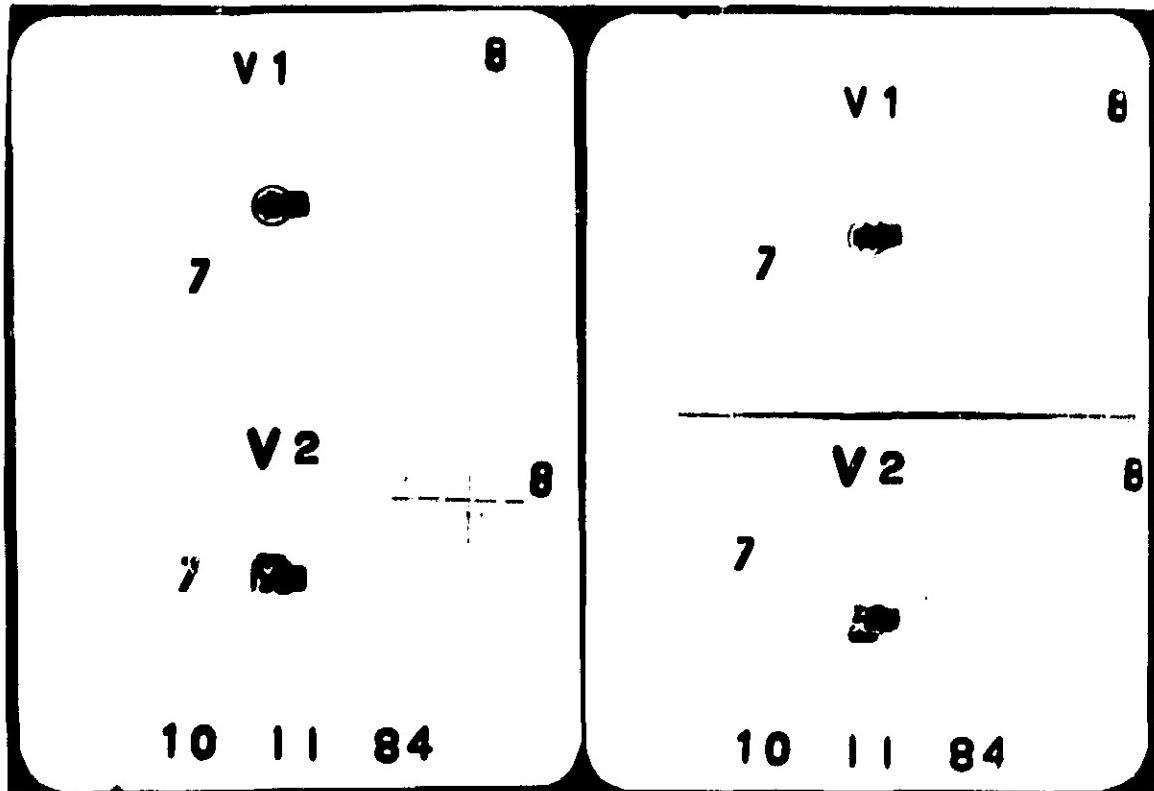
Figure 5. X-Ray Radiograph of Electronic Component

3.5 ACOUSTIC EMISSIONS

Acoustic emissions (AE) monitoring has been widely utilized in the inspection of pressure vessels in the nuclear industry and in-situ monitoring of commercial airplane wings. Since sound waves can travel within a metal for one or two hundred feet without appreciable attentuation, the main advantage of AE is its adaptability for remote sensing. The AE test program was performed to:

a) Examine the constraints that a vacuum environment has on AE monitoring in terms of equipment modifications, signal distortions, couplant requirements, etc.

b) Conduct AE tests on Ti-6Al-4V tensile specimens, both cracked and in the unflawed condition. Signal characteristics associated with plastic deformation and crack propagation were identified.

15

c) Conduct AE monitoring on a pressure vessel containing an intentional crack in vacuum. The purpose of this task was to prove the ability of the zone location program to locate the crack.

3.5.1 Vacuum Versus Ambient Tests

AE measurements on Ti-6A1-4V specimens were conducted at atmospheric pressure and at 10^{-2} torr vacuum. Table 4 lists the AE parameters for a repeatable pulse source in ambient and vacuum environments. Although the pulser does not simulate actual AE signals, it does provide a consistent and repeatable signal for the vacuum studies. The range in values is within experimental scatter and no significant differences were noted in the ringdown counts (RDC), event duration (ED), peak amplitude (PA), energy (ENG), or rise time (RT). Actual AE signals generated by loading the specimen were not used for observing vacuum effects, since material variations are expected to produce considerable scatter in the data. In addition, event distributions by RDC, ED, and PA (see Figure 6) indicated similar results for ambient and vacuum tests.

3.5.2 Titanium Specimens

Acoustic emissions of unflawed and flawed Ti-6A1-4V specimens were distinguishable during loading, unloading, and reloading in vacuum. Crack-containing specimens characteristically emitted more signals and their amplitude distributions indicated higher amplitudes. The most significant characteristics of flawed specimens is the absence of the Kaiser effect. This refers to the absence of AE signals upon reloading until the previous load level has been exceeded. This behavior is demonstrated in Figures 7 and 8 for the unflawed parent metal. Here, load history and events are shown as a function of time in the upper plots and the distribution of events by peak amplitude is shown in the bottom plot. A small number of low-amplitude (<46 dB) signals were observed during initial loading (up to 2500 pounds) below macroyield (0.2 percent YS) in Figure 7. The source of the emission is the motion of dislocations during microyield. In Figure 8, the same specimen was reloaded up to 6000 pounds. No AE events were observed during reloading up to 2500 pounds since dislocations are already pinned at inclusions or other barriers. No further movement can take place until dislocations are freed or when new dislocations can be generated at a higher stress level. Note that signals were absent during unloading.

16

Table 4. Output of Events for Ambient and Vacuum Tests

TI-6AL-4V WELDED, NO CRACK (W) AMBIENT TEST

SENS		EVENT TIME	RDC	ED	PA	ENG	RT	SLOPE
#	1	00:00:04.32	37	208	55	78	1	561
#	1	00:00:05.58	37	208	55	78	1	561
#	1	00:00:06.84	37	208	56	79	1	629
#	1	00:00:08.10	38	204	55	78	1	561
#	1	00:00:09.36	38	204	54	77	1	500
#	1	00:00:10.62	38	208	54	77	1	500
#	1	00:00:11.88	38	208	55	78	1	561
#	1	00:00:13.14	38	204	55	78	1	561
#	1	00:00:14.40	38	204	54	77	1	500
#	1	00:00:14.67	2	4	50	56	1	315
#	1	00:00:15.66	39	204	55	78	1	561
#	1	00:00:16.92	36	204	55	78	1	561
#	1	00:00:18.18	38	204	55	78	1	561
#	1	00:00:19.44	36	204	55	78	1	561
#	1	00:00:20.70	37	204	54	77	1	500
#	1	00:00:21.97	38	204	55	78	1	561
#	1	00:00:23.23	37	208	55	78	1	561
#	1	00:00:24.49	38	208	55	78	1	561
#	1	00:00:25.75	38	208	54	77	1	500

TI-6AL-4V WELDED, NO CRACK (W) VACUUM TEST

SENS		EVENT TIME	RDC	ED	PA	ENG	RT	SLOPE
#	1	00:00:04.22	37	204	53	76	1	446
#	1	00:00:05.48	37	204	52	75	1	397
#	1	00:00:06.74	39	204	53	76	1	446
#	1	00:00:08.00	36	204	53	76	1	446
#	1	00:00:09.26	38	204	52	75	1	397
#	1	00:00:10.52	38	204	53	76	1	446
#	1	00:00:11.78	36	204	53	76	1	446
#	1	00:00:13.04	37	204	53	76	1	446
#	1	00:00:14.31	39	204	54	77	1	500
#	1	00:00:15.57	37	204	53	76	1	446
#	1	00:00:16.83	37	204	54	77	1	500
#	1	00:00:18.09	37	204	53	76	1	446
#	1	00:00:19.35	37	204	53	76	1	446
#	1	00:00:20.61	37	204	53	76	1	446
#	1	00:00:21.20	3	4	53	59	1	446
#	1	00:00:21.87	37	204	53	76	1	446
#	1	00:00:23.13	38	204	53	76	1	446
#	1	00:00:24.39	38	204	53	76	1	446
#	1	00:00:25.65	36	204	54	77	1	500
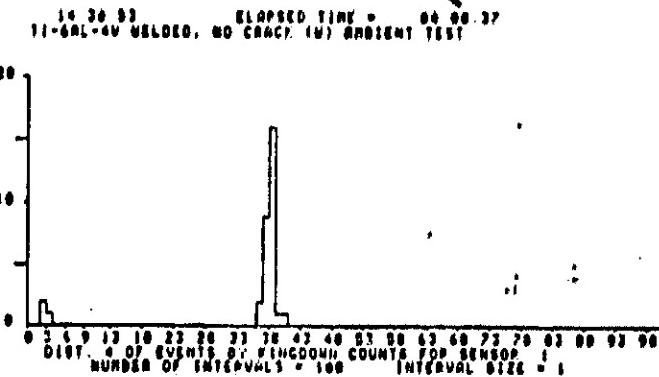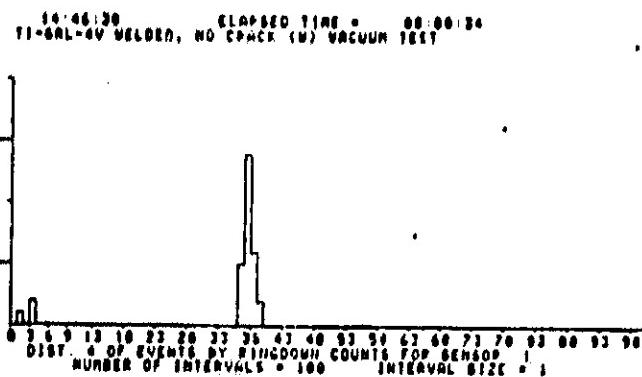
R5-010-85
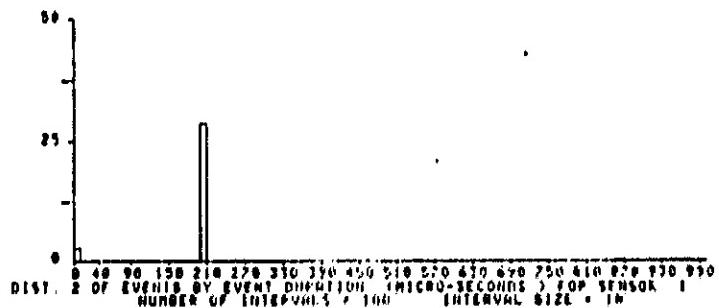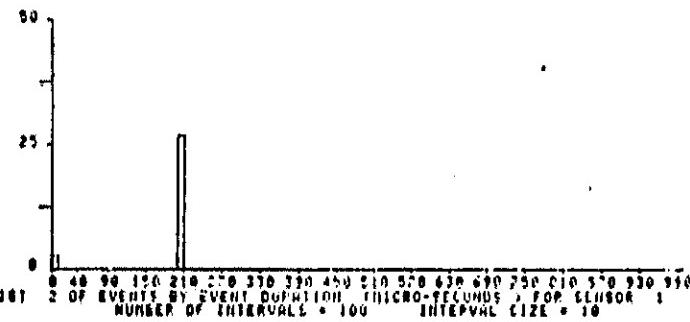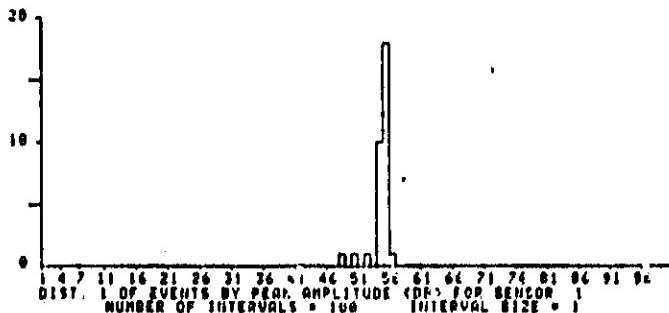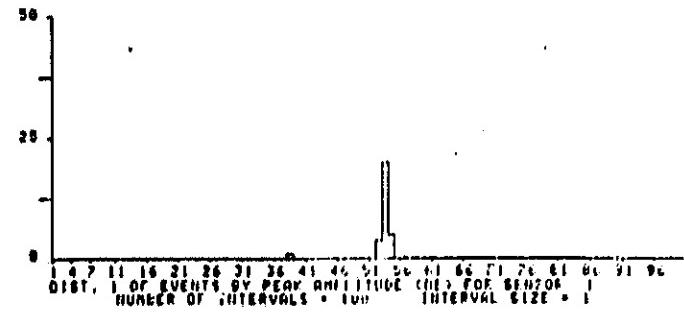
AMBIENT   VACUUM

Figure 6. Distribution of Events by Ringdown Counts, Event Duration
and Peak Amplitude for Ambient and Vacuum Tests

18
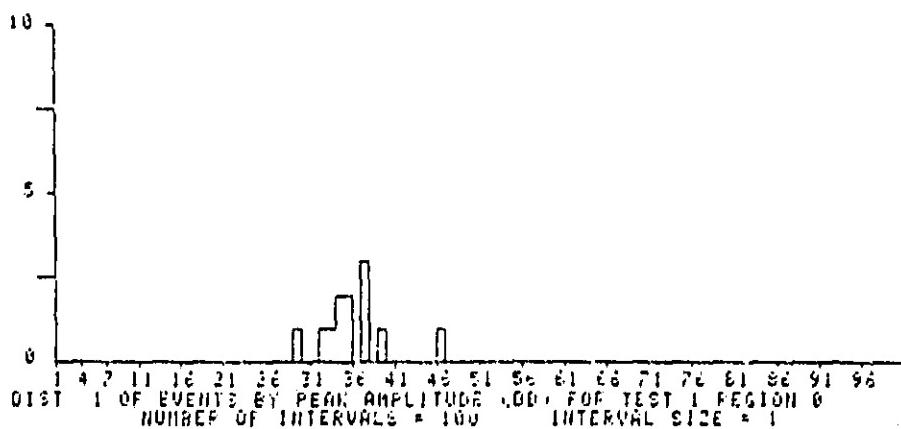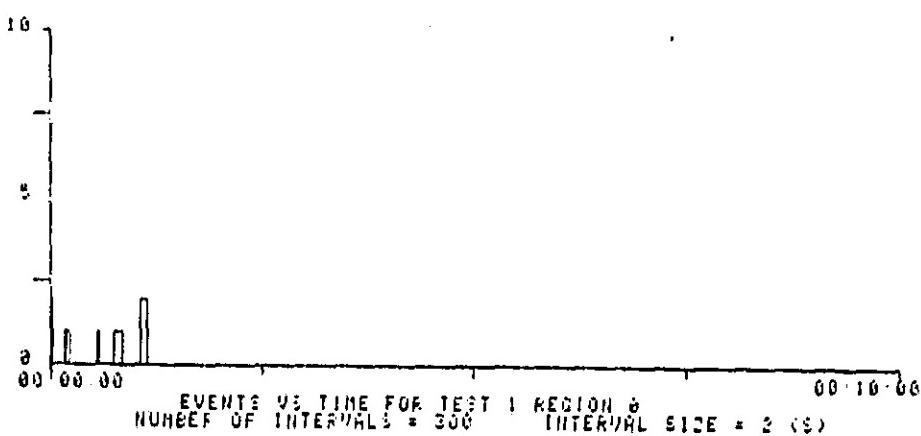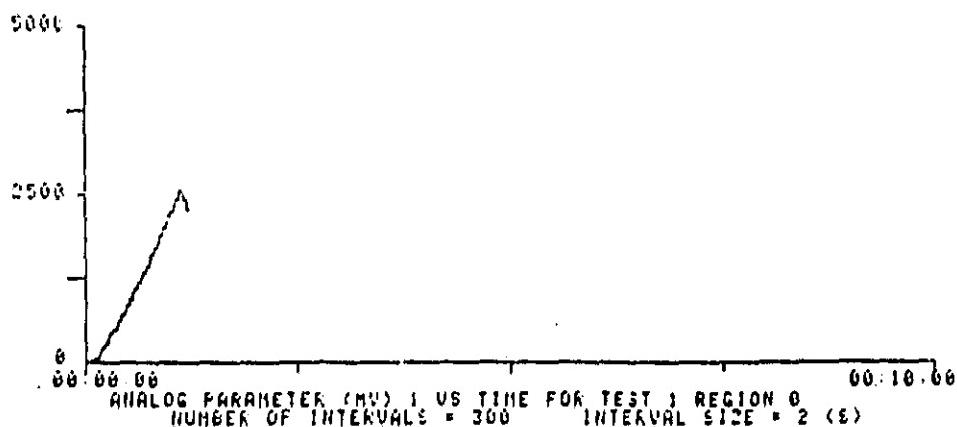
Figure 7. Load, Events, and Distribution of Events by Peak
Amplitude for Unflawed Ti-6A1-4V - Loaded to
2500 Pounds

19

TI-6AL-4V PARENT METAL, NO FLAW, LINEAR LOCATION TEST

ANALOG PARAMETER (MV) 1 VS TIME FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 300   INTERVAL SIZE = 2 (S)

EVENTS VS TIME FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 300   INTERVAL SIZE = 2 (S)

DIST 2 OF EVENTS BY PEAK AMPLITUDE (DB) FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 100   INTERVAL SIZE = 1
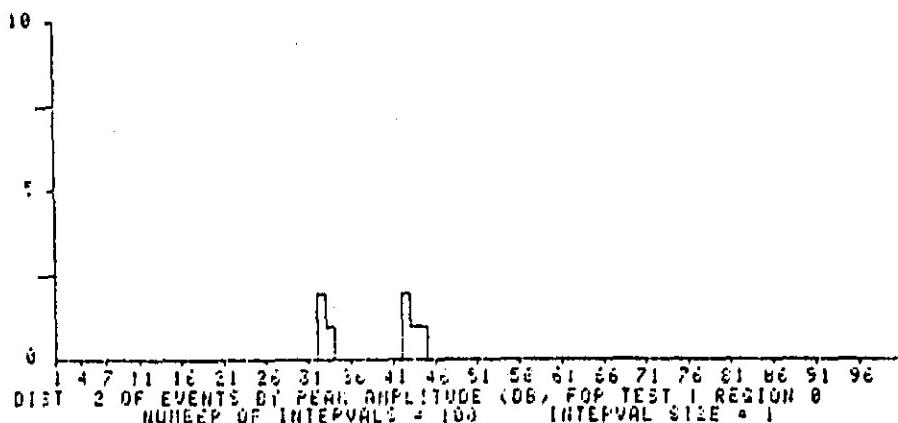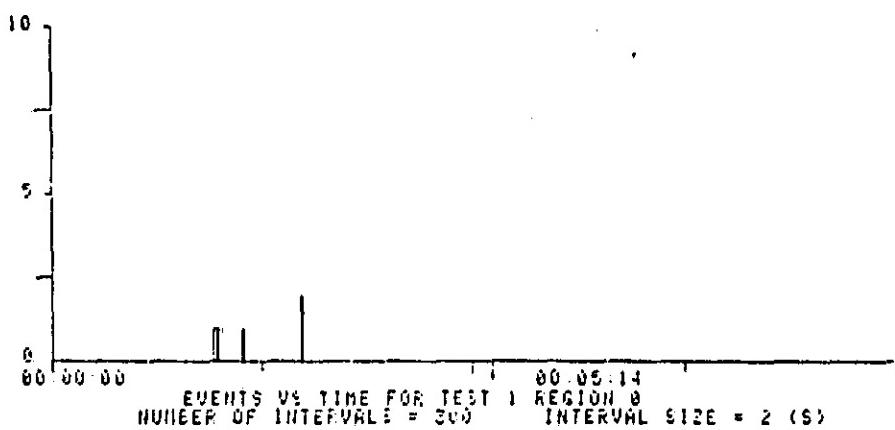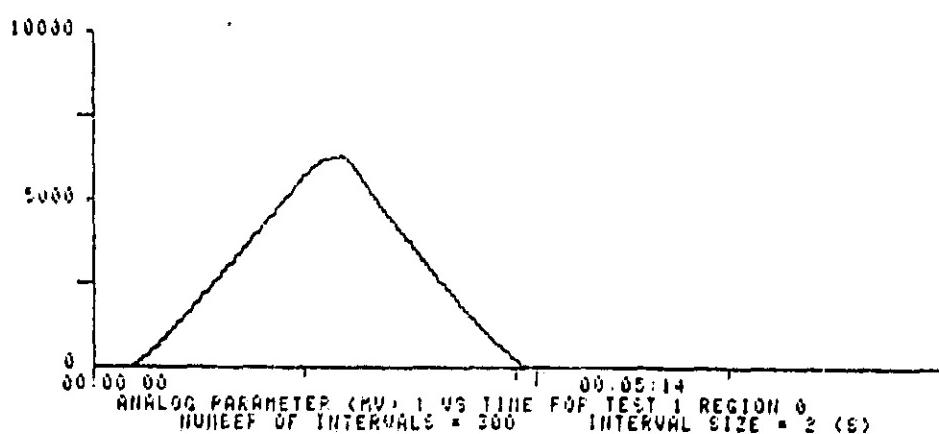
Figure 8.   Load, Events, and Distribution of Events by Peak
            Amplitude for Unflawed Ti-6Al-4V - Reloaded to
            6000 Pounds

20

In contrast, the cracked weld specimen (W2) exhibited many more events during loading. Figure 9 shows the load and corresponding events as a function of time for two consecutive loadings to 5000 pounds. The most significant difference between the cracked and unflawed specimen behavior is the absence of the Kaiser effect in the former. In this case, crack propagation is the source of AE. As long as crack extension occurs, we can expect to observe AE. Cracked specimens also exhibit AE during the unloading cycle. Apparently, closure of the crack faces produces AE signals.

Crack propagation is associated with high-amplitude, burst-type signals, which is consistent with our observation of signals in the 60 to 70 dB range (see Figure 10). Comparing the amplitude distributions for cracked specimens (Figure 10) with those of uncracked samples (Figure 8), it is clear that crack propagation is associated with signals in the 50 to 77 dB range, whereas plastic deformation produced signals with amplitude below 46 dB.

21

84 NOV 12 15:33:34   ELAPSED TIME =   00:07:29
        TI-6AL-4V WELDED, CRACKED, LINEAR LOCATION   (W2)

ANALOG PARAMETER (MV) 1 VS TIME FOR TEST 1 REGION 0
        NUMBER OF INTERVALS = 300   INTERVAL SIZE = 2 (S)

EVENTS VS TIME FOR TEST 1 REGION 0
        NUMBER OF INTERVALS = 300   INTERVAL SIZE = 2 (S)
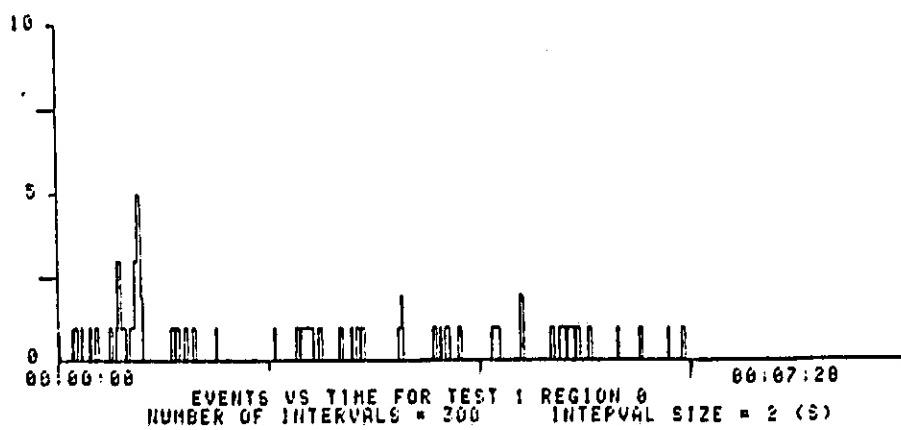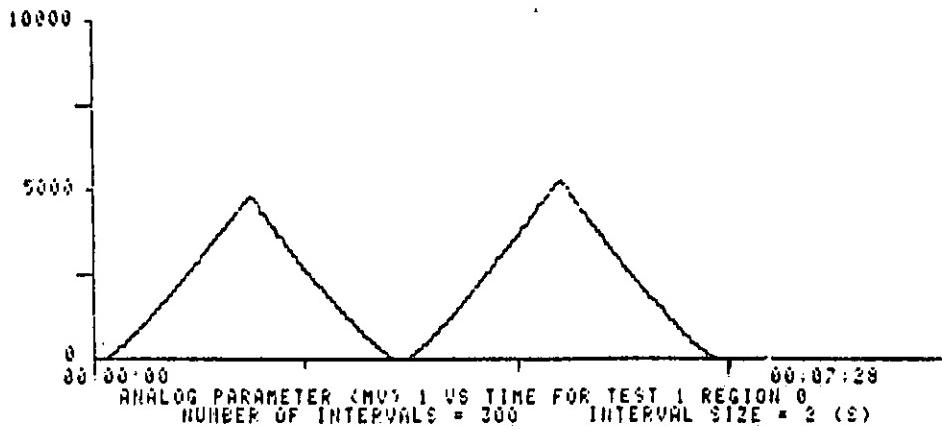
Figure 9. Load and Events for Cracked Welded Ti-6Al-4V

22
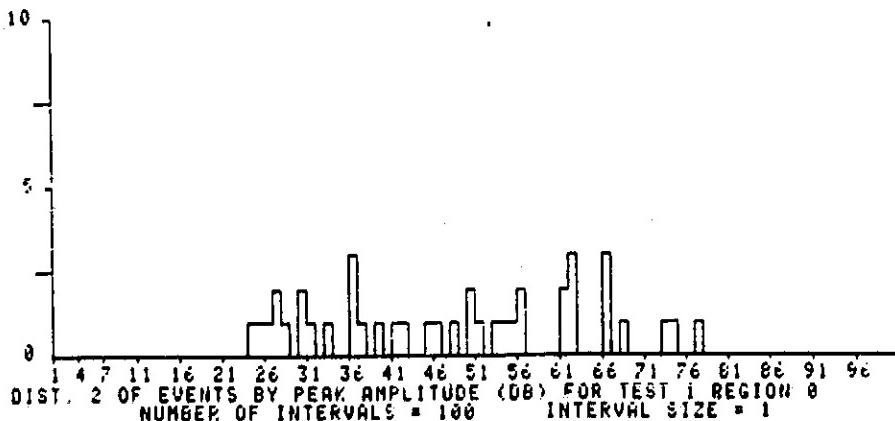
Figure 10. Distribution of Events by Peak Amplitude for
Specimens PM1, PM3, and W2

23

R5-010-85

4. PRESSURE VESSEL STUDY

AE monitoring was conducted during pressurization of a 22-inch diameter, Ti-6Al-4V propellant tank. For safety reasons, the tank was initially filled with water and then pressurized using nitrogen gas. The pressure vessel was placed in a vacuum chamber equipped with the necessary gas and water intervalves and electrical feedthrough (see Figure 11).

The method of locating unknown AE sources using two or more equations of the type:

$$x^2 + y^2 = A^2$$

where A is a calibrated constant, requires a specimen with a regular surface. Furthermore, the acoustic stress wave must propagate uniformly. Acoustic irregularities cause echoes, scattering, or variations in the speed of sound which in turn produce erroneous results. Needless to say, most hardware does not meet these criteria. For these applications, the AE system must utilize a zone calibration system whereby the computer software generates a boundary table during the calibration routine. The table, consisting of a range of time differences of sensor arrival patterns and range of amplitude, is built to identify each zone of AE origin. The system essentially generates a reference table which is used to locate the zone of the AE source during the actual test. A map of up to 200 zones may be created to represent the specimen.

The testing was performed in four steps:

1) <u>Calibration run.</u> A hand-held pulser, producing a repeatable signal, was moved within each zone. Calibration data was generated to define the sensor arrival patterns and the time difference ranges in each zone. Six zones, as shown in Figure 12, were defined and stored in computer memory. A printout of the calibration data is given in Appendix A for Zones 1A, 2A, 1B, 2B, 3B, and 4B. Figure 12 also shows the sensor placement.

2) <u>Verification run.</u> A control run was conducted to verify that the calibration data can accurately locate a simulated AE signal source. The pulser was moved in and out of the calibrated zones and proper location was verified by observing the events output list.

24
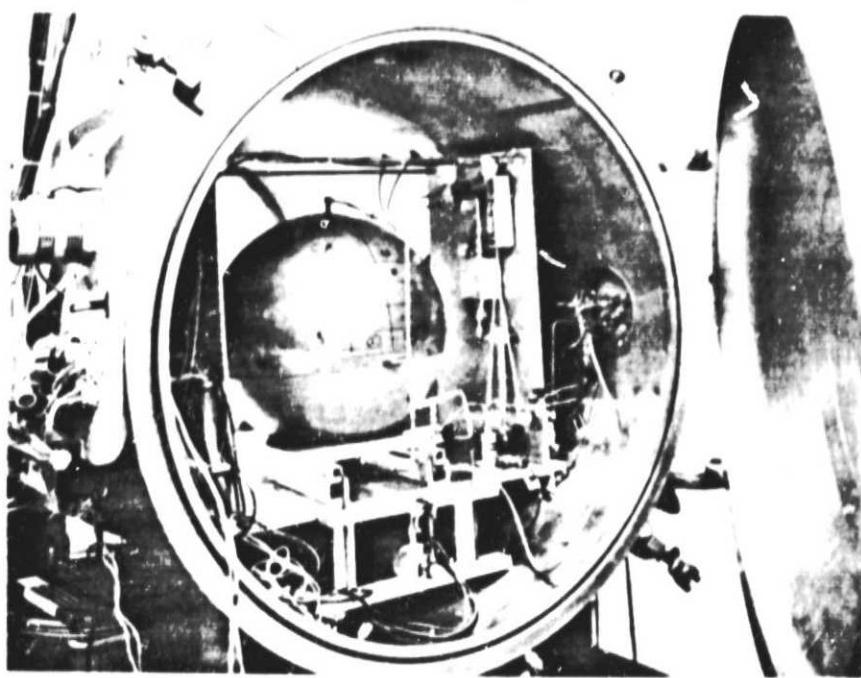
Figure 11. Ti-6Al-4V Pressure Vessel Placed in a Vacuum Chamber for AE Testing
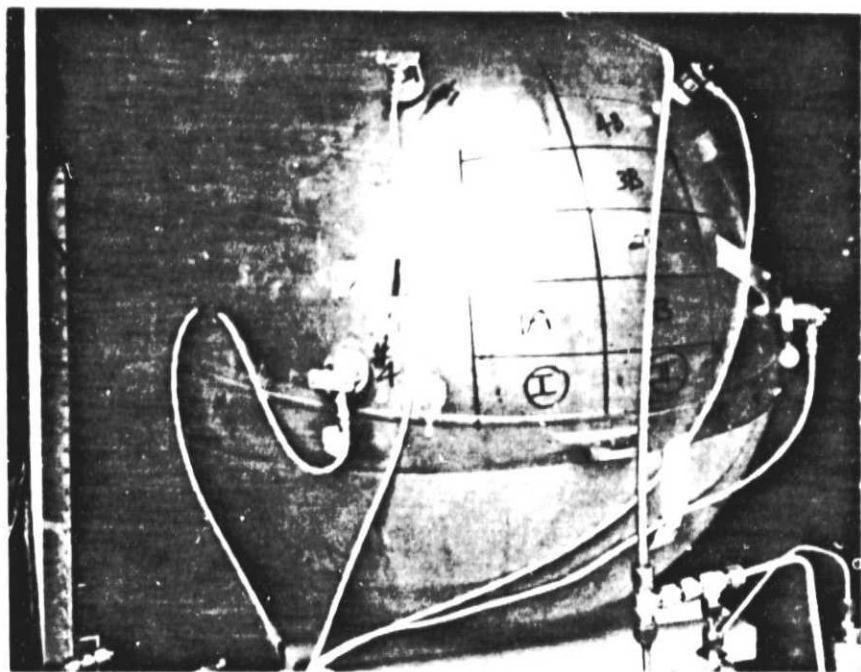
Figure 12. Pressure Vessel Instrumented with Form AE Transducers and Showing Locations of Zones

25

3) <u>Unflawed tank</u>. The unflawed tank was then pressurized to 125 psig while monitoring its AE signals. The purpose of this test was to assure ourselves that the tank is relatively "quiet" in its unflawed state. This provides the baseline data for comparison with subsequent AE data of the cracked tank. The load versus time history and the corresponding events versus time plot are shown in Figure 13. As expected, very few events were observed within the defined regions. Finally, Figure 14 shows the zone event location for this test. Apparently, all of the observed signals originated within Zone 2B (see location of Zone 2B in Figure 14).

4) <u>Crack location</u>. The pressure vessel was removed from the vacuum chamber and the sensor position precisely marked. A crack was introduced into the test pressure vessel in the minimum membrane (0.027 inch thickness). Electrical discharge machining was used to machine a notch in the shape of a circular segment perpendicular to the wall. The notch depth was approximately 0.010 inch while the length on the surface was 0.100 inch. The faces of the notch had an included angle of 20 degrees at the center. The notch radius was approximately 0.001 inch.

Deionized water having a minimum resistivity of 1,000,000 ohm/cm was cyclically pressurized into the vessel at room temperature until a crack formed at the root of the notch. The minimum pressure was 10 psig while the maximum pressure was 140 psig. The pressure rise time was 2.0 seconds and the pressure decrease time was 6.5 seconds. A total of 23,658 pressure cycles were used to produce the crack. The crack was observed with a stereomicroscope at 150 magnifications.

At the time of this report, the tank has been subjected to 23,000 cycles, but there is no indication of crack propagation. When the crack begins to propagate, the tank will be reinstrumented with sensors, replaced into the vacuum chamber and AE signals again monitored during pressurization to 100 psi. The zone location program will be employed to locate the crack.

04 13:41:15   ELAPSED TIME =   00:06:38
TI-6AL-4V PRESSURE VESSEL, NO CRACK, PRESSURIZE 125 PSIG

10000

5000

0
00:00:00   00:06:38
ANALOG PARAMETER (MV) 2 VS TIME FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 400   INTERVAL SIZE = 1 (S)
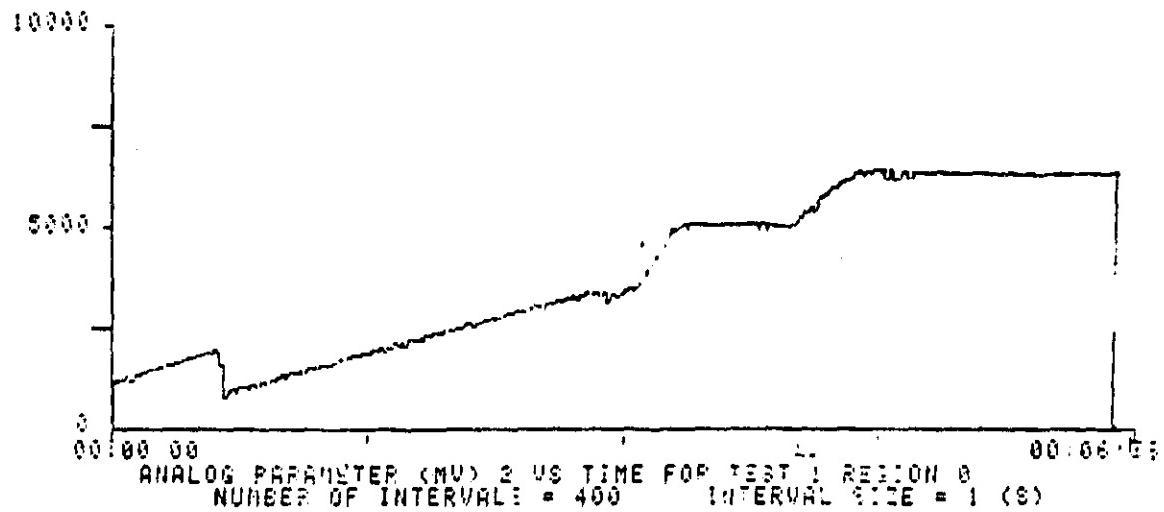
04 13:45:47   ELAPSED TIME =   00:06:38
TI-6AL-4V PRESSURE VESSEL, NO CRACK, PRESSURIZE 125 PSIG

10

5

0
00:00:00   00:06:38
EVENTS VS TIME FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 400   INTERVAL SIZE = 1 (S)
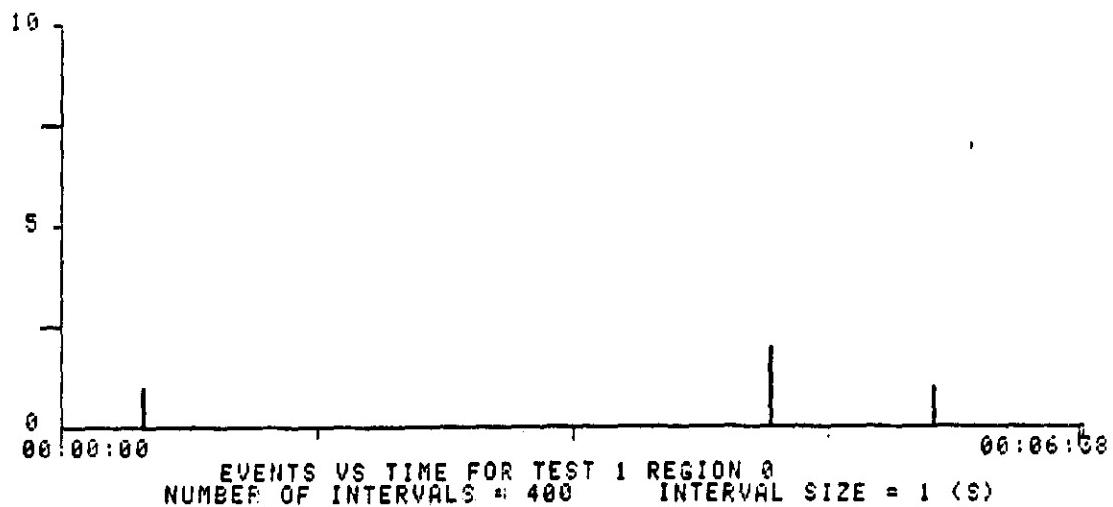
Figure 13.   Load Versus Time and AE Events Versus Time for
             Unflawed, Ti-6A1-4V Pressure Vessel Pressurized
             to 125 psig

27

R5-010-85
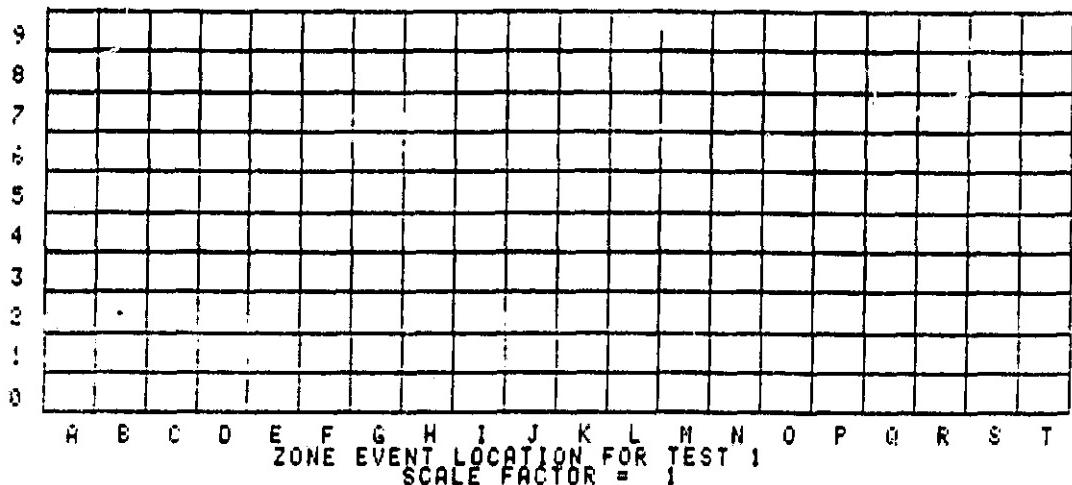
Figure 14. Zone Event Location for Unflawed, Ti-6A1-4V
Pressure Vessel Pressurized to 125 psig

R5-010-85

5. SUMMATION

This report just scratches the surface of the possibilities of using nondestructive methods for flaw detection of space station components under space environments. The study does show that there are several methods that can be successfully applied in the space environment, and that combinations of these and other methods may be necessary. No one method can do it all under all conditions. Thus each method should be tailored to the specific application. For future programs this study suggests:

- Continuing the investigation of NDE methods for flaw detection of composite structures.

- Designing a relatively simple proof of principle in-situ testing program employing samples with known flaws for use with the orbiter.

- Pursuing the application of existing NDE methods in greater depth.

- Devising EVA programs that can demonstrate the use of robotic arms or astronauts for inspection of flawed samples.

R5-010-85

APPENDIX A — ACOUSTIC EMISSION SYSTEM

TRW's Materials Engineering Department purchased an acoustic emission measuring system last year to further expand their NDE capabilities in the NDT area (see Figure A-1). The AET 5000 system is microcomputer based and makes full use of computer technology to allow high data rates and multi-test processing. The unit presently consists of a four-channel system with real-time monitoring capability including extensive capability for data discrimination based upon AE characteristics or external parameters. The system can be updated cost-effectively up to an eight-channel system when the need arises.

The following parameters can be measured on all active channels: ringdown counts, event counts, event duration, amplitude, rise-time, signal level, and external analog inputs. With standard AE software, logarithms and averages of these parameters can be taken. The system also has standard software algorithms for linear, planar, and zone-calibrated locations.

AET computer-based acoustic emission system

Figure A-1. Computer-Based Four-Channel Acoustic Emission Equipment

A-1

LIST ZONE BOUNDARIES FOR TEST = 1 , ZONE = 1A
COMBINE OVERLAPPING BOUNDARIES (NO)? NO

S1	S2	S3	S4	---DT 1---		---DT 2---		---DT 3---		-AMP-		ZN	R
		2	3	14	18	20	24	210	214	61	61	1A	1
4	1	2	3	6	10	20	24	202	206	59	59	1A	1
4	1	2	3	0	6	4	11	71	82	54	59	1A	1
4	1	3	3	19	76	52	39	84	105	1	0	1A	1
4	1	3	2	20	24	37	41	91	95	60	60	1A	1
4	1	3	2	28	32	52	58	97	104	60	61	1A	1
4	1	3	2	28	32	46	50	81	85	60	60	1A	1
4	1	3	2	28	32	43	47	97	101	61	61	1A	1
4	1	3	2	27	31	60	61	94	98	61	61	1A	1
4	1	3	2	5	17	8	21	16	27	54	60	1A	1
4	1	3	2	2	6	5	9	33	37	52	52	1A	1
4	1	3	2	1	15	4	18	63	82	53	57	1A	1
4	1	3	2	10	14	17	21	37	41	57	57	1A	1
4	1	3	2	36	47	41	49	70	79	58	59	1A	1
4	1	3	2	35	47	35	54	45	66	58	60	1A	1
4	1	3	2	19	36	35	42	54	63	60	61	1A	1
4	2	1	3	27	36	36	45	105	116	63	63	1A	1
4	2	1	3	15	27	24	43	71	96	55	63	1A	1
4	2	1	3	27	46	24	52	35	65	54	63	1A	1
4	2	3	1	0	28	3	41	9	51	52	60	1A	1
4	2	3	1	30	46	35	51	37	58	59	62	1A	1
4	2	3	1	0	10	5	18	106	114	55	56	1A	1
4	3	1	2	29	43	35	47	43	66	59	60	1A	1
4	3	2	1	3	15	4	16	28	47	52	58	1A	1

LIST ZONE BOUNDARIES FOR TEST = 1 , 2ZONE = 2A
COMBINE OVERLAPPING BOUNDARIES (NO)? NO

S1	S2	S3	S4	---DT 1---		---DT 2---		---DT 3---		-AMP-		ZN	R	
1	2	4	3	0	9	0	19	14	28	59	63	2A	1	
1	2	4	3	0	6	1	7	36	42	1	0	2A	1	
1	4	2	3	0	6	1	12	16	26	59	62	2A	1	
1	4	2	3	0	6	4	12	28	42	60	61	2A	1	
1	4	2	3	0	6	5	11	67	73	62	62	2A	1	
2	1	4	3	0	8	3	12	16	23	63	63	2A	1	
2	1	4	3	0	6	3	9	36	42	1	0	2A	1	
2	1	4	3	0	8	3	12	25	34	1	63	2A	1	
2	4	1	3	0	6	3	9	68	74	3	1	2A	1	0
2	4	1	3	0	6	3	9	54	60	1	0	2A	1	
2	4	1	3	1	7	15	21	117	123	1	0	2A	1	
2	4	1	3	0	7	2	14	8	34	3	3	2A	1	0
2	4	3	1	9	15	17	23	33	39	62	62	2A	1	
4	1	2	3	3	9	3	9	83	100	60	60	2A	1	
4	2	1	3	2	13	12	24	23	42	53	58	2A	1	
4	2	1	3	0	5	1	7	29	35	56	56	2A	1	
4	2	1	3	0	5	7	13	139	145	53	53	2A	1	
4	2	1	3	14	29	23	33	43	53	56	60	2A	1	
4	2	1	3	22	29	24	32	58	65	60	60	2A	1	
4	2	1	3	0	6	1	9	13	25	56	61	2A	1	
4	2	1	3	28	31	26	30	74	80	60	60	2A	1	
4	2	3	1	31	37	67	73	89	95	55	55	2A	1	
4	2	3	1	24	30	47	53	111	117	59	59	2A	1	
4	2	3	1	23	29	44	50	90	96	57	57	2A	1	

LIST ZONE BOUNDARIES FOR TEST = 1 , ZONE = 1E
COMBINE OVERLAPPING BOUNDARIES (NO)? NO

S1	S2	S3	S4	---DT 1---		---DT 2---		---DT 3---		-AMP-		ZN	P
1	1	3	4	0	5	0	5	0	5	25	63	1E	2
1	1	4	3	5	11	5	11	7	13	62	63	1E	2
2	3	1	4	0	6	13	19	5	26	60	63	1E	2
2	3	4	1	0	8	0	14	5	14	61	62	1E	2
2	4	1	3	0	8	19	30	163	171	62	63	1E	2
2	4	1	3	0	16	21	25	7	25	59	62	1E	2
2	4	3	1	0	9	4	15	7	16	61	63	1E	2
3	2	1	4	0	18	3	34	6	37	55	62	1E	2
3	2	4	1	0	12	0	19	0	23	59	31	1E	2
3	2	4	1	0	5	0	12	25	33	57	59	1E	2
3	2	4	1	0	17	20	34	23	39	58	60	1E	2
3	4	2	1	0	7	0	8	8	16	58	60	1E	2
4	3	2	1	4	13	7	15	15	27	57	58	1E	2

LIST ZONE BOUNDARIES FOR TEST = 1 , ZONE = 2D
COMBINE OVERLAPPING BOUNDARIES (NO)? NO

S1	S2	S3	S4	---DT 1---		---DT 2---		---DT 3---		-AMP-		ZN	P
1	4	2	3	0	4	0	5	0	9	25	12	2E	2
2	1	3	4	6	25	2	35	13	44	1	63	2E	2
2	1	3	4	2	10	5	11	6	11	1	62	2E	2
2	1	4	3	25	28	32	41	38	56	61	63	2E	2
2	3	1	4	2	9	6	12	7	13	1	0	2E	2
2	3	1	4	9	21	14	26	62	70	60	61	2E	2
2	3	1	4	7	25	5	28	17	44	1	63	2E	2
2	3	4	1	2	16	17	27	26	30	59	62	2E	2
2	3	4	1	6	17	6	17	15	21	1	62	2E	2
2	4	1	3	9	17	6	18	11	21	3	3	2E	2
2	4	1	3	5	17	7	20	25	33	1	1	2E	2
2	4	1	3	5	17	6	18	61	84	3	3	2E	2
2	4	3	1	10	16	6	17	7	20	1	1	2E	2

LIST ZONE BOUNDARIES FOR TEST = 1 , ZONE = 3B
COMBINE OVERLAPPING BOUNDARIES (NO)? NO

S1	S2	S3	S4	---DT 1---		---DT 2---		---DT 3---		-AMP-		ZN	P
1	2	4	3	0	4	0	4	0	6	19	17	3B	2
1	2	4	3	0	5	42	48	75	81	58	58	3B	2
1	2	4	3	0	4	20	26	29	35	60	60	3B	2
1	3	4	2	0	4	0	4	0	6	7	5	3B	2
2	1	3	4	26	32	13	43	22	56	1	63	3B	2
2	1	4	3	15	21	41	47	230	236	62	62	3B	2
2	1	4	3	0	4	43	49	241	247	62	62	3B	2
2	1	4	3	10	18	49	55	243	253	62	62	3B	2
2	1	4	3	6	12	51	65	76	82	62	62	3B	2
2	1	4	3	0	12	19	29	24	58	3	4	3B	2
2	1	4	3	14	19	20	29	66	72	63	63	3B	2
2	4	1	3	26	32	29	35	32	38	62	62	3B	2

R5-010-85

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LIST ZONE BOUNDARIES FOR TEST = 1 , 4ZONE = 4B
COMBINE OVERLAPPING BOUNDARIES (NO) NO

S1	S2	S3	S4	---DT 1---		---DT 2---		---DT 3---		-AMP-		ZN	R
1	2	4	3	0	6	27	36	35	43	59	60	4B	1
1	2	4	3	2	8	27	33	95	101	59	59	4B	1
1	2	4	3	0	11	27	36	44	68	58	60	4B	1
1	2	4	3	0	11	27	36	144	166	59	60	4D	1
2	1	3	4	28	34	36	42	168	174	1	0	42	1
2	1	3	4	5	11	42	48	43	49	3	1	4B	1
2	1	3	4	19	25	65	71	65	71	62	62	4B	1
2	1	3	4	39	45	40	46	190	196	3	2	4B	1
2	1	3	4	21	27	67	73	89	95	7	5	4B	1
2	1	3	4	18	24	39	45	165	171	3	2	4B	1
2	1	3	4	16	22	37	43	37	43	3	1	4B	1
2	1	3	4	13	25	26	61	46	69	5	6	4B	1
2	1	4	3	0	7	31	37	153	162	3	0	4B	1
2	1	4	3	0	5	30	37	171	177	1	1	4B	1
2	1	4	3	17	39	51	71	55	91	7	7	4B	1
2	1	4	3	0	16	30	50	40	79	3	3	4B	1

R5-010-85

APPENDIX C — PRINCIPAL TECHNICAL PERSONNEL

Dr. Thomas Chung is a staff engineer of technology of O&SG Product Assurance. He joined TRW in August 1980, with a PhD in physics from the University of Washington, Seattle. His work areas include nondestructive evaluation, and he is a Level III examiner in X-ray, ultrasonics, and dye penetrant methods. He participated in the Titan II structure assessment task in 1981 and several other NDE proposal works.

Dr. May Kwan received a PhD in material science from UCLA in 1983. Her dissertation is on magnetomechanical acoustic emission of ferromagnetic materials. She is a member of the technical staff in the materials engineering department of Manufacturing Division. She has been responsible for material testing, data evaluation of metallic components, acoustic emission studies, and other NDE methods.

Joseph C. Lewis has an MS degree in materials engineering (major in fracture control). He has been active in aerospace engineering since 1960. He has a unique combination of experience in propulsion system and component design, STS safety, compatibility, materials, processes, structural analysis and design, thermal analysis and design, and spacecraft systems analysis.

Martin S. Toll has a BS degree in mechanical engineering and is a registered professional engineer in the state of Pennsylvania. He managed his own engineering and equipment business for 25 years before joining TRW in a staff position. He specialized in the design and building of various types of automated chemical processing machinery associated with the manufacturing of semiconductors.

R5-010-85