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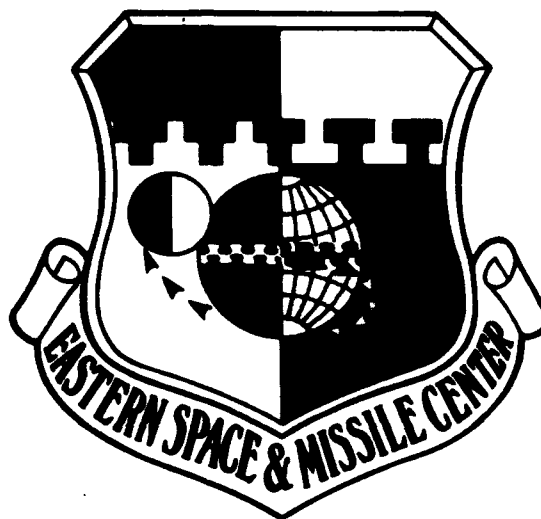
FINAL REPORT
KEVLAR OVERWRAP STUDY

APRIL 1992

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Arde Inc.
500 Walnut Street
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Eastern Space and Missile Center
Air Force Systems Command
Patrick Air Force Base, Florida

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This technical report has been reviewed and is approved for publication.

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April 1992

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for
Eastern Space and Missile Center
Air Force Systems Command
Patrick Air Force Base, Florida

FOREWARD

This final report was submitted by ARDE, INC. to the Eastern Space Missile Command (ESMC), Patrick Air Force Base, under Contract No. FO 8606-84-0029.

This report summarizes the experience and knowledge base for predicting the fail safe features of a Kevlar Overwrap Vessel and has been reviewed and is approved for release and distribution in accordance with the distribution statement on the cover and on the Standard Form 298.

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13. ABSTRACT (Maximum 200 words)

A guide to the design of a Kevlar -49 fiber overwrapped metal composite tank that would "fail safe" in the event the metal liner ruptured suddenly at operating pressure was developed based on the analytic and experimental program performed. The fail safe mode is defined by containment of any ruptured metal liner fragments by the intact fiber shell and benign venting of the contained fluid. Two sudden metal liner failure modes were investigated experimentally and analytically; stable ductile liner crack growth (leak-before-burst, LBB) and liner unstable brittle crack growth/rupture failure mode. The tankage investigated in the program is Kevlar -49 overwrapped cryoformed 301 stainless steel spherical pressure vessels. Liner failure models were postulated and failure predictions made based on tankage dynamic response computer calculations and simple one-dimensional model computation presuming two (2) percent Kevlar -49 fiber strain to failure. Tanks of 16, 22 and 11 inch diameter were tested with high pressure helium gas to compare theory with experiment. The LBB liner failure mode was experimentally investigated by operating pressure cycle testing tanks having liners with intentionally machined defects. Further liner LBB data was obtained from uniaxial R-Curve fracture mechanics tests. The unstable crack growth "catastrophic" failure mode was achieved experimentally by intentionally hydrogen embrittling the liner by charging it with hydrogen gas followed by operating pressure loading.

| 14. SUBJECT TERMS brittle fracture, composite, crack growth, cryoformed, dynamic response, fail safe, fiber, fracture mechanics, fragment containment, high pressure gas, hydrogen embrittlement, Kevlar, leak-before-burst, liner, pressure vessel, prestressed, R-curve, stainless steel, safety | 15. NUMBER OF PAGES |
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LIST OF FIGURES AND TABLES

This report contains a very large number of figures and tables to support and clarify the text. In order to preserve ready continuity of technical discussion, and for reader convenience, the large detailed list of figures and tables is placed at the end of the report in Appendix G.

For convenience of reference, the following scheme is used to aid figure/table ready identification/location.

1. In general, the first character (number or letter) of a figure or table number (e.g., 1-2, 2-3, A-1, C-2, etc.) identifies the report section or appendix in which it is located.

2. An exception is figure and table numbers with letters (A, B, C ... G) after the numerical diget (e.g., 3C) which refer to figures and/or tables in prior independently prepared documentation used to support this report text.

GLOSSARY OF TERMS

Acryonyms (abbreviations) are used throughout the text. They are defined in most instances when first used. For convenience of reference, they are listed below.

AE - Acoustic emmission
BM - Base metal
CCT - Center cracked tension panel R-Curve test specimen
CRES - Corrosion resistant steel
Cryo - Cryoformed
Cryoformed - A plastic deformation forming process at cryogenic (-320°F) temperature
CT - Compact tension R-Curve test specimen
EDM - Electron discharge machining
Elox - another name for EDM
FPS - Frames per second
GHe - Gaseous helium
HAZ - Heat affected zone (of weld)
Hi - Cams - High speed cameras
J_R Curve - A plot of J-integral values proportional to the areas under the load-displacement curves vs. crack growth generated during tests of pre-cracked material specimens.
LBB - Leak-before-burst (failure mode)
PICES 2D - Physics International Corporation two-dimensional transient computer program
PC - Chamber pressure
PSC - Prestressed composite
PV - Vessel pressure
R-Curve - A continuous record of toughness development in terms of crack growth resistance K_R plotted against crack extension in the material as a crack is driven under a continuously increased stress intensity factor, K
SG - Strain gage
SPP - Samples per second
TC - Thermocouple
VHS - Very high speed
WM - Weld metal
2D - Two dimensional
1D - One dimensional
ϕ - Diameter

SUMMARY

Key program results are briefly summarized below. They are more fully described in the main text.

1. **Fail Safe Demonstrated**

   "Fail Safe" (leak/fiber rention of liner fragments) has been demonstrated experimentally at 2500 - 5600 psig gaseous helium (GHe) operating pressure for 16" and 22" diameter (ϕ) prestressed composite (PSC) Kevlar overwrapped tanks. The 301 Cryoformed corrosion resistant steel (CRES) liners were intentionally hydrogen embrittled to achieve a brittle failure mode at operating pressures. Measured fiber strains are predicted by "static" structural response for liner global embrittlement mode. Here, global refers to the entire liner inside surface less bosses. Significant dynamic structural response (about 1.5 - 1.7 dynamic amplification factors) was noted for the liner local girth weld heat affected zone (HAZ) embrittlement mode which experimentally simulated the transient worst case structural model. Similar dynamic fiber strain amplification was measured for local boss/head weld HAZ embrittlement of the liner. Girth embrittlement is considered more critical since the liner fragmented into two pieces at the girth. The embrittled boss region, although cracked, was still attached to the rest of the liner (no fragments) and the liner could still resist some load as an "intact" one piece shell.

   A single small fragment metal liner brittle rupture failure mode was also investigated. Analytic considerations and experimental evidence, as detailed in Appendices E.5, E.6 and F, showed this failure mode to be less critical than local girth or boss embrittled failure modes discussed above.

2. **Failure Modes Predicted**

   Failure pressure and failure mode (metal plus fiber) were predicted and experimentally verified for 16" ϕ PSC sphere "sure fail" designed unit with local girth weld embrittled liner and 50% of baseline fiber thickness. Margin test 16" ϕ vessel (83% fiber thickness and local girth weld embrittlement) gave experimental results very close to expected failure/retention mode values. Dynamic amplification at liner brittle rupture was slightly higher than anticipated. 16" ϕ 90% fiber thickness and 22" ϕ PSC tanks demonstrated fail safe behavior, as predicted.

3. **Leak-Before-Burst (LBB) Mode Demonstrated by Test**

   Operating pressure cycle tests of vessels with Elox (EDM) machined defects in 301 cryoformed CRES liner walls showed benign leak mode for GHe and hydraulic pressurants. A globally embrittled PSC vessel cryoformed 301 CRES liner with hundreds of thru, continuous cracks showed benigh leak mode for a GHe operating pressure test. R-Curve and vessel fracture mechanics tests demonstrated that cryoformed 301 CRES

is a tough, high strength material that gives LBB mode. Significant results obtained were a plane stress critical R-Curve stress intensity

of 180 ksi $\sqrt{in}$ for parent material, weld and HAZ at high tensile strength (200 - 260 ksi). Metal vessel thru cracks grew in a stabile manner up to four (4) times the wall thickness before reaching critical size. This indicated significant LBB safety margin since LBB is considered demonstrated if thru cracks grow to two (2) times wall thickness before becoming unstable.

4. Analytic Predictions Verified

Analytic predictions of fiber strains/failure modes were in reasonable agreement with experimental results. Computer two-dimensional (2D) structural models and a simplified one-dimensional (1D) analytic model were thus verified.

5. A "Fail Safe" Tank Design Guide Developed

A guide for the design of Kevlar -49 fiber overwrapped metal composite tanks that will "fail safe" if the metal liner ruptures suddenly at operating pressure was developed based on structural theory and test data. The design guide simply relates fiber operating stress and metal stress increment (operating stress minus initial stress) to the required fiber to metal thickness ratio to achieve retention by the intact fiber shell of any metal fragments generated. Here, fiber stress refers to the fiber load divided by the fiber less resin cross-sectional area. The resin is presumed to carry zero load.

6. Key Experimental Techniques Developed

Test procedures/technique/set-up/instrumentation were developed as required to accomplish successful transient GHe pressure testing of fiber overwrapped prestressed composite pressure vessels and to accurately monitor the extremely short time fiber strain response/pressure/temperatures. In addition, techniques and parameters required to intentionally hydrogen embrittle the PSC 301 cryoformed (Cryo) CRES liners in a controlled manner so that they failed in a predetermined brittle way at predetermined/pressure/stress/time were developed and experimentally verified.

1.0 INTRODUCTION

Prestressed composite (PSC) fiber overwrapped metal pressure vessels[2],[3]* have wide use for gas storage because of their light weight. Typical maximum operating pressures are in the range of 3000 - 5000 psig which could cause catastrophic damage in the event of tank rupture. Therefore, safety considerations for personnel working in the vicinity of PSC tanks are very important. PSC tanks because of their two load carrying members (fiber and metal) have a potential safety advantage. In the event that the metal component was to fail catastrophically during operation (metal liner ruptures at operating pressure), the load carried by the liner could be possibly transferred to the non-failed fibers so that the metal liner fragments (if any) would be non-hazardously contained and the pressure vented by leaking gas through the porous outer fiber shell.

Up to the present, no appropriate experimental evidence was available to prove these potential safety advantages of PSC tankage and no systematic study had been made to analytically define the pertinent tank parameters relating to fail safe behavior. The Air Force, therefore, funded a research and development program to establish and verify the design basis of PSC pressure vessel construction that can exhibit the desired safety advantages. ARDE, INC., under Patrick Air Force Base Contract No. FO-8606-84-C-0029, "Kevlar Overwrap Study", investigated experimentally and analytically the circumstances under which PSC tankage will "fail safe" at operating pressure load. The objective being to define a test-verified "generic" rationale for the design of fail safe PSC tankage consisting of a metal liner overwrapped with Kevlar -49.

Two sudden metal liner failure modes were investigated; a brittle liner (unstable, crack growth) failure and a ductile liner (stable, leak-before-burst) failure. The metal liner failure mode depends to a large extent upon liner toughness. Fiber toughness is not germain since a basic ground rule of this study is that the fiber wrap has no "initial flaws". The discussion of toughness in this report, therefore, relates entirely to the metal liner. The PSC tankage used in the program is Kevlar -49 fiber overwrapped cryoformed 301 CRES spherical pressure vessels. The cryoformed 301 CRES liner selection was for convenience. The target was to have the program output relate to any liner material. Both 11 inch diameter subscale and 16 and 22 inch diameter full scale vessels were tested. The full scale 16 inch PSC tanks are similar in size and configuration to those produced for high pressure gas storage on British Aerospace's Olympus Satellite (Fig. 1-1). The 22 inch full scale PSC tanks are similar to those built for high pressure helium gas storage on General Dynamics Centaur vehicle (Fig. 1-2). Fiber thicknesses were modified to suit test program requirements. The brittle liner failure mode was achieved through intentional embrittlement of the metal liner by establishing a "battery" for charging the metal liner with hydrogen gas for an extended period to

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* Numbers in superscript refer to references listed in section 4.0.
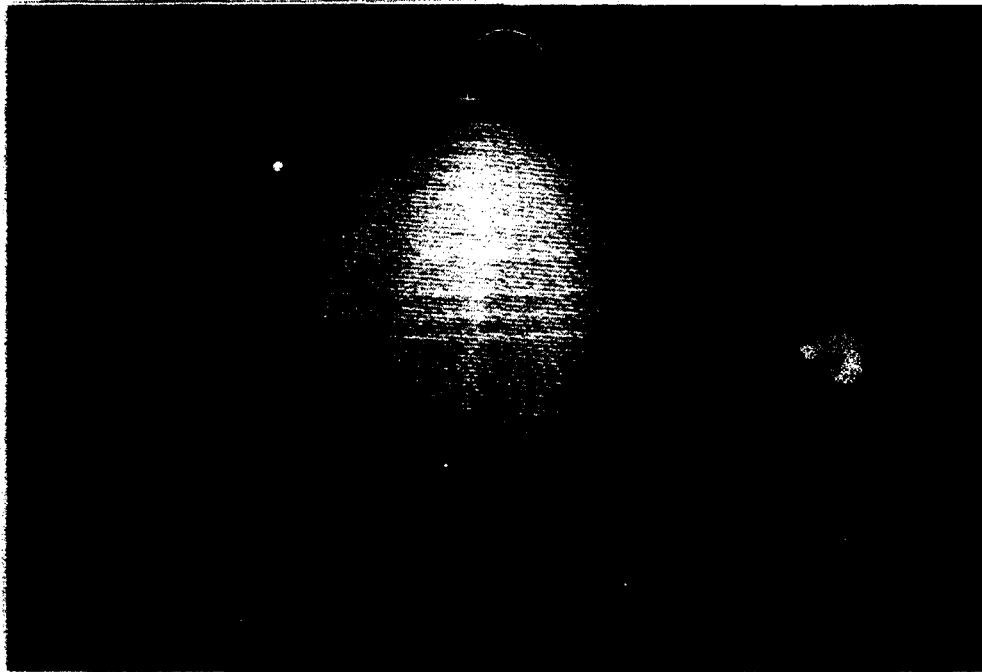
Fig. 1-1

Olympus Cryoformed 301 S/S Kevlar 49 Overwrap Prestressed Composite Pressure Vessel

assure saturation and then applying operating pressure to the tank. In addition, the liner inside surface was "sensitized" by pickling and the hydrogen embrittlement reaction enhanced by the addition of sodium arsenite to the "battery" electrolyte solution. Subscale all metal vessels were tested first to develop hydrogen embrittlement parameters, followed by testing of subscale and full scale PSC tanks. The leak-before-burst (LBB) stable crack growth mode was induced by EDM machining appropriate defects in the liner wall followed by cycling at operating pressure to produce crack wall breakthrough. Both subscale and full scale PSC tanks wer tested. In addition, uniaxial tensile R curve tests of appropriate cryoformed CRES specimens were conducted to provide additional liner fracture mechanics data for LBB verification.

Fig. 1-2

CENTAUR CRYOFORMED 301 S/S KEVLAR 49 OVERWRAP
PRESTRESSED COMPOSITE PRESSURE VESSEL

2.0 TECHNICAL DISCUSSION

This section discusses the various technical program tasks and provides details of analytic and test approaches and results. Both successful and unsuccessful approaches are described since one can learn as much, if not more, from failure compared to success. As an aid to subsequent discussions, Figure 2-1 defines PSC tank components and regions.

2.1 Overview

The basic objective of the program was to provide valid data enabling definition of "fail safe" design criteria for Kevlar -49 fiber overwrapped metal PSC vessels in the event that the metal liner should fail suddenly at operating pressure. To accomplish this objective, program effort involved the tasks outlined below. These tasks and their results are more fully discussed subsequently in the order listed below.

1. Postulate failure models/modes
2. Verify fiber ultimate strain
3. Define and verify metal liner hydrogen embrittlement techniques/parameters.
4. Obtain experimental uniaxial R-Curve fracture mechanics data for the liner and verify its leak-before-burst failure mode by vessel tests.
5. Obtain "fail safe" data for brittle liner failure mode by full scale PSC vessel tests for liner global hydrogen embrittlement, local girth weld heat affected zone and local boss/head weld heat affected zone hydrogen embrittlement cases.
6. Correlate test results and refine structural models/failure modes as required by experiment to facilitate definition of "fail safe" PSC vessel design criteria.

2.2 Failure Mode Postulation and Analysis

The objective of the analysis is to predict the onset of Kevlar -49 fiber overwrap failure in response to an instantaneous metal liner failure of a PSC spherical vessel. This PSC tank structural analysis and failure mode modeling was accomplished by a two-dimensional transient stress analysis using PISCES 2 DELK computer program[4] and a simplified one dimensional lumped transient model as described in Appendix A. One-dimensional static calculations based on a prior formulation[3] were also used in the test data correlation, as appropriate.

Fiber failure was presumed at the test verified 2% fiber less resin ultimate strain value. Two (2) liner failure modes were considered in the PISCES transient analysis; an instantaneous unstable brittle liner girth crack and an instantaneous liner stable polar hole.
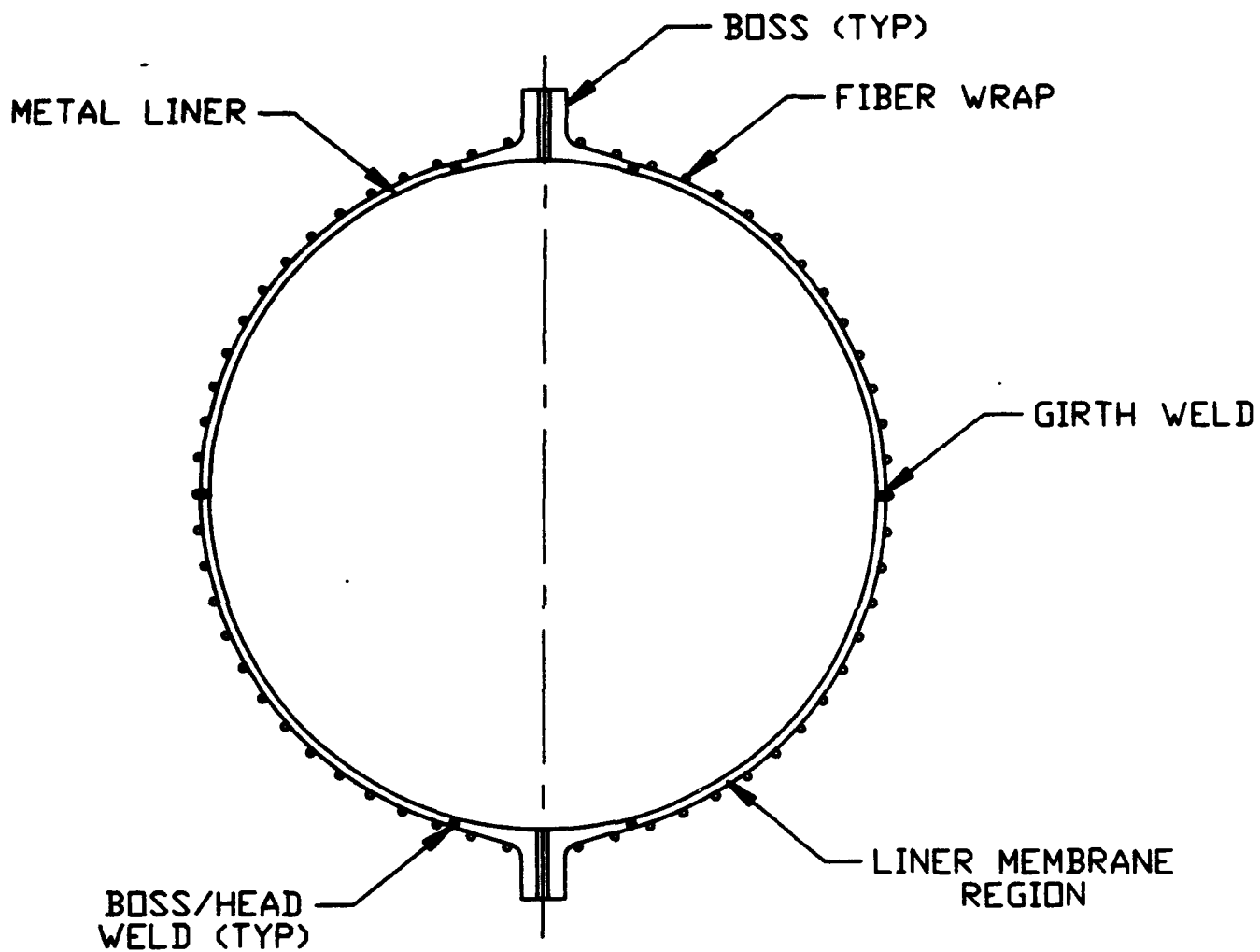
FIG. 2-1 PRESTRESSED COMPOSITE TANK COMPONENTS AND REGIONS

As subsequently discussed, agreement between PISCES analysis predicted and measured strains was reasonable. The one-dimensional models also gave good agreement with test results and failure modes predicted were verified by test.

2.3 - Fiber Ultimate Strain Verification

A fiber ultimate strain of 2% was verified experimentally, in agreement with other data[5], by burst pressure tests of strain gage instrumented 6" ϕ fiber wrapped cylinders having small angle helical fibers in addition to hoop fibers, as sketched on Figure 2-2. The test specimens were designed to fail in the hoop fibers. The hoop fibers correspond to the theoretical "isotensoid" great circle fibers of a spherical fiber wrap. The classical stress/strain transformations[6] for fibers at different orientations and fiber less resin Young's Modulus used in the failure modeling analysis were also confirmed by these tests. Details of the experiments and test data correlation are given in ARDE Report EG 42001-1, contained in Appendix D.

2.4 Liner Hydrogen Embrittlement Parameter Definition and Verification

The requirements/objectives of the intentional liner hydrogen embrittlement were to cause a brittle liner "catastrophic" failure at typical operating stress levels of 45 - 50% of ultimate (100 - 110 ksi) within eight minutes of pressurization. This requirement was dictated by the limited run time of the high speed recording tape or camera film during the test. To meet these objectives, numerous hydrogen embrittlement tests of subscale 11" ϕ all metal and 16" and 22" ϕ PSC spheres were made to define and confirm the appropriate liner embrittlement processing parameters. Liner global embrittlement and local girth and boss weld zone embrittlement modes were investigated. The basic technique used is schematically indicated on Figure 2-3. A lead anode is immersed in the dilute sulphuric acid solution electrolyte contained in the tank interior with the metal liner functioning as the cathode. A controlled source of current is used to complete the circuit generating hydrogen gas which diffuses into the liner wall. These hydrogen embrittlement experiments led to the parameters given in Appendix B. Details of the all metal subscale 11" ϕ vessel and the 16" ϕ and 22" ϕ PSC sphere hydrogen embrittlement tests are given in the Appendices B and E, respectively.

In early experiments, the metal tank (liner) was embrittled in the horizontal position and rotated about the bosses to preclude boss embrittlement. This proved to be impractical and the vertical embrittling mode shown in Figure 2-3 was used for testing. Maskant was utilized to protect selected liner regions against embrittlement.

Acoustic emission monitoring was used initially in attempts to define characteristic acoustic signals indicating sub-critical cracking and onset of brittle liner failure. No characteristic signal(s) indicating onset of brittle liner failure could be determined from the acoustic data obtained.

24.75°
HELICAL WINDING
2 LAYERS
$t_{f\alpha} = .020''$

HOOP
STRAIN
GAGE

HOOP
FIBERS
2 LAYERS
$t_{fH} = .022''$

AXIAL
STRAIN
GAGE

HELICAL
STRAIN
GAGE

$\frac{1}{2}$-14 NPT FEMALE THD
BOTH ENDS
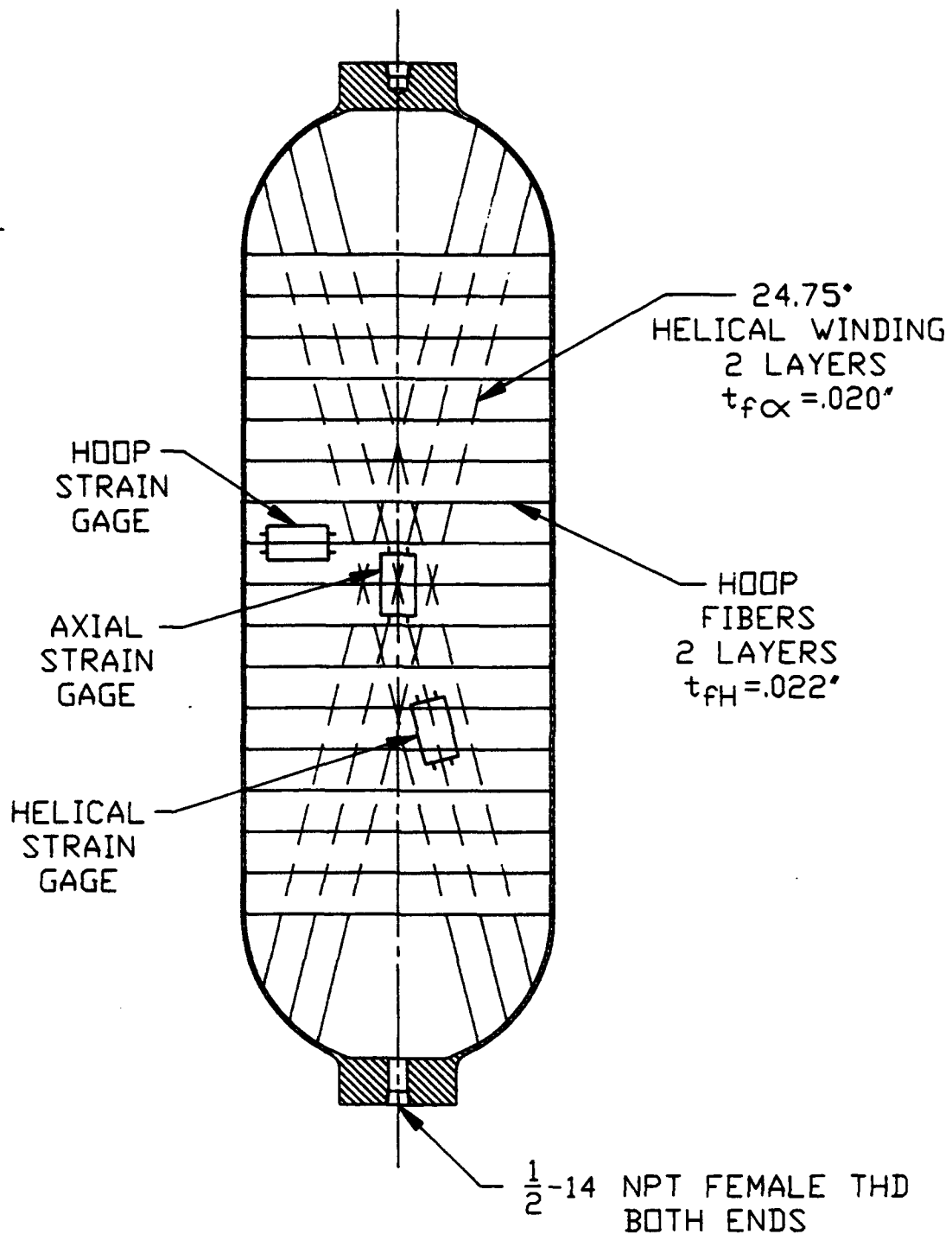
FIG. 2-2   6" Ø KEVLAR 49 FIBER WRAP MATERIAL EVALUATION CYLINDER

D3912 MOD
Test Tank
is Cathode

VOLTAGE REGULATOR

VOLTAGE REGULATOR

Boss Area Masked Off

Anode

h

h

$H_2SO_4 +$ TAP H_2O

$$\frac{20\ cc \quad\quad 980\ cc}{1000\ cc\ solution}$$

Horizontal Mode
(Tank Rotated About
Boss Centerline as Required
Manually or with Fixture)

Vertical Mode
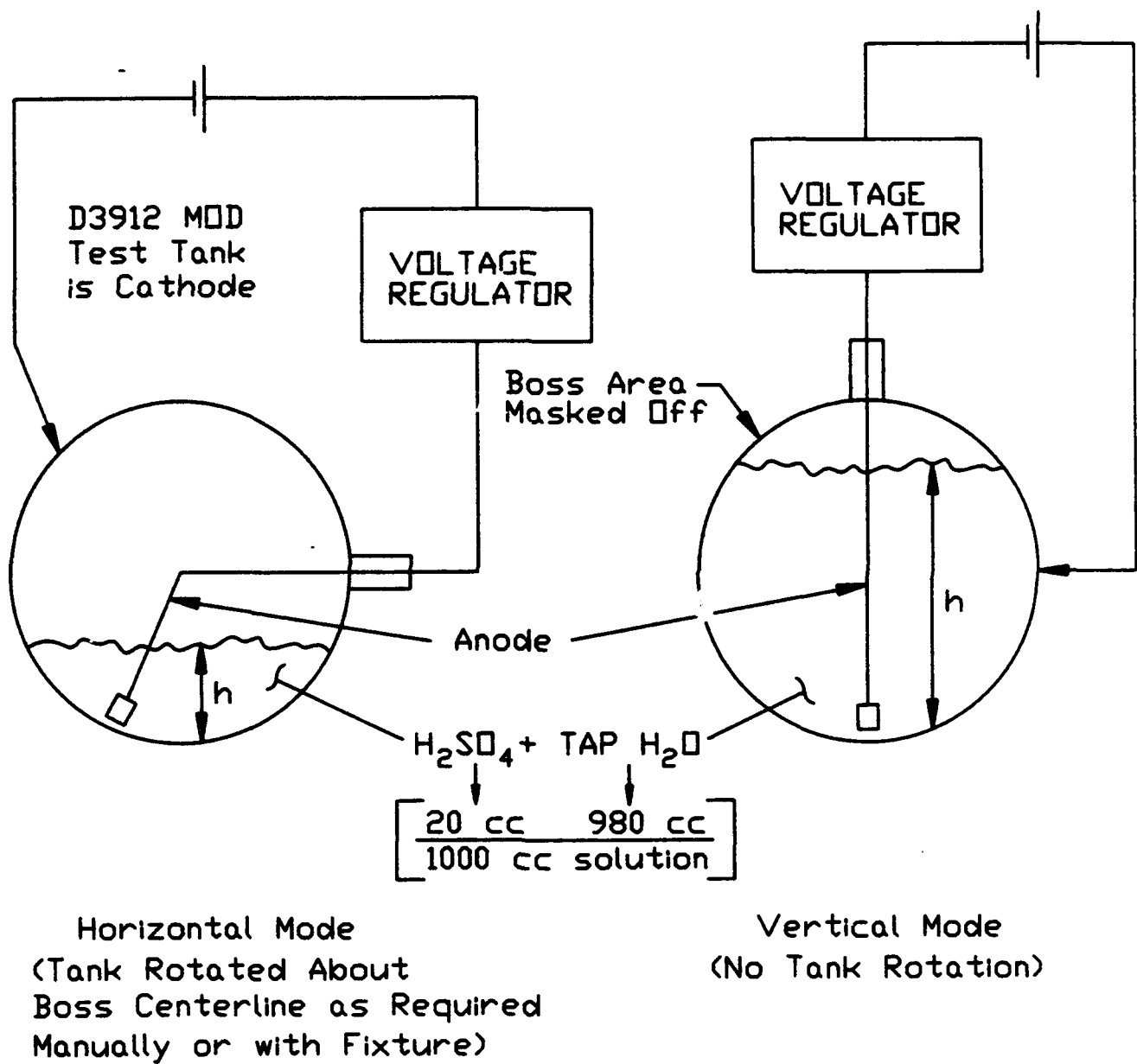(No Tank Rotation)

FIG. 2-3 SUBSCALE HYDROGEN EMBRITTLEMENT TEST MODES

This effort was discontinued because brittle liner failure control had improved due to better hydrogen embrittlement techniques and, in addition, the significant work needed to develop appropriate acoustic emission technology for this application was beyond the scope of the program.

. Different brittle failure modes were noted for the globally embrittled all metal tanks and the globally embrittled fiber overwrapped PSC metal tanks. The embrittled all metal tanks fragmented whereas metal liner fragmentation was suppressed by load transfer of the cracking embrittled metal liner to the fibers. This highlights the advantage of a structure with two members capable of carrying load compared to a structure with a single load resisting element. Figure 2-4 shows a cut apart intentionally globally hydrogen embrittled PSC liner after test. The fiber overwrapped spherical liner was intact in one piece despite the hundreds of continuous through cracks shown. This is in contrast to the post burst test view of a similarly intentionally embrittled all metal single load resisting member tank given on Figure 2-5.

2.5 Fracture Mechanics R-Curve Test Data and Leak-Before-Burst (LBB) Verification

Leak-before-burst (LBB) tests were conducted on 11" ϕ .06 thick prestressed composite (PSC) 301 cryo CRES spherical liners overwrapped with Kevlar -49 fibers and on 11" ϕ and 23" ϕ all 301 Cryo CRES spherical vessels. Elliptical part through thickness flaws were elox machined (EDM) on the O.D. surface of the all metal vessels and on the I.D. surface of the PSC tanks. Typical flaw geometry is shown on Figure 2-6 for the 23" ϕ tank. Operating pressure cycling tests (3500 - 5000 psig) were performed with pressurizing media of hydrulic fluid and gaseous helium. Failure mode was benign leak in all cases with through crack stable growth as long as four (4) times wall thickness before failure. Since LBB is considered proven by stable through crack growth of two (2) times wall thickness before failure, a large LBB safety factor has been demonstrated.

Sustained load tests of all metal 301 Cryo CRES tanks at 4000 psig pressure level were conducted after pressure cycling experiments for durations up to 48 hours without any additional crack growth. This result verified the safe, stable mode of the through cracked tanks under constant operating load.

Uniaxial R-Curve tests were performed on 301 cryo CRES through center cracked tension panels and compact tensile specimens. Figures 2-7 and 2-8 show test specimen geometry. The R-Curve test results gave a plane stress critical stress intensity, K_c of 180 ksi $\sqrt{in}$ for parent material, weld or heat affected zone as well as a crack initiation stress intensity, $K_I E >$

100 kis $\sqrt{in}$ for uniaxial strengths as high as 260 ksi. These uniaxial R-Curve tests, verified by vessel tests, showed that 301 cryo CRES is a tough, high strength material that demonstrates leak-before-burst (LBB).
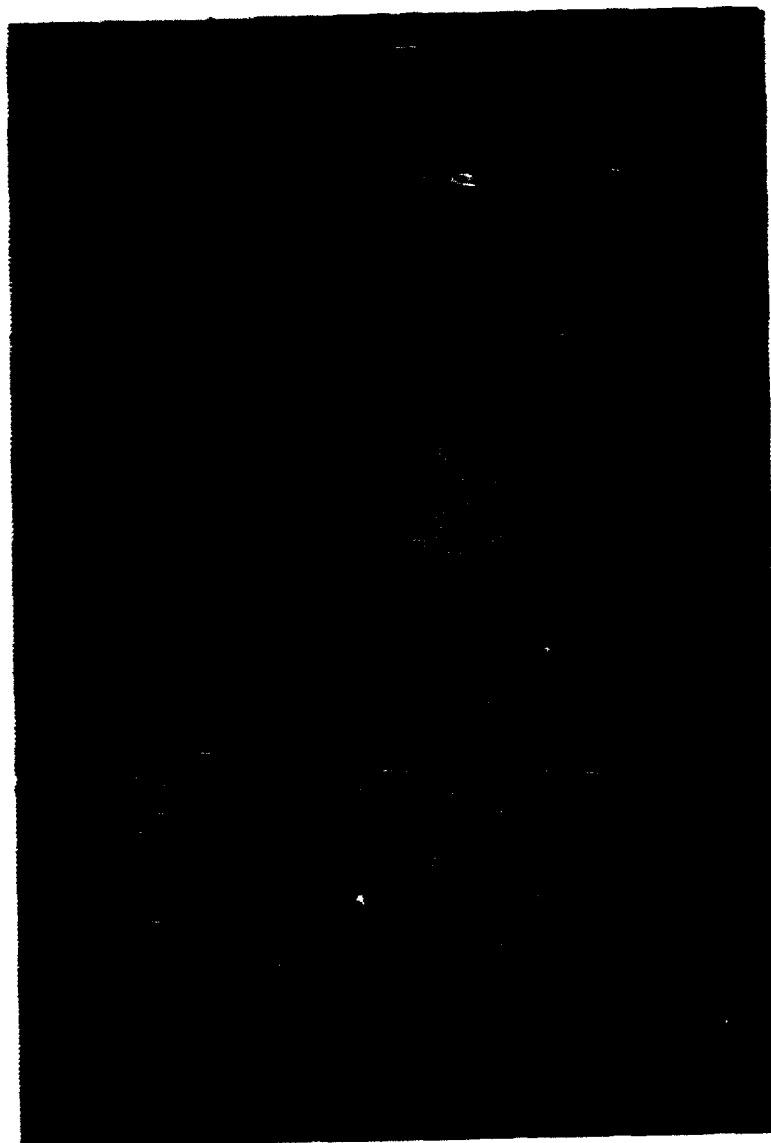
FIG. 2-4 GLOBALLY HYDROGEN EMBRITTLED PSC LINER AFTER TEST

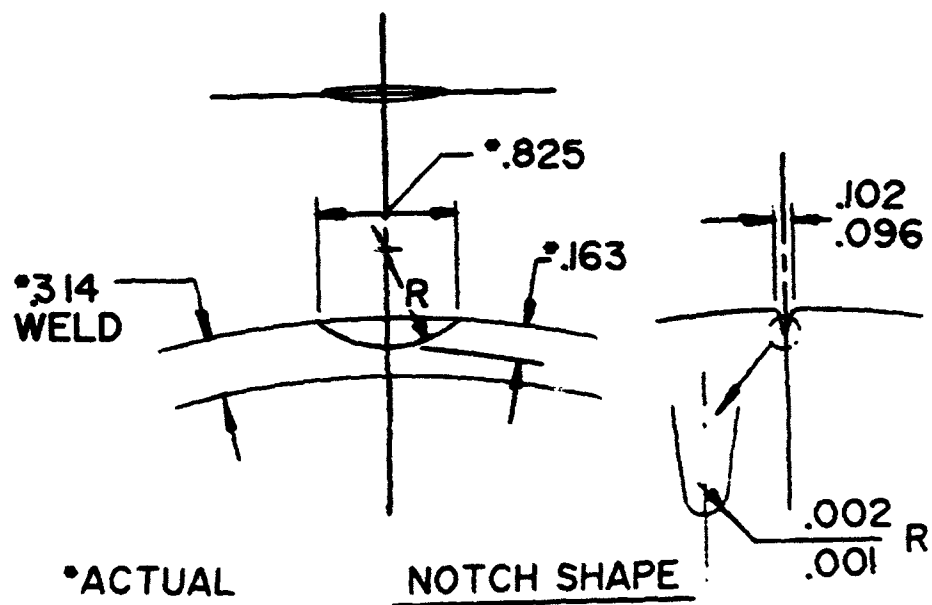FIG. 2-5 POST TEST VIEW OF HYDROGEN EMBRITTLED ALL METAL
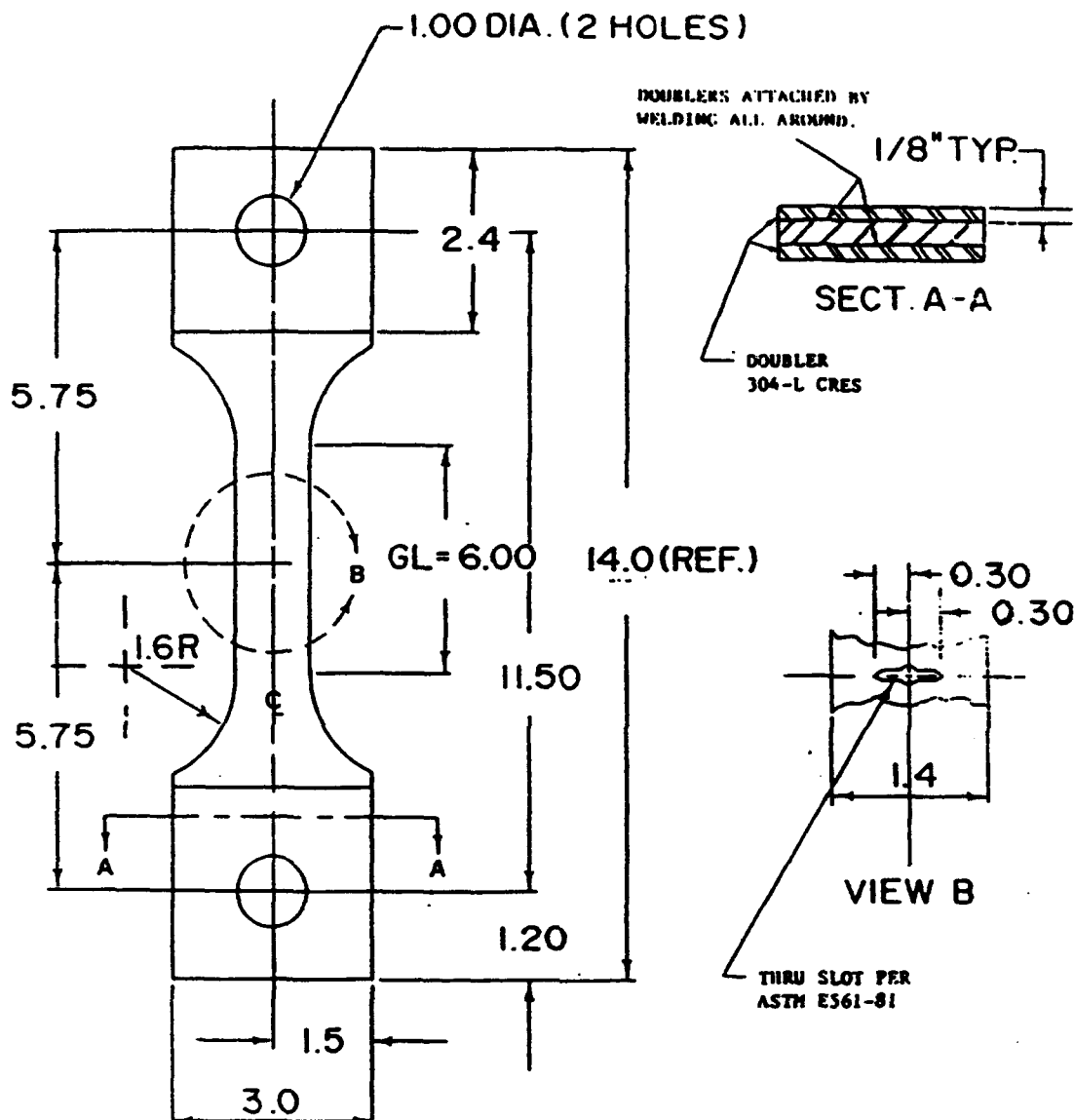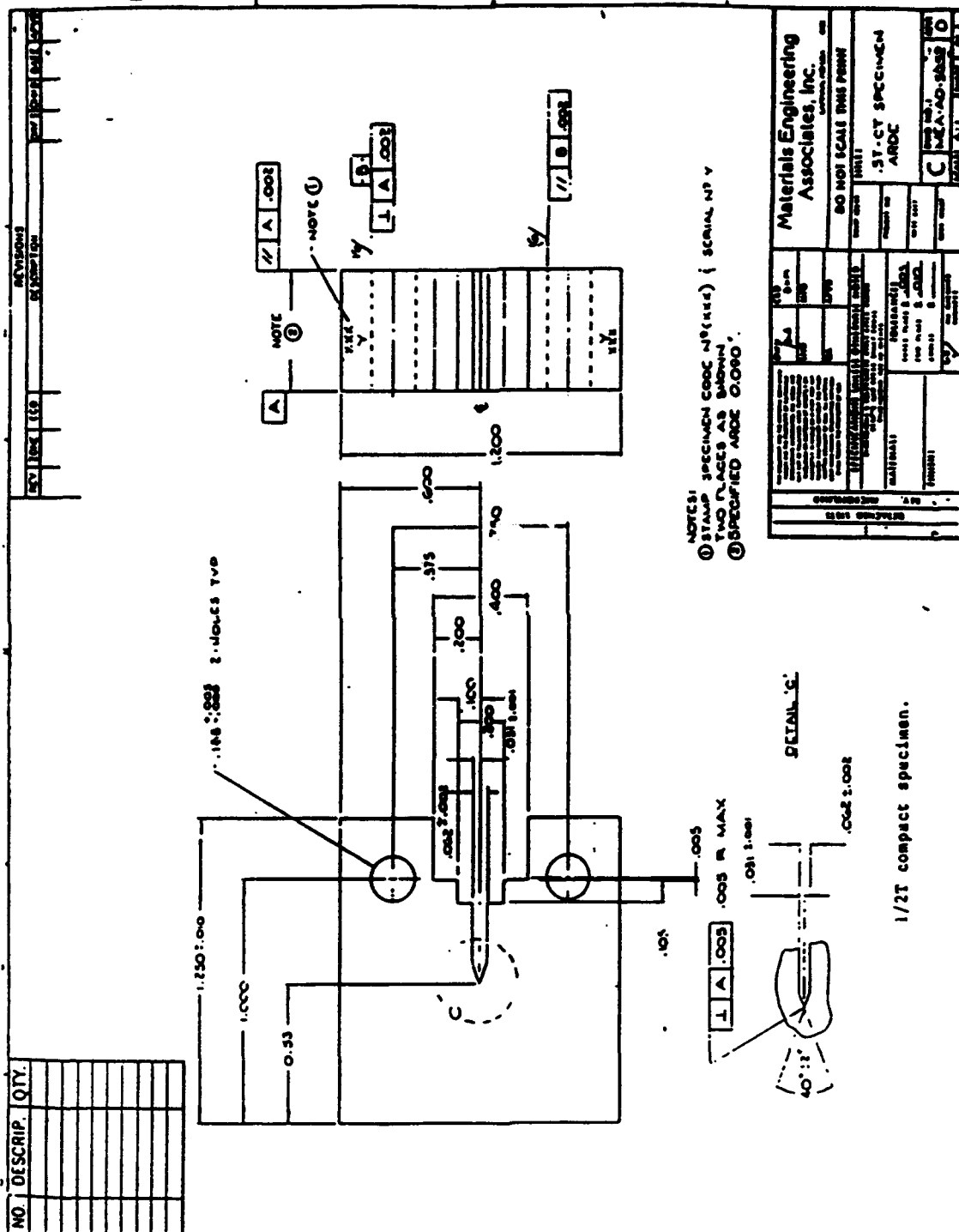
FIG. 2-6 PRESSURANT TANK, 23" DIA.

FIG. 2-7 Center cracked tension panel. Dimensions in inches.

FIG. 2-8   COMPACT TENSILE SPECIMEN

Details of the vessel LBB experiments and the uniaxial R-Curve tests are given in ARDE Report EG 42001-14 contained in Appendix C.

2.6 Full Scale 16" φ and 22" φ PSC Vessel Tests

2.6.1 Overall Test Description

2.6.1.1 Test Vessel Description

Full scale (16" and 22" φ) PSC operating pressure tests with 2500 - 5600 psig gaseous helium were conducted by AFAL, Edwards AFB, California, at Area 1-52, D-Pad. The Kevlar overwrapped 301 cryo CRES spherical composite vessels, Figures 1-1 and 1-2, had intentionally hydrogen embrittled liners. The 16" φ tank liner thickness was kept constant at .05 inch, nominal. Kevlar -49 fiber thickness was varied to suit program needs. The baseline 16" φ tank fiber (less resin) "average" thickness (100%) was .154 inch, the same as the flight units delivered to British Aerospace for their Olympus Satellite high pressure gas tank. The 22" φ composite tank configuration, Figure 1-2, was the same as the flight high pressure gas tanks delivered to General Dynamics for their Centaur vehicle. Average Kevlar fiber (less resin) thickness was .192 inch with a .044 inch thick 301 cryo CRES liner. The original program plan called for the use of all 16" φ full scale test tanks for consistency of data base, but one 16" φ tank was ruptured in fabrication due to inadvertent damage during the resin cure operation of the fiber wrapped tank. The failed 16" φ tank was replaced by an existing 22" φ tank asset to minimize schedule and cost impact.

2.6.1.2 Measurements

Pressures, fiber strains, girth diametral displacements and temperatures were monitored to provide "fail safe" brittle liner failure mode test data. In some instances, air blast and fragmentation data was obtained. The 16" and 22" φ PSC vessel test matrix is given in Appendix E.2.

2.6.2 Test Procedure. Set-up. Instrumentation

2.6.2.1 Overview

Testing and monitoring PSC vessel structural response after sudden brittle liner failure presented some experimental technique challenges. Primary areas of concern were the monitoring of the extremely short fiber strain transient events of interest (the order of 10^{-4} to 10^{-6} seconds) and the mounting of strain gages on the uneven, bumpy, fiber matrix surface to measure the strains. In addition, gas compression work, due to the necessary rapid pressurization rate to reach operating pressure before embrittled liner failure, could raise test tank temperatures to unacceptable levels. These primary test challenges were successfully met by development of a suitable strain gage mounting technique and utilization of high strain response, post yield strain gages coupled to a

high frequency response recording system. In addition, use of a liquid nitrogen heat exchanger and properly sequenced pressurization mode provided sufficiently cool helium gas into the test tank.

2.6.2.2 System Checkout Tests

The instrumentation requirements/test procedure guidelines to achieve the testing objectives were defined by ARDE document EG 42001-5, given in Appendix E.1. These requirements/procedures were modified, as required, based on a series of system checkout tests using various size/configuration vessels. Initial system checkout utilizing a practice vessel approximating the size of the actual test articles determined the selection of gaseous helium in lieu of gaseous nitrogen as a pressurizing agent. Initial checkout tests showed that helium reduced cycling time and/or time to operating pressure by more than 50%. Additionally, many of the vessel tests required high pressurization rates to obtain 5000 psig test vessel pressure within 90 seconds, which gaseous nitrogen could not achieve.

Follow-on system checkout tests, described in ARDE letters 52001-KOS-084 (3 Feb. 1986) contained in Appendix E.1, herein, defined test system operational parameters and resolved testing problems. As aforementioned in section 2.6.2.1, test vessel temperatures during pressurization were expected to exceed the maximum allowed value (140°F). To prevent damage to the Kevlar fiber overwrap, a heat exchanger was installed to cool the incoming helium pressurizing gas. Many tests were needed to determine the required heat exchanger tube length and cooling medium. Only liquid nitrogen was found to be able to safely and adequately supercool the gaseous helium to overcome the compression heating.

Additional problems were encountered during initial pressurization due to the volume of ambient air trapped in the system and test vessel. Two vent valves were installed, one to vent warm air from the system and one to vent incoming gas from the test vessel. When these valves were cycled in series with the pressurization valve, the test vessel metal boss temperature could be reduced to 60° F and the test vessel gas temperature to 20° F. These temperatures were required in order not to exceed the maximum allowable test vessel temperature of 140° F during final pressurization.

2.6.2.3 Test System Description/Schematics

Figure 2-9 is a schematic sketch of the instrumentation/test set-up initial projected. The actual plumbing and component placement used, as influenced by the system checkout test experiences, are shown on Figure 2-10.

FIG. 2-9   SCHEMATIC, TEST TANK INSTRUMENTATION

FIG. 2-10   SKETCH, TEST SETUP AREA 1-52, D PAD

2.6.2.3.1 Mechanical System Components

Helium for testing was provided by a dual bank trailer. Bank 1 was pressurized to 6,000 psi and bank 2 was pressurized to 8,000 psi. Total trailer volume is 100 cubic feet at 10,000 psi. Gaseous nitrogen for valve actuation was obtained from a 120 psi source on D-Pad. Valve SV-0-001 is a 20,000 psi remote actuated 3/8 inch valve and is used as a system isolation valve only. Valves SV-0-002, SV-0-003, and SV-0-004, located in the valve box, are remote single action valves rated at 10,000 psi. Their port orifices are 0.125 inch, with seat orifices of 0.093 inch, and have a flow coefficient of 0.135. Valve SV-0-002 is the vessel pressurization valve, while SV-0-003 and SV-0-004 are the line and vessel vent valves respectively. All pressure lines are 3/8 inch outside and 1/8 inch inside diameters and are rated at 10,000 psi. Total length of line from the isolation valve to the test article is 280 +/-5 feet. A series of three complete loops totaling 60 feet is contained in the heat exchanger box.

2.6.2.3.2 Witness Panels

The witness panels, as shown on Figure 2-11, consist of an angle iron frame measuring 8 x 8 feet. Each panel contains two 4 x 8 foot sheets of 1 inch thick "Celotex" (TM) backed by 0.0940 inch aluminum. This configuration closely approximates the environment where the vessels to be tested are currently utilized. Each panel assembly is anchored to hinge points imbedded in concrete and are mounted approximately one foot above ground level. They connect at the top to form a 12 sided polygon 30 feet in diameter with one section deleted to facilitate camera viewing. The fra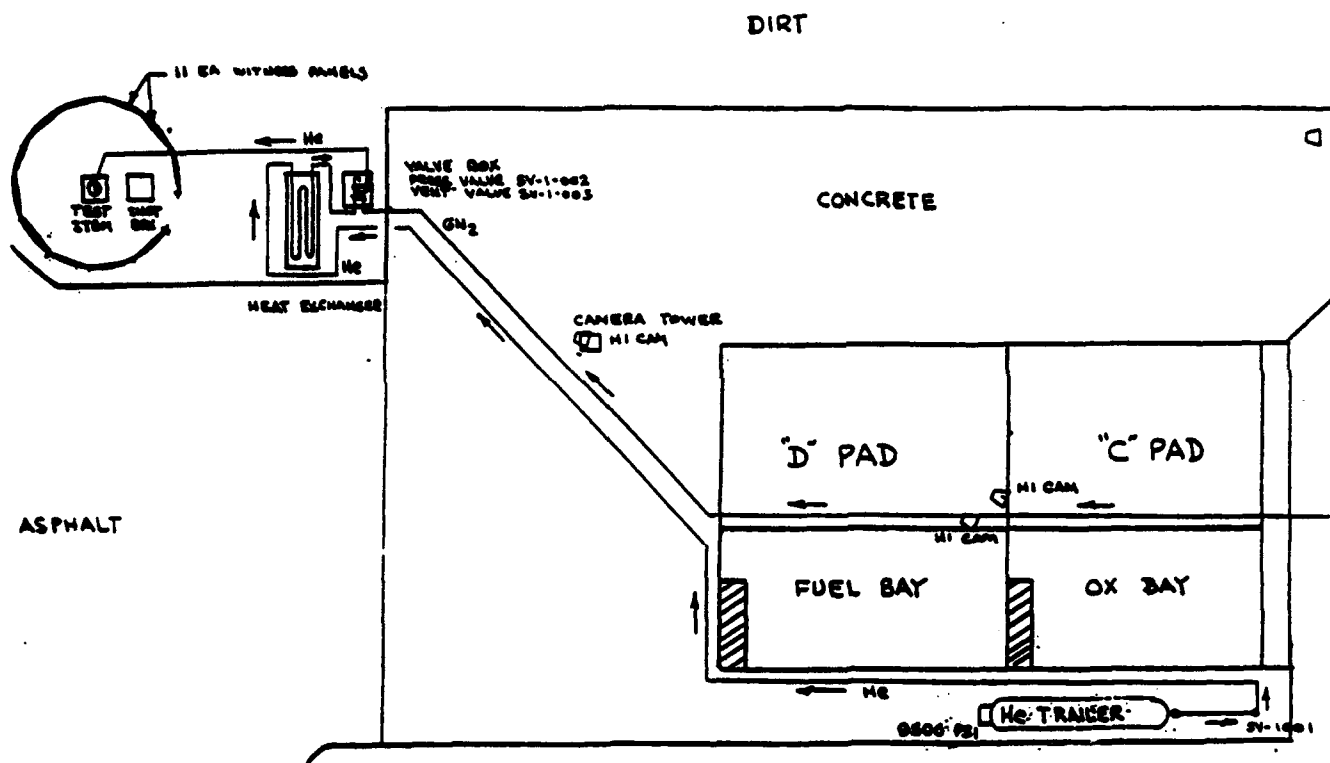mes are designed to break away and fold back to prevent excessive damage due to overpressure or for stowage in high winds.

2.6.2.3.3 Photographic Coverage

Pre and post test stills were taken, of each vessel tested. Three Hi-Cams (1000 FPS) were used in an attempt to record events. The cameras were activated in series along the pressure curve at points selected by the test engineer as the most likely to be the start of an event. Early attempts were not always successful. The unknown behavior of the test article combined with the short run time of the cameras resulted in many missed events. The addition of a high speed video monitor connected to a very high speed (VHS) recorder allowed for more continuous coverage. Exposure at 1/60th of a second, combined with the slow motion play back capability provided excellent fragmentation coverage.
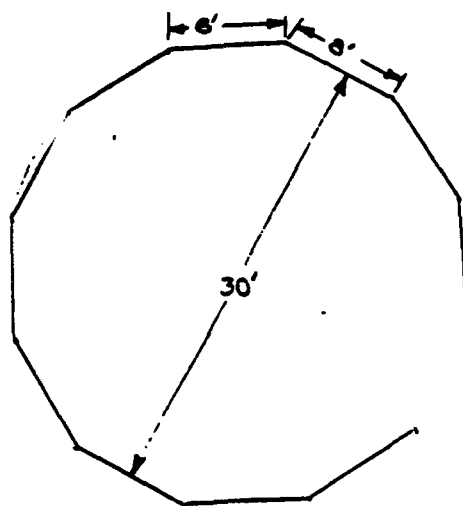
11 EA 8'×8' WITNESS
PANELS. 1 FT ABOVE
GROUND LEVEL

BREAK AWAY
POINT

30'

6'

8'

8'

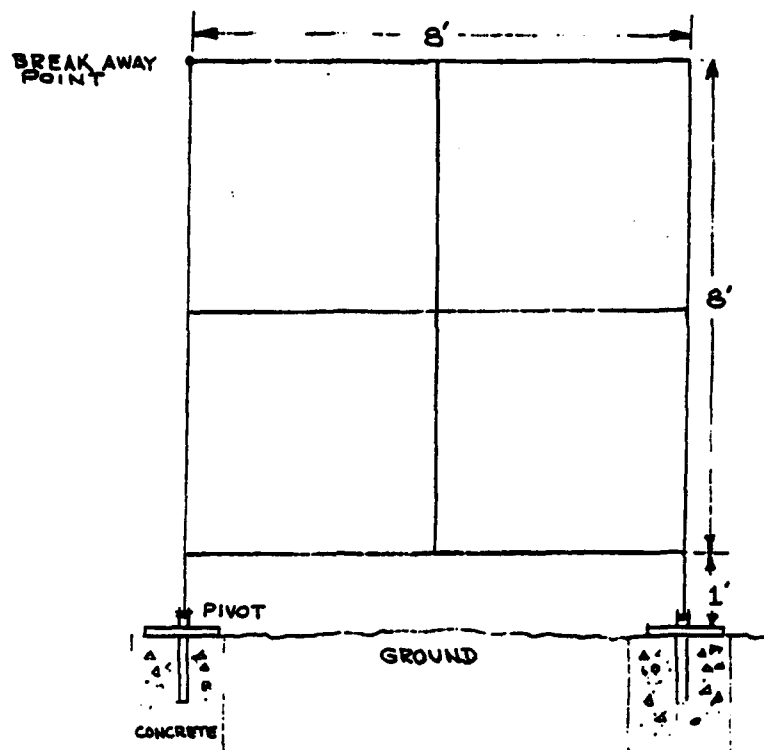8'

1'

PIVOT

GROUND

CONCRETE

FIGURE 2-11   WITNESS PANEL SKETCH

2.6.3 16" and 22" φ PSC Vessel Test Results

The full scale 16" φ and 23" φ PSC vessel GHe pressure test results are summarized in Table E-1 of Appendix E.2. The effects of varying hydrogen embrittlement electrolyte solution charging current density, pickling the liner I.D. and adding sodium arsenite to enhance the embrittlement reaction and global versus local girth and boss weld area embrittlement were investigated in the experiments. The investigation was limited in nature since hydrogen embrittlement, by itself, was not the primary research and development issue. Fiber thickness was varied as required to achieve "fail safe" liner fragment retention/benign pressure venting mode, "sure failure" of liner plus fibers and "fail safe" margin data at operating pressure.

As shown in Table E-1, tests RV-4 and RV-5 demonstrated fail safe mode at operating pressure for the globally embrittled 100% fiber thickness 16" φ PSC vessel configuration. Test RV-5 showed the enhanced intentional embrittlement effect due to increased GHe charging time, pickling of liner I.D. and adding sodium arsentite to the electrolyte solution. Fiber strain response data was correlated by static structural behavior. A photograph of prior discussed cut apart RV-5 "fail safe mode" test tank is shown on Figure 2-4. The enhancement in the intentional hydrogen embrittlement is evidenced by the multitudes of connected through cracks seen in the photograph.

Experiments RV-7 and RV-9 with 16" φ tanks demonstrated the fail safe/fragmentation retention/benign leak mode at operating pressure with local girth weld heat affected zone (HAZ) intentionally embrittled liners. These tests simulated the worst case structural model which assumes an instantaneous unstable crack of the entire girth weld. The liners broke at the girth and separated into two halves during the test. The fibers were intact. Large dynamic fiber strain spikes were observed. Figure 2-12 shows the strain spike monitored by strain gage 12. Tension is negative.

The as designed intended "catastrophic" brittle liner and fiber both fail mode was demonstrated by test RV-10 of a local girth region 16" φ PSC test sphere at design operating pressure with reduced fiber thickness (50% of baseline). Liner separation/fragments were as predicted. Large fiber strain spikes were observed at/near failure. Fragmentation and overpressure data were obtained. Typical fragments are shown on Figure 2-13.

Both the fibers and the local girth area embrittled liner failed in the RV-11 experiment with the 83% of baseline fiber thickness 16" φ PSC test vessel. The failure pressure was very close to the predicted value. The expected large fiber dynamic strain spikes were observed. Overpressure and fragmentation data were obtained. Strain gage measurements indicate that the fibers came very close to remaining intact per the no failure prediction.
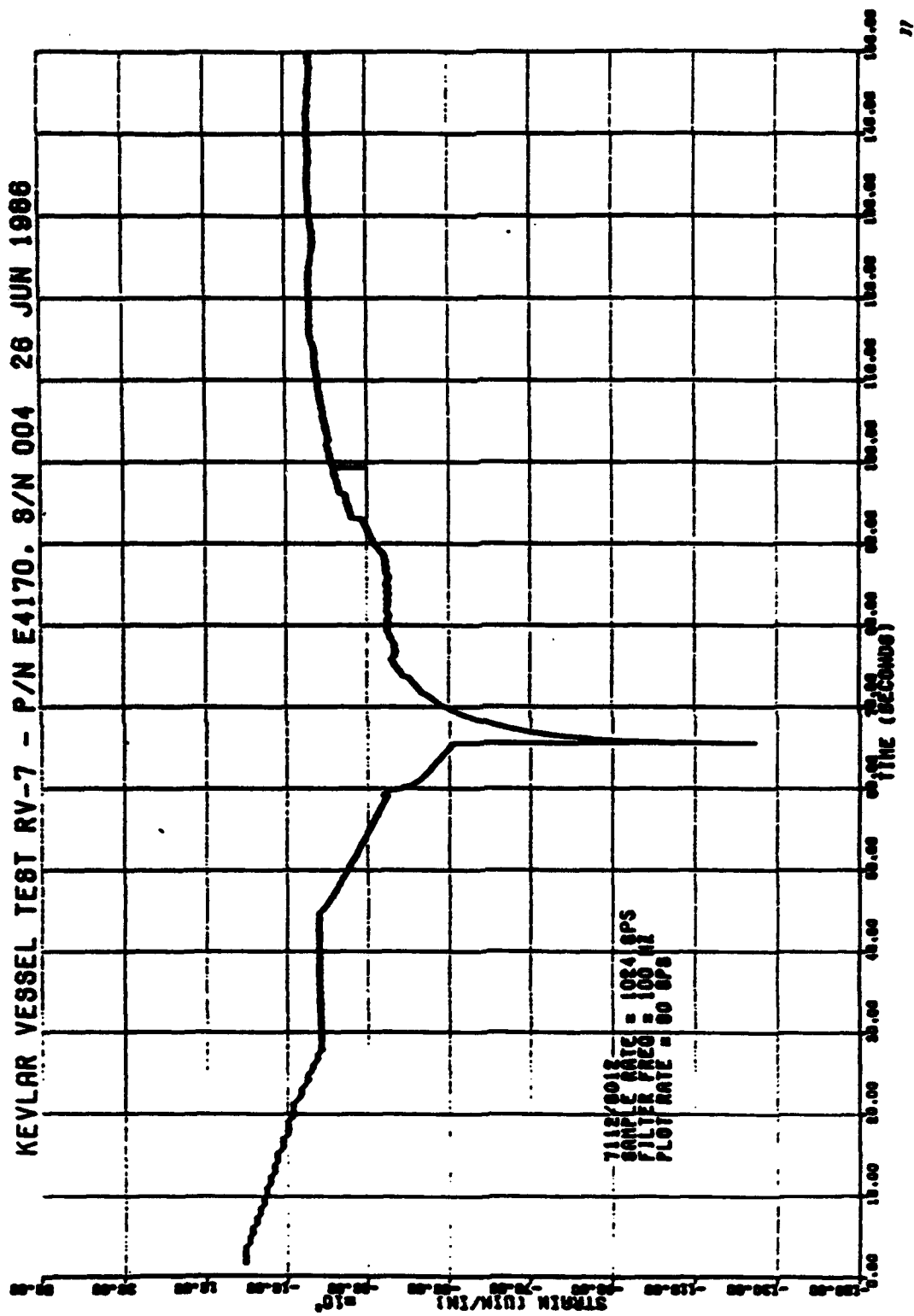
FIG.   2-12   DYNAMIC FIBER STRAIN SPIKE RV-7 TEST
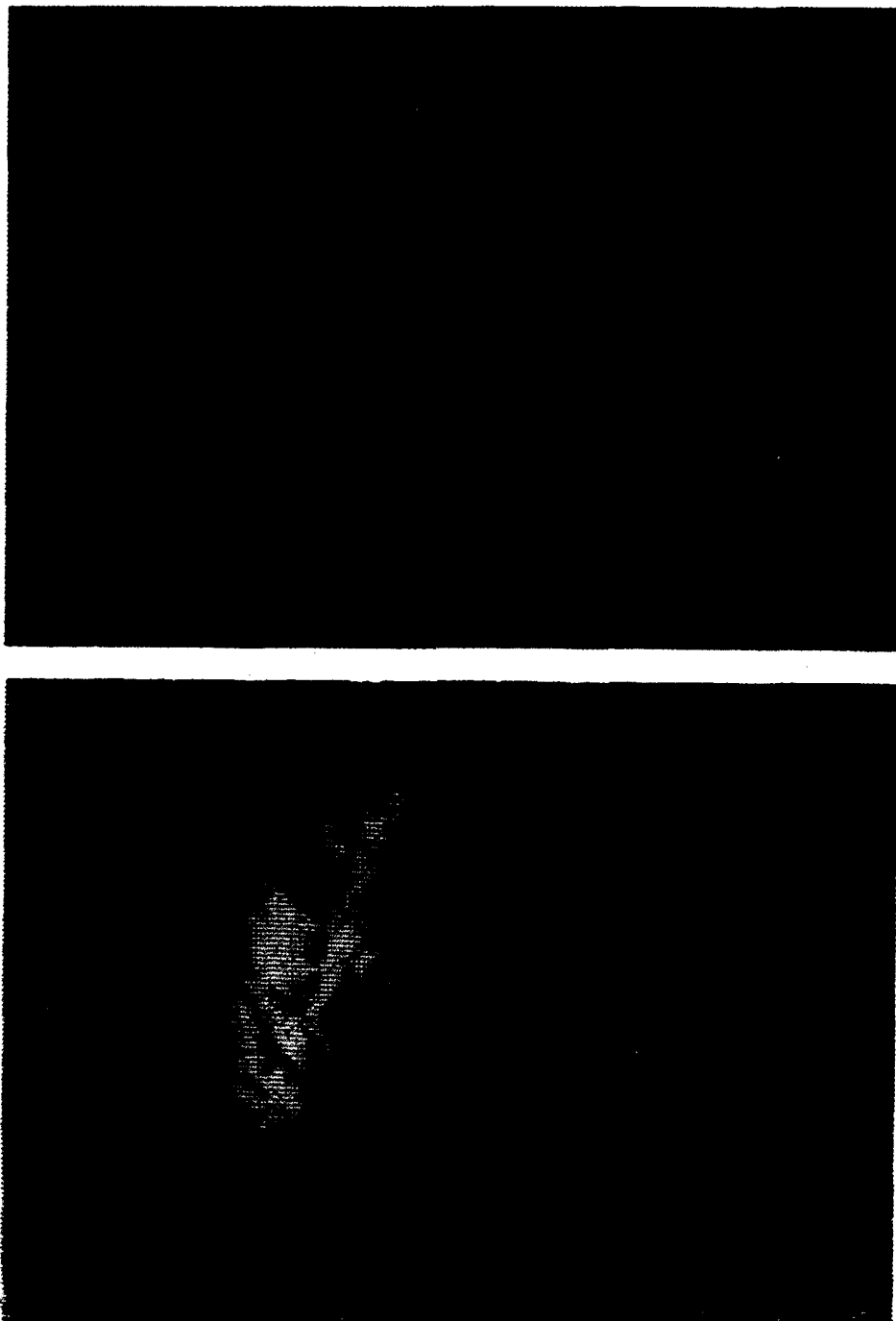
FIG. 2-13 INTENTIONAL "SURE FAIL" BRITTLE LINER RV-10

TEST TANK FRAGMENTS

2-20

A "fail safe" benign leak failure mode was demonstrated by RV-14A tests with 90% of baseline fiber thickness 16" ϕ test vessels. Based on RV-7 to RV-11 and RV-14 and 14-A tests, one estimates that the "dividing line" between "fail safe" fragment retention and catastrophic failure for the critical girth weld embrittled liner mode 16" ϕ test tanks is at a fiber thickness slightly greater than 83% of baseline (say 85% of baseline). A more meaningful and proper "fail safe" criterion in terms of fiber stress and metal stress increment at operating pressure and fiber to metal thickness ratio is detailed in section 2.7 based on the test data correlations discussed in section 2.6.4 which follows.

Tests RV-12 and RV-12A demonstrated fail safe modes for local boss/head weld embrittled liners of the 22" ϕ PSC test tanks. Although significant liner cracking occurred in the local boss/head weld embrittled region, the boss did not separate from the liner head. Dynamic fiber strain amplification effects were similar to those measured in the local girth weld embrittled tests. Girth embrittlement is considered more critical since the liner fragmented at the girth into two pieces whereas the boss embrittled liner was still in one piece and could resist load as an "intact" shell.

2.6.4 PSC Vessel Test Data Correlation

The full scale PSC test data was correlated utilizing the two-dimensional finite difference transient computer program PISCES 2 DELK[4] and simplified one-dimensional models as discussed in Appendix A. The test data was used to refine the models and derive equivalent dynamic amplification factors that would result in 2% fiber ultimate strain. In general, agreement between strains calculated from theory and strains measured during test was reasonably good. Predicted failure modes were verified by the experiments. Sample test data correlation calculations and pressure and strain versus time plots are given in Appendix F.

Agreement between measured strains and values predicted by PISCES computer program was reasonable. PISCES computed results were conservative since they were greater than the measured strains. Typical results obtained were 13505 to 13870 maximum computed meridional micro delta strains compared to the 10600 to 11900 maximum micro delta meridional strains measured as detailed in Appendix F. Predicted PICES 2D strains were thus 22% higher on average compared to measured strains. Improved strain test data correlation was obtained using a slip boundary condition at the fiber/metal interface, rather than a completely bonded condition. The slip condition gave higher strains than the completely bonded case as shown on Figure 2-15.

The simple one-dimensional (1D) transient model which presumed instantaneous total liner loss of strength/stiffness gave even better results. The strains predicted by the simple 1D model, while still generally conservative, were less than the PISCES results (Figure 2-14) and, therefore, closer to the measured strains. Figures 2-16 to 2-19 show typical measured transient fiber strains for experiments RV-7, RV-9 and RV-11. Tensile strain is negative. Superposed on these figures are the strains computed from the one-dimensional transient model. The quantity e_{max} is the maximum transient fiber strain after liner failure, e_1 the static fiber strain prior to liner failure and e_2 the static equilibrium fiber strain presuming liner loss of strength/stiffness. It is seen that agreement between simple one-dimensional theory and test is quite good.

The one-dimensional equivalent static model constructed, based on prior developments[3], assumes that the pressure to cause 2% ultimate fiber strain is composed of the static pressure the fibers were carrying before liner sudden failure plus a dynamic amplification factor, Φ, times the static pressure the liner was carrying before it failed. Based on the test data, dynamic amplification factors in the range of $\Phi = 1.5 - 1.7$ were derived for the critical local girth weld heat affected zone (HAZ) embrittlement and the local boss/head weld embrittled liner failure modes. Measured fiber strains for the liner global embrittled failure mode were correlated by static structural behavior ($\Phi = 1$). This equivalent static model, together with the test derived Φ values were used to derive the design guides discussed in section 2.7.

PISCES CALCULATION WITH ZERO FRICTION BETWEEN LINER AND OVERWRAP

GIVES HIGHER STRAINS THAN PREDICTED BY THE ANALYTICAL MODEL
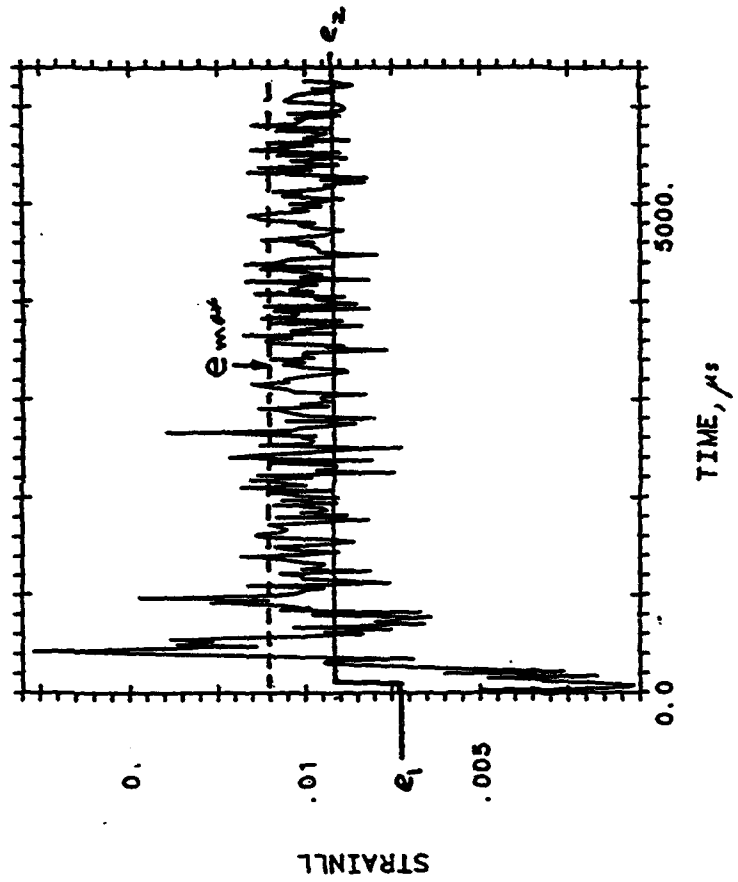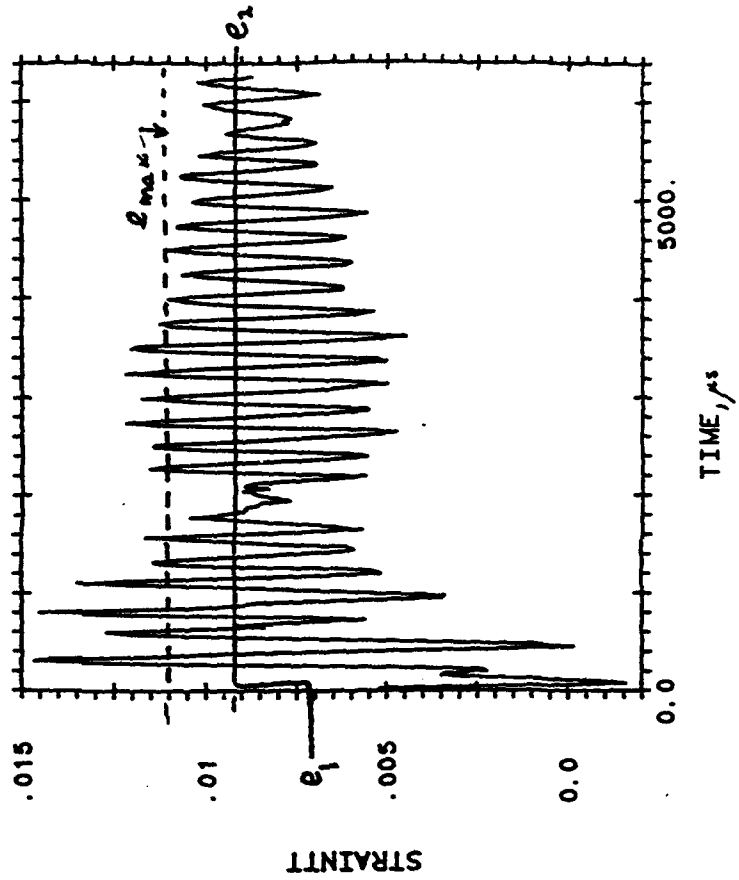
FIG. 2-14 PISCES 2D vs. 1D ANALYTIC MODEL COMPUTED STRAINS

2-23

TWO-DIMENSIONAL CALCULATIONS AT 4000 PSI
PEAK MERIDIONAL STRAIN VS. ANGLE

OVERWRAP IS ATTACHED TO THE LINER

- Longitudinal strain envelope for baseline case.
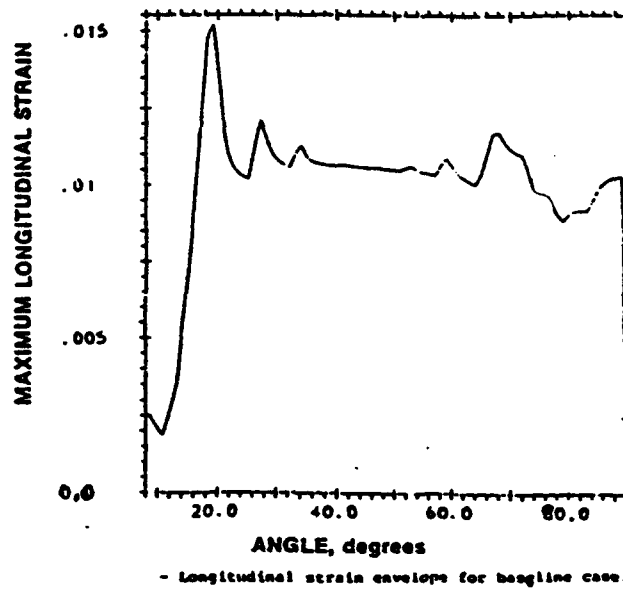
ZERO FRICTION
OVERWRAP IS NOT ATTACHED TO THE LINER
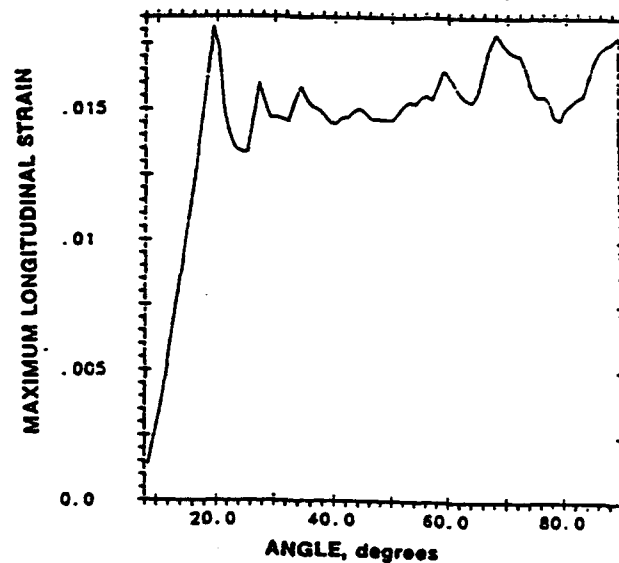
FIG. 2-15 TWO-DIMENSIONAL CALCULATION PEAK MERIDIONAL STRAIN VS. ANGLE
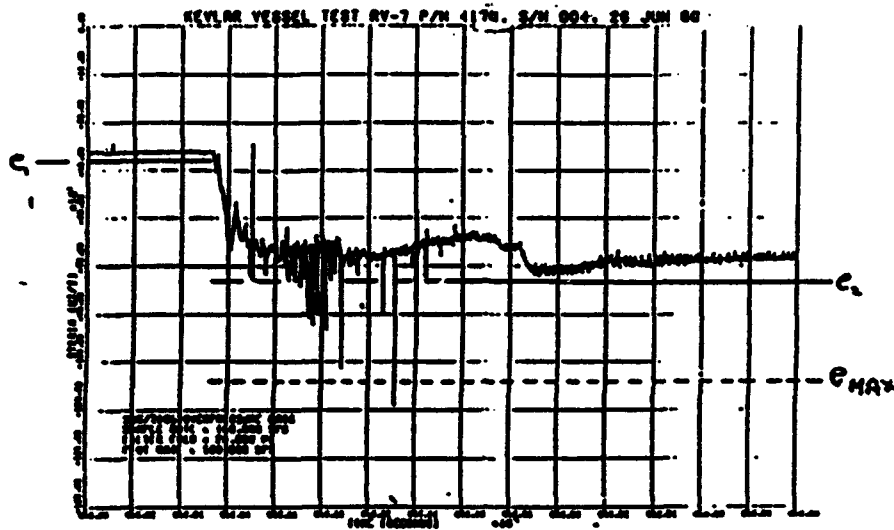
FIG. 2-16 FIBER STRAIN VS. TIME, TEST RV-7,
STRAIN GAGE NO. 6
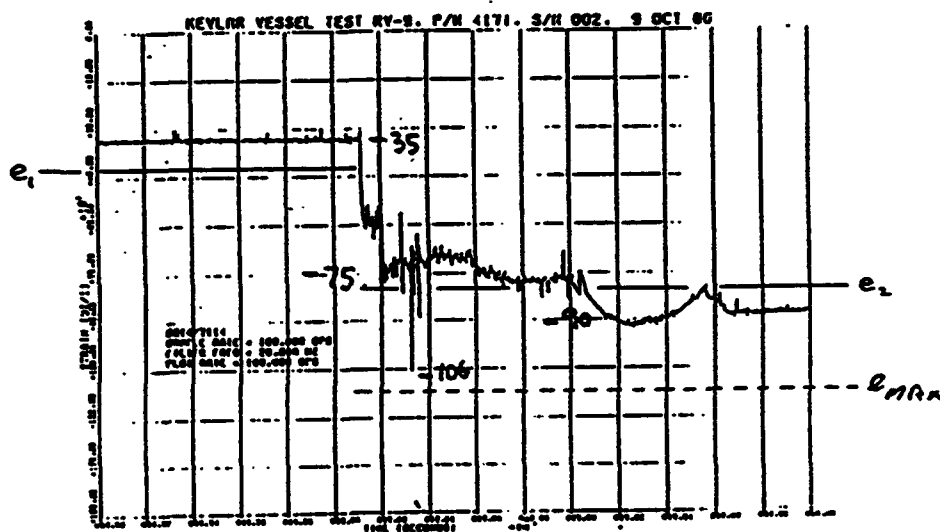
FIG. 2-17 FIBER STRAIN VS. TIME, TEST RV-9
STRAIN GAGE NO. 14

TEST RV-11,   SG 4, 12, 20

N Equator Meridional
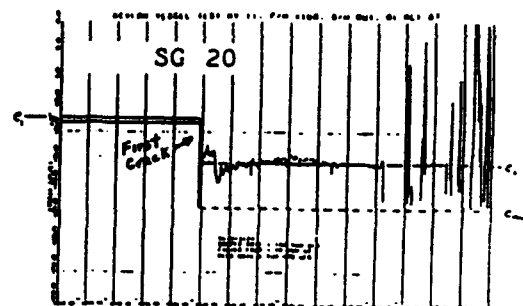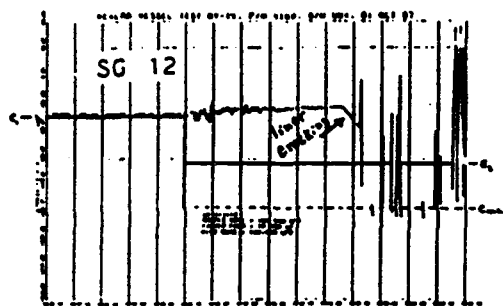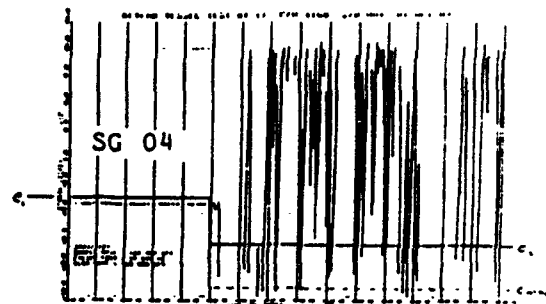
FIG. 2-18 FIBER STRAIN VS. TIME, TEST RV-11,
           STRAIN GAGES 4, 12, 20

TEST RV-11,   SG 2, 10. 18

N Pole Meridional
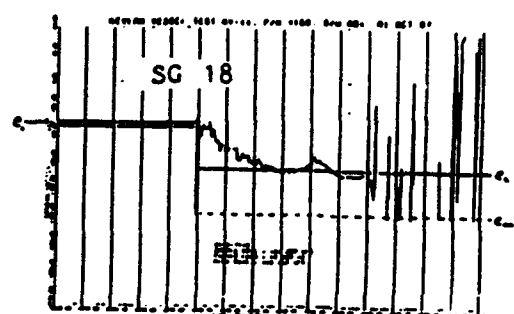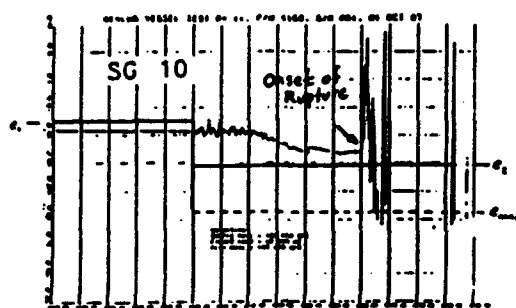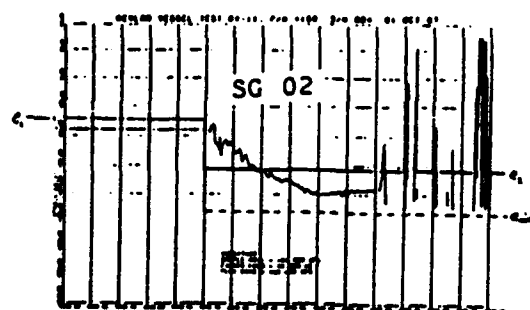
FIG. 2-19   FIBER STRAIN VS. TIME, TEST RV-11,
            STRAIN GAGES 2, 10, 18

2.7 Fail Safe Design Guide

2.7.1 Spherical Vessels

A "fail safe" spherical prestressed Kevlar fiber overwrapped tank design guide, based on test data and structural models obtained/utilized on this program is derived and defined in Appendix A. The pertinent equation, given below again for convenience, is plotted on Figure 2-20.

$$\sigma_{fo} = 345 - \frac{3.4}{t_f/t_M} \, \Delta\sigma_{MO} \quad \text{--- (A-24)}$$

Here,

σ_{fo} = maximum allowable fiber (less resin) stress

(ksi) at operating pressure for "fail safe" fiber retention of liner fragments generated by sudden liner brittle failure at operating pressure.

σ_{MO} = design metal stress at operating pressure (ksi)

σ_{Mi} = Metal initial stress (ksi)

$\Delta\sigma_{MO} = \sigma_{MO} - \sigma_{Mi}$ = Metal operating stress increment

t_f/t_M = fiber (less resin) to metal liner thickness ratio.

This design guide enables one to check a given prestressed composite vessel design for fail safe liner fragment retention if the liner fails suddenly in a brittle manner at operating pressure. Referring to Figure 2-20 or equation (A-24), if for example, $\Delta\sigma_{MO}$ = 100 ksi for t_f/t_M = 3, the maximum allowable fiber operating stress, σ_{fo}, is 231 ksi. Liner fragment retention by the fibers at operating pressure is thus indicated for fiber operating stress, $\sigma_{fo} \leq$ 231 ksi. Conversely, one can find the minimum fiber to metal thickness ratio for "fail safe" mode, given the fiber and metal operating stresses. if σ_{fo} = 250 ksi and $\Delta\sigma_{MO}$ = 100 ksi, the required minimum fiber (less resin) to metal thickness ratio from equation A-24 is 3.58.

The fail safe design guide defined by equation (A-24) of Appendix A is based on test data for Kevlar -49 fibers and cryoformed 301 CRES liners. Test data for other fibers, especially graphite, are needed in order to define applicable design guides.
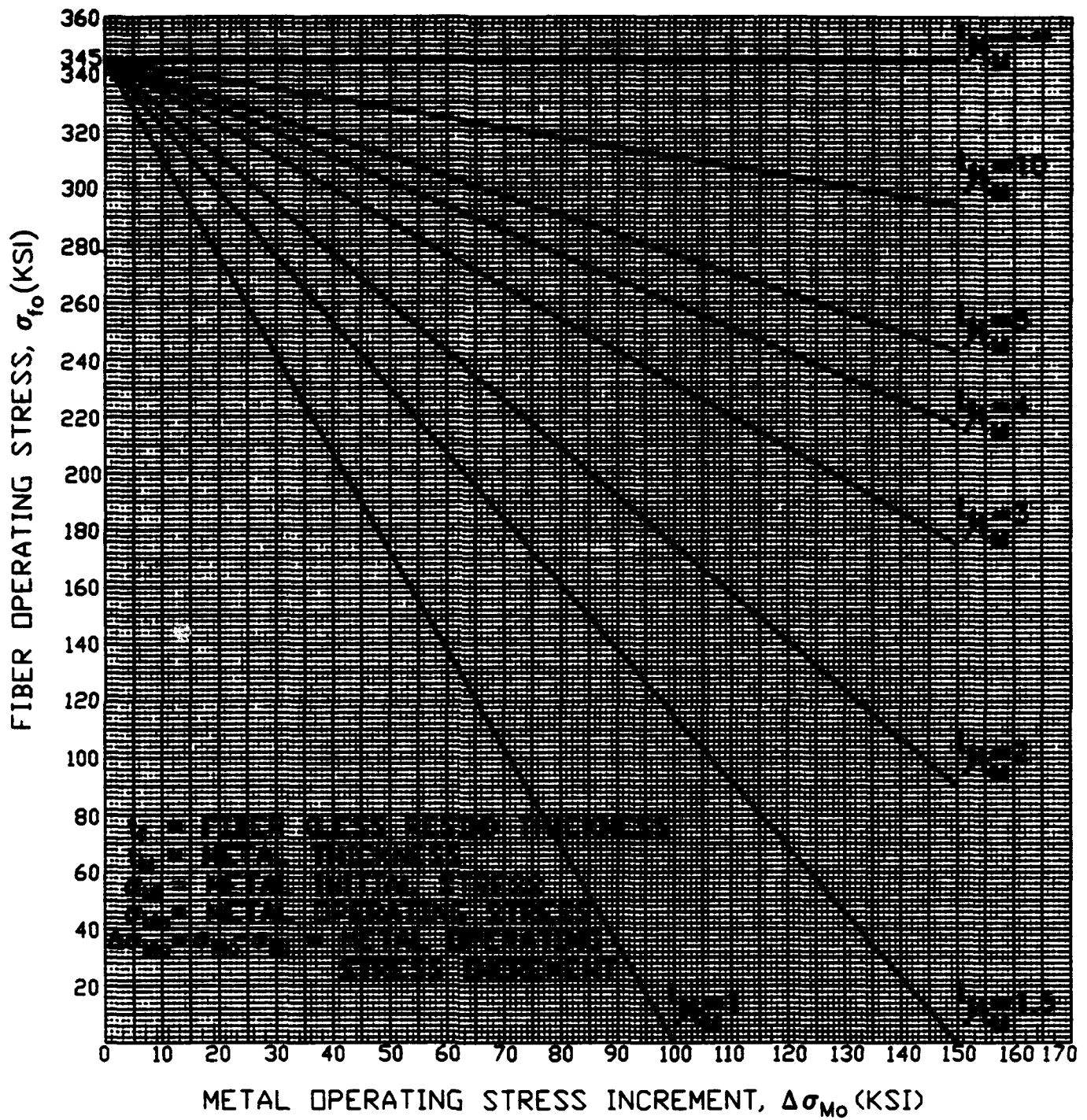
FIG. 2-20 KEVLAR OVERWRAPPED COMPOSITE SPHERE "FAIL SAFE"
FIBER OPERATING STRESS VS. METAL OPERATING STRESS INCREMENT

A program objective was to develop a "generic" prestressed composite vessel design guide, valid for any liner material overwrapped with Kevlar - 49 fibers, that would describe the circumstances under which the Kevlar fibers would retain any fragments generated by sudden liner brittle failure at operating pressure and permit benign venting to ambient of the contained gas. Test data generated on the current program indicate that the results are a function of the specific liner failure mode. Globally embrittled 301 cryo-CRES spherical liners with multitudes of through the thickness cracks remained in one piece as load carrying shells at operating pressure and the fiber structural response was essentially static. On the other hand, locally girth weld heat affected zone embrittled liners separated into two pieces and there was significant dynamic amplification of fiber static operating pressure strains. It seems likely, therefore, that liner failure modes for different liner materials would be a function of their material properties, particularly toughness, which relate to the number and size of fragments generated by the sudden liner brittle rupture at operating pressure, corresponding to different levels of fiber strain dynamic amplification. Additional tests with different liner materials wrapped with Kevlar -49 fibers would be required to define/verify the appropriate structural behavior/fail safe scenario and check the validity of the design guide presented in this report.

2.7.2   Cylindrical Vessels

A preliminary "first cut" design guide for fail safe liner fragment containment by the fibers of a prestressed composite cylindrical vessel whose metal liner fails suddenly in a brittle manner at operating pressure is derived in Appendix A.   It is plotted on Figure 2-22 and set forth again below for continuity of text in equations A-31 and A-32. The equation is based on the assumptions that the structural models/test data generated on this program for spheres and 6" ϕ fiber wrapped cylinders are valid and that the hoop fibers in the cylindrical region fail at .02 hoop strain subsequent to sudden liner brittle failure at operating pressure. Test data for Kevlar -49 overwrapped prestressed composite cylindrical vessels are obviously needed to verify/improve the preliminary design guide postulated.

$$\sigma_{fHO} + \frac{1.7}{\beta} \, (\Delta\sigma_{MHO}) \leq 345 \quad \cdots \text{(A-31)}$$

$$\beta = \frac{n_\theta \, A_{fH}}{L t_M} \quad \cdots \text{(A-32)}$$

As defined in the nomenclature of Appendix A and Figure 2-21,

A_{fH} = hoop fiber (less resin) cross-sectional area per fiber (in^2)

L = cylindrical length (in)

n_θ = number of hoop fiber turns

t_M = metal liner thickness (in)

σ_{fHO} = hoop fiber (less resin) operating stress (ksi)

σ_{MHO} = metal liner hoop operating stress (ksi)

σ_{MHi} = metal liner hoop initial stress (ksi)

$\Delta\sigma_{MHO} = (\sigma_{MHO} - \sigma_{MHi})$ = metal liner hoop operating stress increment (ksi)
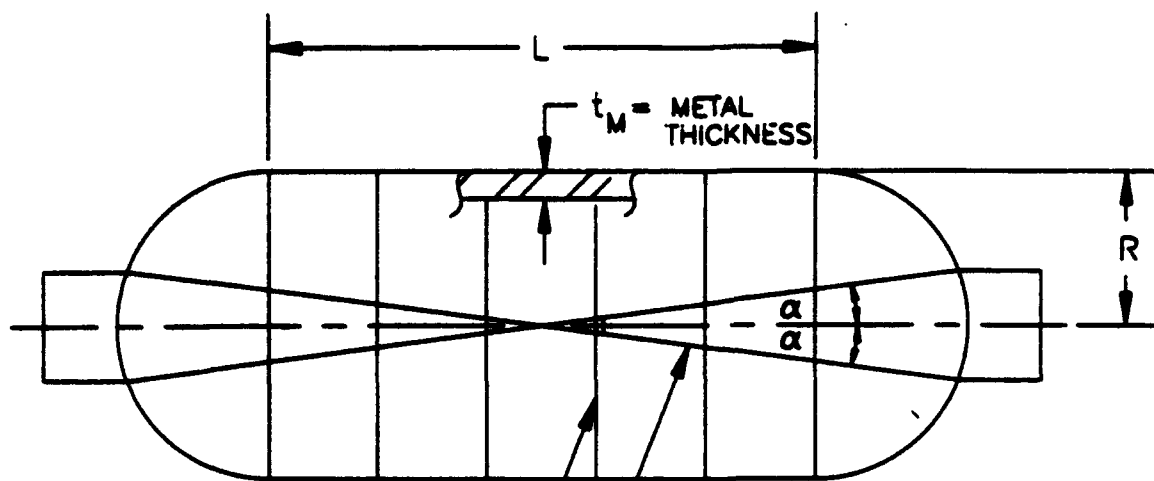
HOOP FIBER (n_θ TURNS) —————— ——HELICAL FIBER (n_α TURNS)

AREA/FIBER = A_{fh} AREA/FIBER = $A_{f\alpha}$

NUMBER OF HOOP FIBER TURNS   NUMBER OF HELICAL FIBER TURNS PER

PER UNIT LENGTH = $\dfrac{n_\theta}{L}$ UNIT CIRCUMFERENTIAL LENGTH = $\dfrac{n_\alpha}{2\pi R}$

a) CYLINDER FIBER WRAP GEOMETRY

σ_{fh} (HOOP FIBERS)

$\sigma_{f\alpha}$
(HELICAL FIBERS)

HELICAL FIBER

$\sigma_{f\alpha}$

$\sigma_{f\alpha}$ SIN $^2\alpha$

$\sigma_{f\alpha}$ COS $^2\alpha$
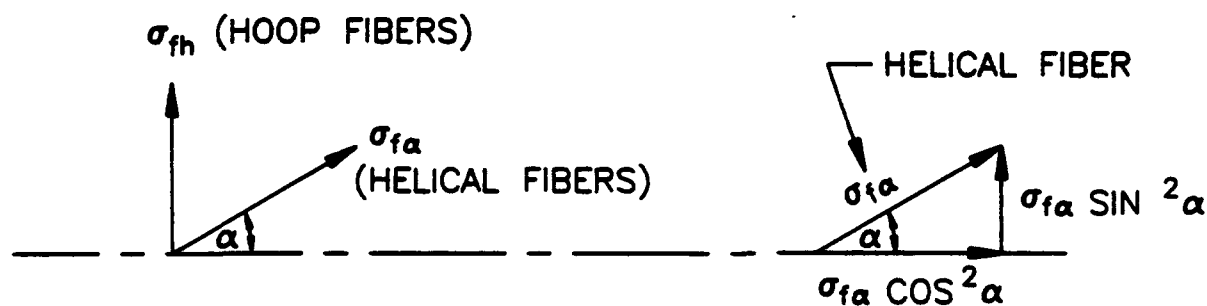
b) CYLINDER FIBER WRAP STRESSES

FIG. 2-21 FIBER OVERWRAPPED CYLINDER GEOMETRY AND STRESSES
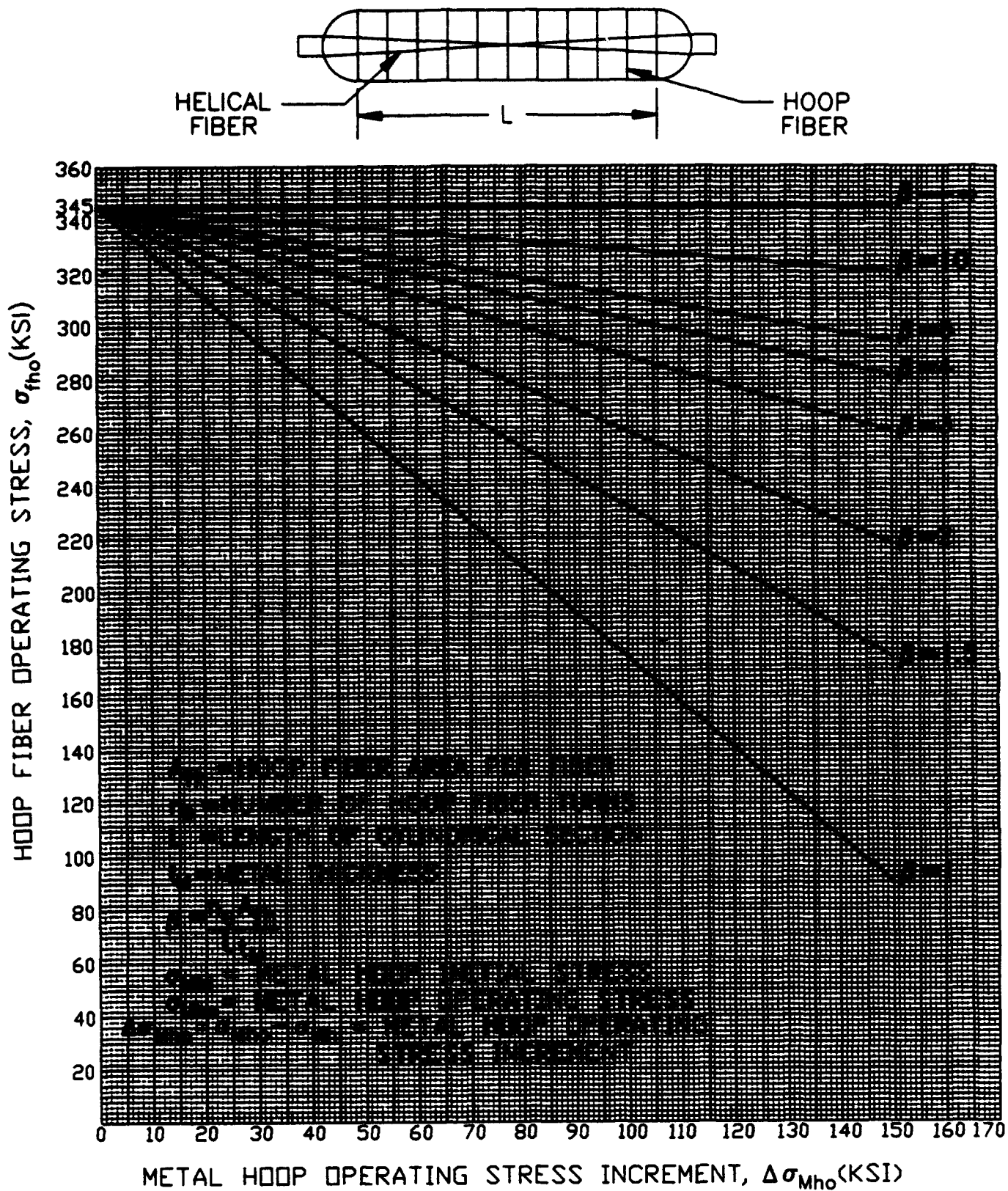
FIG. 2-22 KEVLAR OVERWRAPPED COMPOSITE CYLINDER "FAIL SAFE" HOOP FIBER OPERATING STRESS VS. METAL HOOP OPERATING STRESS INCREMENT

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

3.1.1 Fail Safe Demonstrated

"Fail Safe", benign leak/fiber retention of liner fragments has been demonstrated experimentally for a range of tank structural and geometric parameters at 2500 to 5600 psig GHe operating test pressures for PSC Kevlar fiber overwrapped 301 cryo CRES spherical liners. The liners were intentionally hydrogen embrittled to achieve sudden brittle failure modes at operating pressure.

3.1.2 Fail Safe Design Guides Defined

Based on structural theory and test data obtained in this program, "Fail Safe", benign leak/fiber retention of liner fragments at operating pressure for Kevlar overwrapped metal composite tanks is a function of fiber operating stress, metal stress increment (operating minus initial) and fiber to metal thickness ratio. Guides to fail safe composite tank design are defined in terms of these parameters for both spheres and cylinders. It is presumed that test data generated for spherical geometry is valid for cylinders. This hypothesis is based on similarity between geodesic isotensoid fiber wraps (great circle sphere and hoop cylinder) and validity of the dynamic amplification factor model. Tests are obviously required to verify these assumptions.

3.1.3 Leak-Before-Burst (LBB) Mode Demonstrated by Test for 301 Cryoformed CRES

Operating pressure cycle tests of composite tanks with Elox machined defects in 301 cryoformed CRES liner walls showed benign leak mode for GHe and hydraulic pressurants. R-Curve and vessel fracture mechanics tests demonstrated that cryoformed 301 CRES is a tough, high strength material that gives LBB mode. Significant results obtained were a plane stress

critical R-Curve stress intensity of 180 ksi $\sqrt{in}$ for parent material, weld and HAZ at high tensile strength (200 - 260 ksi). Metal vessel thru cracks grew up to four (4) times the wall thickness before reaching critical size, demonstrating a large LBB safety factor. No further crack growth occurred after up to 48 hours of sustained operating pressure subsequent to benign leak. This verified the safe, stable mode of the thru cracked tank under constant operating load.

3.1.4 Analytic Predictions/Models Verified

Analytic predictions by 2D transient computer code model and simple 1D lumped models of fiber strains/failure modes were in reasonable agreement with experimental results.

3.1.5 Key Experimental Techniques Developed/Verified

Test procedures/techniques/set-up/instrumentation were developed to accomplish successful transient high pressure GHe testing of fiber overwrapped prestressed composite pressure vessels and to accurately monitor the extremely short time fiber strain response/ pressure/ temperatures. Accurate experimental simulation of sudden metal liner brittle failure computer model was accomplished. Techniques and parameters required to intentionally embrittle the PSC Cryo CRES liners in a controlled manner so that they failed in a predetermined brittle way at predetermined pressure/stress/time were developed and experimentally verified.

3.2 Recommendations

3.2.1 The use of high strength and high modulus graphite fiber overwrap for PSC vessel construction is becoming more and more prevelant because of the significant weight reduction possible. Indications are that graphite fiber behavior may be different from Kevlar. Continuation of the "fail safe" data base work of this program to encompass graphite fiber overwrapped PSC vessels appears warranted and mandatory.

3.2.2 Tests of cylindrical fiber overwrapped PSC composite tanks are recommended to verify the fail safe design guide for cylindrical geometry defined herein which was extrapolated from results on spheres.

3.2.3 Test data obtained on the program indicate that fiber dynamic strain amplification is a function of the failure mode of the liner. Large dynamic strain amplification occurred when the liner fragmented into two pieces. On the other hand, essentially static behavior was observed for the cracked liner which remained intact and capable of resisting load as a whole shell. It is anticipated that more severe fragmentation would occur, all else the same, for a less tough liner material compared to a more tough liner material. it is recommended, therefore, that PSC fiber overwrapped tanks with different liner materials be tested to evaluate this effect.

4.0 REFERENCES

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2. Gleich, D., "High Performance Positive Expulsion Tankage and Pressure Vessel Constructions", Paper 78-WA/Aero-19, Presented at the ASME Winter Annual Meeting, San Francisco, CA, December 10 - 15, 1978.

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4. PISCES, "Physics International's Scientific Codes for Engineering Service", Physics International Co., San Leandro, CA.

5. Gerstle, F. P., "Analysis of Filament Reinforced Spherical Pressure Vessels", ASTM STP 546, pp. 604-631, Composite Materials 3rd ASTM Conference, Williamburg, VA., 21 - 22 March, 1973.

6. Tsai, W. W. and Pagano, N.J., "Invariant Properties of Composite Materials" in "Composite Materials Workshop",Technomic, 1968, pp. 233-253.

7. Kevlar 49 Data Manual, E. T. DuPont De Nemours and Co., Wilmington, Del.

8. Handbook of Engineering Mechanics, edited by W. Flugge, First Ed., pp. 61-27, McGraw-Hill Book Co., 1962.

APPENDICES

This section contains the Appendices used to amplify the discussions given in the main text.

The Appendices consist of newly generated text and reference documents that were prior generated on the program. For purposes of clarity and ease of reference, figures/tables in the prior generated reference documents have letters following the figure or table number, e.g., Figure 1A, Figure 2B, etc. The newly generated appendices text figures/tables numbers have letters preceding the algebraic digits (e.g., A-1, B-2, C-2, etc.) indicating their specific appendix location. A complete list of figures and tables together with their locations is given in Appendix G, herein.

Appendix A - Analytic Models

This appendix describes the analytic models used to investigate the "fail safe" potential of Kevlar fiber overwrapped PSC tanks at operating pressure and to evaluate and correlate the experimental data obtained in the program.

The following items are treated in detail herein.

A.1   Nomenclature

A.2   Two-Dimensional Spherical PICES Computer Model

A.3   One-Dimensional Transient and Static Models and "Fail Safe" Design Guides

A.1 Nomenclature

A_{fH} = Hoop Fiber Area

$A_{f\alpha}$ = Helical Fiber Area

d = Distance

E_1 = Composite (fiber + Resin) Young's Modulus in Fiber Direction

E_2 = Composite Young's Modulus Perpendicular to Fiber Direction

E_f = Fiber Less Resin Young's Modulus in Fiber Direction

E_M = Metal Young's Modulus

$\hat{E}_M$ = $E_M/1-\nu_M$ = Metal Effective Young's Modulus for Spherical

Membrane

E_W = Effective Isotropic Composite Young's Modulus

F.S. = Factor of Safety

G = Composite Average Shear Modulus

h_M = Metal Thickness

h_W = Composite Thickness

k_f = Fiber Less Resin Extensional Stiffness = $\dfrac{E_f t_f}{2}$

k_M = $\hat{E} t_M$ = Metal Extensional Stiffness

L = Length

n_θ = Number of hoop Fiber Turns

n_α = Number of Helical Fiber Turns

A-2

P = Pressure

P_i = Initial Stress Pressure

P_o = Operating Pressure

P_f = Pressure Carried by Fiber Less Resin

P_{fo} = Operating Pressure Carried by Fiber Less Resin

P_M = Pressure Carried by Metal

P_{Mo} = Operating Pressure Carried by Metal

$P_{f\theta o}$ = Portion of Operating Pressure Resisted by Fibers in Hoop

      Direction

P_{MHO} = Portion of Operating Pressure Resisted by Metal in Hoop

      Direction

$\Lambda_{P_{\theta f}}$ = Pressure Hoop Fibers Have to resist Upon Sudden Liner

      Failure

P^* = Static Fiber Stress Pressure

P_W = Equivalent Static Pressure Metal Transmits to Fiber Wrap

Q = Average Composite Stiffness in the Principal Directions

R = Radius

t = Time

t_f = Fiber Less Resin Thickness

t_M = Metal Thickness

u = Radial Displacement

A-3

V = Volume

α = Helix Fiber Winding Angle

$\alpha_M = E_M/1-\nu_M$

$\alpha_W = E_W/1-\nu_W$

$\beta = \dfrac{n_\ell A_{fH}}{Lt_M}$

Δ = Increment

γ = Shear Strain

ϵ = Strain

$\epsilon_i = \dfrac{1}{3}\dfrac{\Delta V}{V}$ = prestrain (initial strain)

ϵ_1, e_1 = Fiber Equilibrium Strain Prior to Liner Failure

ϵ_2, e_2 = Fiber Equilibrium Strain After Liner Failure

ϵ_{MAX} = Maximum Fiber Strain

$\hat{\epsilon}_f$ = Effective Static Fiber Less Resin Strain

$\hat{\epsilon}_{\Theta f}$ = Effective Static Hoop Fiber Less Resin Strain

μ = Mass Density Per Unit Area

ν_M = Poisson's Ratio of Metal

ν_W = Effective Isotropic Composite Poisson's Ratio

σ_f = Fiber Less Resin Stress

σ_{fo} = Operating Fiber Less Resin Stress

σ_{fHo} = Operating Hoop Fiber Less Resin Stress

$\sigma_{f\alpha o}$ = Operating Helical Fiber Less Resin Stress

$\sigma_{f\alpha i}$ = Initial Helical Fiber Less Resin Stress

σ_{fi} = Initial Fiber Less Resin Stress

σ_{fHi} = Initial Fiber Less Resin Hoop Stress

$\hat{\sigma}_f$ = Equivalent Static Fiber Less Resin Stress

σ_M = Metal Stress

σ_{MO} = Operating Metal Stress Before Liner Failure

σ_{MHO} = Operating Metal Hoop Stress Before Liner Failure

σ_W = Composite Fiber Wrap Stress

σ_{Mi} = Metal Initial Stress

σ_{MHi} = Metal Hoop Initial Stress

σ_{Wi} = Composite Fiber Wrap Initial Stress

τ = Shear Stress

Φ = Dynamic Amplification Factor

ω = Natural Frequency

A.2 Two-Dimensional Model

The description of the two-dimensional spherical model used for the brittle liner failure mode analysis is outlined on Figure A-1. It is based on the use of PISCES finite difference transient computer program[4]. A worst case scenario assumes an instantaneous complete girth crack in the brittle liner at zero time. A set of simplified Kevlar/epoxy composite isotropic material constants used in the calculations are based on the equations of Tsai and Pagano[6]:

$$Q = \frac{1}{8} \left(3E_1 + 5E_2 \right) \quad \ldots \quad (A-1)*$$

$$G = \frac{1}{8} \left(E_1 + 2E_2 \right) \quad \ldots \quad (A-2)$$

For $E_1 = 2/3 \times 19 \times 10^6 = 12.67 \times 10^6$ psi,

and $E_2 = 2/3 \ (0.95 \times 10^6) = .633 \times 10^6$ psi, we obtain[7] from A-1 and A-2,

$$Q = 5.15 \times 10^6 \text{ psi}$$

$$G = 1.74 \times 10^6 \text{ psi}$$

---

* Refers to equation numbers (typical)
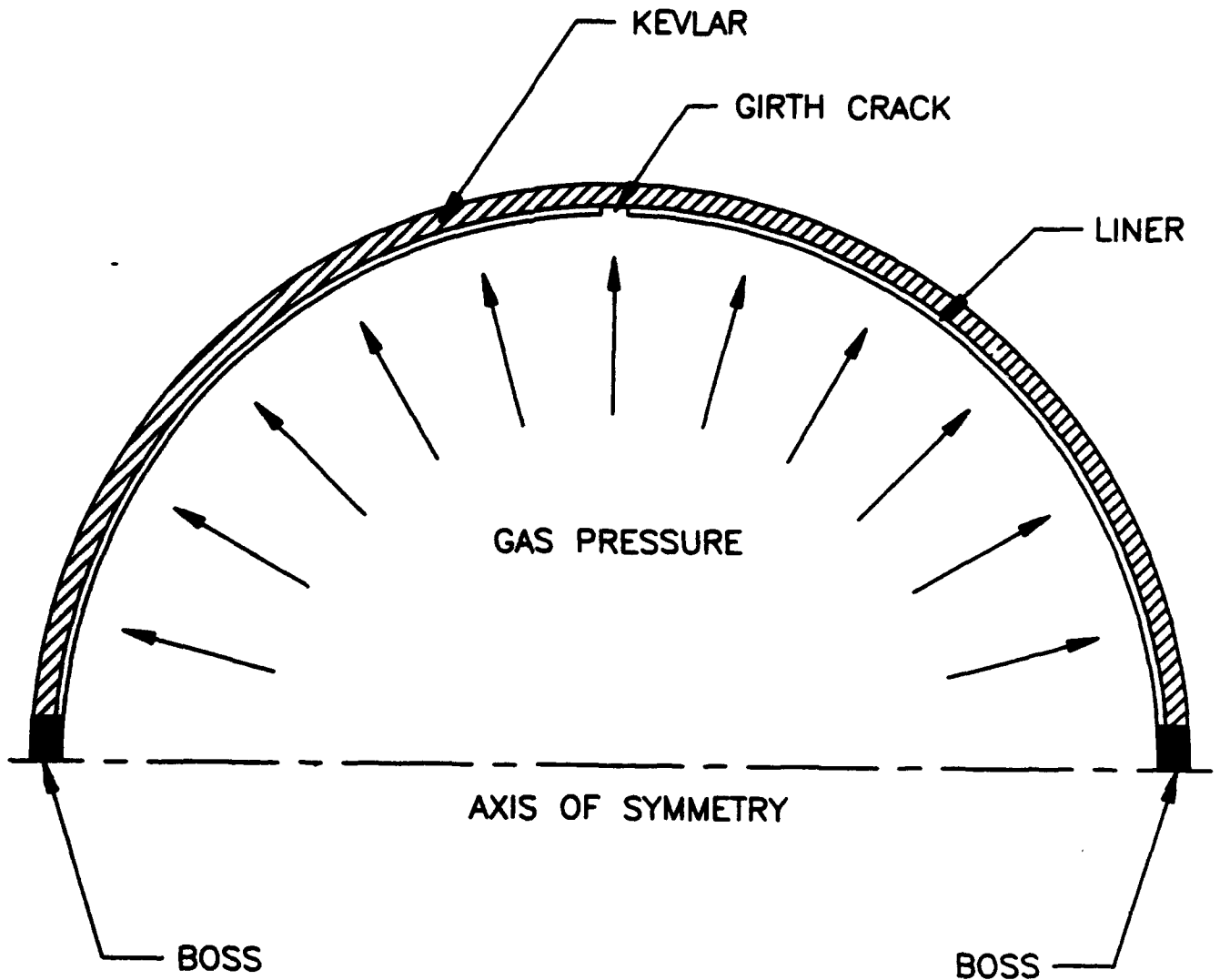
FIG. A-1 BRITTLE LINER ANALYSIS

The equivalent isotropic Young's modulus and Poisson's ratio are found from,

$$\frac{E_w}{1-\nu_w^2} = Q \quad \ldots \text{(A-3)}$$

$$\frac{E_w}{2(1+\nu_w)} = G \quad \ldots \text{(A-4)}$$

yielding upon substitution of above numerical values,

$$E_w = \frac{4G}{1-G/Q} = 4.6 \times 10^6 \text{ psi}$$

$$\nu_w = \frac{1-2G}{Q} = 0.32$$

as the effective isotropic constants for Kevlar/epoxy overwrap. Computer calculations were carried out for the structural model schematically shown on Figure A-2 using appropriate test PSC vessel pressures, geometries and materials properties assuming complete slip and complete bonding at the fiber/metal interface. The complete slip interface condition resulted in higher fiber strains and better agreement with the strains measured in the tests.

A-8

KEVLAR OVERWRAP

LOCATION OF
INSTANTANEOUS
BRITTLE CRACK

METAL LINER

AXIS OF SYMMETRY

BOSS

BOSS
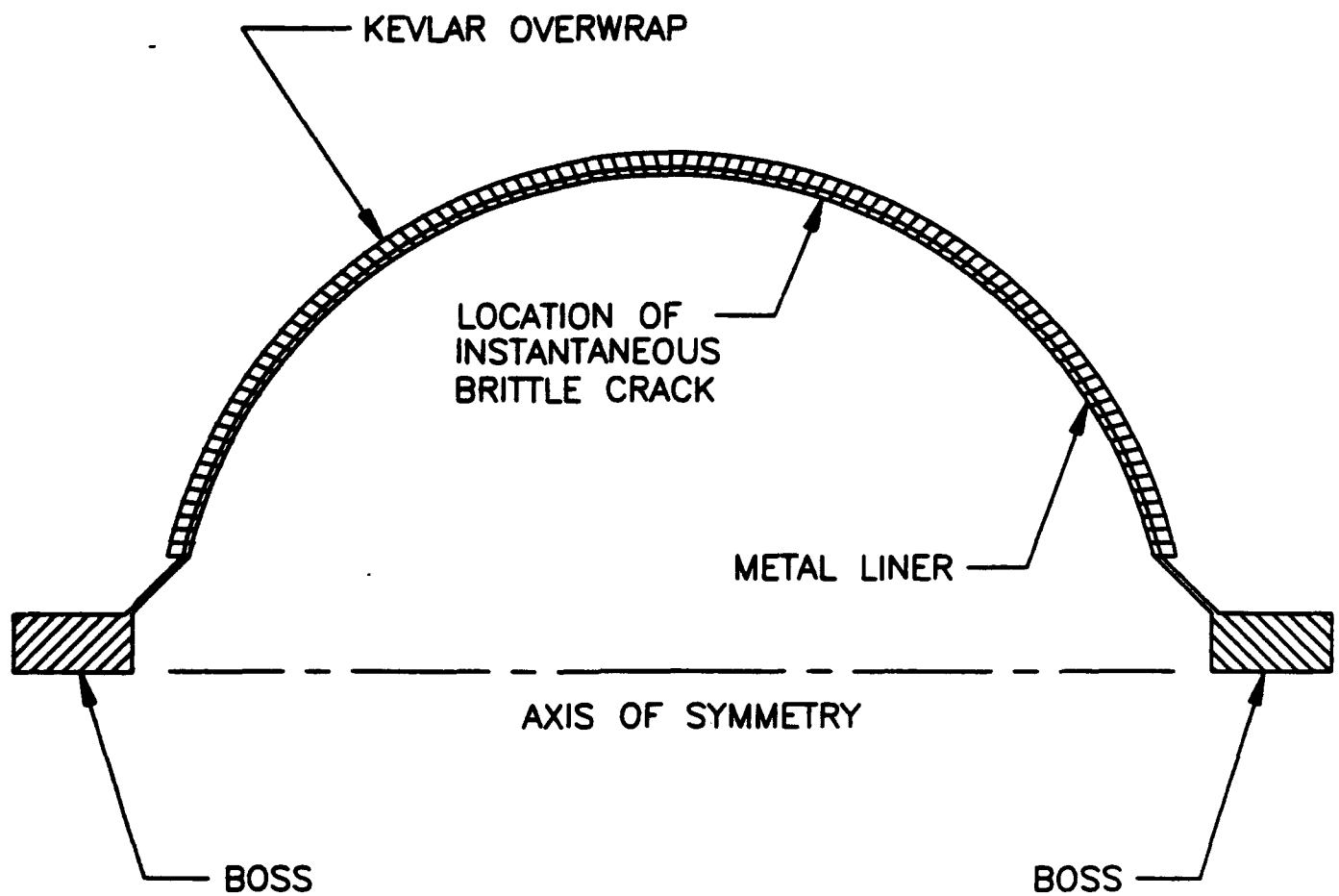
FIG. A-2 PISCES SHOCK-RESPONSE MODEL DEVELOPMENT

A.3 One-Dimensional Models

A.3.1 Transient Model

A.3.1.1 Static State

For static equilibrium at pressures P and zero (prestress state) we have,

$$\sigma_M h_M + \sigma_w h_w = \frac{PR}{2} \quad \cdots \quad (A\text{-}5)$$

$$\sigma_{Mi} h_M + \sigma_{wi} h_w = 0 \quad \cdots \quad (A\text{-}6)$$

Assuming linear elasticity, strain compatibility between pressure P and zero requires,

$$\frac{\sigma_M - \sigma_{Mi}}{\sigma_M} = \frac{\sigma_w - \sigma_{wi}}{\alpha_w} \quad \cdots (A\text{-}7)$$

From (A-5) → (A-7) one obtains for the static composite shell,

$$\sigma_M - \sigma_{Mi} = \frac{PR}{2h_M} \quad \frac{1}{1 + \dfrac{h_w \alpha_w}{h_M \alpha_M}} \quad \cdots \quad (A\text{-}8)$$

$$\frac{\sigma_w - \sigma_{wi}}{\alpha_w} = \frac{PR/2}{h_M \alpha_M + hw\alpha_w} = \epsilon_1 - \epsilon_i \quad \cdots \quad (A\text{-}9)$$

If the fiber wrap is intact and the liner loses strength ($\sigma_M = 0$), we determine from (A-5) and the fiber stress/strain relation, the static fiber strain, ϵ_2, referenced to the fiber zero stress state as,

$$\epsilon_2 = \frac{\sigma_w}{\alpha_w} = \frac{PR}{2hw\alpha_w} \quad \cdots \quad (A\text{-}10)$$

A-10

A.3.1.2 Transient State

Assuming the entire liner instantly loses strength, the equation of motion for a spherical shell for rotationally symmetric radial motion, u and extensional strain, $\epsilon = u/R$, loaded with time varying pressure can be written[8],

$$\ddot{\epsilon} + \omega^2 \epsilon = \frac{P}{R\mu} \quad \dots \quad (A-11)$$

$$\text{with } \omega^2 = \frac{2hw\alpha_w}{R^2\mu} \quad \dots \quad (A-12)$$

The mass per unit area, μ, contains the liner mass only if the liner remains attached to the overwrap and participates in the motion.

The solution of (A-11) with the initial condition, $\epsilon = \epsilon_1$ at $t = 0$, is,

$$\epsilon = \epsilon_2 + (\epsilon_1 - \epsilon_2) \cos wt \quad \dots \quad (A-13)$$

The maximum strain occurs for $\cos wt = -1$ and is given by,

$$\epsilon_{MAX} = \epsilon_2 + (\epsilon_2 - \epsilon_1) \quad \dots \quad (A-14)$$

The peak strain is the same regardless of the amount of liner mass participating in the motion; only the frequency differs.

Test data fiber strain correlation calculations were made using equations A-9, A-10 and A-14, together with PSC test vessel geometry, effective fiber wrap isotropic constants, 301 cryo CRES liner material properties and fiber prestrain values, ϵ_i. Typical results are illustrated by the ϵ_1, ϵ_2 and ϵ_{MAX} values given on Figures 2-17, 2-18 and 2-19.

A.3.2 <u>Static One-Dimensional Model - Dynamic Amplification Factor/"Fail Safe" Design Guide</u>

A.3.2.1 Dynamic Amplification factor

Just prior to composite vessel liner failure at pressure, P, the fiber stress is σ_f and it resists a pressure P_f, while the metal liner carries the balance of the pressure, $P_M = P-P_f$. When the liner fails suddenly, the fibers have to carry an additional pressure, P_1, and their stress and strain are increased to $\overset{\Lambda}{\sigma}_f$ and $\overset{\Lambda}{\epsilon}_f$, respectively. It is postulated that the additional fiber pressure P_1 is given by a dynamic amplification factor Φ times the static pressure P_M that the metal was carrying just before it failed. If P_1 is large enough, fiber failure will occur at the test verified 2% ultimate strain value. This model is formulated analytically below using, for convenience, the results of prior work[3]. Terms are defined in the nomenclature.

$$\overset{\Lambda}{\sigma}_f = \sigma_f + {}^{\Phi P}M \frac{R}{t_f} = \sigma_{fi} + \frac{\Delta\sigma_f \Delta P}{\Delta P} + \Phi P_M \frac{R}{t_f} = E_f \overset{\Lambda}{\epsilon}_f \cdots (A-15)$$

A-12

with,

$$\frac{\Delta\sigma_f}{\Delta_p} = \frac{E_f}{E_m} \times \frac{R/2t_M}{1 + \frac{k_f}{k_M}} \quad \cdots \text{(A-16)}$$

$$\frac{P_M}{P} = \frac{1}{1 + k_f/k_M} \quad \cdots \text{(A-17}$$

$$\sigma_{fi} = E_f \, \epsilon_i = E_f \, \frac{1}{3} \frac{\Delta V}{V} \quad \cdots \text{(A-18)}$$

Correlation of pertinent test data to date, using

$\hat{\epsilon}_f$ = .02, gave values of dynamic amplification factor Φ

range of 1.5 - 1.7 for the local girth and boss weld regions

embrittled liner failure modes. Measured fiber strains for the

spherical liner global embrittled failure mode were correlated by

static structural behavior (Φ = 1).

A.3.2.2 "Fail Safe" Design Guide

A.3.2.2.1 Spheres

Recasting (A-15) specifically at operating pressure, with subscripts,

o, as defined in the nomenclature and specifying fiber and metal operating

pressures in terms of their static operating stress increments (measured

from the prestressed state) yields,

$$P_{fo} = \Delta\sigma_{fo} \, \frac{t_f}{R} \quad \cdots \quad \cdots \text{(A-19)}$$

$$P_{MO} = 2\Delta\sigma_{MO} \, \frac{t_M}{R} \quad \cdots \text{(A-20)}$$

with $P_{fo} + P_{MO} = P_o$ ... (A-21)

Here,

$$\Delta\sigma_{fo} = \sigma_{fo} - \sigma_{fi}$$

$$\Delta\sigma_{MO} = \sigma_{MO} - \sigma_{Mi} \quad ... \quad (A-22)$$

Substituting in (A-15) one obtains,

$$E_f \hat{\epsilon}_f = \frac{R}{t_f} \left[\sigma_{fo} \frac{t_f}{R} + \Phi 2\Delta\sigma_{MO} \frac{t_M}{R} \right] \quad ... \quad (A-23)$$

Taking for Kevlar -49, $E_f = 19000$ ksi,

$\hat{\epsilon}_f = .02$ fiber less resin ultimate strain and allowing for a design

factor of safety, F.S., we have from (A-23) the relation between

allowable static fiber operating stress, given metal static operating

rating stress increment and fiber to metal thickness ratio for "fail

safe" liner fragment retention by the fibers as,

$$\sigma_{fo} = \frac{380}{F.S.} - \frac{2\Phi\Delta\sigma_{MO}}{t_f/t_M} \quad ... \quad (A-24)$$

A-14

Taking now, $\Phi = 1.7$ (worst case embrittled dynamic amplification factor) and FS = 1.1, we obtain as a spherical prestressed composite tank "fail safe" design guide the allowable static fiber operating stress,

$$\sigma_{fo} = 345 - \frac{3.4 \Delta \sigma_{MO}}{t_f t_M} \quad \ldots \quad (A-25)$$

This relation is plotted on Figure 2-20 of section 2. Values of fiber operating stress, σ_{fo}, equal to or less than the values shown on the figure for given metal operating stress increment $\Delta \sigma_{MO}$, and specified fiber to metal thickness ratio, t_f/t_M, indicate "fail safe" retention of spherical liner fragments by the Kevlar -49 fibers and benign pressure venting to ambient. For example, at $\Delta \sigma_{MO} = 100$ ksi and $t_f/t_M = 3$, values of fiber operating stress, $\sigma_{fo} \leq 231$ ksi indicate "fail safe" fragment retention behavior for sudden spherical liner failure at operating pressure.

A.3.2.2.2 Cylinders

Based on the structural models/test data obtained for spheres and successful test data correlation of 6" ϕ fiber wrapped cylinders on the current program, we derive below a simplified "first cut" liner fragment retention design guide for cylindrical shapes, assuming a hoop fiber failure mode in the cylindrical (non-head) region when the metal liner fails suddenly at operating pressure. Differences in geometry and fiber wrap pattern between spherical and cylindrical configurations may affect

A-15

the accuracy of the results. Test data are obviously needed to verify/improve the model.

The cylindrical vessel of radius, R and cylindrical length, L, has a metal liner of thickness, t_M, as sketched on Figure 2-21 of section 2. The liner is fiber wrapped with hoop fibers with fiber area A_{fh} per fiber, having $\frac{n_\theta}{L}$ turns per unit of cylindrical length as well as helical fibers of area $A_{f\alpha}$ per fiber, inclined at an angle, α, with the axial centerline of the cylinder as shown on the figure. The helical fiber turns per circumferential length is $n_\alpha/2\pi R$ as noted. The composite tank is prestressed. At zero pressure, the metal liner is in hoop compression, σ_{MHi}, and the hoop and helical fibers are in tensions, σ_{fHi} and $\sigma_{f\alpha i}$, respectively. The composite cylindrical vessel with closed ends is then loaded with an internal operating pressure, P_o.

Using netting analysis theory and measuring stress increments (operating minus initial stress) from the zero stress state, we write the well known hoop equilibrium equation in the form,

$$\Delta\sigma_{MHO}\,\frac{t_M}{R} + \frac{n_\theta\,A_{fH}\,\Delta\sigma_{fHO}}{LR} + \frac{n_\alpha\,A_{f\alpha}\,\sin\alpha\tan\alpha\,\Delta\sigma_{f\alpha o}}{2\pi R^2} = \Delta P_o = P_o$$

$$\ldots\ (A\text{-}26)$$

A-16

The first term on the left hand side of (A-26) is the "hoop pressure" resisted by the metal. The second term represents the hoop pressure reacted by the combined hoop plus helical fibers. Symbodically, (A-26) then becomes,

$$\Delta P_{M\theta o} + \Delta P_{f\theta o} = \Delta P_o = P_o \quad \dots \text{(A-27)}$$

Assuming, as for spheres, that the pressure, $\Delta \hat{P}_{\theta f}$, the fibers have to resist at sudden liner failure is the sum of the static pressure it carried before liner failure plus a dynamic amplification factor, Φ, times the pressure the metal was carrying before liner failure, we have,

$$\Delta \hat{P}_{\theta f} = \Delta P_{\theta o} + \Phi \Delta P_{M\theta o} \quad \dots \text{(A-28)}$$

Noting that the hoop fiber strain increment is given by,

$$\Delta \hat{\epsilon}_f = \frac{\Delta \sigma_f}{E_f} = \frac{1}{E_f} \frac{\Delta \hat{P}_{\theta f} R}{n_\theta A_{fH/L}} \quad \dots \text{(A-29)}$$

and using A-26 through A-28, we obtain,

$$E_f \Delta \hat{\epsilon}_f = \Delta \sigma_{fHo} + \frac{n\alpha A_{f\alpha/2\pi R}}{n_\theta A_{fH/L}} \sin \alpha \tan \alpha \, \Delta \sigma_{f\alpha o} \quad \dots \text{(A-30)}$$

For practical designs, $\dfrac{n\alpha A_{f\alpha/2\pi R}}{n\alpha A_{fH/L}}$ is the order of unity,

A-17

$\Delta\sigma_{f\alpha o} = \frac{3}{4}\Delta\sigma_{fH}$ and α is a small angle, 15° or less. The second term

on the left hand side of (A-30) is then about 5% or less of the first term

and is conservatively neglected.

Adding now the effect of initial fiber strain, $\epsilon_{fHi} = \sigma_{fHi}/E_f$, to

obtain the total fiber strain, $\hat{\epsilon}_f = \Delta\hat{\epsilon}_f + \epsilon_{fHi}$ and noting that $\sigma_{fHo} =$

$\Delta\sigma_{fHo} + \sigma_{fHi}$, we obtain,

$$E_f\hat{\epsilon}_f = \sigma_{fHo} + \frac{\Phi\,t_M}{n_\theta\,A_{fH/L}}\,\Delta\sigma_{MHO} \ldots \text{(A-31)}$$

Taking in A-31 E_f = 19000 ksi, $\hat{\epsilon}_f$ = .02, Φ= 1.7 and allowing for a

factor of safety, FS = 1.1 yields,

$$\sigma_{fHO} + \frac{1.7}{\beta}\,\Delta\sigma_{MHo} \leq 345 \ldots \text{(A-32)}$$

with the effective hoop fiber to metal thickness ratio, β, given by,

$$\beta = \frac{n_\theta A_{fH}}{Lt_M} \ldots \text{(A-33)}$$

Equation (A-32), the preliminary design guide for cylindrical liner

fragment retention by Kevlar fibers is plotted on Figure 2-22 of section 2.

It defines the maximum allowable hoop fiber operating stress for given

metal operating hoop stress increment and effective hoop fiber to metal

thickness ratio, β. Fragment retention and fail safe behavior is defined

by the region bounded by the applicable β = constant curves.

APPENDIX B - Hydrogen Embrittlement Parameters/Test Data

This appendix discusses in detail the derivation of the hydrogen embrittlement parameters used in the controlled intentional embrittlement of the 301 Cryo CRES liners of the Kevelar fiber overwrapped PSC tanks. Hydrogen embrittlement was used to provide the sudden brittle liner failure mode at operating pressure required to obtain "fail safe" experimental data as described in section 2 of the text.

Hydrogen embrittlement parameters and test data are summarized and they are discussed in detail in ARDE Report EG 42001-3 "Interim Report Kevlar 49 Overwrap Study Liner Failure Inducement by Hydrogen Embrittlement Sub Scale Tests," contained in this appendix.

B.1 Hydrogen Embrittlement Parameters

Intentional 301 CRES liner hydrogen embrittlement parameters derived from the 11" ϕ and full scale 16" ϕ PSC vessel tests are listed below.

- Electrolyte solution: 20cc H_2SO_4 + 980cc tap water + 500 mg $NaASO_2$. Additional solution volumes in same proportions.

- Sensitize liner inside surface: cold pickle - nitric/hydrofluoric acid solution (70°F-90°F).

- Charging current: 6 mili amps/in^2 of surface to be embrittled.

- Charging time: 72 hours

- Hold time after charging: Pressure test within 3 hours after end of charging.

- Mask off areas not to be embrittled: Adcoat AC818T liquid maskant

B.2 11" ϕ Hydrogen Embrittlement Test Data Summary

Subscale (11" ϕ) hydrogen embrittlement test data for 301 cryo CRES spheres, P/N D39.   , Figure B-1, are given in Table B-1. Hydrogen embrittlement test modes and hydrogen embrittlement vessel burst test schematic are sketched on Figures B-2 and B-3, respectively. Additional test details are given in ARDE Interim Report EG 42001-3 contained in this Appendix.

B-2

TABLE B-1

SUB-SCALE HYDROGEN EMBRITTLEMENT TEST DATA (P/N B3912 HSG)

CHARGING SOLUTION (30 oz H₃PO₄ + 900 oz TAP H₂O PER LITER OF SOLUTION)

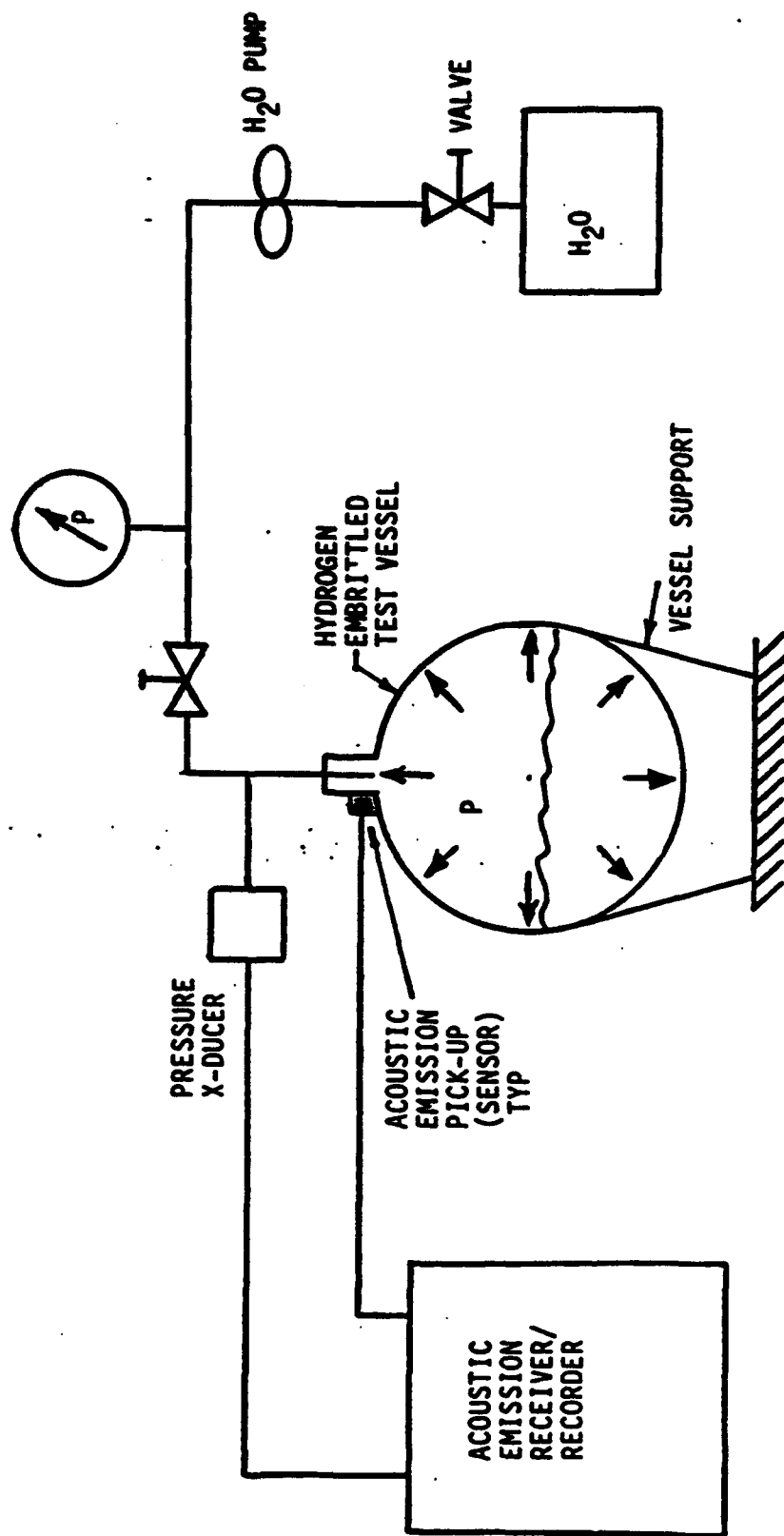| S/N	30% CASE HEAT NO.	CHARGE SOLUTION FILL VOL (ML)	SOLUTION DEPTH IN TANK (IN)	TANK POSI-TION	TANK WALLS PENETRATED MARKED	DOES ANODE POSITION	CHG TIME (HRS)	CURRENT CHARGE MA/TSH	NA	HOLD TIME AFTER CHARGE (HRS)	HYDRO T PRESSURE (PSIG) 0 PSIG	TIME OF PRESS. EST. %σu	ACOUSTIC EMISSION SIGNALS	FAILURE MODE SEVERITY CALL OUT INDEX	REMARKS
004	88019	2850	3.3	Hor	Yes 180° 6str	No	0/16/4	400	3.3	24	3000	90 min .40	Single Sensor, high sensitivity	Did not fail	Overlay charging 4,6,8,10,20 & 24 hours
004		2850	3.3	Hor	No	No	40	600	4.0	24	3260	2.5 min .45 (hold)	Single Sensor, sensitivity	Hydrogen Embrittlement Fracture surface ductile 50% cross/50% shear	The piece
006		2850	3.3	Hor	Con-clu-sive	No	90	600	4.0	24	3400	38 min .46	Two Sensor Low Sensitivity	Did not fail	Decision made to preshim heat area from being embrittled
006		11400	9.125	Vert	No	Yes	48	1600	4.0	24	2760	85 sec. .48	Two Sensor Linear, Low Sensitivity	Hydrogen Embrittlement Fracture surface was same as 1/4 dial Embrittlement ductile/brittle	Numbers area not considered. Test broke into three pieces
008		11400	9.125	Vert	No	Yes	48	1600	4.0	24	2810	6 min .58	Two Sensor Linear, Low Sensitivity	Did not fail	Core embrittled crack growth detected by benescope/radiography
008		11400	9.125	Vert	No	Yes	48	1600	4.0	24	2260	28 sec. .47	Two Sensor Linear, Low and high sensitivity	Hydrogen Embrittlement Fracture surface has net ductile crack, ductile shear thru embrittled area	Numbers clearly visible propagation. Log cracks welded
008	88470	1450	2.4	Vert	No	No	53	4000 △9.0(A)/16.0 (39)	0	3300	(5 sec.) .45 (60 sec) hold	None	Hydrogen Embrittlement Fracture battery charge on Fracture sur- face (apply igniter 3600P-53 hrs.)	Test (4) amp battery charge as power source
009	88470	11400	9.125	Vert	No	Yes	60	1600	4.0	12	2720	2.10 min .50 (1.5 min) (hold)	Two Sensor, high Sensitivity	Hydrogen Embrittlement	2 pieces
013	88470	11400	9.125	Vert	No	Yes	60	1600	4.0	12	2900	1.82 min .50 (1.0 min) hold	Two sensor, high Sensitivity	Hydrogen Embrittlement	Single piece
004	90740	11400	9.125	Vert	No	Yes	72	1600	4.9	24	3350	14 sec. .50 (20 sec) (hold)	None	Hydrogen Embrittlement	Cold Pickled 10 min. 6 pieces
109	1X2295	N/A	Girth Bond	Girth Vert	No	Girth Bond	72	1150	6.	1	3750 Gas	4.7 min .50 hold	None	Hydrogen Embrittlement	Fragmentation
10	88470	1140	9.125	Vert	No	No	72	1600	3	24	2600 Gas	70 sec. 50μ/σ	No	Gas Hydrogen Embrittlement	Fragmented

FIGURE B-1

D3912 MOD
Test Tank
is
Cathode

Voltage
Regulator

Anode

h

Horizontal
Mode
(Tank Rotated
About Boss ¢
as Required -
Manually or
with Fixture)

H_2SO_4 + TAP H_2O

$$\left[\frac{20cc \quad 980cc}{1000cc \text{ solution}} \right]$$

Voltage
Regulator

Boss Area
Masked
Off

h

Vertical
Mode
(No Tank Rotation)
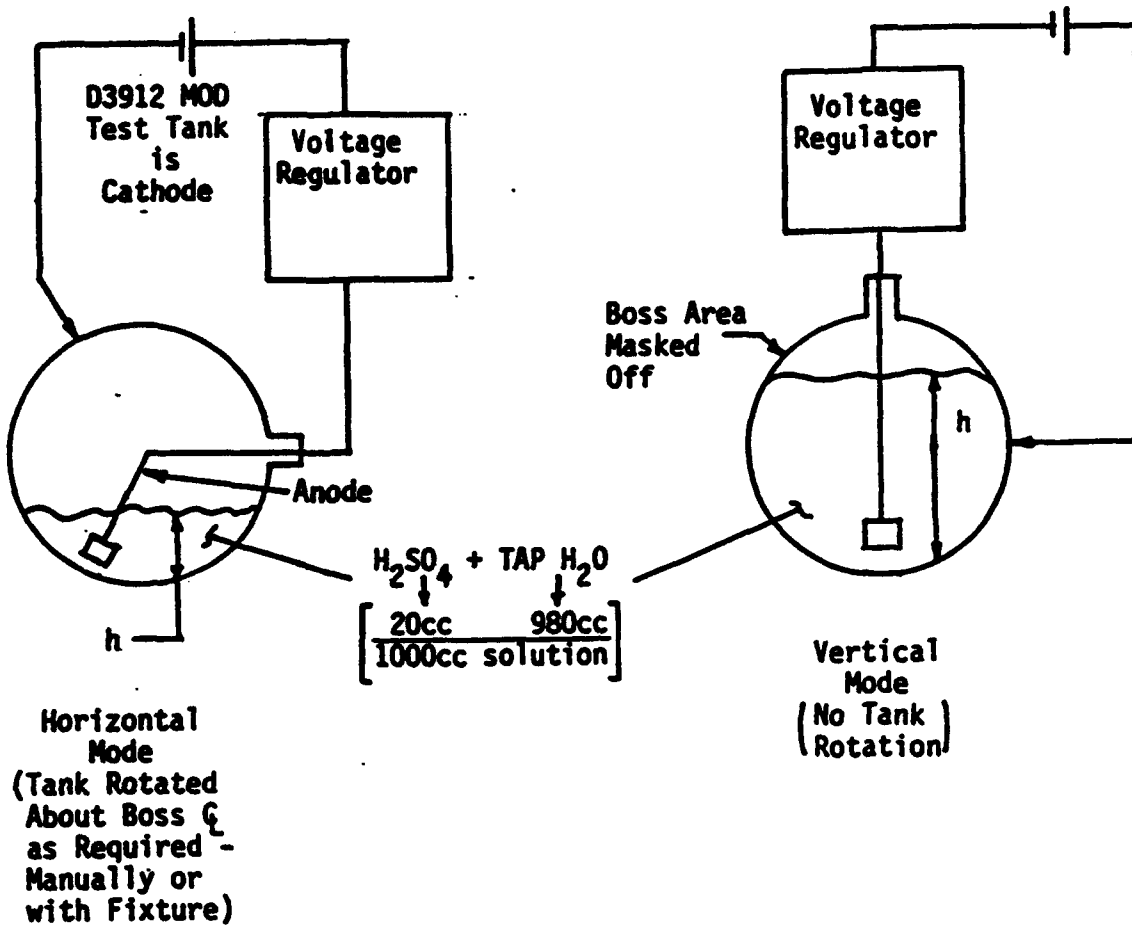
SUB SCALE
HYDROGEN EMBRITTLEMENT
TEST MODES

FIGURE B-2

SUB - SCALE
HYDROGEN EMBRITTLEMENT VESSEL
BURST TEST SCHEMATIC

FIGURE B-3
B-6

INTERIM REPORT

KEVLAR 49 OVERWRAP STUDY

LINER FAILURE INDUCEMENT
BY
HYDROGEN EMBRITTLEMENT

SUB SCALE TESTS

Submitted to:

PATRICK AFB
Eastern Space and Missile Command
Florida 32925

Contract: FO8606-84-C-0029

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LIST OF FIGURES

1.0 Introduction

1.1 Purpose

The "catastrophic" failure mode testing program of the Kevlar Overwrap Study requires that the vessel liner fail in a brittle, unstable manner at a stress range of 35% to 50% of metal liner UTS, which is the liner operating pressure stress range for practical composite vessel designs. For controlled testing, it is desired that gas pressure cycling requirements be minimized in order to be at the desired stress when the vessel fails. The approach for achieving this is to intentionally charge a cryoformed Cres liner with hydrogen such that gas can be charged during a single cycle to the desired pressure and that this pressure cause rupture of the hydrogen embrittled structure. A second aspect of the test program is to establish the appropriate vessel signature which indicates onset of failure. This interim report describes the results of testing three (3) sub-scale all metal vessels and the readout obtained by acoustic emission equipment. This testing effort is part of contract Task II, Liner Failure Inducement Study (subscale validation tests).

A difficult aspect of the test program was the need to:

a) Not embrittle the boss area so as to insure membrane failure.

b) Balance time between post charging and test such that hydrogen does not leave the vessel during test set-up.

c) Pick up acoustic emission signals with probes attached to the boss extensions only.

1.2 - **Approach and Summary of Results**

1.2.1 **Tank Embrittlement**

In order not to embrittle the boss area, Arde intentionally partially filled and rotated the tank on a continuous basis. It was, however, determined that metal membrane exposure to hydrogen gas was not sufficient to balance out the rate of gas escape from the unexposed area. The solution to the problem was to apply a common strippable coating to the desired area on the tank inside surface. All vessels were held 24 hours prior to pressure test.

1.2.2 **Acoustic Emission Testing and Summary of Results**

Utilizing Arde equipment, AET Model - 5000, hydrogen embrittled tanks were monitored to try and discern onset of failure. Initial difficulties were associated with efforts to establish correct gain settings and to find the best locations for "taping" off the equipment circuitry. Results to date indicate that meaningful signals can be generated from the acoustic emission equipment.

1.3 Summary of Conclusions to Date and Continuation of Testing

All tanks tested to date indicate achievement of rapid crack growth within the stress range of interest while Acoustic Emission equipment demonstrates an ability to discern the onset of failure, but not without problems.

With the exception of the pre-proposal test vessel, which had no 24 hour hold period after charging, all vessels were charged and pressurized twice before operating stress rupture occurred. It has become apparent that a more reliable approach to virgin vessel rupture can only occur by an over-kill set of parameters. This will result in shorter pressurization periods which AF/RPL must consider in their pneumatic system while assuring that pressurization rate will not result in vessel over heating. This could well require a heat exchanger. It is suggested that set-up vessels be used in the program for the pneumatic and other instrumentation shake downs.

Final resolution of the charging parameters will be achieved by additional sub-scale testing. The thrust of further testing will hinge on the following aspects:

1. more charging and less hold time with virgin (one pressurization) rupture as an objective.

2. further development of Acoustic Emission
    techniques to reliably detect sub-critical
    crack growth so that rupture prediction
    can be definitized.

A summary of test results follows in Table 1A.

2.0   **Test Set-Up**

2.1   **Test Articles**

Arde's standard material evaluation spheres P/N D3912 (Figure 1 were used for hydrogen induced failure demonstration. Existing vessels used to evaluate specific heats of material were electrolytically charged with hydrogen and hydrostatically pressurized to failure. Arde's pre-proposal test was heat #88470, annealed for this investigation, and tested as described in Appendix .. Three (3) post award subscale vessels were fabricated from Heat #88019.

2.2   **Test Equipment:**

2.2.1 Flasks capable of mixing electrolyte, .1 molar solution of sulphuric acid. Add 10 ml. of conc. H_2SO_4 to make 1000 ml. solution.

2.2.2 Power Supply: Lambda LA-200

2.2.3 Lead Anode: 3 in. long x 3/8" diameter, approx. dimensions. It is important that anode current densities remain constant from test to test. Full scale vessels will require larger anodes.

TABLE I △

SUB-SCALE HYDROGEN EMBRITTLEMENT TEST DATA (P/N D3412 MOD)   S/N 42001-0-2

CHARGING SOLUTION (20 CC H_2SO_4 + 980 CC TAP H_2O PER LITER OF SOLUTION)

301 CRES HEAT No.	S/N	CHARGE SOLUTION FULL Vol (ml)	SOLUTION DEPTH at TANK (in)	TANK BOSS POSITION	TANK POSITION	BOSS MASKED	CHARGING TIME (hrs)	CHARGING CURRENT MA	CATHODE CHARGE MA/IN²	HOLD TIME AFTER CHARGE (HRS)	HYDRO TEST PRESSURE (PSIG)	TIME OF PRESSURE	EST σ/6ℓ	ACOUSTIC EMISSION SIGNALS	FAILURE MODE (HYDROSTATICALLY TESTED)	REMARKS
88015	004	2850	3.5	Hor	Yes 120° incr	No	8/16/4	400	3.2	24	3000	50 min	.60	Single Sensor, too high sensitivity	Did not fail	Overlap chargings 4,8,12,16,20, and 24 hrs.
	004	2850	3.5	Hor	No	No	48	600	4.8	24	2240	2.5 minutes	.45	Single Sensor, high sensitivity	Hydrogen Embrittlement Fracture Surface: ductile SCZ craze/50% shear	One piece
	006	2850	3.5	Hor Continuous	No	No	90	600	4.8	24	3400	32 min	.60	Four Sensor Low Sensitivity	Did not fail	Rotation used to preclude boss area from being embrittled.
	006	11400	9.125	Vert	No	Yes	48	1600	△ 4.9	24	2760	85 Sec	.49	Two Sensor Linear, low sensitivity	Hydrogen Embrittlement Fracture Surface same as S/N004 Extensive sub-critical cracks	△ Maskant area not considered. Tank broke into three pieces.
	003	11400	9.125	Vert	No	Yes	48	1600	△ 4.9	24	2810	6 min	.52	Two Sensor Linear, low sensitivity	Did not fail	Some subcritical crack growth detected by borescope/radiography
	003	11400	9.125	Vert	No	Yes	48	1600	△ 4.9	24	2260	35 Sec	.42	Two Sensor Linear, low and high sensitivity	Hydrogen Embrittlement Fracture Surface has uneven crazing. Ductile shear thru masked area	Maskant clearly works Pre-existing cracks existed.
38470	△ 008	1450	2.4	Vert	No	No	53	△ 4000	△ 8.0(24) 16.0(29)	0	3300	5 sec @P max	.46	None	Hydrogen Embrittlement Fracture Surfaces similar to S/N 004	△ Four (4) amp battery charge as power source. 24 + 29 = 53 hour charge One piece.

△ PRE-PROPOSAL TEST

2.2.4   Maskant: Adcoat AC-818-T

2.2.5   Acoustic Emission Monitor System: AET 5000

2.2.6   Appropriate pre-cautionary measures for hydrogen
           generation.

2.3   -   Baseline Parameters

2.3.1   Current densities: Anode (lead) density varied
           depending on amount of electrolyte, but,
           cathodic (vessel) density remained constant.
           Two (2) cases of tests were performed. One in
           which a 3½" electrolyte level was used; another
           where 9-1/8" level was used. The vessels are
           eleven (11) inch diameter and the current was
           0.6 amps at the 3½" level/1.6 amps at 9-1/8 level.

2.3.2   Electrolyte concentration: Same for all tests,
           10 ml. of conc. H_2SO_4 to make 1000 ml. of solution.

3.0   Specific Tests and Results

               After hydrogen charging, all vessels were
           subjected to burst testing as shown in Figure 2A.
           With the exception of the pre-proposal test
           article, all tests utilized Acoustic Emission
           monitoring techniques. Hydrogen charging fell
           into two basic categories as shown in Figure 3A.
           Discussion as to the reason for each mode is
           presented under the specifics below.

3.1 Heat #88470 S/N 008

Pre-proposal test article; results of which are contained in Appendix 2. Basically, current densities were very high. Vessel was charged in vertical mode and immediately hydrostatic burst tested after charging. The vessel burst 5 seconds after achieving 110 ksi or 46% of burst. Acoustic Emission monitoring techniques were not used for this vessel. Post test examination revealed approximately 50% through-wall embrittlement. Vessel remained in one piece.

3.2 Heat #88019 S/N 004

This is the first subscale test of a series of three performed under contract. This test article took two (2) separate chargings and pressurizations to cause "operating pressure failure". The first charging was in the horizontal mode shown in Fig. 3A and Photo #1. An attempt was made to zero in on an appropriate charging time by manually rotating the vessel over a 28 hour period. The vessel was rotated three times (120° apart) for 8 hours, 16 hours, and finally 4 hours to provide over-lap chargings of 4, 8, 12, 16, 20, and 24 hours duration. The cathodic (vessel) current density was such that the 11" diameter vessel was filled with 3½" of electrolyte and charged with 0.4 amps. The vessel was then given

a 24 hour hold period before pressurization.
Pressurization occurred on December 5, 1984. The
vessel was pressurized to a maximum pressure of
3000 psig or 60% of calculated burst. The test set-up
is shown in Fig. 2A and Photo #2. The vessel did not
rupture   after approximately 50 minutes under
pressurization.

Acoustic Emission monitoring was attempted with
a single transducer mounted on the inlet pole. Gain
settings were such that too high a sensitivity was
achieved where false events due to background noise
were a problem.

Since the vessel did not rupture, a second
charging and test was initiated. The horizontal
charging mode was used again, but, no rotation and
current level increased to 0.6 amps for 48 hours.
The 24 hour hold period was maintained and vessel
pressurization/rupture occurred on December 10, 1984.
The rupture pressure was 2240 psig which is approximately
45% of burst. The pressurization time to failure was
approximately 2½ minutes. This is cumulative time from
0 to 2240 psig, including a 12 second hold at 2240 psig.

The single probe, high sensitivity, Acoustic Emission
technique was used. Again, many noise level events
were recorded so that in arriving at a reasonable data
presentation, all events with "ring-down"counts less than

10 were discriminated. "Ring-down" count is a measurement of how many times the decaying sinusoid crosses the threshold voltage. Strong AE signals have many "ring-down" counts, whereas syste noise will have few. See Fig. 4Afor Acoustic signature.

3.3 -Heat #88019 S/N 006

Since the previous vessel indicated that a 24 hour hold period was feasible, this vessel's first charging was done in a configuration that would embrittle the entire vessel membrane less bosses. The vessel was rotated during charging. See Photo #4. The cathodic current density remained at 0.6 amps at the 3½ electrolyte level, but, the time was increased to 90 hours to adjust for approximately 3 times surface area. Normalized to the prior test, this represented 30 hours effective versus the 48 hours used in the successful test of S/N 004. The vessel was pressurized on 16 January 1985 to the pressure profile shown in Fig. 5A.

The set-up and Acoustic Mission sensor location is shown in Photo #5. The Acoustic Emission sensitivity level was decreased for this test to be above noise. The vessel did not rupture. There was no acoustic activity recorded.

A second charging was initiated where the vertical mode of charging was used. (Same position as pre-proposal article) In this case, the bottom of the vessel was protected from electrolyte/hydrogen via Adcoat Maskant AC 818-T. The vessel was filled to a 9-1/8" electrolyte

level and the cathodic current density remained the same, i.e., 0.6 amps: 3½" as 1.6 amps: 9-1/8". Charging time 48 hours with 24 hour hold before rupture test.

- Vessel pressurization/rupture occurred on 21 January 1985. Test set-up is shown in Photo #6. The ruptured vessel is shown in Photos #7 and #8. There is an extensive network of sub-critical crack growth at the vessel I.D. The vessel broke into three pieces even under hydrostatic pressure. The pressure profile is shown in Figure 6A;rupture occurred at 2760 psig or approximately 49% of burst after 85 seconds of pressurization.

Figures 7A and 8A show the acoustic signature of this test. The same decreased sensitivity level was used as above. A linear type two sensor test was set up. Figure 8A shows a distribution of acoustic activity, 0 represents port boss sensor and 98 represents the opposite dome. Significant acoustic activity initiated at 2000 psig or 30 seconds prior to rupture.

3.4   Heat #88019 S/N 003

This vessel was first charged to the 1.6 amp/9-1/8" electrolyte level in the vertical mode. Maskant of apex again used. 48 hour charging with 24 hour dwell before pressurization. This test was a duplicate of the prior test with S/N 006.

Pressurization occurred on 28 January 1985 to
the profile shown in Figure 9 A. The maximum pressure
achieved was 2810 psig or 52 % of estimated burst for
approximately 6 minutes. No failure; no Acoustic signals.

Acoustic Emission technique was a two sensor
linear type test at low sensitivity. The same
test as S/N 006 failure.

Post test examination via borescope and
radiography revealed some sub-critical crack growth.

The vessel was then recharged in a similar manner
as the first charging. Two acoustic emission techniques,
high (Test #2) and low (Test #1) sensitivity were used
during pressurization/rupture test. Sensor location
is shown in Photo #9. The pressurization profile is
shown in Figure 10 A. Failure occurred after approximately
35 seconds from start of pressurization. Rupture occurred
at 2260 psig or 42% of ultimate. See Photo #10 and Figure 10.

Figures 11A, 12A, 13 A and 14A show the acoustic
signatures and distribution of events by the two sensor
linear location software. It is noted that this data
discriminates ring-down counts less than 10.
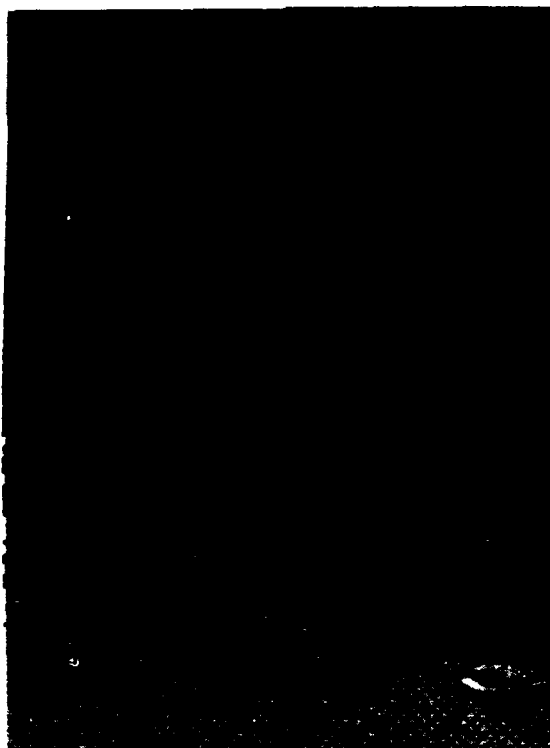
B-20
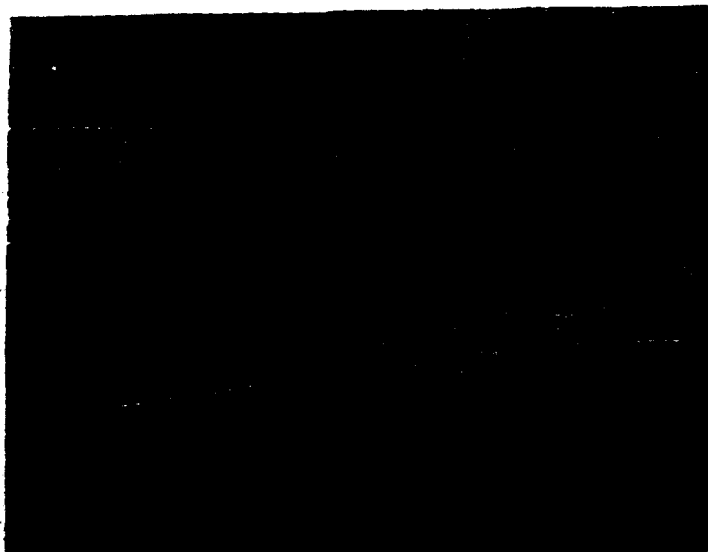
PHOTO #1
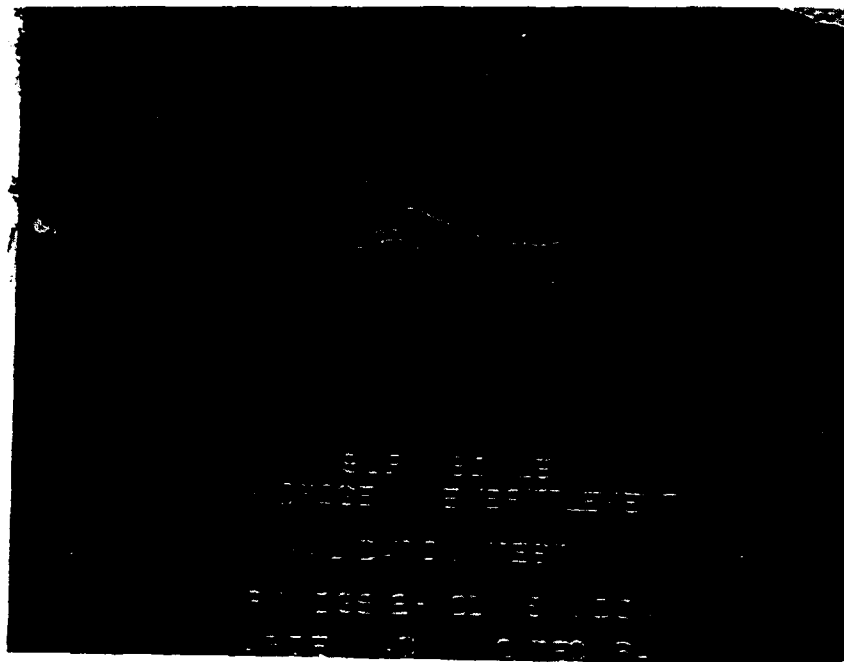Heat #88019 S/N 004

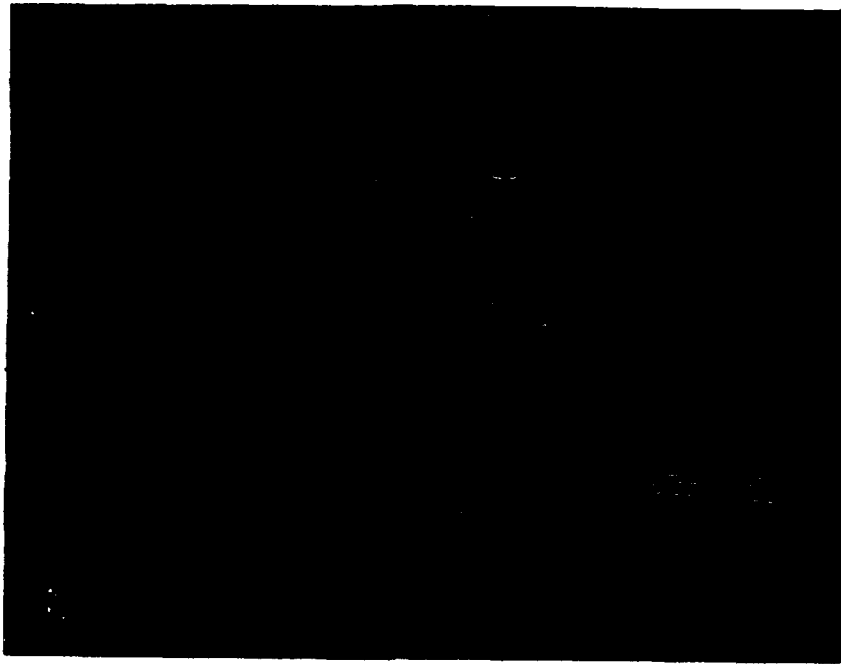
PHOTO #2
Heat #88019 S/N 004

PHOTO #3
Heat #88019 S/N 004
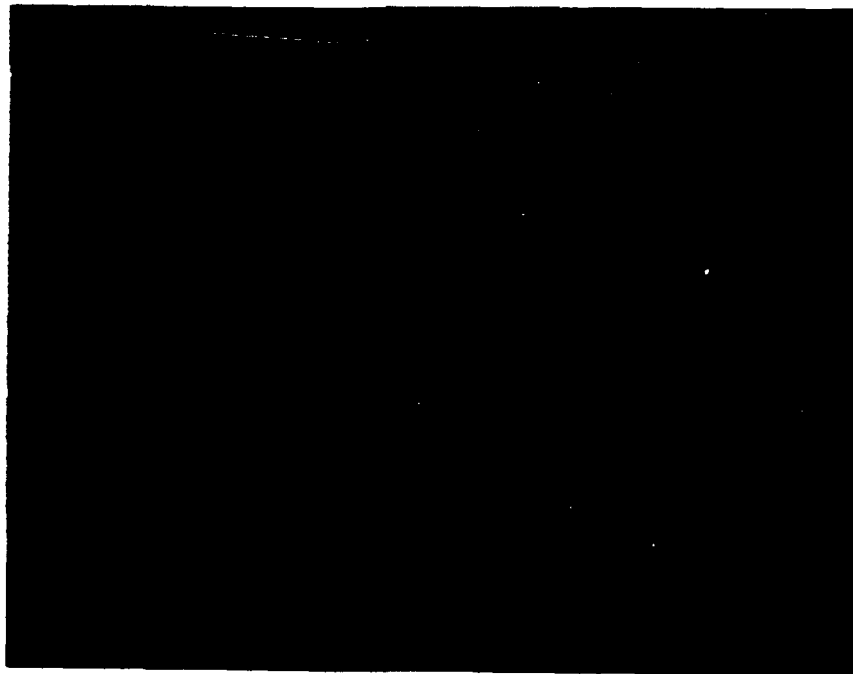
PHOTO #4
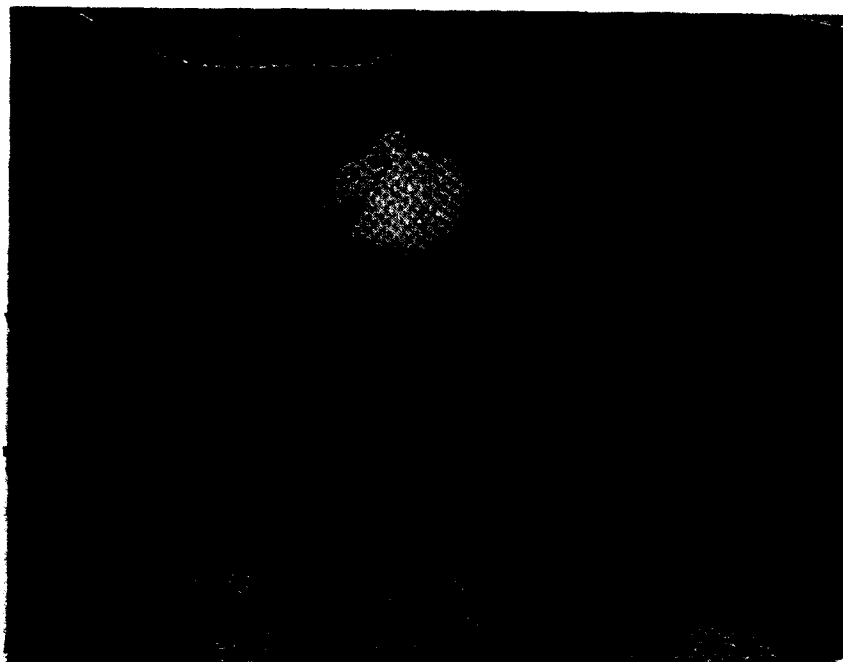**Heat #88019 S/N 006**

PHOTO #5
Heat #88019 S/N 006

PHOTO #6
Heat #88019 S/N 006

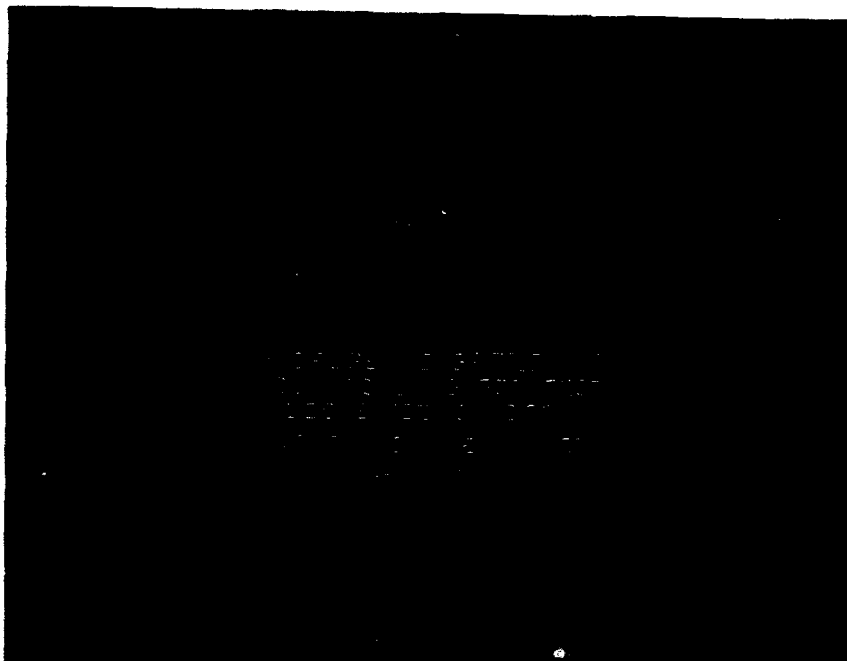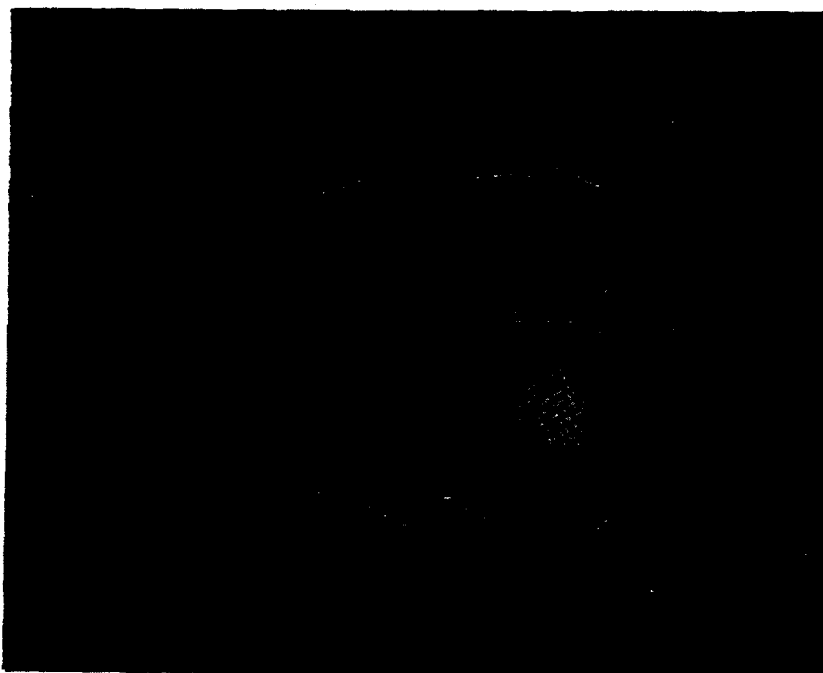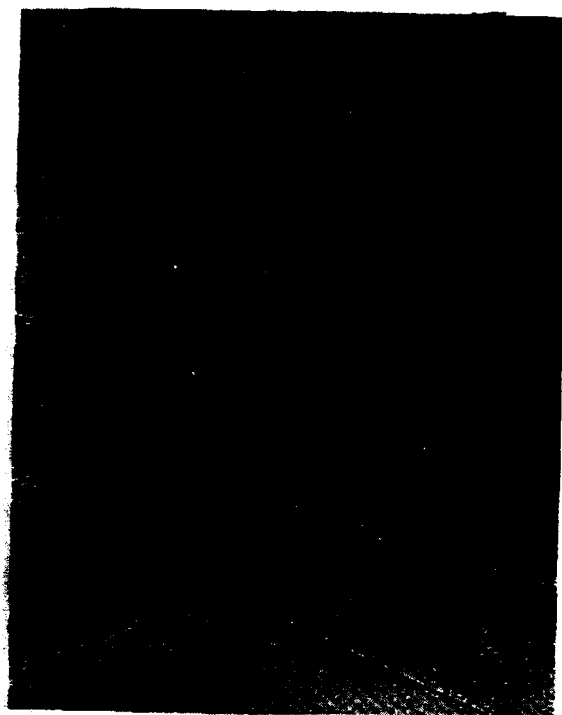PHOTO #7
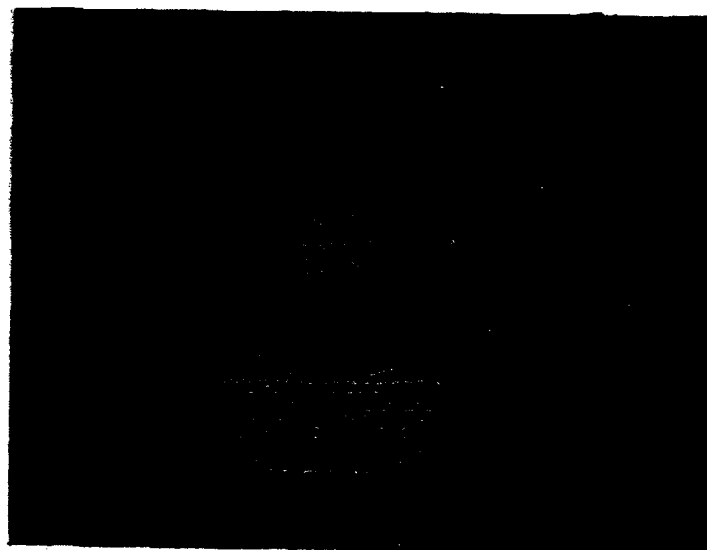Heat #88019 S/N 006

PHOTO #8
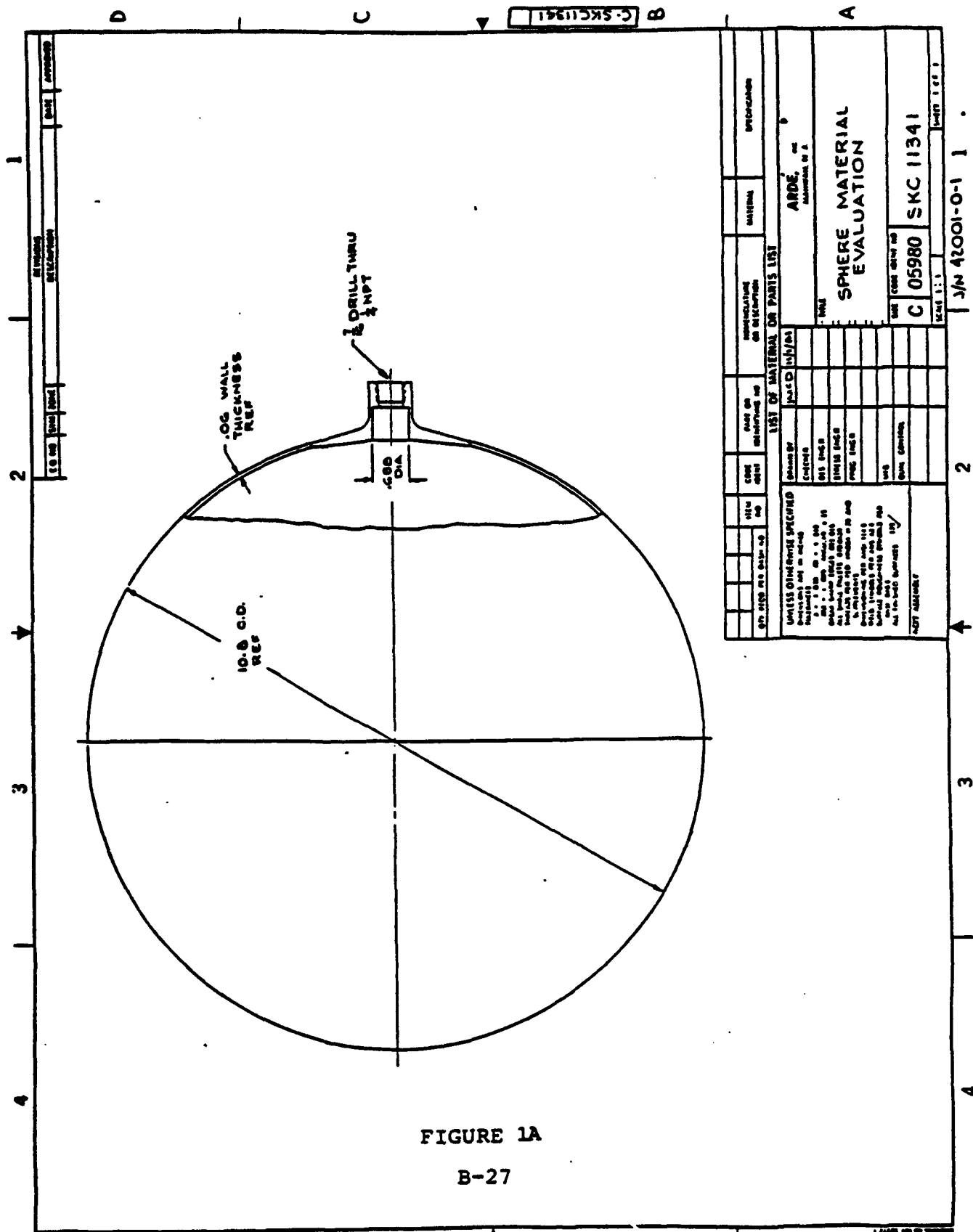Heat #88019 S/N 006

B-25

PHOTO #9
Heat #88019 S/N 003

PHOTO #10
Heat #88019 S/N 003

B-26

FIGURE 1A

B-27
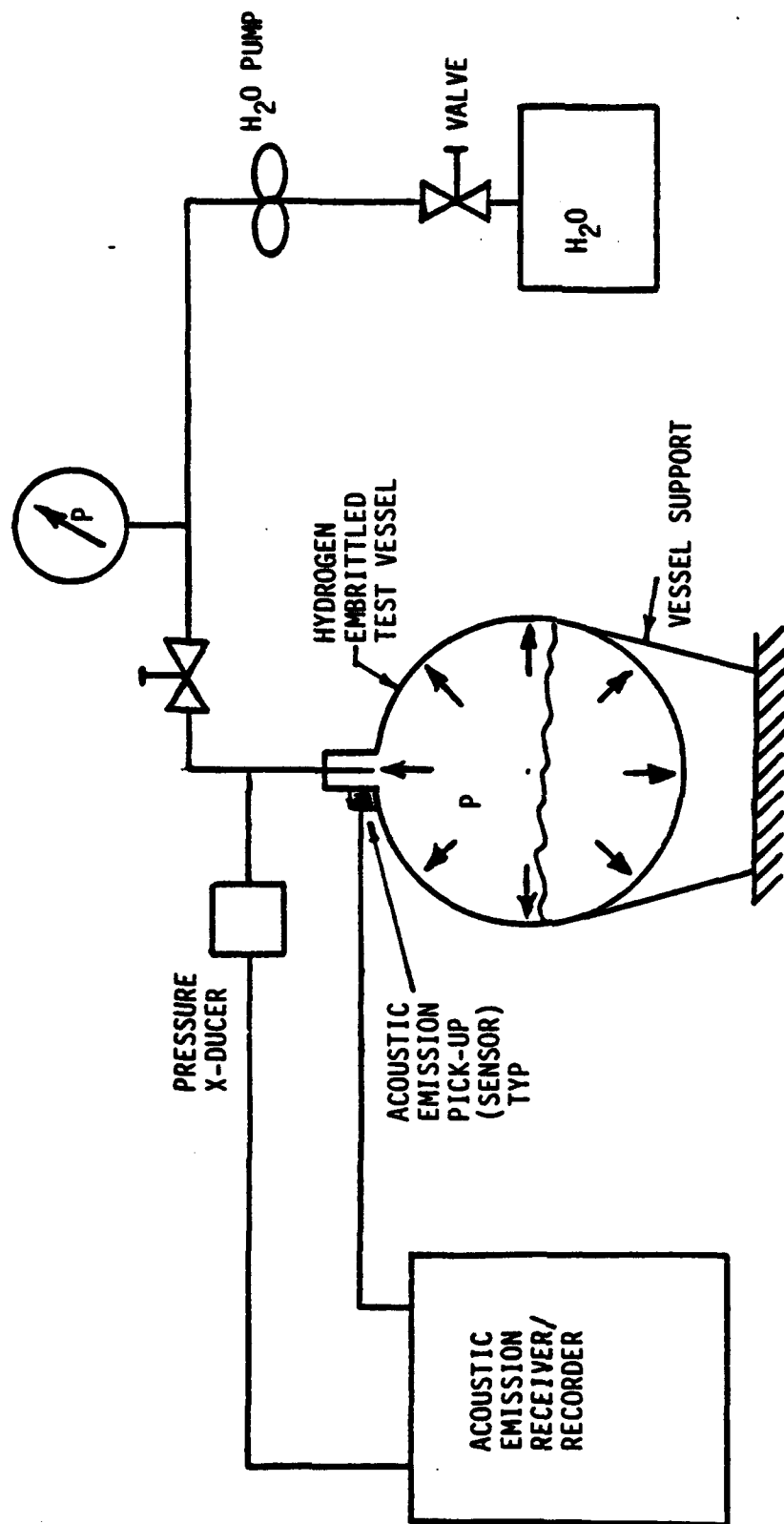
FIGURE 2A

SUB - SCALE
HYDROGEN EMBRITTLEMENT VESSEL
BURST TEST SCHEMATIC

D391ᄃ MOD
Test Tank
is
Cathode

Voltage
Regulator

Anode

Horizontal
Mode
(Tank Rotated
About Boss $\mathcal{C}$
as Required -
Manually or
with Fixture)

h

Voltage
Regulator

Boss Area
Masked
Off

h

Vertical
Mode
(No Tank
Rotation)

H_2SO_4 + TAP H_2O

$$\left[\frac{20cc \qquad 980cc}{1000cc\ solution} \right]$$
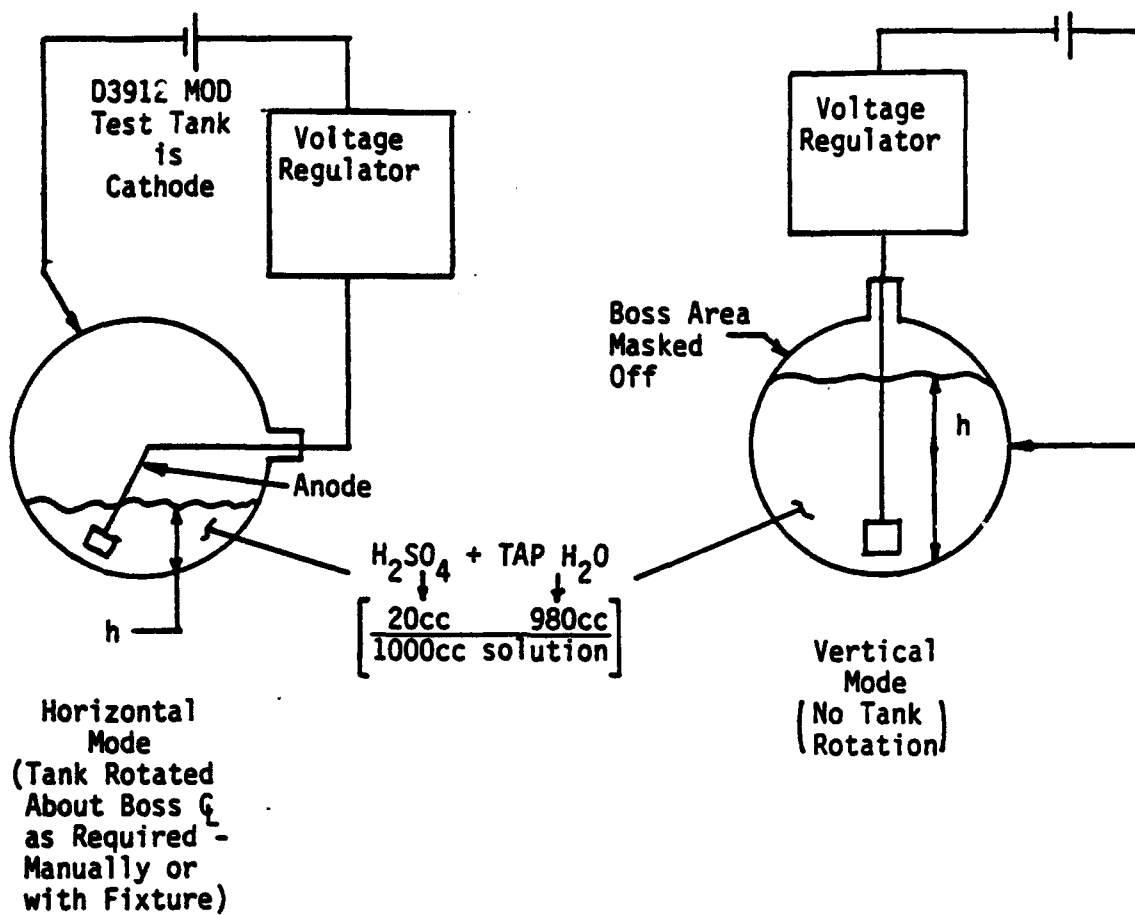
SUB SCALE
HYDROGEN EMBRITTLEMENT
TEST MODES

FIGURE 3A

● SUB-SCALE HYDROGEN EMBRITTLEMENT TEST
DATA ANALYSIS SUMMARY

(+)

- CAN HYDROGEN EMBRITTLE CRYOFORMED 301 CRES LINER TO CAUSE SUDDEN BRITTLE RUPTURE AT $P/P_{ult} \approx .4 \rightarrow .5)$ (REQUIRED $P/P_{ult} = .35 \rightarrow .55$)

- CRACK GROWTH/RUPTURE READILY DETECTED BY ACOUSTIC EMISSION SIGNALS.

- CAN PREVENT HYDROGEN EMBRITTLE-MENT OF LOCAL REGIONS (E.G. BOSSES) BY USE OF MASKING. TANK ROTATION NOT REQUIRED.

(-)

- NOT ENOUGH HYDROGEN IN VESSEL WALL TO CAUSE BRITTLE RUPTURE IN A TIMELY FASHION AT REASONABLE PRESSURE LEVELS AFTER FIRST CHARGING CYCLE AND 24 HR. HOLD (HYDROGEN LEAK RATE OVERPOWERED HYDROGEN CHARGED).

- JUST STABLE SUB-CRITICAL CRACKS FORMED.

- AFTER SECOND CHARGE CYCLE AND 24 HR. HOLD, BRITTLE RUPTURE MOST OFTEN OCCURRED IN A SHORT TIME ON THE WAY UP TO DESIRED TEST "BURST" PRESSURE.

PROJECTED CORRECTIVE ACTION

- ADDITIONAL TESTS REQUIRED TO REFINE BURST PRESSURE PREDICTION
  - OBJECTIVE: PREDICT BURST PRESSURE REASONABLY CLOSE AND REPEATABLY.
    - HAVE RELEASED THREE (3) MORE SUB-SCALE VESSELS FOR FABRICATION.
    - CHARGING PARAMETER OPTIONS
      - LONGER CHARGING TIMES ($>$ 48 HOURS)
      - HIGHER CHARGING AMPS ($>$ .6 AMPS)
      - LESS HOLD TIME   ($<$ 24 HOURS)

84 DEC 18 11:05:41   ELAPSED TIME =   00:03:40
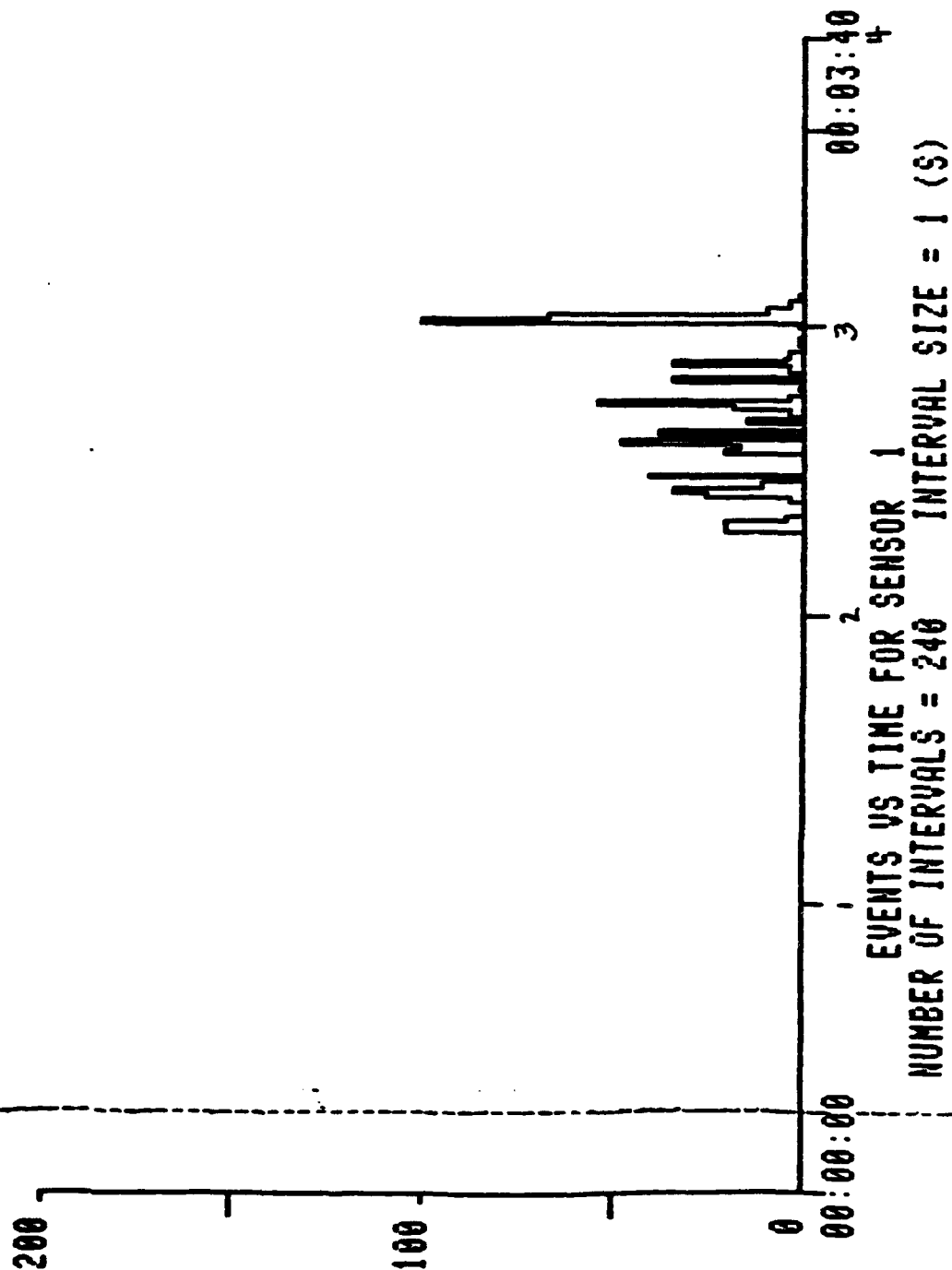HYDROGEN EMBRITTLEMENT TEST 2 PN 03912,SN4 1

EVENTS VS TIME FOR SENSOR 1
NUMBER OF INTERVALS = 240   INTERVAL SIZE = 1 (S)

FIGURE 4A

B-31
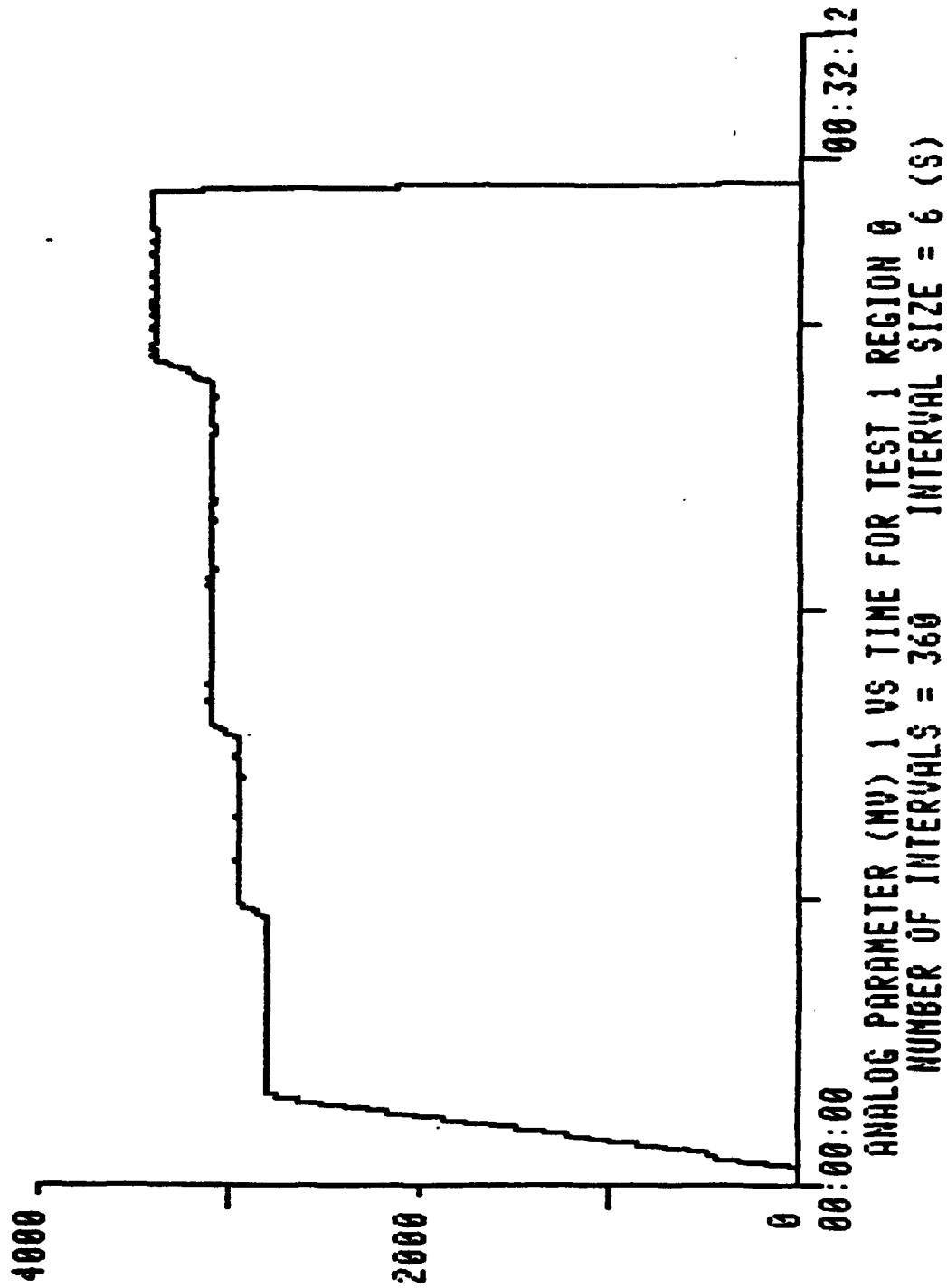
FIGURE 5A

85 JAN 21 03:50:04   ELAPSED TIME =   00:01:59
HYDROGEN EMBRITTLEMENT SUBSCALE TEST D3912 MOD SN 006

2760 psig.

~ 30 sec

30 sec

180 sec

270 sec

00:01:59

ANALOG PARAMETER (MV) 1 VS TIME FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 360   INTERVAL SIZE = 1 (S)

4000

2000

0

00:00:00
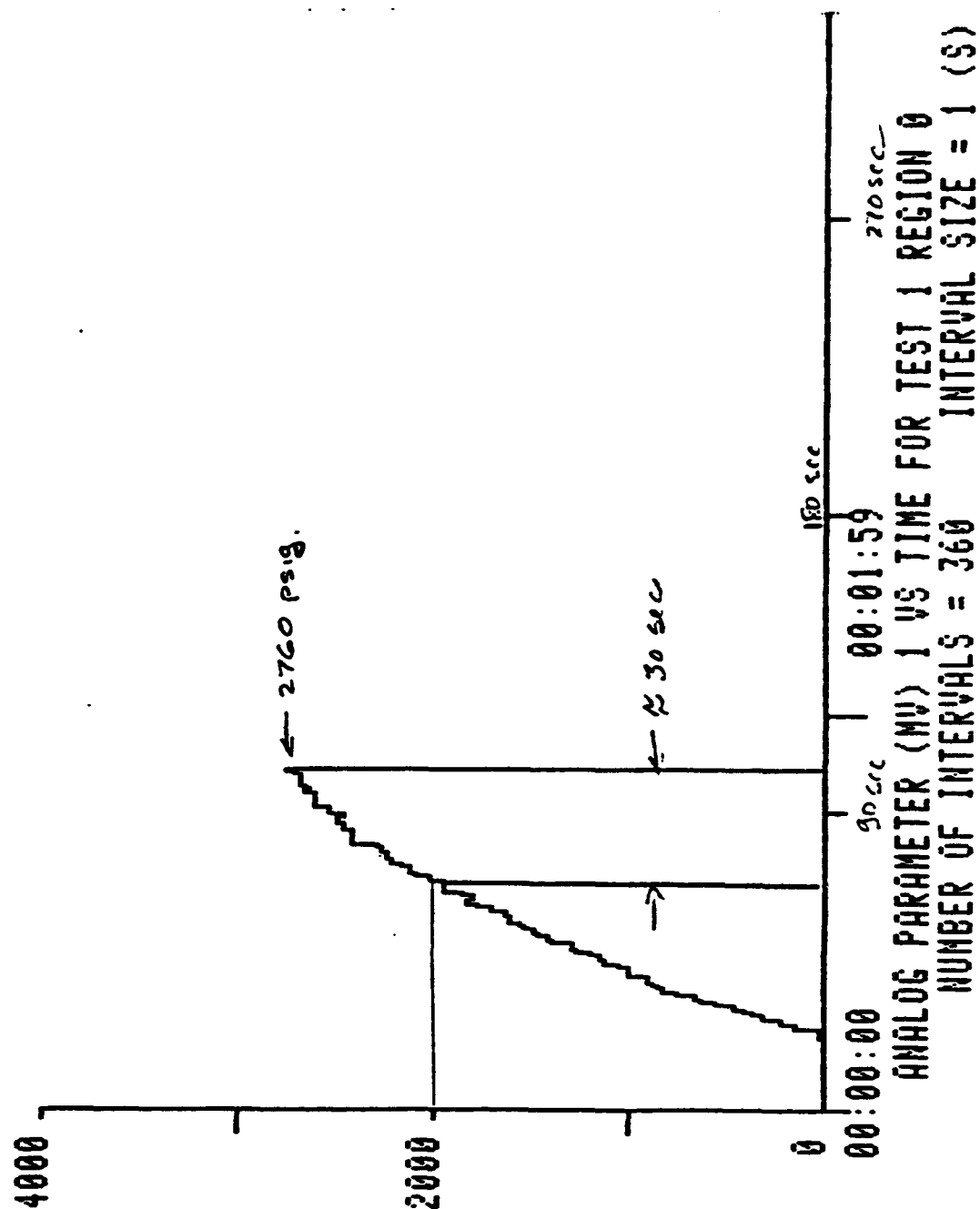
FIGURE 6A

85 JAN 21 03:44:53 ELAPSED TIME = 00:01:59
HYDROGEN EMBRITTLEMENT SUBSCALE TEST D3912 MOD SN 006

EVENTS VS ANALOG PARAMETER 1 FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 100 INTERVAL SIZE = 40 (MV)

FIGURE 7A

B-34
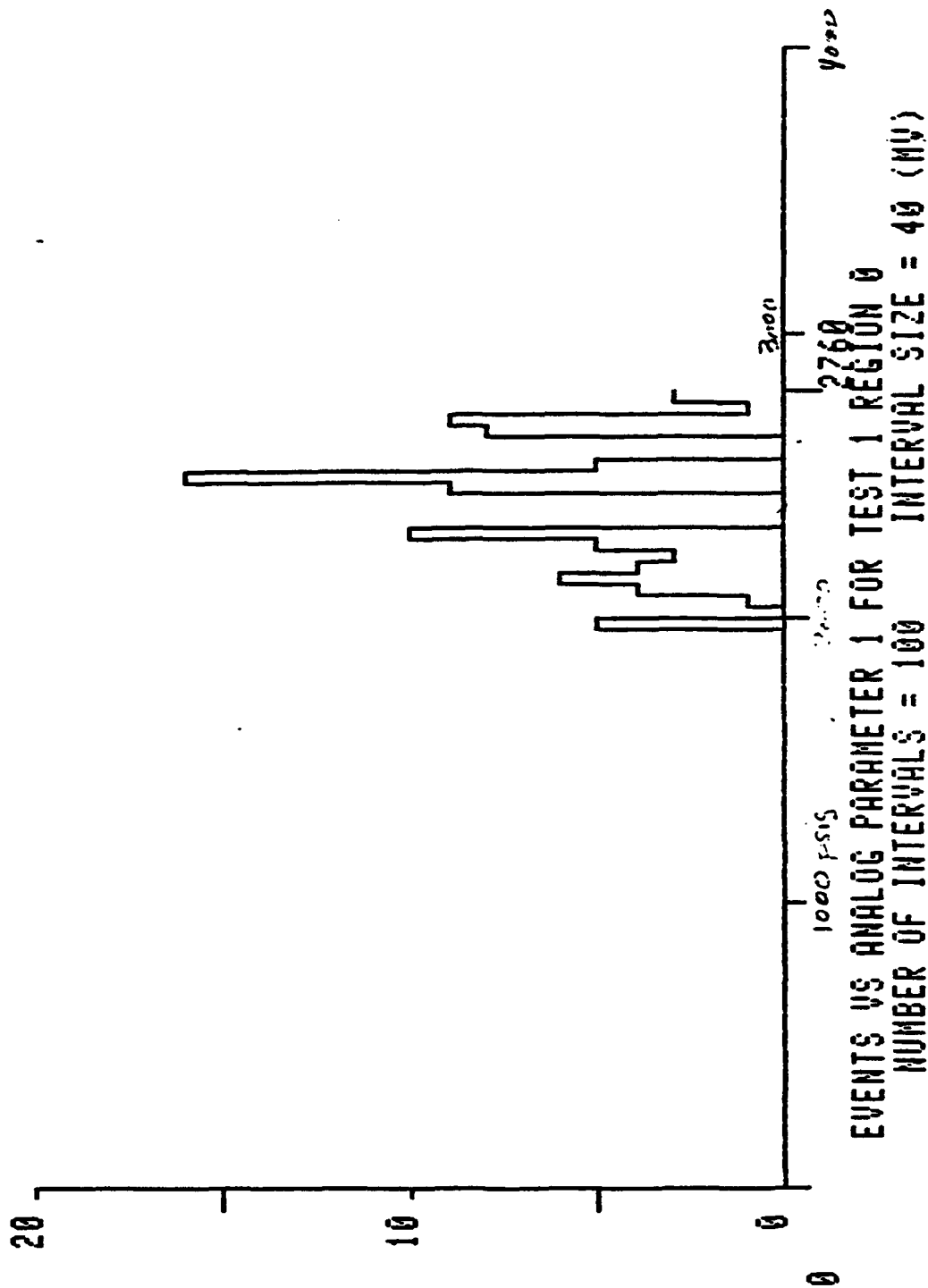
85 JAN 21 04:19:23   ELAPSED TIME =   00:01:59

HYDROGEN EMBRITTLEMENT SUBSCALE TEST D3912 MOD SN 006

DIST. 1 OF EVENTS BY LOCATION FOR TEST 1 REGION 0

NUMBER OF INTERVALS = 100   INTERVAL SIZE = 1
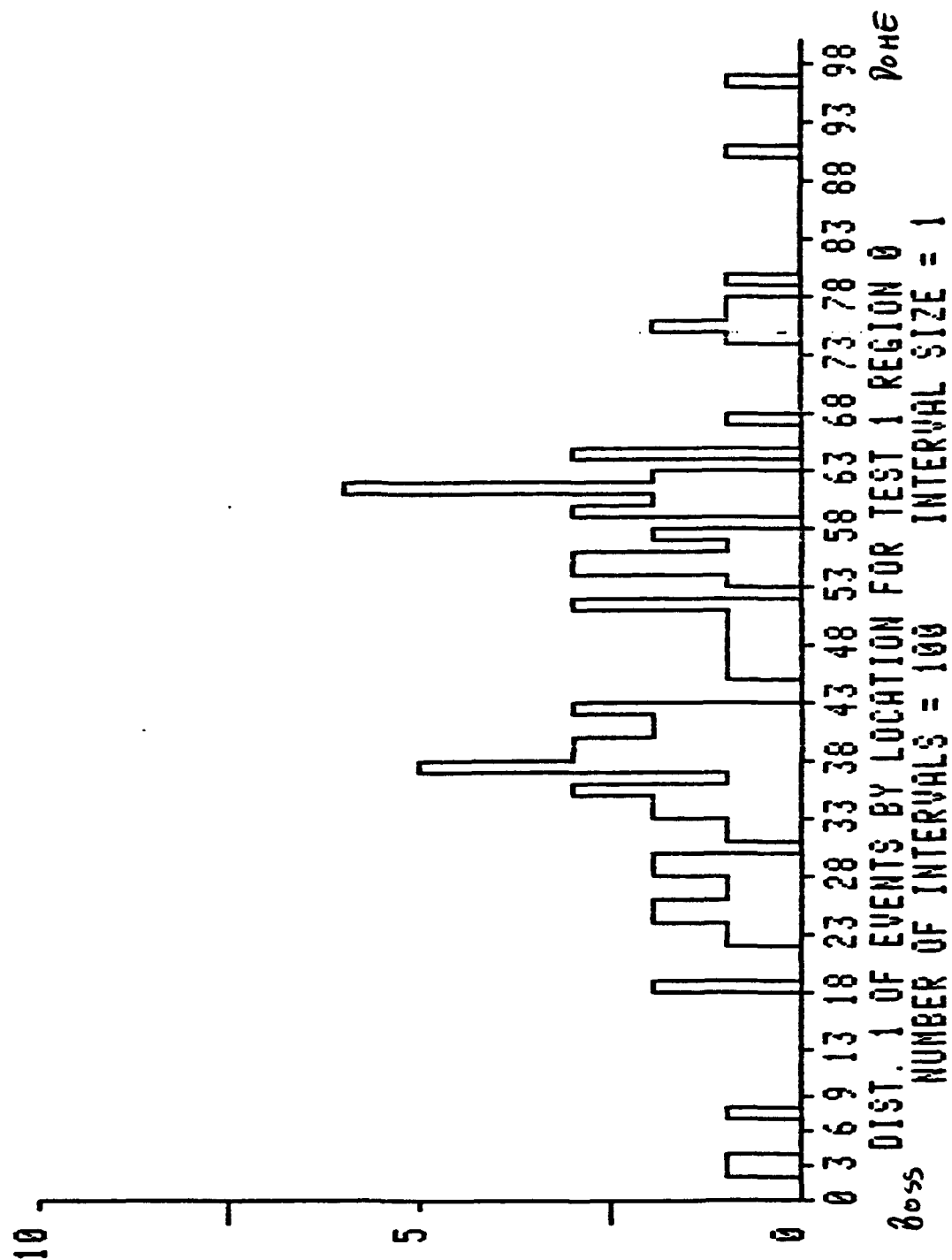
FIGURE 8A

85 JAN 28 18:16:29   ELAPSED TIME =   00:06:38
HYDROGEN EMBRITTLEMENT SUBSCALE TEST 03912 MOD SN 3 HT 8801

ANALOG PARAMETER (MV) 1 VS TIME FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 400   INTERVAL SIZE = 1 (S)
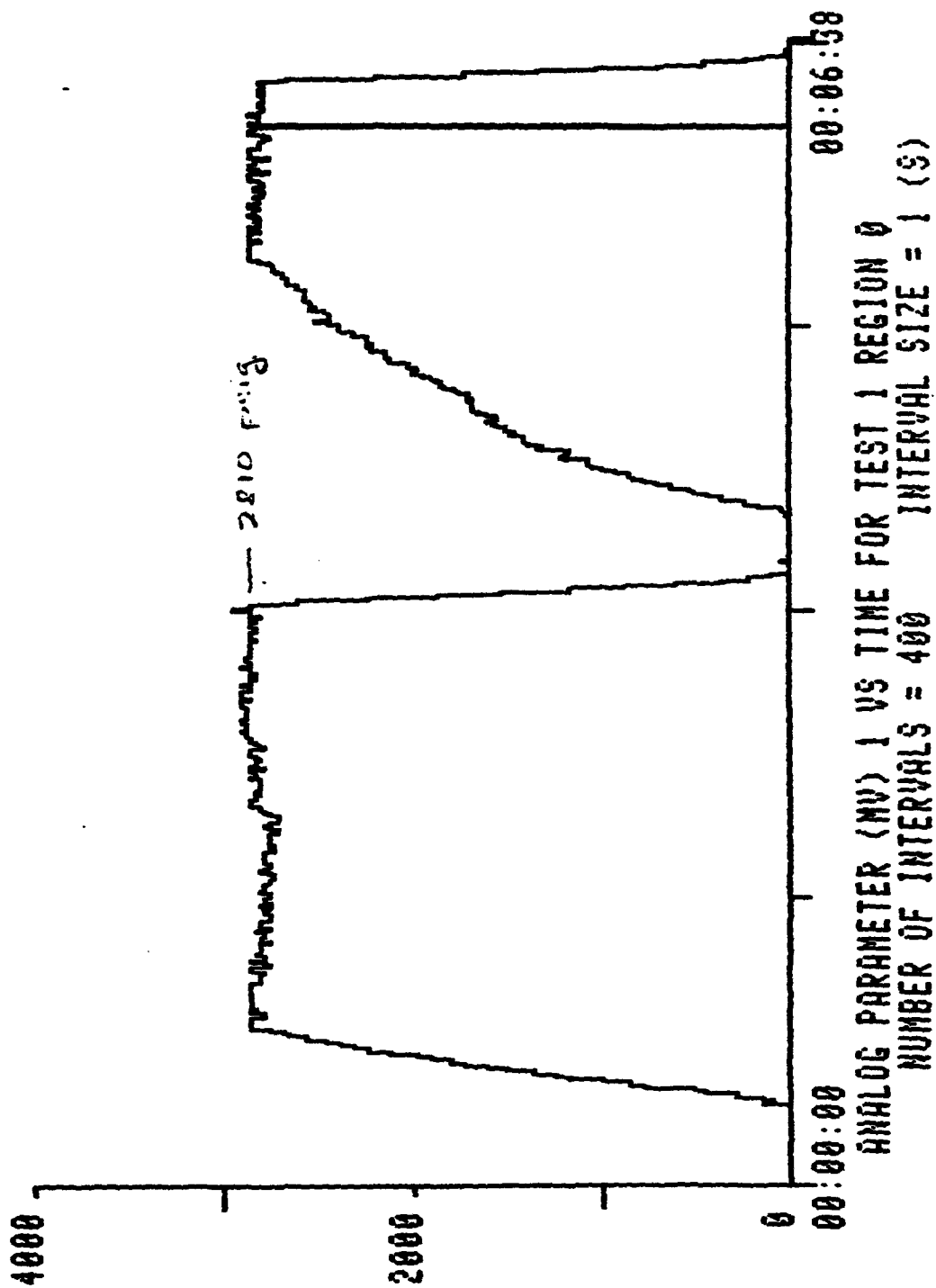
FIGURE 9A
B-36

85 FEB 01 04:15:31   ELAPSED TIME =   00:01:27
HYDROGEN EMBRITTLEMENT SUBSCALE TEST D3912 SN 3 HT 88019

ANALOG PARAMETER (MV) 1 VS TIME FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 120   INTERVAL SIZE = 1 (S)

FIGURE 10A

B-37

85 FEB 01 04:04:24 ELAPSED TIME = 00:01:27
HYDROGEN EMBRITTLEMENT SUBSCALE TEST 03912 SN 3 HT 88019

EVENTS VS ANALOG PARAMETER 1 FOR TEST 2 REGION 0
NUMBER OF INTERVALS = 100 INTERVAL SIZE = 40 (MV)

FIGURE 11A

B-38
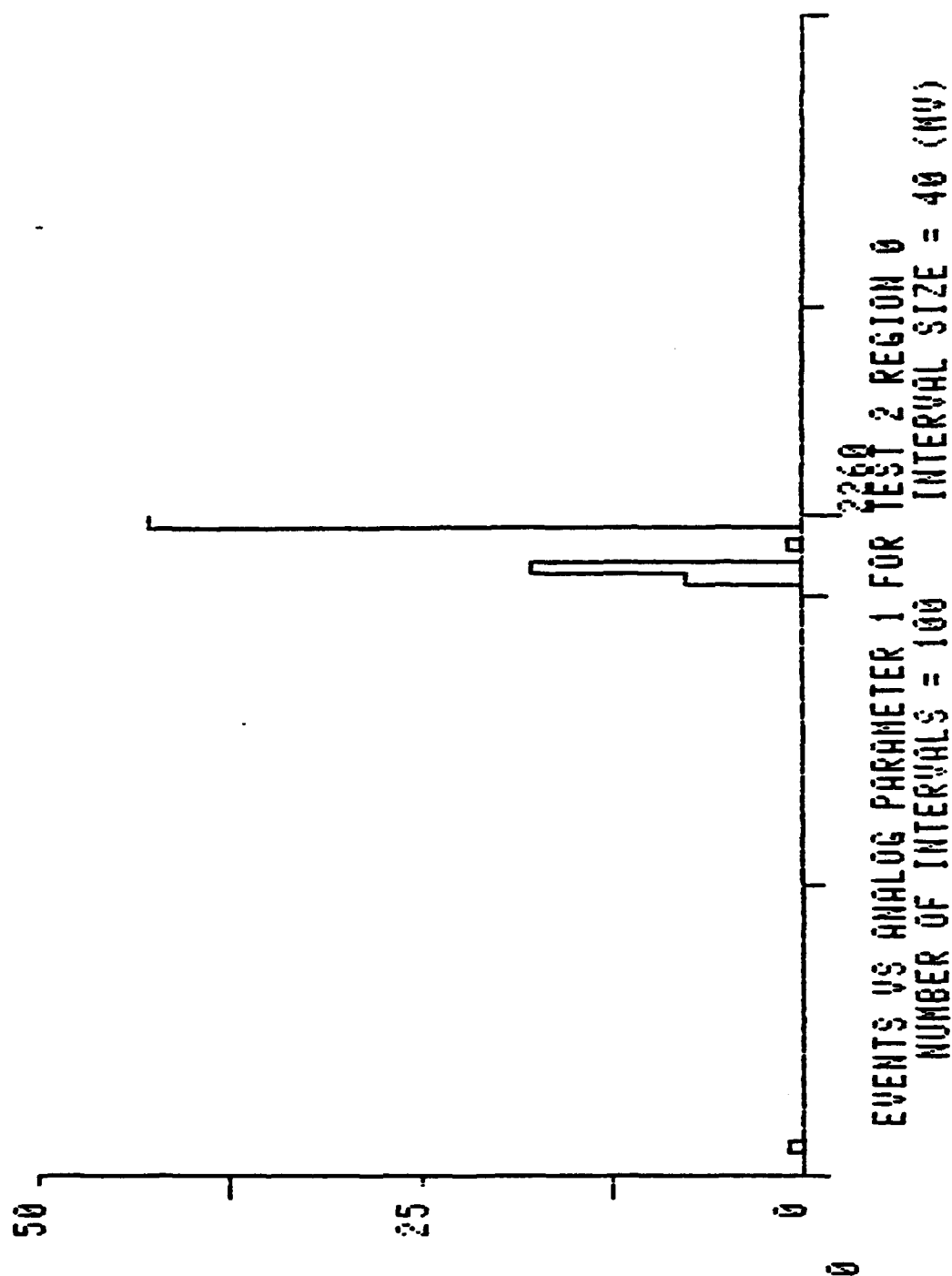
85 FEB 01 04:01:48   ELAPSED TIME = 00:01:27
HYDROGEN EMBRITTLEMENT SUBSCALE TEST D3912 SN 3 HT 88019

EVENTS VS ANALOG PARAMETER 1 FOR TEST 1 REGION 0
NUMBER OF INTERVALS = 100   INTERVAL SIZE = 40 (MV)

FIGURE 12A

B-39
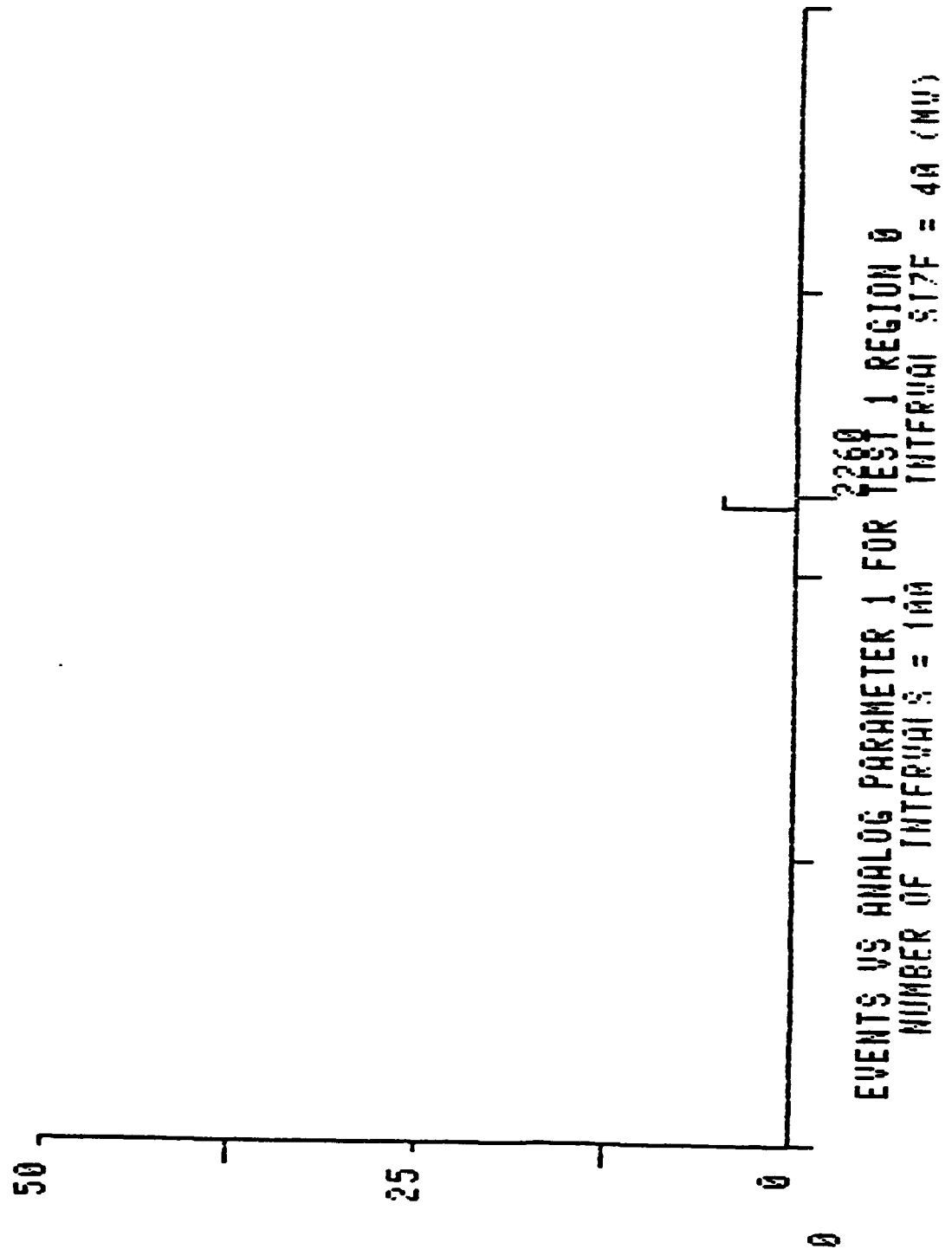
85 FEB 01 04:36:50   ELAPSED TIME = 00:01:27
HYDROGEN EMBRITTLEMENT SUBSCALE TEST D3912 SN 3 HT 88019

DIST. 1 OF EVENTS BY PEAK AMPLITUDE (DB) FOR TEST 2 REGION 0
NUMBER OF INTERVALS = 100   INTERVAL SIZE = 1

FIGURE 13A

B-40

85 FEB 01 04:34:17   ELAPSED TIME =   00:01:27
HYDROGEN EMBRITTLEMENT SUBSCALE TEST D3912 SN 3 HT 88019

DIST. 1 OF EVENTS BY PEAK AMPLITUDE (DB) FOR TEST 1 REGION 0
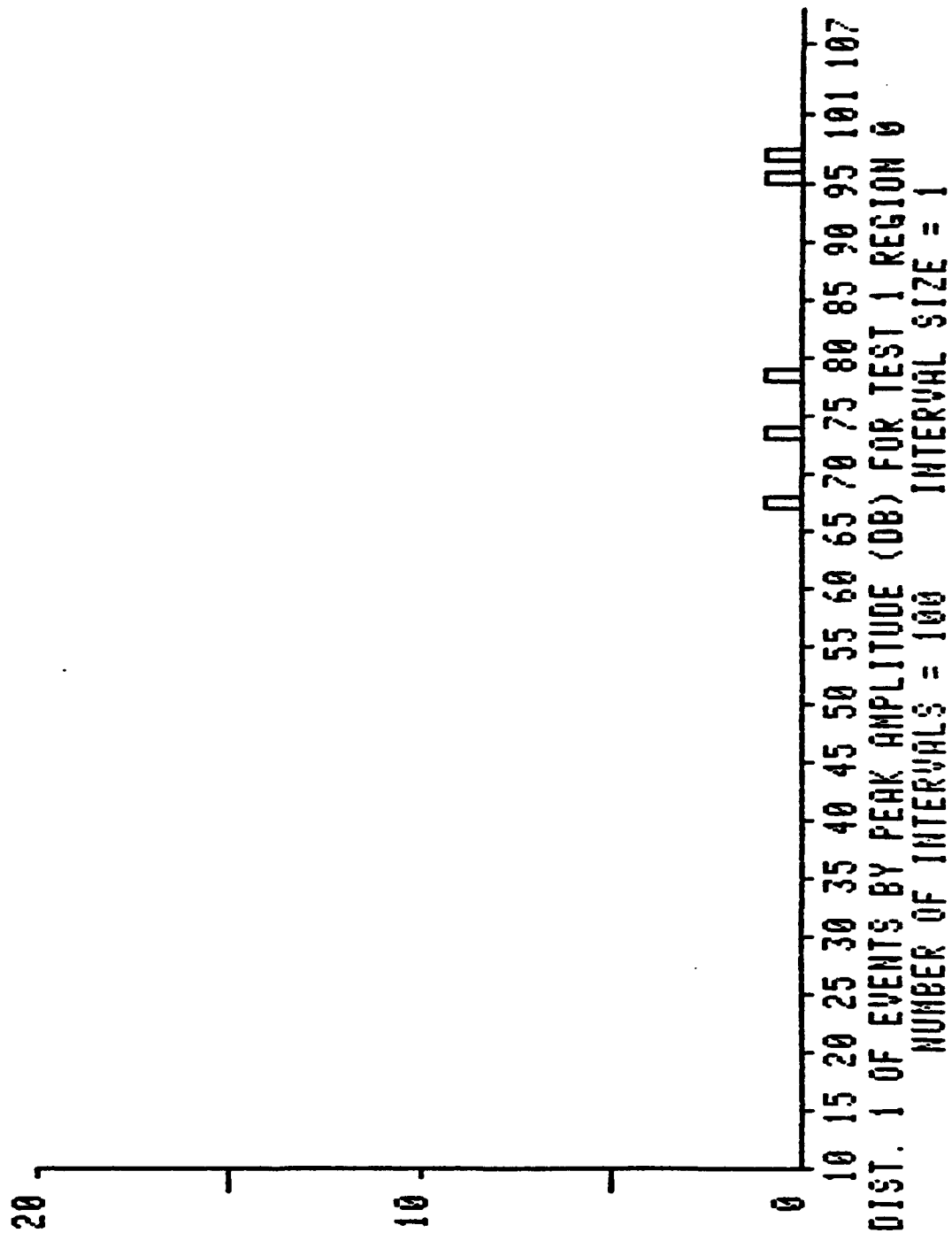NUMBER OF INTERVALS = 100   INTERVAL SIZE = 1

FIGURE 14A

B-41

APPENDIX B-1

Hydrogen Concentration in the Wall

of the Pressure Vessel During

Charging, Hold and Test

TO: DAVE GLEICH & STEVE BERKO

FROM: NORMAN FEIGE

SUBJECT: HYDROGEN CONCENTRATION IN THE WALL OF THE PRESSURE
         VESSEL DURING THE CHARGING, HOLD CYCLE AND TEST
         CYCLE.

     The hydrogen diffusion reaction rates are defined by
Fick's Law for the concentration of hydrogen through the
steel wall of the vessel. The rate reaction is an
exponential function. Equilibrium or constant hydrogen
levels are never established because the hydrogen is charged
from the inside diameter surface only and the gas readily
leaks out of the vessel wall at the outside diameter surface.
The net effect is a very high concentration of hydrogen at
the inside surface which readily embrittles the metal and a
outside surface which is highly ductile. Based on very
limited experimental data combined with the rate reaction
equations the best guess as to the shape and concentration of
hydrogen in the vessel wall is as follows:
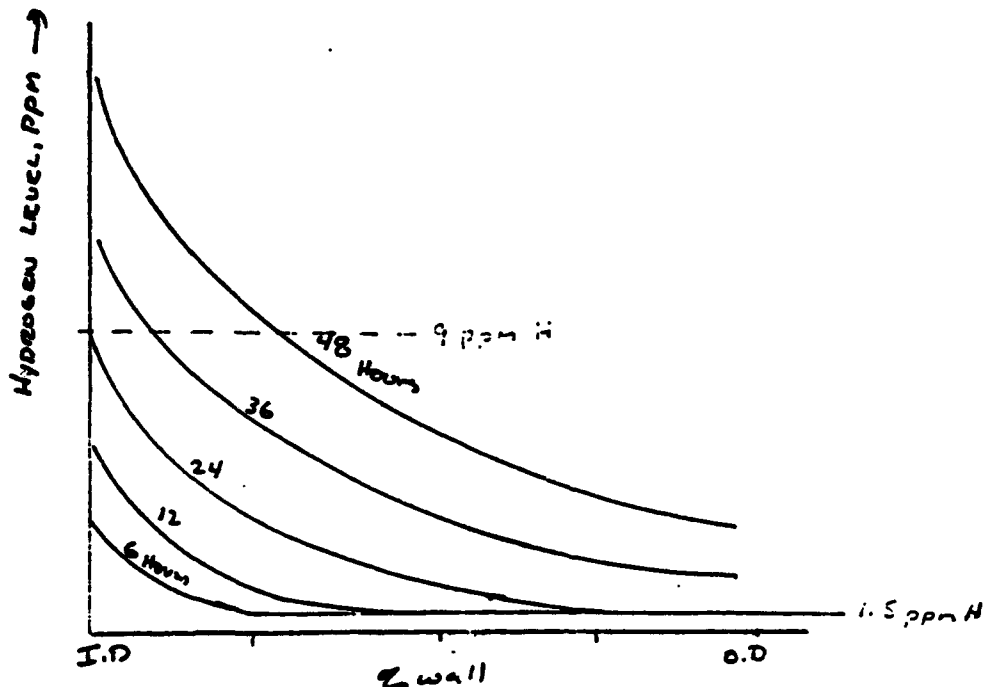
     With the rather dilute acid used in the experiment the
charging time must exceed 24 hours to obtain a sufficient
hydrogen gradient to initiate the cracking of the vessel near
the inside diameter surface. As the bottle is stored in air
the hydrogen continues to diffuse out or leak out from both
the inside and outside surfaces and no hydrogen effects are
observed. Fick's Law also controls the loss of hydrogen with
time. The predicted shape of the hydrogen concentration
curve verses wall thickness and time is shown as follows:
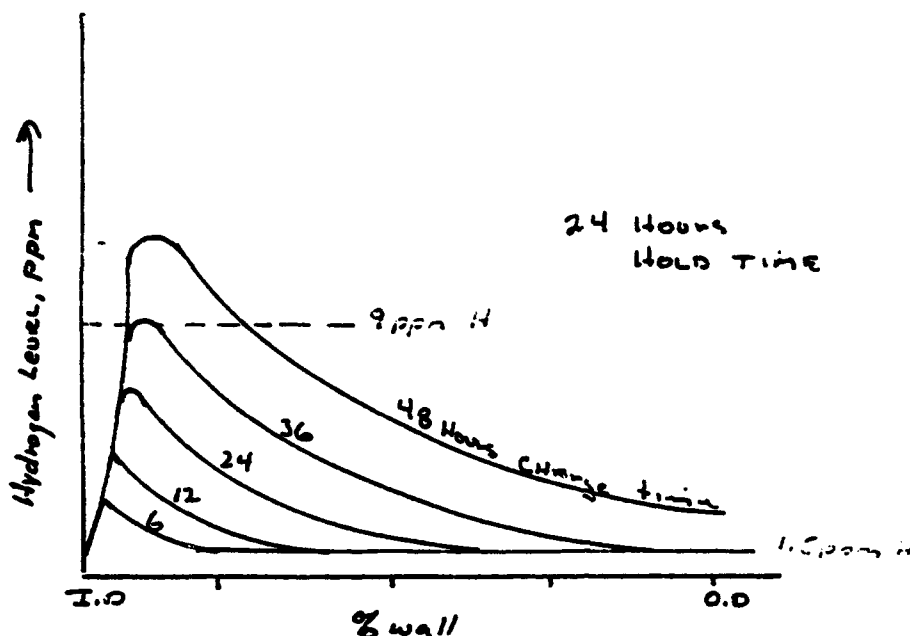
As the bottle is pressurized the region of the bottle
exceeding 9 ppm hydrogen will rupture almost immediately at
approximately 35% of the predicted burst pressure. The flaws
created are subcritical in size for bottle burst and the
flaws blunt with the observed crazed pattern on the bottle
inside diameter surface and the lateral contraction of the
outside diameter of the surface of the shell wall. Of the
bottles burst to date the region exceeding 9 ppm hydrogen
represents between 40 to 60% of the vessel wall thickness.

Based upon very limited test data it appears that the
sonic indications initially increase in intensity as the
bottle breaks up into platelets supported by an outer ductile
surface. As the strain is redistributed the sonic
indications decrease with increasing pressure. The burst
pressure of the bottle is now dependent upon the ductile
ligaments between the platelets to support the load. If the
critical hydrogen level has exceeded 50% of the wall the
burst pressure will be reduced accordingly.

The rate controlling reaction to failure with a
subcritical flaw now becomes dependent upon the rate of
diffusion of the hydrogen in the lattice diffusing to the
crack tip, and the stress intensity of the crack tip which
lowers the critical hydrogen level to cause rupture. One has
the following three options to reduce the rate of the
reaction:

1. Lower the hold pressure to reduce the stress
   intensity at the crack tip to increase the time to
   failure.

2. Attempt to reduce the size of the high hydrogen region to reduce the initial flaw size.

3. Pressurize the bottle quickly to override hydrogen diffusion which extends the flaw length and reduces
   - the section thickness supporting the load.

In the first case the frequency of cracking should slowly increase with time at the lower hold pressure as the increasing stress intensity at the crack tip lowers the required hydrogen level at the tip to extend the flaw. In the second case the initial number of sonic indications should be lower with the time to failure extended. The limiting factor is the control of the amount of hydrogen charged. If the hydrogen level is below 5 ppm, no initial flaw is created at the inside diameter surface. In the third case the ability to reach the desired burst pressure of 50% of design burst may not be achieved.

It would appear that through wall tank embrittlement can only be obtained by simultaneously charging hydrogen on both the inside diameter and outside diameter surfaces of the vessel. The time to failure will be abrupt at 35% of the design burst pressure if the hydrogen level exceeds 9 ppm at the surfaces. The experiment in a practical sense is difficult with a fiber wound bottle.

Increasing the hold time after charging does not establish an equilibrium hydrogen level throughout the vessel wall. Plating the vessel with copper, aluminum or silver to prevent hydrogen adsorption has been reported successful. However, the technique does not work in the reverse as the hydrogen either diffuses through the coating or comes out at defects forming gas blisters under the plate. Therefore, plating the outside diameter surface of the vessel to prevent the loss of hydrogen does not appear feasible.

If bottle fragmentation is desired in the bottle burst experiment the most pragmatic approach is to craze the inside diameter wall surface with brittle hydrogen cracks and obtain burst between 35% to 50% of predicted burst by rapid pressurization.

Of the options available the most reliable appears to be the rapid pressurization of the vessel above 35% of the design burst pressure of the vessel or just after the first sonic indication is recorded. Lowering the hold pressure to increase the time to failure has no technical advantages other than guaranteeing a lower gas temperature in the bottle at burst. Lowering the hydrogen level runs the risk that no failure occurs, requiring recharging with hydrogen.

APPENDIX B-2

PRE-PROPOSAL TEST

OF

HYDROGEN ENDUCED FAILURE

ARDE AMR #279

HYDROGEN EMBRITTLEMENT TEST

OF

CRYOFORMED VESSEL

Prepared by:

1.0   SCOPE

To demonstrate the effect of hydrogen contamination
to cryoformed vessel.

2.0   DISCUSSION

A cryoformed, unaged spherical vessel per P/N 3912,
S/N 008 of Heat No. 88470 was charged with hydrogen
from its internal surface per procedure defined in
Appendix 3. This vessel was leftover from the
material evaluation where it was cryostrained at 8.36%
and hydrotested at room temperature to a maximum
yielding pressure of 7160 psi and vented when it dropped
to 7060 psi. The vessel did not break and its computed
burst strength was 238 ksi. See Appendix 4 , Heat 88470
Material Evaluation Test Report.

Hydrogen was then charged to the vessel as outlined in
Appendix 3 and hydrotested at 3300 psi to simulate the
working pressure stress of 110 ksi when used as a liner
in Prestress Composite Assembly. The vessel burst in a
brittle manner after holding for about five (5) seconds.
The brittle fracture surface was clearly evident and it
extended about 50% of the wall thickness around the
electolyte/air interface. The vessel did not break into
pieces (See Figure 15A)as compared to the normal material
evaluation failure where it usually breaks into 2 or 3
pieces. The fracture line followed the hydrogen

penetration at the electrolyte/air interface with secondary fracture beyond this hydrogen attack. There was no indication of stress corrosion or prior damage of the vessel wall prior to brittle fracture. The burst at 3300 psi was about 47% of the estimated strength indicating a 53% deterioration of strength which coincided with the degree of hydrogen attack through the wall.

3.0 CONCLUSION

Hydrogen contamination of the cryoformed vessel promotes a brittle manner of failure. The procedure of hydrogen introduction to the vessel is defined in Appendix A.
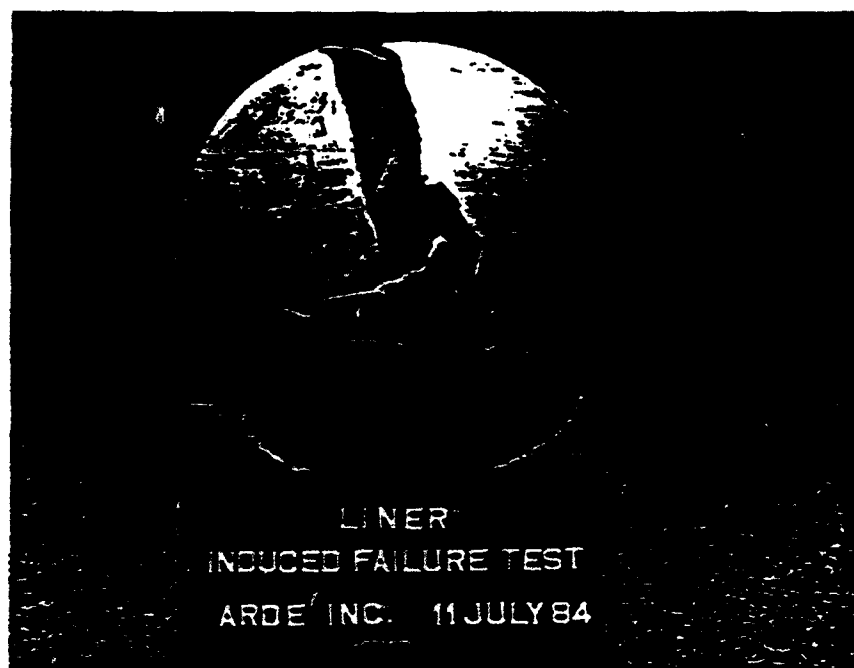
LINER
INDUCED FAILURE TEST
ARDE' INC.   11 JULY 84

FIGURE 15A

APPENDIX B-3

HYDROGEN EMBRITTLEMENT PROCEDURE

HOFFMANN & FEIGE, INC.
MATERIALS AND METALLURGICAL ENGINEERING
QUALITY ASSURANCE
223 KATONAH AVENUE, KATONAH, NEW YORK 10536

RICHARD A. HOFFMANN
NORMAN G. FEIGE

TELEPHONE
(914) 232-5733
(914) 232-7773

July 13, 1984
435-LTR-25

Mr. Tony Orsini
Arde, Inc.
19 Industrial Avenue
Mahwah, New Jersey 07430

RE: HYDROGEN EMBRITTLEMENT OF SMALL TANK

Dear Tony:

To document the experimental procedures, the following
conditions were established:

1. ELECTROLYTE

   The established standards are sufficient sulfuric acid
   must be added to obtain electrical conductivity. The
   concentration must also be sufficiently diluted so
   that one's finger may be dunked in the solution with-
   out an acid burn. Dilute sulfuric acid, the initial
   concentration was 20 cc. concentrated sulfuric acid
   in 1000 cc. water. The concentration after the
   initial charge was highly variable depending upon
   dilution and concentration of electrolyte during
   operation.

2. POWER SOURCE

   Inexpensive battery charger, 4 amp. max. capacity.
   The vessel was the cathode (black wire), and the anode
   was lead and connected to the red wire. Place the
   anode 2" from the bottom surface and immerse the anode
   approximately 2" in the initial electrolyte.

3. CURRENT DENSITY AND TIME OF CHARGE

   The cathodic current density for the first 24 hrs. was
   8 milliamps/in.sq. The second half of the charge cycle

for 29 hrs. was at 16 milliamps/in.sq. The anodic
current density for the first 24 hrs. was 1/2-amp/sq.in.
and the balance of the 29 hrs. varied from 1 amp/in.sq.
to 1.2 amps/in.sq. as the anode slowly dissolved. The
anode was being operated somewhat beyond its maximum
current density. The usual accepted figure would be
less than 1 amp/in.sq.

4. <u>MODE OF BOTTLE FAILURE WAS BY HYDROGEN EMBRITTLEMENT</u>

Brittle fracture extended approximately 50% of the wall
thickness for an extended length at the electrolyte/air
interface. There was no indication of stress corrosion
or prior perforation of the vessel wall prior to brittle
fracture. Analysis of the brittle fracture length
indicates that the time and current density of charging
was way in excess of that required and will result in
short term fracture at less than 50% of the designed
burst strength of the vessel.

                              Yours truly,

                              HOFFMANN & FEIGE, INC.

NGF:ird   Norman G. Feige

APPENDIX 4

MATERIAL EVALUATION OF HEAT 88470

MATERIAL EVALUATION... TEST REPORT

Heat No. __88470__

Specimen: __Sphere__
     __*__
__Aged/Unaged__ __**__

Date __2/10/84__

Tested by: _[signature]_

S/N	Pcryo (psi)	D_o (in.)	t_o (in.)	S_2 (ksi)	E_{np} (%)	D_F (in.)	t_f (in.)	P_y (psi)	P_B (psi)	σ_y (ksi)	σ_B (ksi)	P_B/P_C	
008**	8450	10.19	(.09255) .0892	230	(7.57) 8.36	(10.933) 10.859	(.091325) .05036	7060	7160	(2337) 235	(237.1) 235.3-		Not Broken but yielded E=.57x10⁶
009*	8300	10.19	(.0938S) .0928	220	(7.33) 7.92	(10.915) 10.931	(.08205) .0824	8000	8060	(262) 261	(264) 263		Not Broken but Yield E=59.2x10⁶
010*	8650	10.19	(.09398) .09414	230	(7.60) 8.59	(10.955) 10.876	(.09075) .0882	8000	8030	(266.6) 265	(267.6) 266		Not Broke, but welded E=59.5x10⁶
011	9100	10.19	(.0937) .09328	244	11%	(EXPLODED TEST)	(EXPLODED TEST)	— Broke At		NONE			
012**	7900	10.19	(.09395) .09382	210	(6.74) 7.29	(10.166) 10.823	(.08276) .0815	6710	6870	(218.2) 221	(222.1) 224.6		Broke @ ? yielded E=56.3x10⁶
013*	8100	10.19	(.0934S) .0941	215	(6.96) 7.41	(10.862) 10.846	(.0826) .08288	7900	8050	(256) 254	(201) 257		Not Broke, but yielded E=56.7x10⁶
014**	7150	10.19	(.0907S) .09002	170	(6.06) 6.03	(10.600) 10.648	(.08175) .08406	6250	6740	(203) 195	(215) 210.		Broke @ Boss/Hd. ? yield E=56.5x10⁶

** UNAGED SPHERES WERE TESTED 7 DAYS AFTER CRYO

APPENDIX C - Leak-Before-Burst Data and R-Curve Tests for Cryoformed 301 CRES

ARDE Interim Report EG 42001-14, which details the leak-before-burst (LBB) vessel experiments and the uniaxial R-Curve tests of cryoformed 301 CRES, is contained in this section. This report includes Appendices C-I and C-II described on page C-3, herein.

INTERIM REPORT

R-CURVE TESTING AND

LEAK-BEFORE-BURST DATA

FOR CRYOFORMED 301 CRES

Submitted to:

Patrick Air Force Base, FLA
Contract No. FO 8606-84-C-0029

Prepared by: Approved by:

D. Gleich   Program Management
Principal Investigator

Interim Report of CCN P00002 Effort Under Contract F08606-84-C-0029

ARDE, INC.
Norwood, N. J.

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1. INTRODUCTION

This report describes R-Curve and other fracture mechanics experiments and presents test and analytic fracture mechanics data for cryoformed 301 CRES. Unaged cryoformed 301 CRES is used as the metal liner for the Kevlar-49 fiber overwrapped composite prestressed spheres utilized on the Kevlar Overwrap Study under Contract No. F08606-84-C-0029, Patrick Air Force Base, Florida. Fracture mechanics data was, therefore, needed to characterize 301 CRES toughness and leak-before-burst failure mode potential as an aid in defining a "fail safe" composite vessel configuration required under the Kevlar Overwrap Study contract.

Both tensile coupon and vessel test data are analyzed and reported. Aged as well as unaged cryoformed 301 CRES base metal, heat affected zone (HAZ) and weld metal results are presented for completeness. R-Curve experiments were performed using through cracked center tension panels (CCT) and compact tension specimens (CT) of unaged and aged 301 CRES. Vessel leak-before-burst (LBB) tests were conducted on 11"ϕ aged and unaged all metal 301 CRES spheres, 11"ϕ prestressed Kevlar-49 overwrapped unaged 301 CRES spherical liners and a 23"ϕ aged 301 CRES spherical tank. Elliptical-shaped part through defects were EDM machined in the 301 CRES liner surfaces and the vessels were cycle tested at operating pressure using oil or oil followed by gaseous helium (GHe). Sustained load and overpressure experiments were also included in the test program.

Unaged 301 CRES CCT panel experiments and 11"⌀ unaged 301 CRES all

metal and composite vessel tests were funded by the Air Force under PAFB

Contract No. FO8606-84-C-0029 with ARDE, INC. while the aged CCT and aged

and unaged CT tensile specimens as well as the 11"⌀ and 23"⌀ aged vessel

experiments were funded by ARDE. For completeness, all test data are

presented and discussed in this report written in fulfillment of a PAFB

Contract No. FO8606-84-C-0029 (CCN P00002) task requirement.

R-Curve fracture mechanics test panel data are discussed in detail

in the final report, "R-Curve Testing of 301 CRES Material," prepared for

ARDE by D. E. McCabe of Materials Engineering Associates. This report

is included herein as Appendix I. Part through and through the thickness

tensile and vessel 301 CRES fracture mechanics data, together with

analytic assessments of leak-before-burst (LBB) mode and experimental

verification of LBB by vessel tests, are given in Appendix II in an AIAA-

86-1503 paper by Dr. K. H. Cotter of Fracture Proof Design Corporation.

2.0 SUMMARY

2.1 301 Cryostretched *CRES R-Curve Tests

- Fifteen (15) center cracked tensile (CCT) panels and six (6) compact specimens were tested with cracks machined in base metal (BM), weld heat affected zone (HAZ) and weld metal (WM). Test samples were strengthened by cryostretching only as well as by cryostretching and ageing, thus covering an ultimate strength range from 204 ksi to 265 ksi.

J_R - curve development was made by recording load versus displacement of the test specimens. Stable crack growth initiation toughness, $K(J_{Ic})$, and crack instability toughness, K_c, were calculated from the R-curve data. The test results summarized in Table 1B and 2B on the following pages show retention of equivalent toughness in BM, HAZ, WM with approximate equivalence of $K(J_{Ic})$ over the total strength range and some improvement of K_c for the higher strength levels as enhanced by the ageing process. The test matrix is shown in Table 3B while the test samples are shown in Figure 1B and 2B. Complete test data are given in Appendix I.

---

* Work hardened at -320°F to achieve high strength

Table 18 Summary Data Comparing CCT and CT Results

	Power Law, $K(J_{Ic})$ (ksi in.)	Δa_p (in.)	K_c (ksi in.)	Yield Strength (ksi)
Base Metal Aged				
CCT Avg.	96.1	0.036	180	261
CT	162.3	0.247	224	
Weld Metal Aged				
CCT Avg.	98.8	0.040	190	229
CT	133	0.210	187	
CT	102.2	0.216	219	
Weld Metal Unaged				
CCT Avg.	101.4	0.036	177	198
CT	114.7	0.237	171	
CT	116.2	0.240	185	
Base Metal Unaged				
CCT	108.2	0.032	163	207
CT	132.9	0.247	169	

Table 28 Summary Data From R-Curve Tests of CCT Specimens

Specimen Number	K(J_{Ic}) Power Law (ksi√in.)	(Δa_p) Clip Gage (in.)	(Δa_p) Visual (in.)	(K_c) (ksi√in.)	(σ_n^a) (ksi)	Yield Strength (ksi)
BM006A	108.1	0.032	0.0395	191	238	
007A	88.0	0.044	0.017	180	238	261
008A	92.2	0.032	0.025	169	238	
WM006A	118.3	0.040	0.040	194	240	
007A	87.6	0.052	0.037	204	240	229
008A	90.5	0.028	0.025	171	235	
HAZ009A	136.2	0.026	0.015	213	256	
WM001	101.5	0.043	0.050	183	214	
002	98.5	0.040	0.011	168	223	192
003	104.3	0.025	0.022	179	207	
BM001	130.9	0.036	0.021	185	217	
002	103.5	0.024	0.020	147	218	207
003	90.1	0.035	0.038	157	213	
HAZ004	116.5	0.022	0.015	184	228	
005	126.6	0.017	0.022	174	223	

$$(\sigma_n^a) \text{ Net cross-section stress} = \frac{P/B}{W - 2(a_o + \Delta a_p)}$$

A = Aged

Table 3θ Test Matrix - Specimen Identification

Conditions	Specimen Type	Base Metal	Weld Metal	HAZ
Aged	CCT	40-006	40W-006	40W-009
	CCT	40-007	40W-007	
	CCT	40-008	40W-008	
	CT	BM-008	WM 13A	
	CT		WM 14A	
Unaged	CCT	40-001	40W-001	40W-004
	CCT	40-002	40W-002	40W-005
	CCT	40-003	40W-003	
	CT	BM-003	WM 11	
	CT		WM 12	

Fig. 1B   Center cracked tension panel. Dimensions in inches.

Fig. 2B 1/2T compact specimen.

NOTES:
1. STAMP SPECIMEN CODE N°(XXX) { SERIAL N? V
   TWO PLACES AS SHOWN
2. SPECIFIED ARDE 0.000.

DETAIL 'C'

.5T-CT SPECIMEN
ARDE

Materials Engineering Associates, Inc.

DO NOT SCALE THIS PRINT

C-13
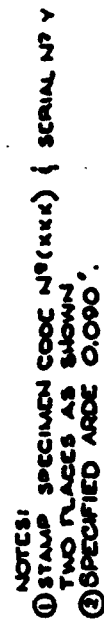
2.2 Part Through and Through Crack Tensile and Vessel Data and Leak-Before-Burst Assessment

Part through and through thickness crack 301 CRES tensile fracture mechanics data obtained by various investigators[1]-[7] (Table 4) was reviewed and analyzed. Based on this data, crack stability and LBB predictions were made for 11"∅ and 23"∅ cryoformed 301 CRES spherical vessels and LBB tests were run to confirm the analytical results. Figures 3, 4, 5 show 11"∅ all 301 CRES, 11"∅ Kevler-49 overwrapped 301 CRES composite and 23"∅ all 301 CRES spherical test vessels. Elliptical surface flaws (part through defects) were EDM machined in the tank walls and the tanks were cycle and sustained load tested at operating pressures. Figure 6 depicts a typical EDM initial flaw geometry.

The analytic LBB predictions were verified by these vessel tests. The test data/results are given in Tables 5-8. The stable LBB mode was maintained for wall break-through surface crack lengths $2C_{eff}$, 2.83 to 4.30 times wall thickness. This is contrasted with an expected length at breakthrough for in-service defects of 2 times the wall thickness. Figure 7, a plot of the analytic prediction for the 23"∅ aged 301 CRES vessel with an EDM flaw in the weld shows that the stable crack growth length after wall breakthrough is more than 5 wall thicknesses (5t). The test points at stable crack breakthrough length 4.3t are shown on the figure. Magnified views of the I.D. weld crack and fracture surface after crack breakthrough and LBB demonstration are given on Figures 8 and 9, respectively. Note the EDM flaw (Figure 9), showing the

fatigue crack growth and the shear lips associated with a tough material, that were generated at crack breakthrough.

Stable crack growth initiation toughness and crack instability toughness values obtained ranged from 96 to 108 ksi $\sqrt{in}$ and 163 to 190 ksi $\sqrt{in}$, respectively, in reasonable agreement with R-Curve test results. Figures 10 and 11 show typical cryoformed base and weld metal microstructures at 500X. The weld and base metal microstructures are similar, consisting of a tough austenitic matrix with interlocking platelets of high strength martensite. The high toughness exhibited by cryoformed 301 CRES results from this favorable microstructure configuration.

Table 46 Room Temperature Fracture Toughness Data

Material (1)	Weld Wire	Specimen type (2)	Number of tests	Average Toughness (ksi·√in)	σ_y (ksi)	σ_u (ksi)	t (in)	Source
BM/A		CTC	3	188	201	205	.004	Ref. 1
WM/A	308L	CTC	3	190	228	231	.004	
HAZ/A		CTC	3	213			.004	
WM/A	308L	CTC	3	196	220	231	.004	
BM/UA		CTC	3	163	207	215	.004	
BM/UA		PTC/TC	1	158	190	196	.125	Ref. 2
BM/UA		PTC	1	74	190	196	.125	
WM/UA	308L	PTC	1	86			.125	
WM/UA	308L	PTC	1	94			.125	
WM/UA	308L	PTC/TC	1	134			.125	
WM/UA	308L	PTC/TC	1	137			.125	
WM/UA	308L	PTC	1	57			.125	
BM/A		PTC(PV)	1	98.5	~200		.004	Ref. 4
BM/A		PTC	1	102.6	220		~.200	Ref. 5
BM/A		PTC	1	106.8	220		~.200	
WM/A	308L	PTC	1	103.6	219		~.200	
WM/UA	308L	PTC	3	88.5	175		.063	Ref. 6
HAZ/UA		PTC	3	86.8	~205		.063	
BM/UA		PTC	2	86.5	215		.063	
WM/A	308L	PTC	2	83.0	236		.063	
HAZ/A		PTC	2	97.3	~254		.063	
BM/A		PTC	2	102.8	256		.063	
BM/UA		PTC	10	118.5	174	210	(.100	Ref. 7
WM/UA	308L	PTC	7	92.3	181		&.028)	

1) BM= base metal; WM= weld metal; HAZ= heat-affected zone; /A= aged;
   and, /UA= unaged

2) CTC= center through-crack; PTC= part-through crack; PTC/TC= PTC became TC
   after penetrating thickness; and, CT= compact tension

3) ~ approximately

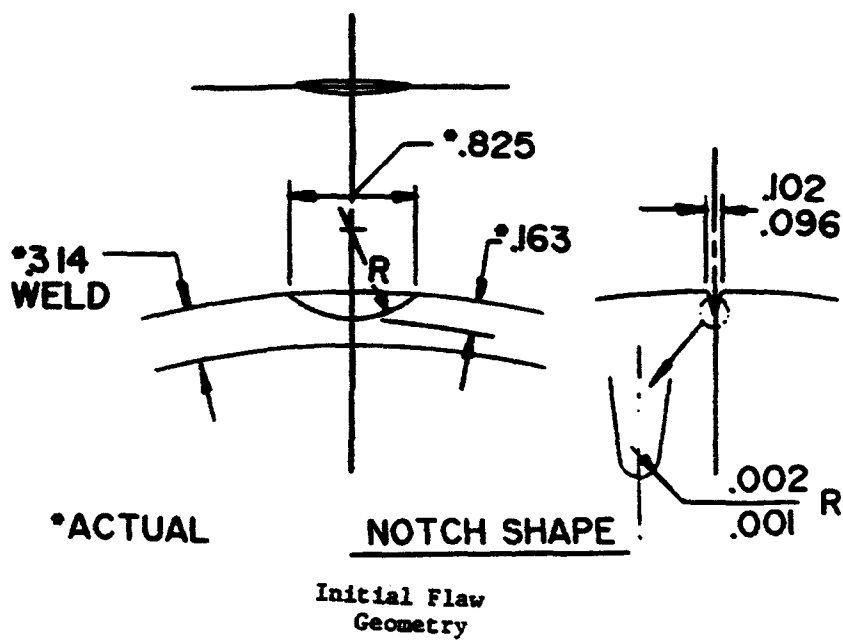Fig. 3B   11" ⌀ CRYOFORMED 301 CRES SPHERE

Fig. 4B

DESIGN BURST PRESSURE   : 9800 PSI MINIMUM

DESIGN MEOP   : 4900 PSI

SERVICE MEOP   : <3800 PSI

MINIMUM WALL   : 0.215 INCH THICK

TYPE OF WELD   : TIG, MODIFIED U-PREP
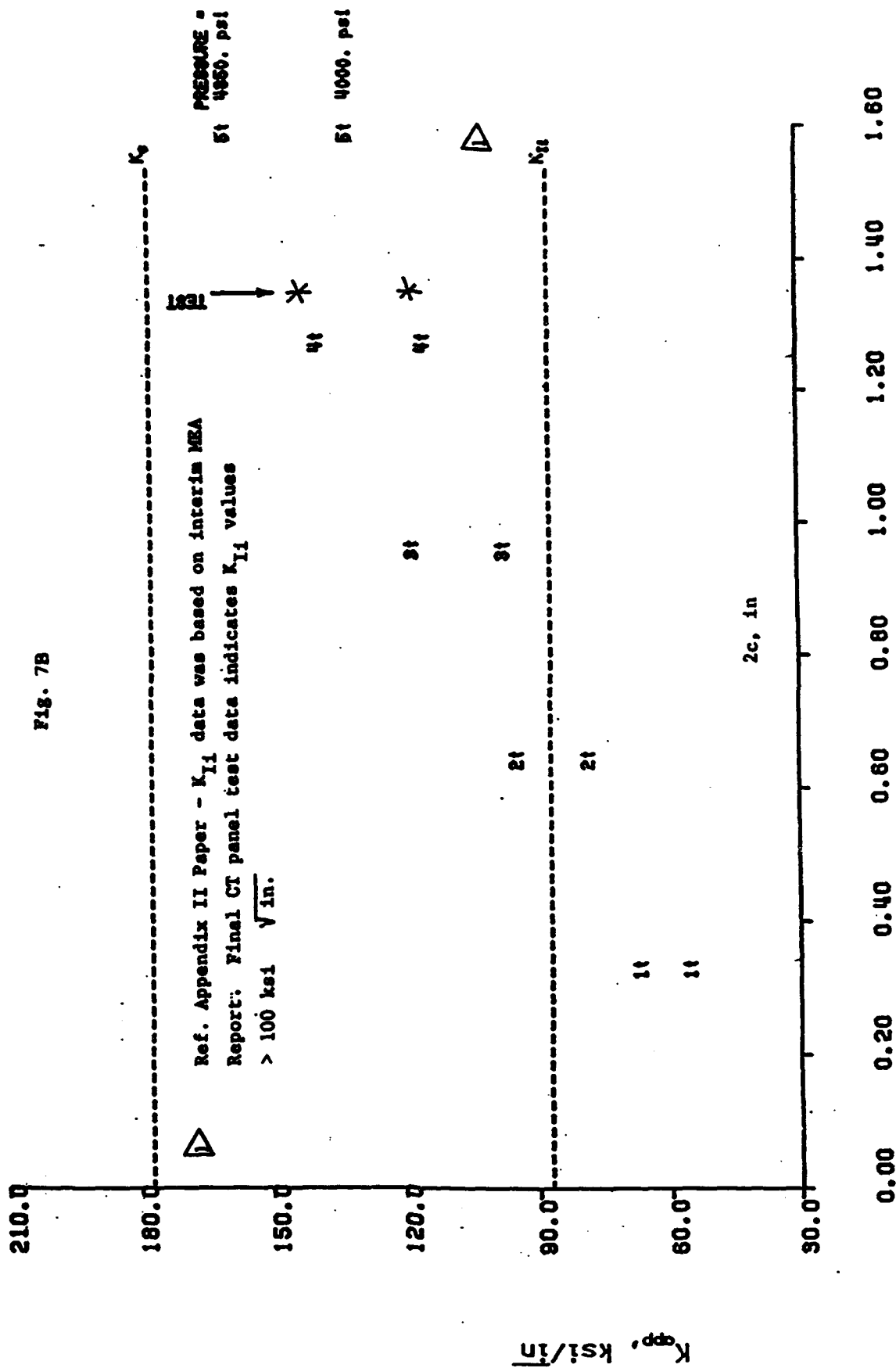
(0.215 INCH THICK)

PRESSURANT TANK, 23" DIA.

Fig. 5B

*.825

.102
.096

*.314
WELD

*.163

R

.002
.001 R

*ACTUAL   NOTCH SHAPE

Initial Flaw
Geometry

PRESSURANT TANK, 23″ DIA.

Fig. 6B
C-20

LBB EVALUATION

CRYOFORMED TP301 STAINLESS STEEL SPHERICAL TANK
S/N 118, D = 23 IN, FLAW IN WELD METAL

Fig. 7B

Ref. Appendix II Paper - K_{Ii} data was based on interim MSA
Report; Final CT panel test data indicates K_{Ii} values
> 100 ksi $\sqrt{in.}$

PRESSURE =
5t 4860. psi

5t 4000. psi

test →

K_s

K_{it}

K_{app}, ksi$\sqrt{in}$

2c, in

210.0   180.0   150.0   120.0   90.0   60.0   30.0

0.00   0.20   0.40   0.60   0.80   1.00   1.20   1.40   1.60

TABLE 5: TEST PARAMETERS

TANK NO.	TANK P/N	TYPE	TANK S/N	301 HEAT	CONDITION	FLAW LOCATION	NOMINAL DIAMETER (IN)	NOMINAL a_1/t_{off}
1	SKA11419A	Metal	105	88019	Aged	OD-SM	11	.5
2	SKA11458	Metal	003	90740	Aged	OD-SM	11	.5
3	SKA11425	Metal	104	88019	Aged	OD-SM	11	.5
4	SKA11463	Metal	113	88570	Aged	OD-SM	23	.7
5	D3912 MOD	Metal	003	88690	Unaged	ID-SM	11	.7
6	D4163	Composite	001	88690	Unaged	ID-SM	11	.7
7	D4163	Composite	002	88690	Unaged	ID-SM	11	

TABLE 6: CYCLES TO LEAK

TANK NO.	P_{oper} (psi)	t_{off} (in)	$(a/2c)_1$	a_1 (in)	N (Cycles)
1	4200	.089	.21	.041	2590
2	4000	.121	.24	.074	2948
3	3900	.090	.23	.044	2338
4	4000	.314	.20	.163	2977
5	2450	.057	.20	.038	540
6	4000-7000-4000	.057	.20	.038	1140
7	3000-6000-3000	.057	.17	.034	1987

TABLE 7: SUSTAINED LOAD TESTS

TANK NO.	DURATION (HR)	P_{oper} (psi)	K_{app} (ksi $\sqrt{IN}$)	CRACK GROWTH
1	27	3475 to 4130	84.9	None
3	48	3850 to 4000	82.2	None
5	48	4050	71.0	None

TABLE 8: LBB VERIFICATION

TANK NO.	$2c_{off}$ (in)	$\dfrac{2c_{off}}{t_{off}}$	P_{max} (psi)	K_{app} (ksi $\sqrt{IN}$)	K_{IE} (ksi $\sqrt{IN}$)	K_{II} (ksi $\sqrt{IN}$)	K_C (ksi $\sqrt{IN}$)	PRESSURANT
1	.252	2.83	6100	131.7	96.1	96.1	180	OIL
2	.363	3.00	6800	119.2	98.8	98.8	190	OIL
3	.266	2.94	4050	80.9	96.1	96.1	180	OIL THEN GAS
4	1.350	4.30	4850	135.9	98.8	98.8	190	OIL THEN WATER
5	.090	1.58	2600	64.8	108.2	108.2	163	OIL
6	.193	3.39	7150	88.4	108.2	108.2	163	OIL
7	.200	3.51	6150	93.1	108.2	108.2	163	OIL

1. Cryoformed 301 CRES per ARDE ABS 258
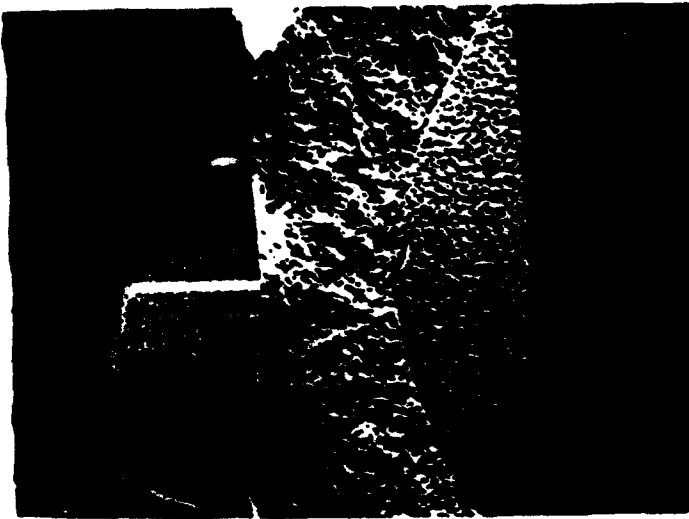2. Unaged Cryo CRES 301 Plus Kevlar 49 Type 969 Per DPHS-1
3. Toughness Value is an Average of Three Tests per Condition/Flaw Location Type - See MSA Final Report MSA-2151 (Appendix I)
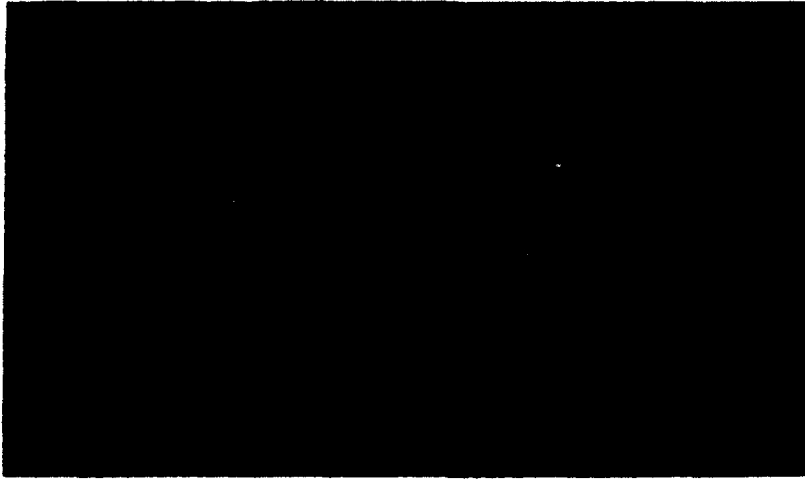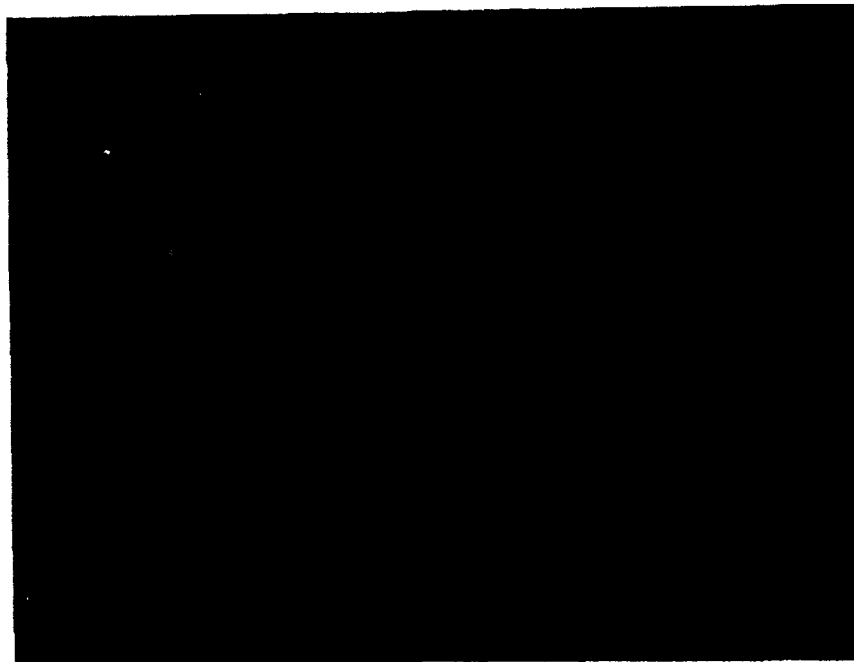
- I.D. CRACK AFTER LEAK BEFORE BURST DEMONSTRATION

- MAX PRESSURE   : 4850 PSI

- CRACK LENGTH   : 0.71 INCH

- LOCATION   : WELD

PRESSURANT TANK, 23" DIA.

Fig. 8B
C-23

LEAK BEFORE BURST TEST

- EDM FLAW ON VESSEL O.D.
- FATIGUE REGION IN CENTER
- SHEAR LIPS ON VESSEL I.D.

BASE METAL

(500X—Electrolytic Oxalic Acid Etch)

- ORIGINAL AUSTENITIC GRAIN BOUNDARIES ARE CLEARLY RETAINED

- NO VISIBLE PRECIPITATES ALONG GRAIN BOUNDARIES

- UNIFORM TRANSFORMATION THROUGHOUT STRUCTURE

- AUSTENITIC MATRIX WITH INTERLOCKING PLATELETS
  OF HIGH STRENGTH MARTENSITE
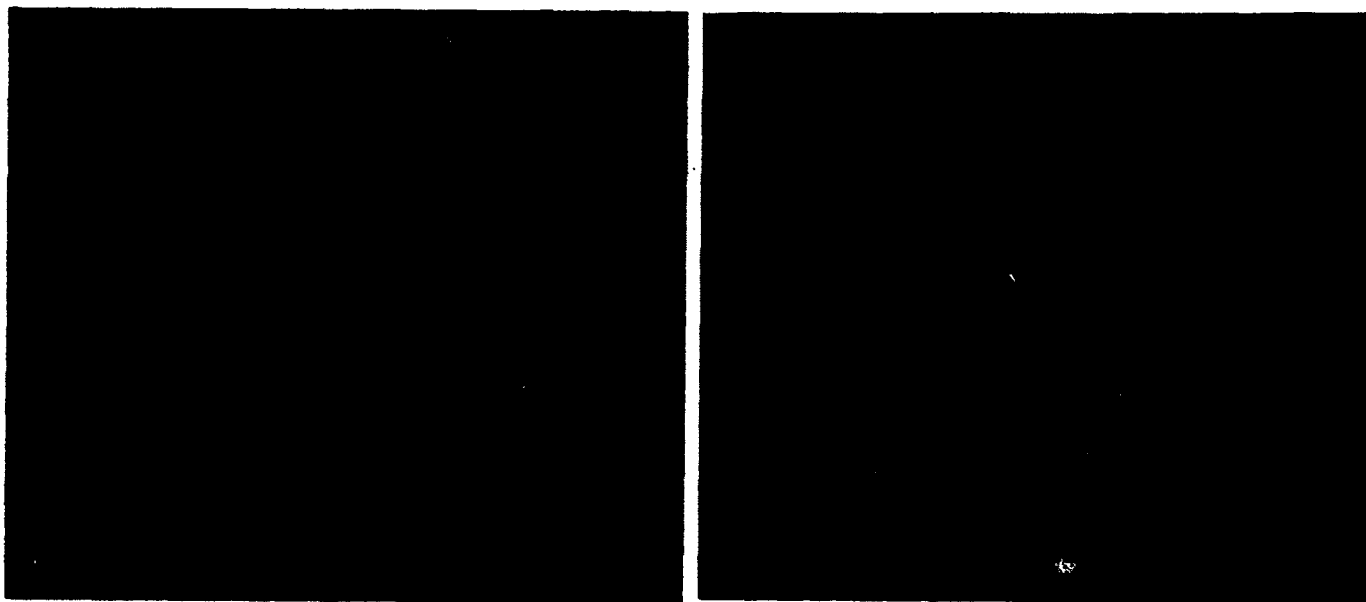
SINGLE PASS SQUARE BUTT WELD   MULTI PASS MODIFIED U-PREP WELD

(500X —Electrolytic Oxalic Acid Etch)

- WELDS TRANSFORM IN UNIFORM MANNER
- NO EVIDENCE OF RESIDUAL AS CAST STRUCTURE
- NOTE SIMILARITY TO BASE METAL

3. CONCLUSIONS

3.1   Cryoformed 301 CRES is a high strength material with very excellent toughness.

3.2   Leak-before-burst (LBB) mode with large margins has been confirmed by vessel tests for wall breakthrough surface crack lengths much greater than 2 times wall thickness, the expected breakthrough LBB crack length for in-service defects.

3.3   Cryoformed 301 CRES material toughness is independent of flaw location. Essentially, no difference in tolerance to defects was noted between base metal, weld metal or HAZ material.

4. REFERENCES

1. McCabe, D. E., preliminary fracture properties of cryoformed TP301 stainless steel, March 21, 1986, Materials Engineering Associates, Inc., Lanham, MD, to be published.

2. Beck, E. J. & Schwartzberg, F. R., "Fracture Behavior of Cryogenically Stretched 301 Stainless Steel Used in the M-509 Pressure Vessel," Martin Marietta Report MCR-71-53, February 1971, prepared under NASA Contract NAS 9-9339.

3. Private communication with A. Cozewith, Arde, Inc., Mahwah, NJ, March 1986.

4. Campbell, J. E., DMIC Review of Recent Developments - Mechanical Properties of Metals, DMIC, Battelle Memorial Institute, Columbus, OH, February 16, 1968.

5. Tests conducted by Thiokol Chemical Corporation under NASA Contract NAS 8-11977.

6. Forman, R. G., "Environmental Crack Growth Behavior of High Strength Pressure Vessel Alloys," NASA TN D-7952, April 1975.

7. Bixler, W. D., "Fracture Control Method for Composite Tanks with Load Sharing Liners," "NASA CR-134758, July 1975.

5. **APPENDICES**

C-29

5.1   APPENDIX C-1

R-CURVE TESTING OF
301 CRES MATERIAL

Prepared by

D.E. McCabe

Materials Engineering Associates, Inc.
9700B Martin Luther King, Jr. Highway
Lanham, Maryland 20706-1837

July 14, 1986

Prepared for

ARDE, Inc.
19 Industrial Avenue
Mahwah, New Jersey 07430

Contract
#FO-8606-84-C-0029

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FIGURE CAPTIONS

Fig. 1 C   Center cracked tension panel. Dimensions in inches.

Fig. 2 C   Clip gage attachment setup for
6-inch gage length.

Fig. 3 C   View of DSST gage and traveling
stage microscope for measuring
slow-stable crack growth.

Fig. 4 C   1/2T compact specimen.

Fig. 5 C   Representative load-displacement
record, CCT panel.

Fig. 6 C   Representative load-displacement record, compact specimen.

Fig. 7 C   Magnified view of crack tip region
after considerable slow-stable crack
extension.

Fig. 8 C   Compact specimen and center cracked panel J_R-curves for
unaged base metal.

Fig. 9 C   Compact specimen and center cracked panel J_R-curves for
aged base metal.

Fig. 10 C   Compact specimen and center cracked panel J_R-curves for
unaged weld metal.

Fig. 11 C   Compact specimen and center cracked panel J_R-curves for
aged weld metal.

Introduction

The purpose of this program was to test specimens of CRES Ḧᴜ̃ material provided by ARDE for J_R-curve and for J_{Ic}-like values that can be obtained from J_R-curves. The material is an extremely high strength stainless steel that has good toughness by ultra-high strength materials standards.

Center cracked tension panels (CCT) were prepared by ARDE; 1/2T (plan view) compact specimens were machined under MEA control. All specimens were nominally 0.090-in. to 0.095-in. (2.3 mm to 2.4 mm) thickness. Doubler pads had been welded on the ends of the CCT specimens, the fabrication of which caused various degrees of kinking at the ends of the specimens. Fifteen CCT panels and six compact specimens were tested in conditions representing base metal, weld metal and HAZ in aged and unaged conditions (Table 1G). The compact specimens of base metal were made from broken halves of CCT specimens.

J_R-curve development was made by recording load vs—displacement, measuring work done on the specimens. The CCT panels were 1.4-in. (35.5 mm) wide with a 6-in. (152 mm) parallel section and a nominal 0.6-in. starting fatigue crack for a crack size ratio, $2a_o/W$ of 0.43 (Fig. 1C). Extension arms and an MTS clip gage were used to measure elongation over the 6-in. gage length. The attachment points for the clip gage were razor blade tips (Fig. 2C). A second gage (DSST-type) was attached across the crack mouth at a span of 0.5-in. (12.7 mm) to measure crack growth by unloading compliance (Fig. 3C). The 1/2T compact specimen is shown in Fig. 4C, and in this case, displacement is measured under the loading pins (on the load line) in the region of the cutout. Again, the clip gage was attached across razor blade tips. Load coupled with displacement measurement indicates work done.

All of the clip gages discussed above were calibrated and example calibration information is enclosed in Appendix IV.

Periodic partial unloading of specimens gives linear unloading traces, the slope of which corresponds to currently existing physical crack sizes (Figs. 5C and 6C). Linear regression was used to fit the unloading slope and elastic compliance was used to calculate crack size. All of the above had been performed during the test using a computer. Generally the unloading slopes were linear, having correlation coefficients of the order of 0.999XX. For the CCT panels, the crack size measurement accuracy was within 0.002 to 0.005-in., depending upon the initial distortion of the specimens at the doubler plates. Sensitivity, which is important for the R-curve accuracy, was usually good to 0.002 in. of crack growth increment. The compact specimens had been initially ground flat and both precision and accuracy were of high resolution.

To verify the unloading compliance measurements, we also used visual measurements on one of the two surfaces using a traveling stage microscope. This was definitely less precise compared to unloading compliance because the crack tunnels at midthickness which cannot be seen on the surface. Additionally, surface growth tended to be slightly uneven from front to back of the specimens. Also, when plastic zones of appreciable size develop at the crack tips, as they did here, the exact location of the physical crack tip becomes a matter of judgment. The situation is illustration in Fig. 7C.

The fracture toughness of the material was evaluated in terms of J-integral. The J solutions for the CCT geometry [M(T)] have not been as thoroughly developed and standardized to the extent that they have been for the compact specimen, [C(T)]. Therefore we had selected a compromise computational procedure that is most likely to lead to geometry independent J. Here we use the term Merkle-Corten J_{mc} for the reason that it resembles the Merkle Corten computational approach used on compact specimens. Specifically all load vs. displacement measurements are treated as total work done on the specimen, and no special provision is used to correct for the slow-stable crack growth. Following Reference 1:

$$J_p = \frac{2 \text{ (Area} - 1/2 \text{ P v})}{B \text{ (W-2a)}} \tag{1}$$

where:

J_p	=	the plastic component of J
Area	=	total work done
a	=	initial half-crack size
P	=	load
v	=	total displacement
W	=	specimen width
B	=	specimen thickness

Total J (i.e., J_{mc}) is obtained after adding elastic J calculated as follows:

$$J_e = \frac{K^2}{E} = \frac{\sigma^2 \, \pi a}{E} \, \text{Sec} \, \frac{\pi a}{W} \tag{2}$$

σ	=	gross stress
E	=	elastic modulus

$$J_{mc} = J_e + J_p \tag{3}$$

As had been stated before, dimension "a" is not updated for crack growth. Nevertheless, the above procedure is likely to give J_{mc} near in value to modified J (Ref. 2) as opposed to deformation theory J (Ref. 3).

As an exercise to assure the reasonableness of the J for R-curve plots and to verify the performance of the instrumentation, two alternative fracture toughness computations were made. See the tabulated data in Appendix III. One was a plasticity corrected stress intensity factor, K_r, obtained using a procedure described in ASTM method E561 (Ref. 4). The equations are as follows:

$$K_r = \sigma \left[\pi a_e \, \text{Sec} \, \frac{\pi a_e}{W} \right]^{1/2} \tag{4}$$

where a_e is plastic zone corrected crack size, and:

$$J(K_r) = K_r^2/E \qquad (5)$$

A second alternative (J_{bt}) procedure that we added violates accepted J analysis testing practices but the results were found useful here to evaluate the compatibility of displacement measurement between the two gages. Displacement from the DSST mouth gage was used in place of total displacement (v), to calculate work done (Area) and the plastic component of work done (Area - 1/2 P v) in Eq. 1. Values of "J_{bt}" were calculated using Eqs. -1- through 3. Comparison of J_{mc}, J (K_r) and J_{bt} are included in the tabulations of Appendix III.

Toughness Calculations - CT Specimens

The CT specimen, C[T] is the most thoroughly studied fracture mechanics specimen. Testing techniques have been highly refined and J can be calculated with better conformance to theoretical considerations. However, from the three computational options available, (Merkle-Corten, Deformation Theory J, and Modified J) we will again choose Merkle-Corten J_{mc} as the primary one simply to make comparisons to the CCT panel results. In this case, the J_{mc} values can be verified through a comparison to modified J values which are better justified by theory. Modified J (J_M) will be treated herein as the alternative method number 1.

For the compact specimen, it is not necessary to subdivide the computation of J_{mc} into its elastic and plastic components and so the following simple formula can be used to calculated total J_{mc}:

$$J_{mc} = \frac{\eta \text{ Area}}{B\, b} \qquad (6)$$

where,

    Area = total area under load vs. displacement
    b   = W - a
    a   = initial crack size
    B   = specimen thickness
    η = 2 + 0.522b/W

Modified J had been developed to handle cases where there is substantial crack growth with respect to the initial remaining ligament size. It is computed from the following equations:

$$J_M = G + \frac{1}{B} \int_0^v P\, \frac{\eta}{b}\, P dv_p \qquad (7)$$

where:

$b \quad = \quad W - a_i$

$a_i \quad = \quad$ updated crack size

$\eta \quad = \quad 2 + 0.522 \, b/W$

$v_p \quad = \quad$ plastic component of displacement

$G \quad = \quad J$ (elastic)

Despite the fact that equations (6) and (7) differ a great deal in computational approach, it can be seen in the tabulations in Appendix III that the values are nearly the same over the full range of the J_R-curves.

Fracture Toughness Criteria

The work statement of ARDE had asked for material toughness evaluation by J_R curve and for J_{Ic} by ASTM Method E813, "J_{Ic}, A Measure of Fracture Toughness" (Ref. 5). This standard has been revised recently and is currently being balloted within ASTM. The revised practice is used herein as the primary data evaluation procedure. It should be kept in mind that the J_{Ic} values obtained cannot be validated according to the old nor the revised versions of the standard because we will be ignoring the thickness requirements and specimen design recommendations in the case of the CCT specimens.

The procedure for determining provisional values of J_{Ic} involves several procedural steps. A blunting line is developed which is defined by the following equation:

$$\Delta a_p \quad = \quad J/2\sigma_f \qquad (8)$$

where $\sigma_f = (\sigma_{ys} + \sigma_{ts})/2$.

Equation 8 predicts a material crack tip blunting behavior that is graphically constructed. Two "exclusion lines" are drawn parallel to the blunting line, offset by 0.006-in. (0.15 mm) and 0.060-in. (1.5 mm). The purpose of the lower bound exclusion line is to exclude from the J_R-curve model all of the slow stable crack growth near initiation, where Δa_p is very nebulously defined. These data as a general rule cannot be reliably reproduced between investigators. The upper bound exclusion line restricts the Δa_p range so that a simple power law produces a good fit to the data. Hence the qualified data within the exclusion lines is fit with the following power law equation:

$$J_{Pl} \quad = \quad C \, (\Delta a_p)^n \qquad (9)$$

where:

$C \quad = \quad$ fitting constant

$\Delta a_p \quad = \quad$ physical crack growth

In the revised standard, a third parallel offset line is made at 0.008-in. (0.2 mm) of Δa_p and J_{Ic} is defined as the intersection of J_{Pl} with this offset line. This new approach establishes J_{Ic} as a real definable point on the J_R-curve which was not necessarily the case with the practice that is presently in place. It is felt that the 0.008-in. of stable growth necessary to be on the J_R curve will not be relevant to engineering concerns.

Results

Appendix A presents J_R-curves and tabulations of J_R values at each unloading event for all specimens. The units of measure used here were purposely chosen to be English units. To convert to metric use the following:

$$K_I: \quad ksi\sqrt{in.} \times 1.1 = MPa\sqrt{m}$$

$$J_I: \quad in.-lb/in.^2 \times 0.175 = kJ/m^2$$

$$\sigma: \quad ksi \times 6.894 = MPa$$

$$\Delta a_p = in. \times 25.4 = mm$$

Table 2C summarizes the fracture toughness parameters obtained from CCT panels. The symbol $K(J_{Ic})$ used here suggests only that the J_{Ic} procedure and conversion equality $K_{Ic}^2 = J_{Ic}E$ had been used. The values do not necessarily meet all of the validity requirements of standard E813 (new or old version) nor standard E399. For K_c values, the numbers are K converted from J_{mc} and they correspond to the unloading at or just prior to maximum load. For almost all of the CCT panels, maximum load was a crack instability load which terminated the J_R-curve development. The net stress calculations were based on crack size including slow stable crack growth.

Tests on CT specimens can be easily identified in Appendix A by the 0.2-in. or more of slow-stable growth in the J_R curves. This is possible because the compact specimen is an inherently stable geometry. The J_R-curves are the same as those that had been obtained with CCT specimens, however (Figs. 8-C 11C). The $K(J_{Ic})$ values indicated from the CT specimens appear to be slightly higher on average than those obtained with CCT panels, as can be seen in Table 3C. The reason for this becomes clear when we realize that only half of the J_R-curve data between the exclusion lines is developed before instability with CCT specimens. As a result, the power law fits were biased slightly toward higher slopes and lower J_R predictions at the 0.008-in. (0.2 mm) offset line.

Table 4C compares compliance indicated crack growth for CCT panels as measured by the DSST gage to the visually measured growth. In some cases, the compliance-indicated crack growth had been transposed or offset along the abscissa by an amount indicated in the last column. The same visual vs. compliance comparison is made for compact specimen tests in Table 5C With these specimens, however, the testing practice and specimen machining methods are thoroughly refined and initial offset adjustment was not necessary.

Precracking data are given in Table 6C. The total cycles for base metal specimen 002 had been inadvertently not recorded.

Conclusions

J_R-curves were obtained on CRES base metal, weld metal, and HAZ in the aged and unaged conditions. For CCT panels, each J_R-curve was terminated by an onset of crack instability, usually with less than 0.05-in. (1.27 mm) of crack growth. Compact specimens produced essentially the same J_R-curves except there was no instability and the J_R-curve up to 0.20-in. (5 mm) of crack growth was obtained. The J_{Ic}-like crack initiation values resulting from CCT J_R-curves were slightly lower than the J_{Ic}-like values of CT specimens. Apparently, the existence of fewer data points in the zone of data inclusion which are clustered near to the crack growth initiation biases the power law curve to lower J_R values at the 0.008-in. intercept.

References

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2. Ernst, H.A. "Material Resistance and Instability Beyond J Controlled Crack Growth", ASTM STP 803, Vol. 1983.

3. Paris, P.C. "Fracture Mechanics in the Elastic-Plastic Regime", Flaw Growth and Fracture, ASTM STP 631, 1977, pp. 3-27.

4. ASTM Standard E561-81, "R-Curve Determination", ASTM Annual Book of Standards, Section 3, Vol. 03.01, 1985.

5. ASTM Standard E813-81, "J_{Ic}, A Measure of Fracture Toughness", ASTM Annual Book of Standards, Section 3, Vol. 03.01, 1985.

Acknowledgments

Table 1C Test Matrix - Specimen Identification

Conditions	Specimen Type	Base Metal	Weld Metal	HAZ
Aged	CCT	40-006	40W-006	40W-009
	CCT	40-007	40W-007	
	CCT	40-008	40W-008	
	CT	BM-008	WM 13A	
	CT		WM 14A	
Unaged	CCT	40-001	40W-001	40W-004
	CCT	40-002	40W-002	40W-005
	CCT	40-003	40W-003	
	CT	BM-003	WM 11	
	CT		WM 12	

Table 2C Summary Data from R-Curve Tests of CCT Specimens

Specimen Number	$K(J_{Ic})$ Power Law (ksi√in.)	(Δa_p) Clip Gage (in.)	(Δa_p) Visual (in.)	(K_c) (ksi√in.)	(σ_n^a) (ksi)	Yield Strength (ksi)
BN006A	108.1	0.032	0.0395	191	238	261
007A	88.0	0.044	0.017	180	238	
008A	92.2	0.032	0.025	169	238	
WH006A	118.3	0.040	0.040	194	240	229
007A	87.6	0.052	0.037	204	240	
W08A	90.5	0.028	0.025	171	235	
HAZ009	136.2	0.026	0.015	213	256	
WM001	101.5	0.043	0.050	183	214	192
002	98.5	0.040	0.011	168	223	
003	104.3	0.025	0.022	179	207	
BN001	130.9	0.036	0.021	185	217	207
002	103.5	0.024	0.0120	147	218	
003	90.1	0.035	0.038	157	213	
HAZ004	116.5	0.022	0.015	184	228	
005	126.6	0.017	0.022	174	223	

Net cross-section stress $= \dfrac{P/B}{W - 2(a_o + \Delta a_p)}$

Table 3C. Summary Data Comparing CCT and CT Results

	Power Law, $K(J_{Ic})$ (ksi in.)	Δa_p (in.)	K_c (ksi in.)	Yield Strength (ksi)
Base Metal-Aged				
CCT Avg.	96.1	0.036	180	261
CT	162.3	0.247	224	
Weld Metal Aged				
CCT Avg.	98.8	0.040	190	229
CT	133	0.210	187	
CT	102.2	0.216	219	
Weld Metal Unaged				
CCT Avg.	101.4	0.036	177	198
CT	114.7	0.237	171	
CT	116.2	0.240	185	
Base Metal Unaged				
CCT	108.2	0.032	163	207
CT	132.9	0.247	169	

Table 4C Comparison of Visual (V) vs. Compliance Indicated (C) Crack Growth (Δa_p) At Selected Unloading Points for CCT Specimens

Specimen No.		Crack Length Difference (in.)																Offset Mils
40-006	(V)	0	0	0.002	0.001	0.003	0.004	0.005	0.004	0.0065	0.007	0.0095	0.021	0.030	0.0395			
	(C)	0	0.001	0.003	0.005	0.005	0.006	0.0085	0.0086	0.0095	0.013	0.015	0.023	0.030	0.032			(5)
40-007	(V)	0	0	0	0	0	0.0005	0.0015	0.0015	0.0015	0.003	0.0035	0.017					
	(C)	0	0.002	0.002	0.005	0.006	0.007	0.009	0.012	0.018	0.021	0.029	0.044					(0)
40-008	(V)	0	0	0.0015	0.002	0.0025	0.003	0.002	0.0075	0.009	0.014	0.026	0.025					
	(C)	0	0.001	0.0035	0.005	0.006	0.006	0.008	0.014	0.017	0.021	0.025	0.031					(0)
40V-006	(V)	0	0.0015	0.0025	0.003	0.0035	0.0035	0.0045	0.0045	0.0055	0.008	0.010	0.0135	0.0235	0.0235	0.024	0.040	
	(C)	0	0	0	0.0015	0.003	0.003	0.004	0.004	0.006	0.010	0.012	0.014	[illegible]	[illegible]	[illegible]	0.040	(7)
40V-007	(V)	0	0.002	0.004	0.004	0.004	0.004	0.005	0.005	0.007	0.010	0.010	0.020	0.028	0.034	0.037		
	(C)	0	0.001	0.003	0.005	0.005	0.008	0.008	0.011	0.014	0.017	0.019	0.022	0.025	0.030	[illegible]	[illegible]	[illegible]
40V-008	(V)	0	0.002	0.002	0.004	0.004	0.004	0.004	0.006	0.005	0.008	0.010	0.014	0.016	0.017	0.019	[illegible]	
	(C)	0	0	0	0	0.001	0.001	0.003	0.004	0.006	0.011	0.011	0.015	0.017	0.020	0.024	[illegible]	[illegible]
40V-009	(V)	0	0.002	0.002	0.003	0.0035	0.003	0.004	0.005	0.0055	0.005		0.009	0.010	0.0125	0.0125	[illegible]	
	(C)	0	0	0.001	0.003	0.004	0.005	0.006	0.007	0.009	0.010	0.012	0.013	0.017	0.020	0.020	[illegible]	[illegible]
40V-001	(V)																	
	(C)	0	0	0.001	0.002	0.003	0.004	0.005	0.006	0.008	0.011	0.015	0.018	0.021	0.023	0.025	[illegible]	(5)
40V-002	(V)	0	0	0	0	0 0	0.001	0.001	0.003	0.003	0.0035	0.0035	0.005	0.0085	-	0.011		
	(C)	0	0	0.001	0.003	0.0025	0.004	0.004	0.005	0.007	0.0095	0.012	0.015	0.016	0.021	0.026	0.040	(1)
40V-003	(V)	0	0.003	0.005	0.003	0.004	0.0045	0.004	0.005	0.008	0.0065	0.008	0.010	0.016	0.022			
	(C)	0	0	0.002	0.003	0.004	0.005	0.006	0.008	0.010	0.013	0.014	0.017	0.019	0.025			(9)
40-001	(V)	0	0	0	0	0 0	0.001	0.002	0.003	0.003	0.005	0.009	0.010	0.021				
	(C)	0	0	0	0	0.001	0.002	0.003	0.005	0.007	0.011	0.014	0.017	0.024	0.036			(13)
40-002	(V)	0.003	0.002	0.003	0.003	0.004	0.005	0.005	0.006	0.007	0.008	0.009	0.020					
	(C)	0	0.001	0.002	0.002	0.002	0.004	0.006	0.007	0.009	0.012	0.015	0.024					(0)
40-003	(V)	0	0	0	0	0.001	0.003	0.004	0.004	0.005	0.007	0.011	0.018	0.019	0.038			
	(C)	0.001	0.001	0.001	0	0.002	0.003	0.003	0.007	0.010	0.012	0.014	0.019	0.024	0.035			(0)
40V-004	(V)	0	0.003	0.004	0.005	0.005	0.004	0.005	0.004	0.006	0.007	0.006	0.008	0.009	0.011	0.013	0.015	
	(C)	0	0.001	0.002	0.003	0.004	0.004	0.006	0.006	0.007	0.010	0.010	0.012	0.014	0.016	0.017	0.022	(4)
40V-005	(V)	0.001	0.0015	0.0025	0.004	0.0055	0.006	0.009	0.010	0.0125	0.0155	0.017	0.0225					
	(C)	0	0	0	0	0.001	0.004	0.006	0.009	0.0103	0.013	0.0145	0.017					(2)

a) Initial bias in Δa_p from panel straightening

Table 5C Comparison of Visual (V) vs. Compliance Indicated (C) Crack Growth (Δap) at Selected Unloading Points for CT Specimens

Specimen Number		Crack Length Difference (in.)									
BH003	V	0	001	0	.002	.005	.037	.060	.067	.160	.259
	C	.001	.001	.003	.007	.010	.030	.051	.063	.147	.247
BH008	V	0	.0005	.001	.003	.0055	.020	.065	.112	.164	.260
	C	0	0	.004	.006	.012	.024	.051	.100	.156	.248
WM-11	V	.001	.001	.007	.034	.071	.115	.162	.222	.222	.226
	C	0	.005	.011	.029	.062	.109	.158	.192	.216	.237
WM-12	V	0	.002	.006	.031	.058	.103	.126	.157	.206	.247
	C	.003	.008	.016	.035	.058	.095	.132	.184	.219	.240
WM-13A	V	0	.001	.001	.008	.021	.032	.114	.135	.163	.187
	C	.001	.007	.010	.020	.041	.067	.111	.151	.185	.210
WM-14A	V	.002	.014	.026	.050	.062	.105	.166	.203	.218	.249
	C	.006	.013	.022	.042	.061	.107	.144	.160	.180	.216

Table 6 C   Fatigue Precracking Information

Product Form	Spec. No.	Load		Crack Length		Cycles
		P_{max} (lb)	P_{min} (lb)	a_{rear} (in.)	a_{front} (in.)	N
WM-CCT	001	2500	250	0.038	0.041	29,000
	002	2500	250	0.035	0.040	35,000
	003	2500	250	0.045	0.049	35,000
	004	2500	250	0.035	0.040	35,000
	005	2500	250	0.035	0.039	31,000
	006	2840	284	0.041	0.037	25,000
	007	2500	250	0.036	0.038	29,000
	008	2500	250	0.040	0.040	30,000
	009	2500	250	0.039	0.036	30,000
BM-CCT	001	2500	250	0.035	0.038	20,000
	002	2500	250	0.042	0.042	-
	003	2500	250	0.040	0.040	28,000
	004	-	-	-	-	-
	005	2850	285	0.038	0.039	30,000
	006	2500	250	0.038	0.043	30,000
	007	2500	250	0.037	0.037	25,000
	008	2500	250	0.035	0.038	28,000
	009	2840	284	0.044	0.040	25,000
WM-CT	WM11	270	100	0.050	0.050	15,000
	WM12	270	100	0.050	0.054	15,750
	WM13A	270	100	0.053	0.046	18,500
	WM14A	270	100	0.050	0.050	16,500
BM-CT	BM003	270	100	0.050	0.050	16,000
	BM008	270	100	0.050	0.050	16,500

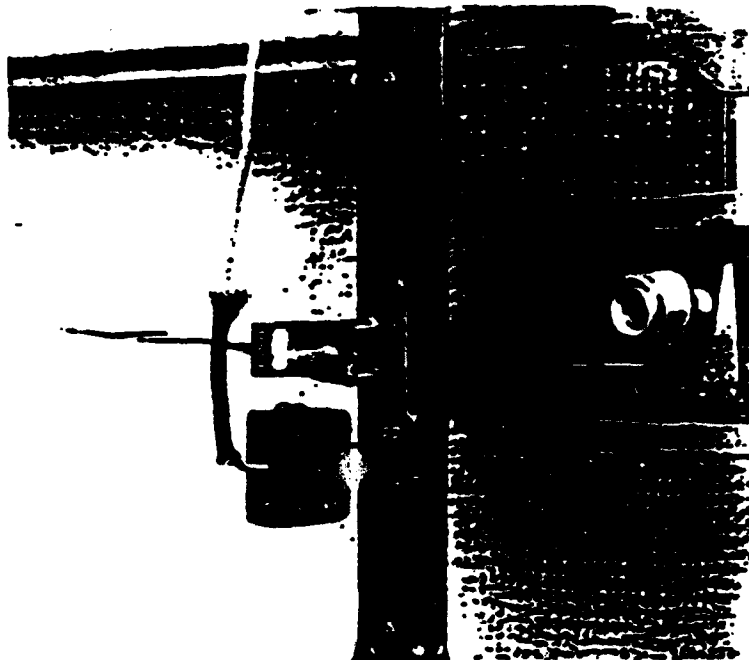Fig. 1C   Center cracked tension panel.   Dimensions in inches.

Fig. 2C Clip gage attachment setup for 6-inch gage length.

Fig. 3C View of DSST gage and traveling stage microscope for measuring slow-stable crack growth.

Fig. 4C   1/2T compact specimen.

LOAD 2000 lb./in.

SPEC. 005

FRACTURE

2,000 lb

0.00991 in.

DEFL. 0.00991 in./in.

Fig. 5C Representative load-displacement
C-51 record, CCT panel.

DEFL. 0.01137 in./in

Fig. 6C Representative load-displacement record, compact specimen.
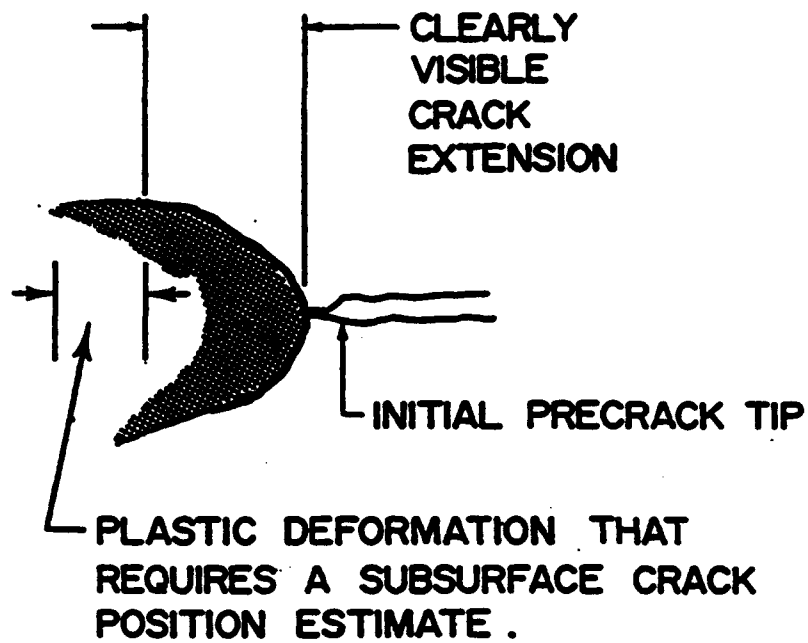
CLEARLY
VISIBLE
CRACK
EXTENSION

INITIAL PRECRACK TIP

PLASTIC DEFORMATION THAT
REQUIRES A SUBSURFACE CRACK
POSITION ESTIMATE .

Fig. 7C Magnified view of crack tip region
after considerable slow-stable crack
extension.

Fig. 8C   Compact specimen and center cracked panel J_R-curves for unaged base metal.

Test Temp   : 77 °F
Flow Stress : 211000 ksi
Young's Mod : 27E6 ksi

○ D3517-40-001 (CCT)
□ BM-003 (CT)

J_{mc} (in-lb/in²)

Δa_p (in.)

21

C-54

Fig. 9C   Compact specimen and center cracked panel J_R-curves for aged base metal.

Fig. 10C   Compact specimen and center cracked panel J_R-curves for unaged weld metal.

Test Temp   : 77 °F
Flow Stress : 198000 ksi
Young's Mod : 27E6 ksi

O D3517-40W 002 (CCT)
□ WM-12 (CT)

J_{mc} (in-lb/in²)

Δa_p (in.)

J_{mc} (in-lb/in^2)

Δa_p (in.)

○ D3517-4BW BB6 (CCT)
□ WM-14A (CT)

Test Temp : 77 °F
Flow Stress : 230000 ksi
Young's Mod : 27E6 ksi

5000
4000
3000
2000
1000
0

0 0.05 0.10 0.15 0.20 0.25 0.30

Fig. 11 C Compact specimen and center cracked panel J_R-curve for aged weld metal.

C-57
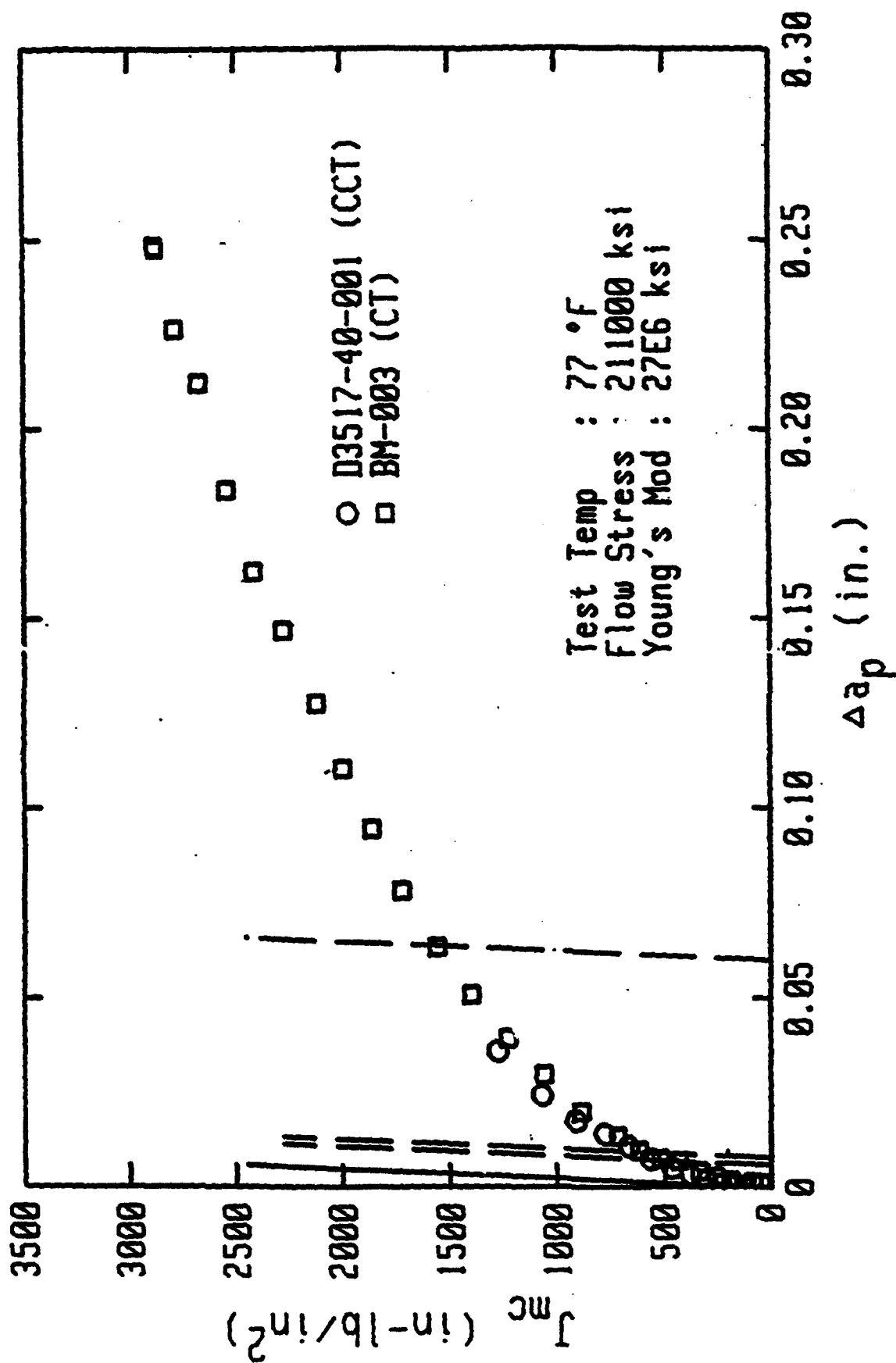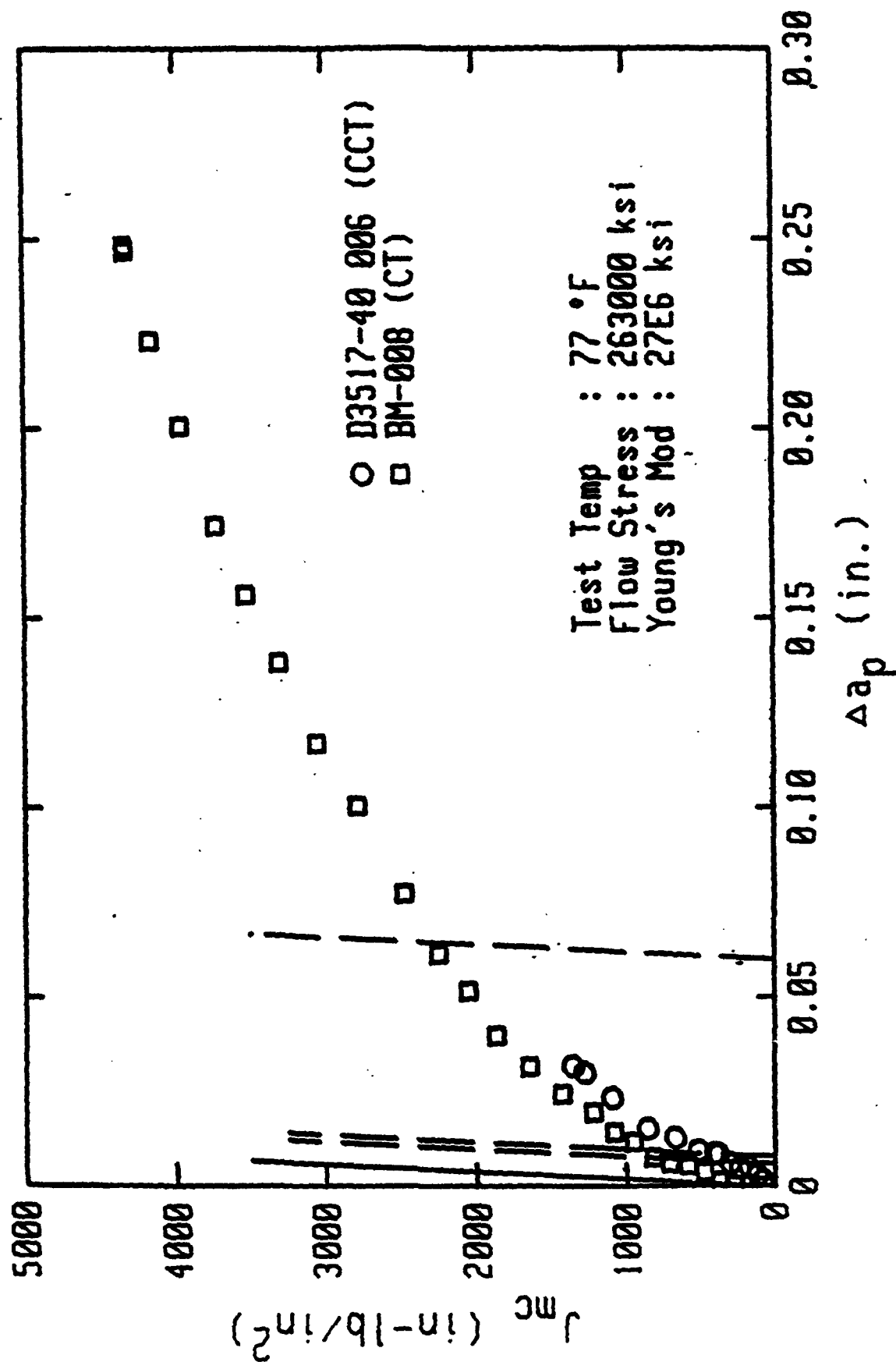
APPENDIX III

R-CURVES AND TABULATED DATA

Definitions:

J_{Pl} The intersection of the power law curve, Eq. 6, with the 0.008-in. offset.

K_{Pl} $\sqrt{J_{Pl}E}$

r Correlation coefficient of regression analysis.

J_{Ic}^{-} The intersection of the linear regression line with the blunting line. Not validated by E813.

K_{Ic} $\sqrt{J_{Ic}E}$ not E399 validated.

J_{mc} J by Eq. 1

J_{bt} J by Eqs. 1 through 3 using DSST gage output

$J(K_r)$ J by Eq. 4

K_c $\sqrt{J_{mc}E}$ at last unload prior to instability.

J_M Modified J

Code : D3517-40 006

Test Temp   : 77 °F
Flow Stress   : 263000 ksi
Young's Mod   : 27E6 ksi
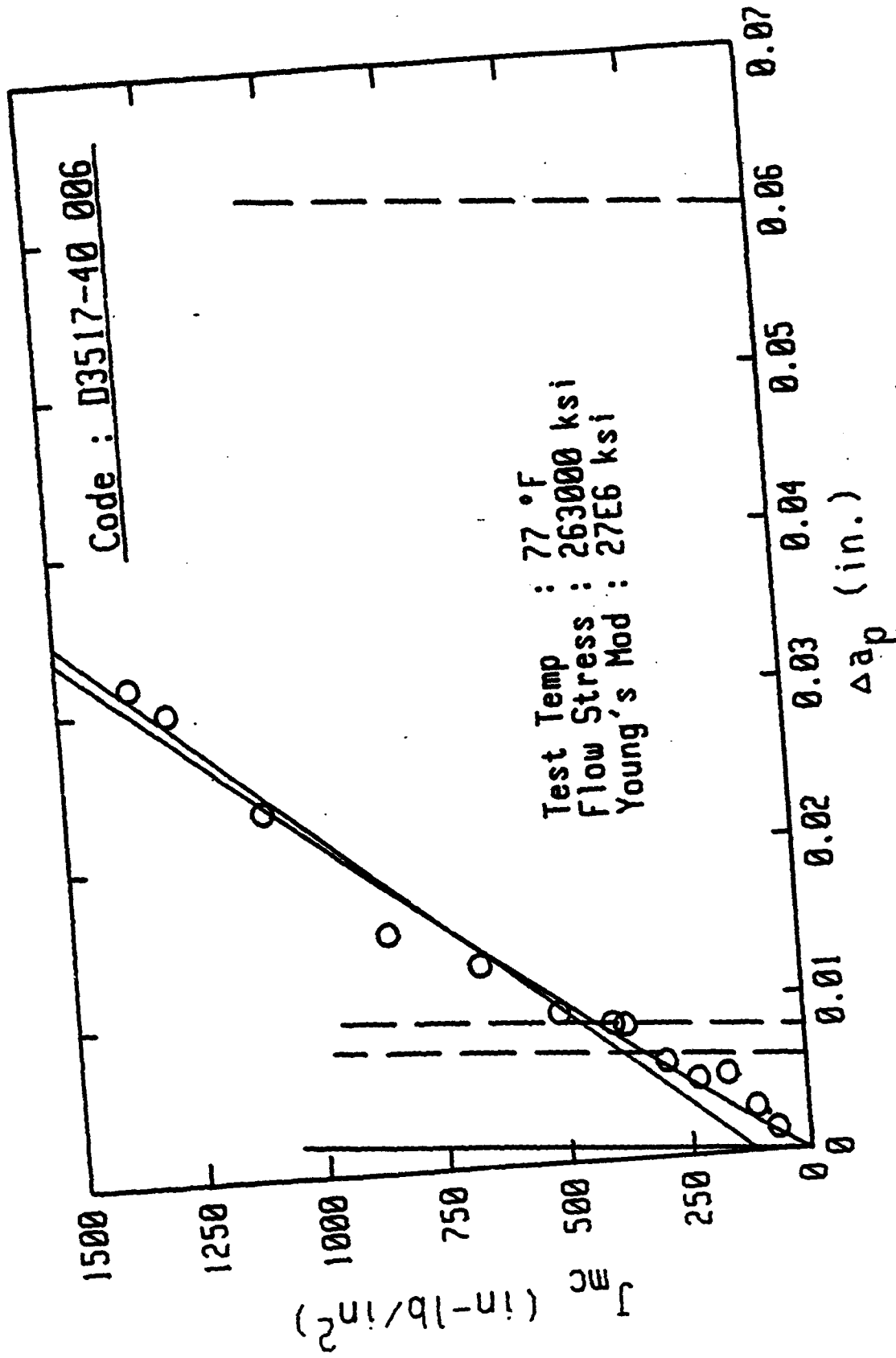
$J_{pl} = 433.1$ in-lb/in^2
$K_{pl} = 100.1$ ksi$\sqrt{in}$
$r = 0.982$

$J_{Ic} = 120.6$ in-lb/in^2
$K_{Ic} = 57.1$ ksi$\sqrt{in}$
$r = 0.9849$

Thickness : 0.094 in.
Initial a : 0.292 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

Toughness J

Event	Load lb	Jac in-lb/in²	Jbt in-lb/in²	J(Kr) in-lb/in²	del-ap in.
1	2522	16.4	16.4	34.3	0.0000
2	3486	34.7	21.3	53.2	0.0000
3	4454	66.4	33.3	82.0	0.0014
4	5683	100.2	52.2	120.0	0.0029
5	6739	166.3	79.8	166.6	0.0051
6	7722	227.7	110.7	214.4	0.0048
7	8717	293.3	143.3	269.9	0.0061
8	9766	373.1	195.2	336.5	0.0085
9	10056	397.7	269.4	356.3	2.0036
10	11282	506.9	278.0	449.4	0.0095
11	12712	662.8	382.1	582.4	0.0120
12	14065	847.6	519.0	746.2	0.0152
13	15257	1088.8	742.0	979.9	0.0233
14	15957	1275.7	926.2	1175.0	0.0298
15	16146	1349.7	992.6	1248.5	0.0316

Pmax = 16340 (lb)
Net Stress = 237860 (psi)

C-61

Code : D33517-40 007

Test Temp : 77 °F
Flow Stress : 263000 ksi
Young's Mod : 27E6 ksi

J_{pl} = 286.9 in-lb/in^2
K_{pl} = 88 ksi$\sqrt{in}$
r = 0.9892

J_{Ic} = 90.5 in-lb/in^2
K_{Ic} = 49.4 ksi$\sqrt{in}$
r = 0.9848

Thickness : 0.092 in.
Initial a : 0.293 in.
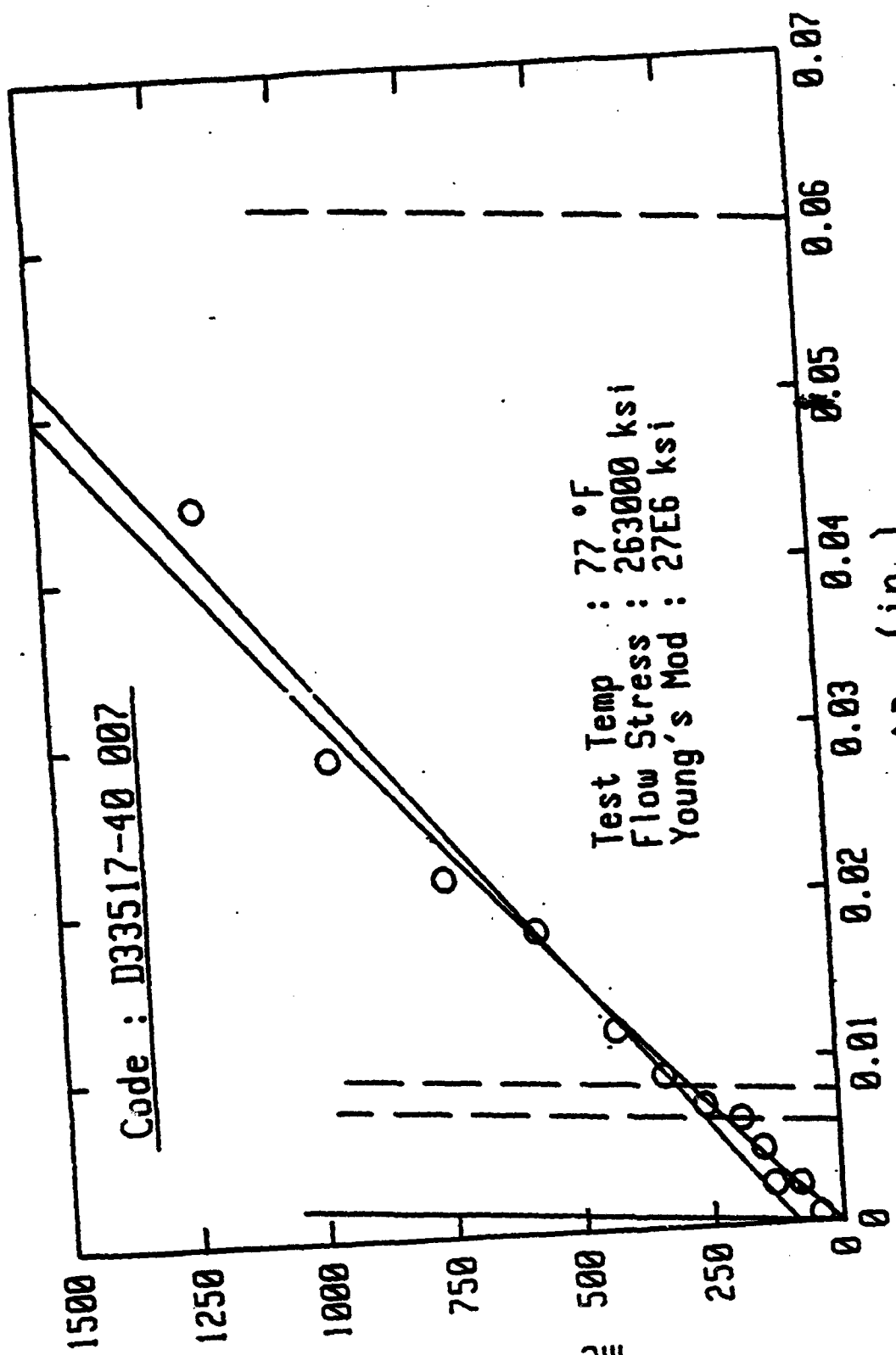
J_{mc} (in-lb/in^2)

Δa_p (in.)

Toughness J

Event	Load lb	Jac in-lb/in^2	Jbt in-lb/in^2	J(Kr) in-lb/in^2	del-ap in.
1	.4003	43.0	43.0	151.2	0.0005
2	4984	79.5	36.2	190.5	0.0024
3	6034	129.7	35.6	240.4	0.0024
4	6484	148.4	35.2	257.9	0.0046
5	7088	188.3	40.6	296.4	0.0064
6	8117	257.4	55.9	362.1	0.0073
7	9087	335.6	76.9	431.5	0.0091
8	10046	423.1	108.9	511.9	0.0120
9	11445	568.9	177.5	653.3	0.0181
10	12767	741.6	265.7	815.0	0.0215
11	13978	955.0	390.8	1010.9	0.0289
12	15133	1195.6	582.9	1277.6	0.0442

Pmax = 15500 (lb)
Net Stress = 238120 (psi)

Code : D3517-40 008

Test Temp : 77 °F
Flow Stress : 263000 ksi
Young's Mod : 27E6 ksi

J_{pl} = 315.1 in-lb/in^2
K_{pl} = 92.2 ksi$\sqrt{in}$
r = 0.9922

J_{Ic} = 31.8 in-lb/in^2
K_{Ic} = 29.1 ksi$\sqrt{in}$
r = 0.9936

Thickness : 0.092 in.
Initial a : 0.289 in.
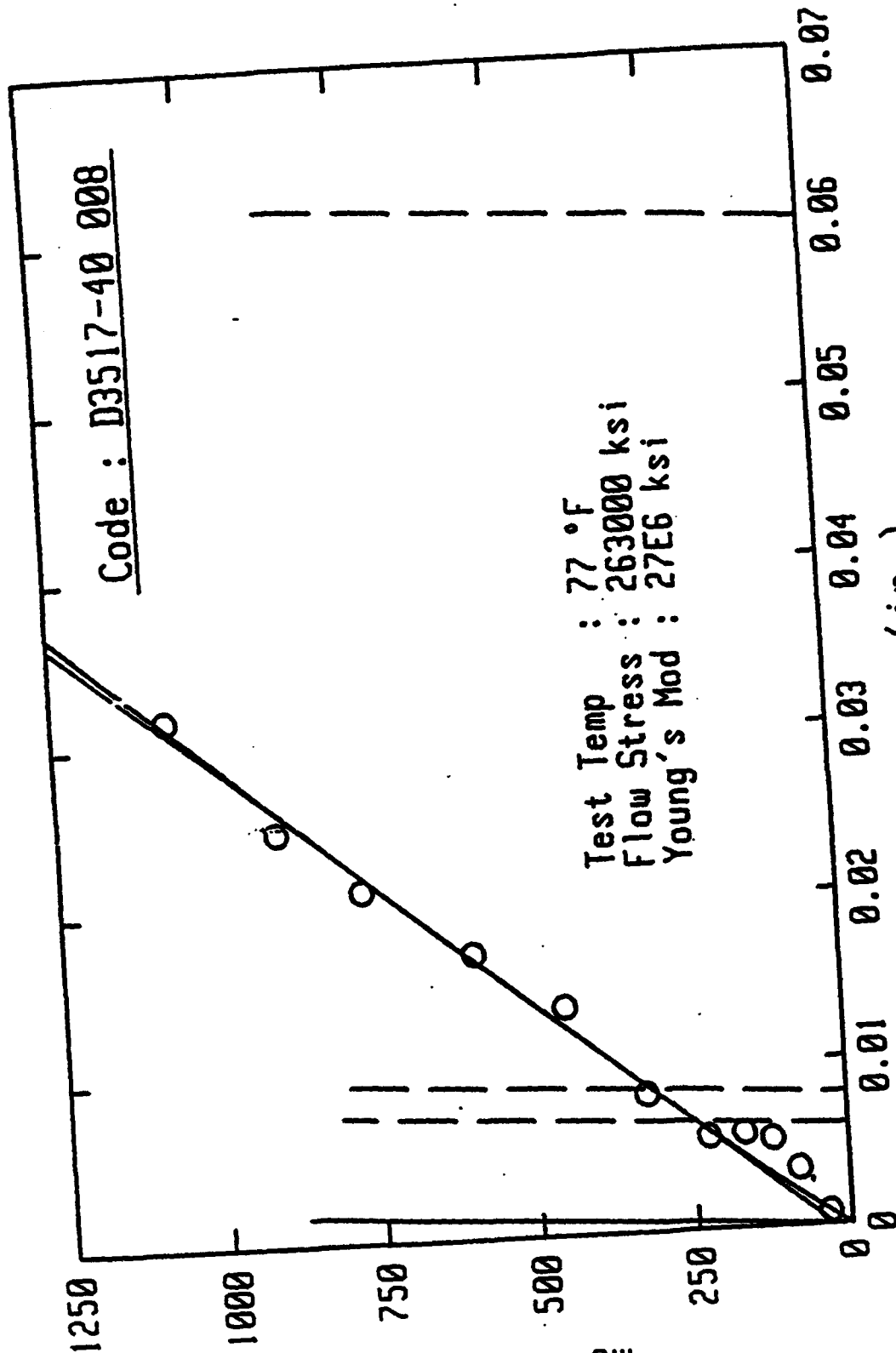
J_{mc} (in-lb/in^2)

Δa_p (in.)

Toughness J

Event	Load lb	Jac in-lb/in²	Jbt in-lb/in²	J(Kr) in-lb/in²	del-ap in.
1	2529	16.9	16.9	38.2	0.0000
2	3428	34.8	20.1	57.4	9.0008
3	5083	88.7	39.3	105.6	0.0035
4	6167	121.5	59.2	144.7	0.0053
5	7144	166.7	84.7	187.2	0.0057
6	8208	224.3	118.3	239.8	0.0055
7	9679	321.7	183.3	329.9	0.0082
8	11146	-447.8	271.7	443.6	0.0136
9	12550	588.7	382.0	579.7	0.0170
10	13835	763.8	516.2	738.9	0.0210
11	14658	896.8	628.3	867.5	0.0246
12	15442	1065.6	778.0	1031.1	0.0315

Pmax = 16288 (lb)
Net Stress = 238310 (psi)

Code : D3517-40W 006

J_{mc} (in-lb/in^2)

Δa_p (in.)

Test Temp   : 77 °F
Flow Stress   : 230000 ksi
Young's Mod   : 27E6 ksi
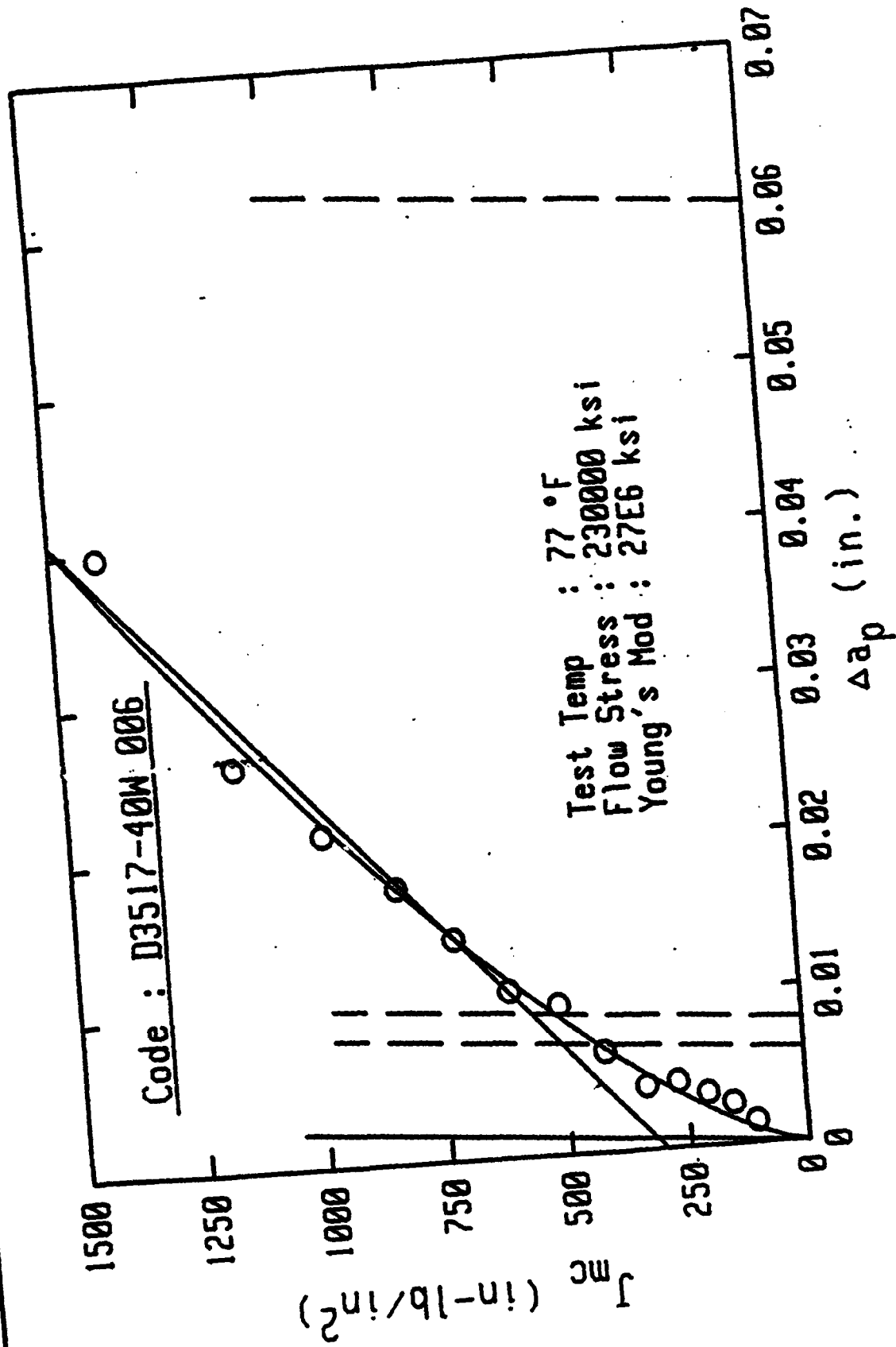
J_{pl} = 518.4 in-lb/in^2
K_{pl} = 118.3 ksi$\sqrt{in}$
   r = 0.9919

J_{Ic} = 319.3 in-lb/in^2
K_{Ic} = 92.8 ksi$\sqrt{in}$
   r = 0.9825

Thickness : 0.095 in.
Initial a : 0.298 in.

Toughness J

Event	Load lb	Jac in-lb/in²	Jbt in-lb/in²	J(Kr) in-lb/in²	del-ap in.
1-	2537	16.6	16.6	35.6	0.0000
2	3523	37.7	22.3	57.5	0.0000
3	4579	67.9	34.6	87.5	0.0000
4	5627	106.0	52.4	123.5	0.0015
5	6631	151.0	75.7	164.7	0.0027
6	7643	204.6	105.2	212.7	0.0034
7	8621	266.9	141.4	267.0	0.0042
8	9520	333.5	181.0	323.0	0.0041
9	10497	416.6	234.3	395.6	0.0064
10	11407	507.1	298.0	476.1	0.0096
11	12301	607.8	373.7	569.0	0.0106
12	13166	715.2	463.9	676.4	0.0141
13	13972	827.2	559.0	793.7	0.0176
14	14791	972.7	686.1	937.1	0.0212
15	15504	1149.0	850.3	1115.7	0.0258
16	16000	1401.3	1109.5	1372.8	0.0398

Pmax = 16100 (lb)
Net Stress = 239000 (psi)

Code : D3517-40M 007

Test Temp. : 77 °F
Flow Stress : 230000 ksi
Young's Mod : 27E6 ksi
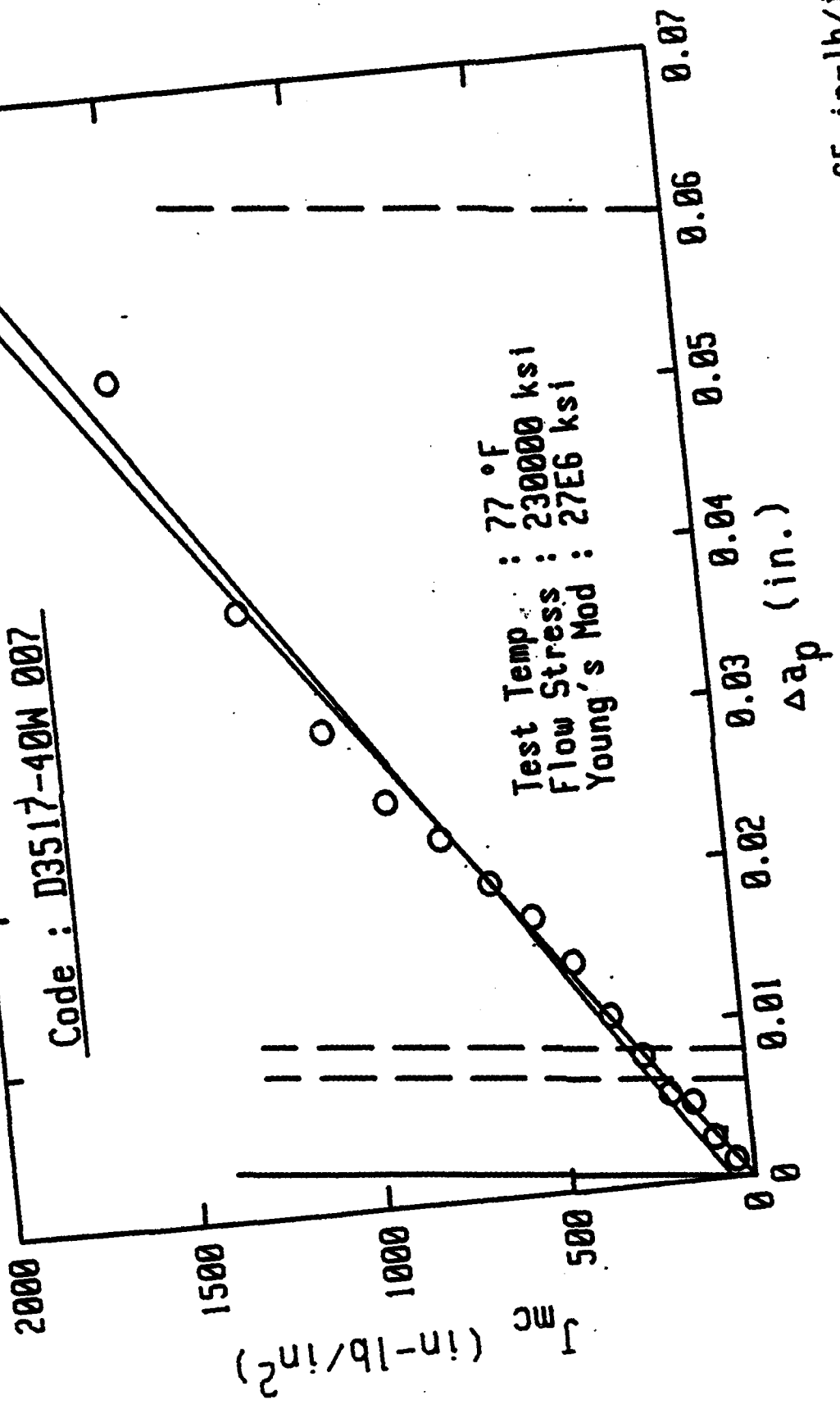
J_{pl} = 284 in-lb/in^2
K_{pl} = 87.6 ksi$\sqrt{in}$
r = 0.9938

J_{Ic} = 65 in-lb/in^2
K_{Ic} = 41.9 ksi$\sqrt{in}$
r = 0.9875

Thickness : 0.092 in.
Initial a : 0.2885 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

C-68

Toughness J

Event	Load lb	Jac in-lb/in²	Jbt in-lb/in²	J(Kr) in-lb/in²	del-ap in.
1	2449	15.8	15.8	35.1	0.0000
2	3602	46.5	22.7	61.8	0.0011
3	5008	98.7	41.3	105.5	0.0026
4	6078	148.2	68.3	144.6	0.0049
5	7134	208.6	86.9	191.2	0.0055
6	8146	273.1	120.1	243.5	0.0080
7	9141	350.9	165.4	306.7	0.0107
8	10097	439.2	220.9	379.6	0.0142
9	11043	538.0	283.3	461.4	0.0171
10	11920	647.0	354.5	551.3	0.0194
11	12778	767.1	436.9	653.6	0.0225
12	13615	901.8	540.7	777.2	0.0250
13	14373	1055.7	659.6	915.8	0.0297
14	15033	1251.0	829.9	1099.0	0.0376
15	15476	1548.2	1115.9	1383.4	0.0525

Pmax = 15400 (lb)
Net Stress = 239810 (psi)

Code : D3517-40W 008
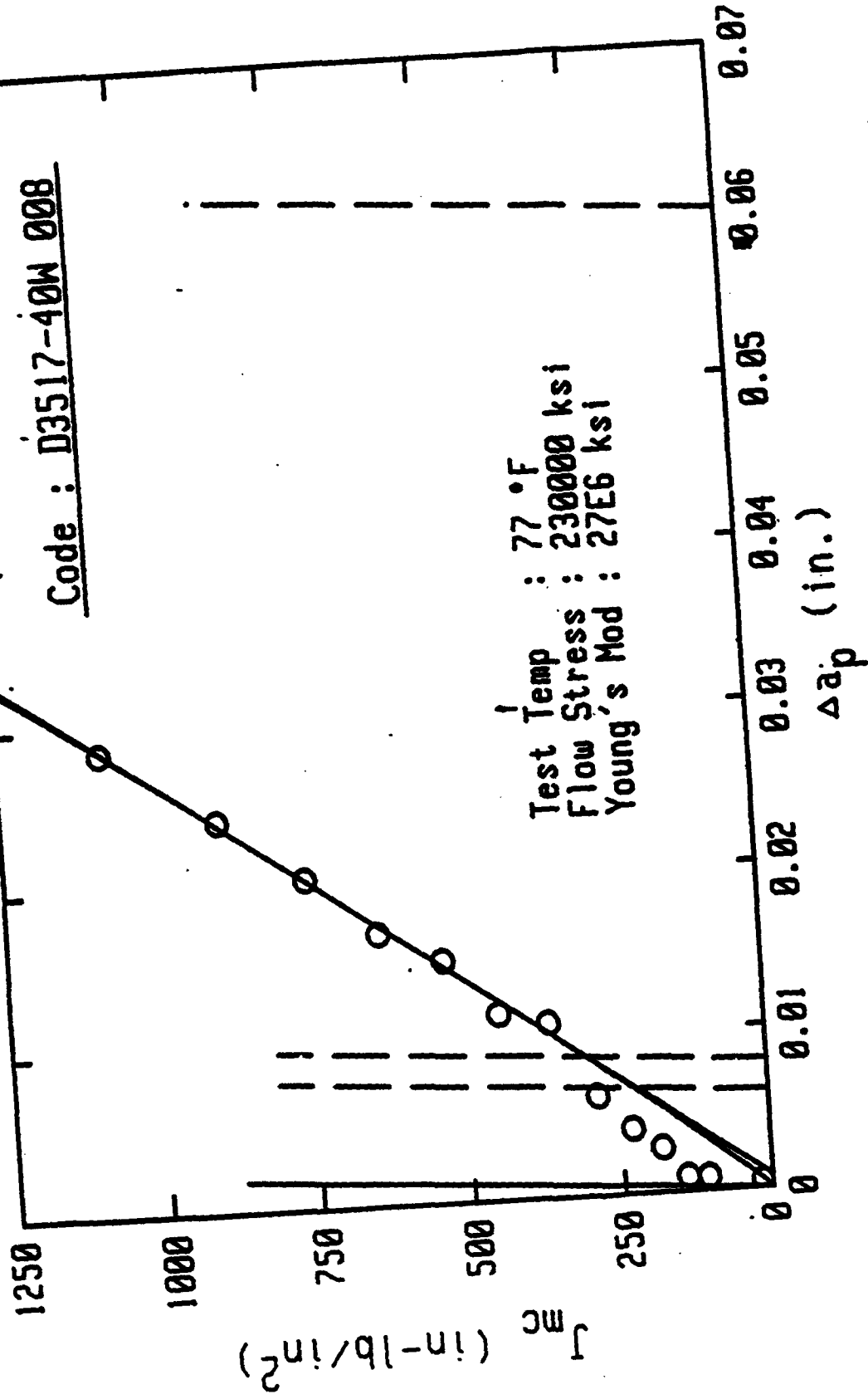
J_{mc} (in-lb/in^2)

1250
1000
750
500
250
0

0   0.01   0.02   0.03   0.04   0.05   0.06   0.07

Δa_p (in.)

Test Temp   : 77 °F
Flow Stress : 230000 ksi
Young's Mod : 27E6 ksi

J_{pl} = 303.6 in-lb/in^2
K_{pl} = 90.5 ksi$\sqrt{in}$
    r = 0.9936

J_{Ic} = -32.9 in-lb/in^2
K_{Ic} = 0 ksi$\sqrt{in}$
    r = 0.9971

Thickness : 0.095 in.
Initial a : 0.2915 in.

Toughness J

Event	Load lb	Jac in-lb/in²	Jbt in-lb/in²	J(Kr) in-lb/in²	del-ap in.
1	2529	16.0	16.0	38.3	0.0004
2	3545	31.9	23.8	51.1	0.0008
3	4469	50.9	35.3	74.8	0.0006
4	5513	77.3	54.7	100.0	0.0009
5	6498	106.3	78.0	144.9	0.0009
6	7493	141.0	107.4	188.8	0.0009
7	8491	182.2	142.5	238.7	0.0027
8	9491	229.7	185.4	296.7	0.0040
9	10432	286.6	236.2	361.2	0.0061
10	11384	361.0	304.4	441.9	0.0107
11	12292	443.0	381.9	532.4	0.0114
12	13158	530.1	464.2	629.9	0.0148
13	13998	634.0	558.5	740.8	0.0167
14	14790	751.1	672.3	870.1	0.0202
15	15525	892.0	813.5	1025.8	0.0240
16	16125	1000.7	1006.2	1225.4	0.0268

Pmax = 16588 (lb)
Net Stress = 234670 (psi)

Code : D3517-40W-009

Test Temp : 77 °F
Flow Stress : 263000 ksi
Young's Mod : 27E6 ksi

J_{pl} = 687 in-lb/in^2
K_{pl} = 136.2 ksi√in
r = 0.9925
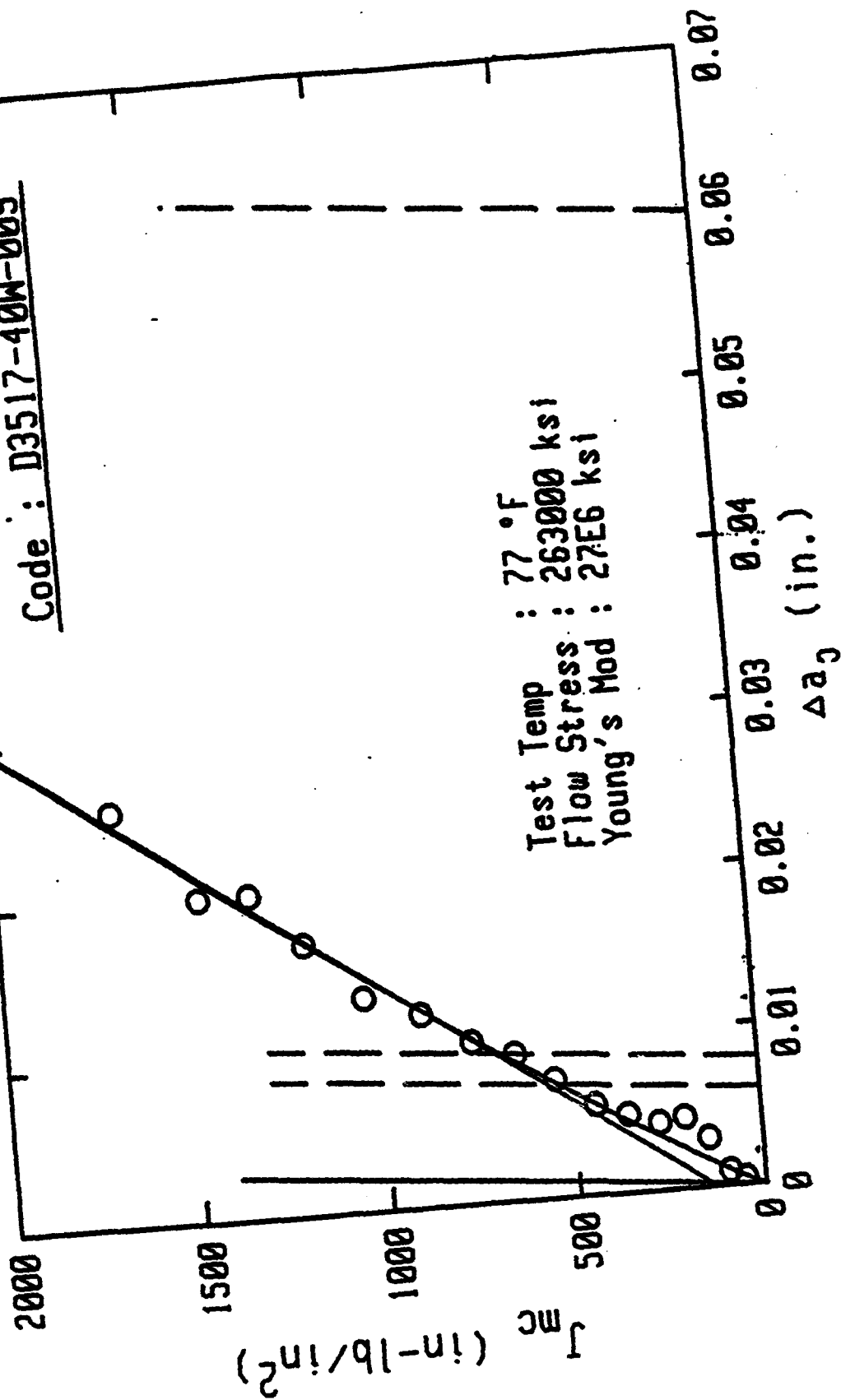
J_{Ic} = 148.9 in-lb/in^2
K_{Ic} = 63.4 ksi√in
r = 0.9896

Thickness : 0.094 in.
Initial a : 0.294 in.

J_{mc} (in-lb/in^2)

Δa_c (in.)

C-72

Toughness J

Event	Load lb	Jac in-lb/in^2	Jbt in-lb/in^2	J(Kr) in-lb/in^2	del-ap in.
1	2530	16.6	16.6	41.6	0.0000
2	4021	50.6	25.8	78.4	0.0005
3	5165	93.3	39.7	115.5	0.0010
4	6292	146.3	61.1	159.3	0.0031
5	7360	207.0	88.1	208.0	0.0044
6	8373	275.4	120.8	261.0	0.0042
7	9447	356.6	162.0	325.8	0.0049
8	10420	448.7	206.2	391.4	0.0056
9	11522	545.6	264.6	475.0	0.0073
10	12441	647.3	323.5	555.3	0.0091
11	13351	759.5	392.4	646.0	0.0100
12	14262	888.9	476.6	752.4	0.0119
13	15149	1036.6	580.7	878.6	0.0132
14	16015	1186.6	687.8	1012.7	0.0167
15	16642	1320.8	798.7	1141.6	0.0200
16	17130	1459.0	916.8	1273.5	0.0200
17	17630	1675.1	1119.8	1489.2	0.0257

Pmax = 17880 (1h)
Net Stress = .255660 (psi)

Code : D3517-40M 001

Test Temp : 77 °F
Flow Stress : 190000 ksi
Young's Mod : 27E6 ksi

J_{pl} = 381.8 $\frac{in\text{-}lb/in^2}{}$
K_{pl} = 101.5 ksi$\sqrt{in}$
r = 0.9901
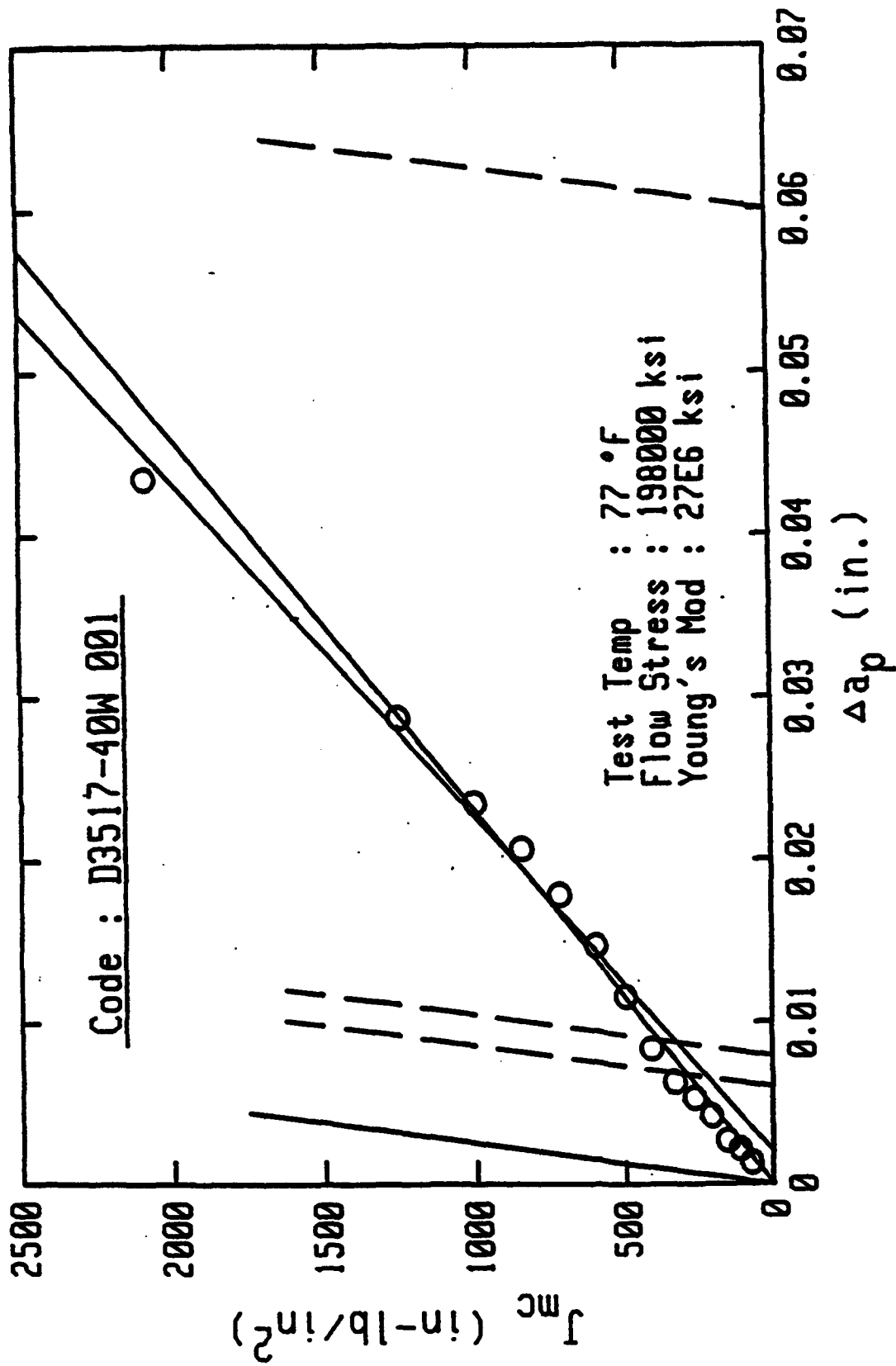
J_{Ic} = -109.2 $\frac{in\text{-}lb/in^2}{}$
K_{Ic} = 0 ksi$\sqrt{in}$
r = 0.9935

Thickness : 0.095 in.
Initial a : 0.288 in.

Toughness J

Event	Load lb	Jac in-lb/in²	Jbt in-lb/in²	J(Kr) in-lb/in²	del-ap in.
1	2516	15.5	15.5	37.9	0.0000
2	3543	39.5	18.8	60.9	0.0000
3	4523	72.2	27.5	88.8	0.0013
4	5522	111.2	41.2	122.8	0.0021
5	6467	155.3	59.2	168.5	0.0027
6	7446	207.6	82.9	205.2	0.0042
7	8387	265.5	113.0	255.5	0.0053
8	9320	332.4	151.2	313.8	0.0063
9	10190	407.6	198.2	379.0	0.0083
10	11030	495.0	260.4	457.6	0.0115
11	11835	595.2	337.1	550.0	0.0146
12	12605	715.3	434.8	662.8	0.0178
13	13300	840.5	536.1	782.1	0.0206
14	13964	997.2	665.8	938.8	0.0234
*15	14350	1250.0	912.5	1175.4	0.0297
16	14254	2001.6	1747.7	2044.8	0.0434

Pmax = 14600 (lb)
Net Stress = 213718 (psi)

$*K_c$ determined at this event.

Code : D3517-40W 002
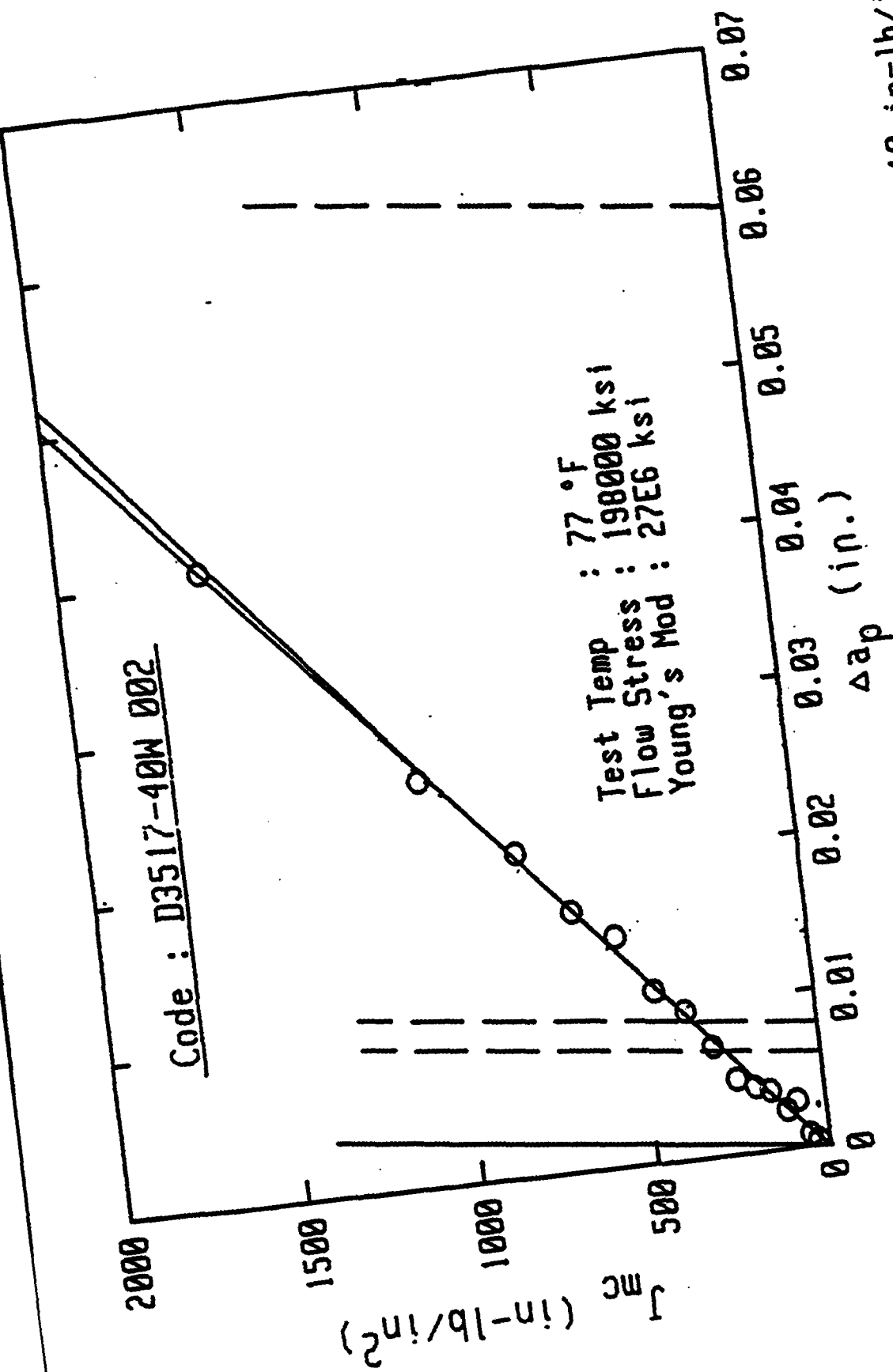
Test Temp : 77 °F
Flow Stress : 190000 ksi
Young's Mod : 27E6 ksi

J_{Ic} = 10 in-lb/in^2
K_{Ic} = 16.4 ksi$\sqrt{in}$
r = 0.9988

J_{pl} = 359 in-lb/in^2
K_{pl} = 98.5 ksi$\sqrt{in}$
r = 0.9972

Thickness : 0.093 in.
Initial a : 0.289 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

Toughness J

Event	Load lb	Jac in-lb/in^2	Jbt in-lb/in^2	J(Kr) in-lb/in^2	del-ap in.
1	2590	17.2	17.2	39.4	0.0000
2	3459	29.8	19.9	58.2	0.0004
3	4458	50.9	29.1	85.7	0.0008
4	5396	78.4	43.4	117.4	0.0030
5	6316	110.2	62.5	153.9	0.0025
6	7341	152.4	89.7	201.0	0.0038
7	8211	193.5	117.8	246.5	0.0042
8	9163	246.3	154.4	302.7	0.0048
9	10065	306.2	202.0	367.5	0.0070
10	10948	374.0	259.4	441.0	0.0095
11	11797	453.7	329.1	527.6	0.0110
12	12613	546.1	411.0	626.3	0.0146
13	13379	663.2	520.6	748.0	0.0165
14	14066	803.5	651.8	898.9	0.0206
*15	14681	1052.6	898.7	1130.3	0.0258
16	14912	1600.8	1433.1	1668.5	0.0420

Pmax = 15000 (lb)
Net Stress = 222700 (psi)

K_c determined at this event.
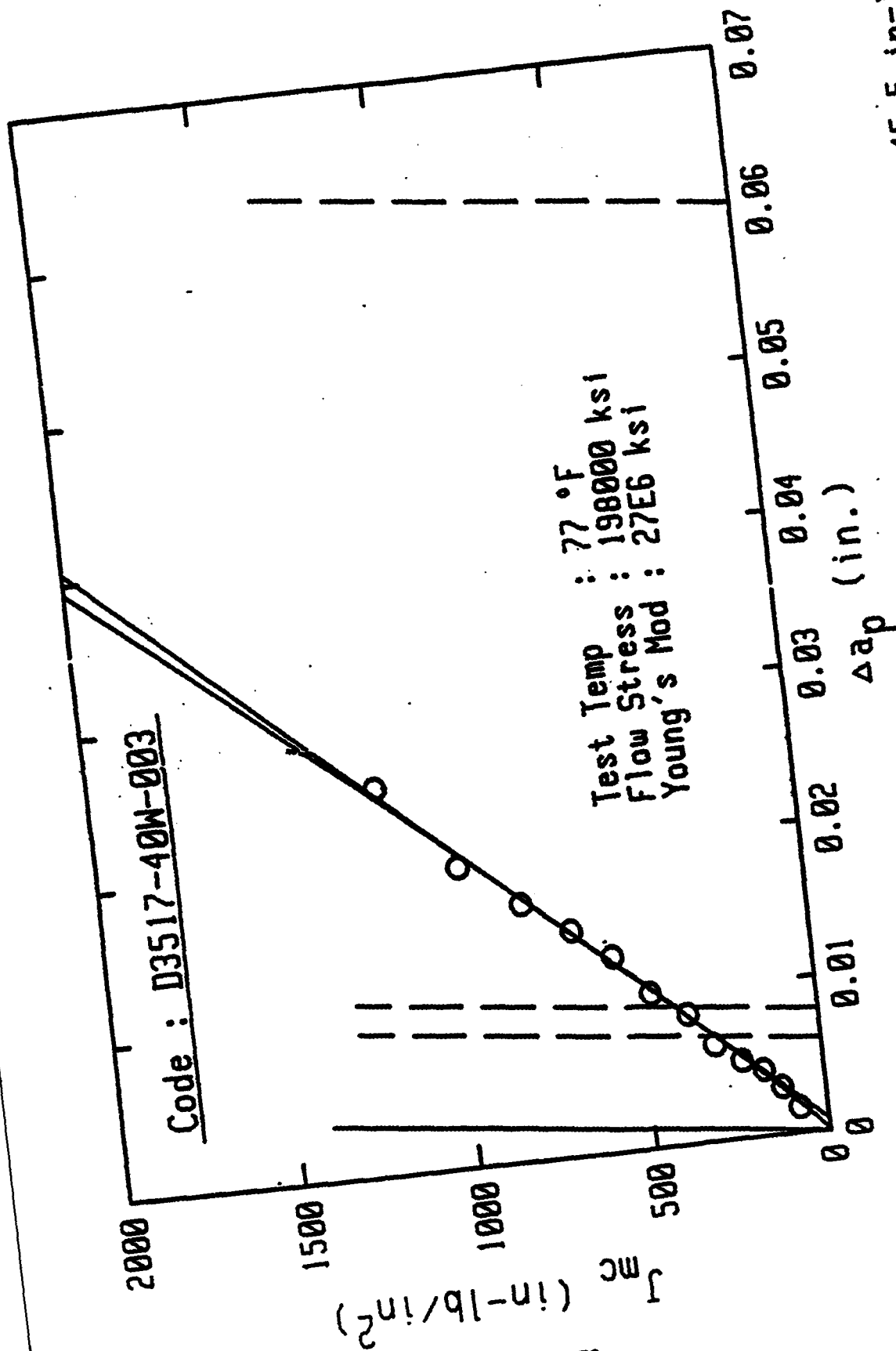
Code : D3517-40M-003

Test Temp   : 77 °F
Flow Stress   : 198000 ksi
Young's Mod   : 27E6 ksi

$J_{pl} = 403.2$ in-lb/in^2
$K_{pl} = 104.3$ ksi$\sqrt{in}$
$r = 0.9967$

$J_{Ic} = -45.5$ in-lb/in^2
$K_{Ic} = 0$ ksi$\sqrt{in}$
$r = 0.9959$

Thickness : 0.093 in.
Initial a : 0.298 in.

C-78

Toughness J

Event	Load lb	Jac in-lb/in^2	Jbt in-lb/in^2	J(Kr) in-lb/in^2	del-ap in.
1	2500	17.0	17.0	40.1	0.0000
2	3560	42.4	22.8	66.6	0.0000
3	4600	78.2	34.4	99.3	0.0016
4	5626	122.5	53.2	139.8	0.0030
5	6600	170.1	75.9	184.4	0.0042
6	7500	229.4	106.8	237.8	0.0050
7	8572	302.8	148.9	303.0	0.0062
8	9300	369.2	191.0	365.4	0.0083
9	10330	470.6	254.4	452.7	0.0099
10	11140	566.4	324.2	544.3	0.0126
11	11933	675.2	407.7	651.6	0.0145
12	12667	808.4	511.7	779.1	0.0166
13	13319	974.0	661.2	949.1	0.0193
14	13856	1182.6	861.5	1172.3	0.0249

Pmax = 14100 (lb)
Net Stress = 206520 (psi)

Code : D3517-40-001
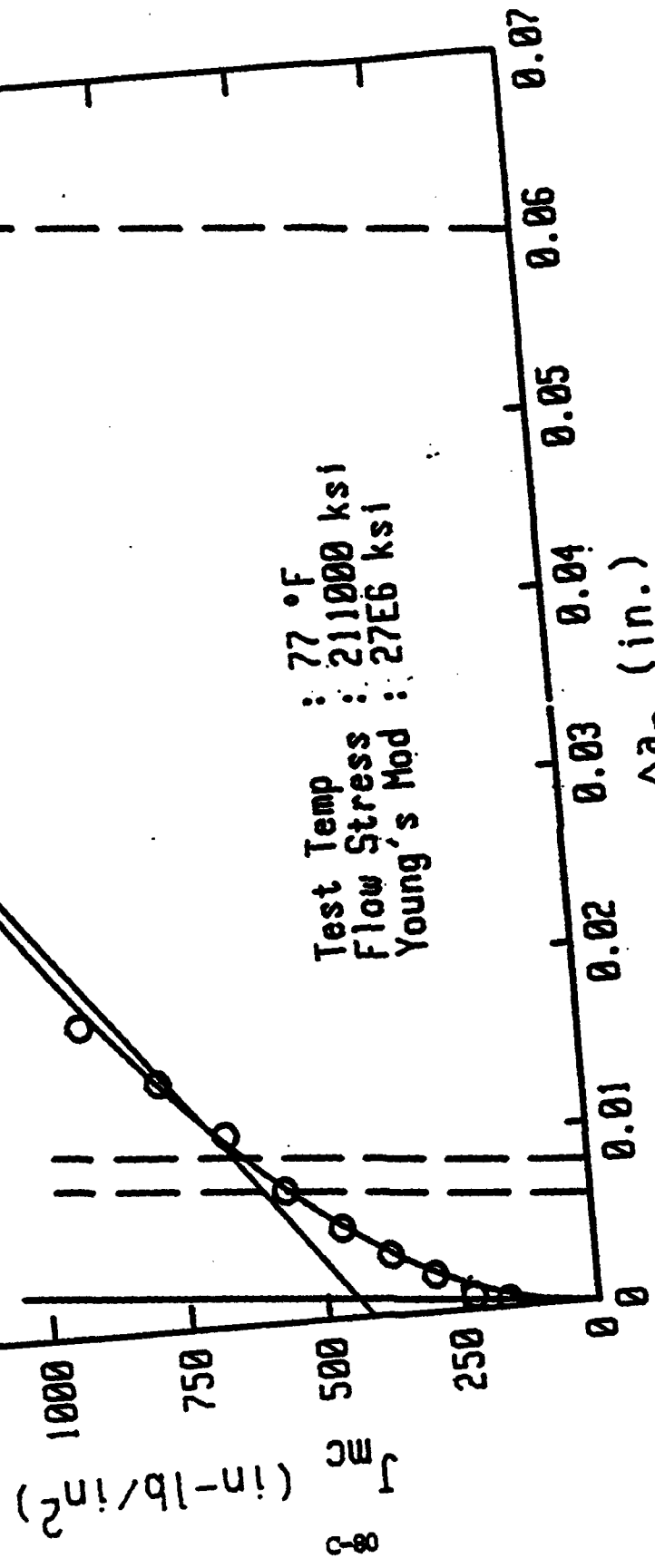
Test Temp : 77 °F
Flow Stress : 211000 ksi
Young's Mod : 27E6 ksi

J_{pl} = 634.4 in-lb/in^2
K_{pl} = 130.9 ksi$\sqrt{in}$
r = 0.9976

J_{Ic} = 443 in-lb/in^2
K_{Ic} = 109.4 ksi$\sqrt{in}$
r = 0.9869

Thickness : 0.092 in.
Initial a : 0.286 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

C-80

Toughness J

Event	Load lbs	Jac in-lbs/in²	Jbt in-lbs/in²	J(Kr) in-lbs/in²	del-ap in.
1	-2513	16.4	16.4	37.0	0.0000
2	4011	57.6	25.4	73.2	0.0000
3	5049	106.2	40.5	107.4	0.0000
4	6091	163.9	60.8	148.0	0.0004
5	7070	227.3	87.8	194.2	0.0008
6	8027	296.4	117.0	244.0	0.0021
7	8966	375.2	154.4	301.5	0.0034
8	9875	461.4	197.6	364.9	0.0050
9	10039	561.0	250.1	446.1	0.0074
10	11693	663.0	323.0	530.7	0.0107
11	12516	776.5	402.2	627.0	0.0139
12	13311	909.4	503.0	746.0	0.0174
13	14025	1066.7	633.3	889.7	0.0241
14	14600	1272.2	821.6	1002.7	0.0357

Pmax = 14700 (lbs)
Net_Stress = 216630 (psi)

Code : D3517-40-002

Test Temp : 77 °F
Flow Stress : 211000 ksi
Young's Mod : 27E6 ksi

J_{Ic} = 79.2 in-lb/in^2
K_{Ic} = 46.2 ksi√in
r = 0.9853
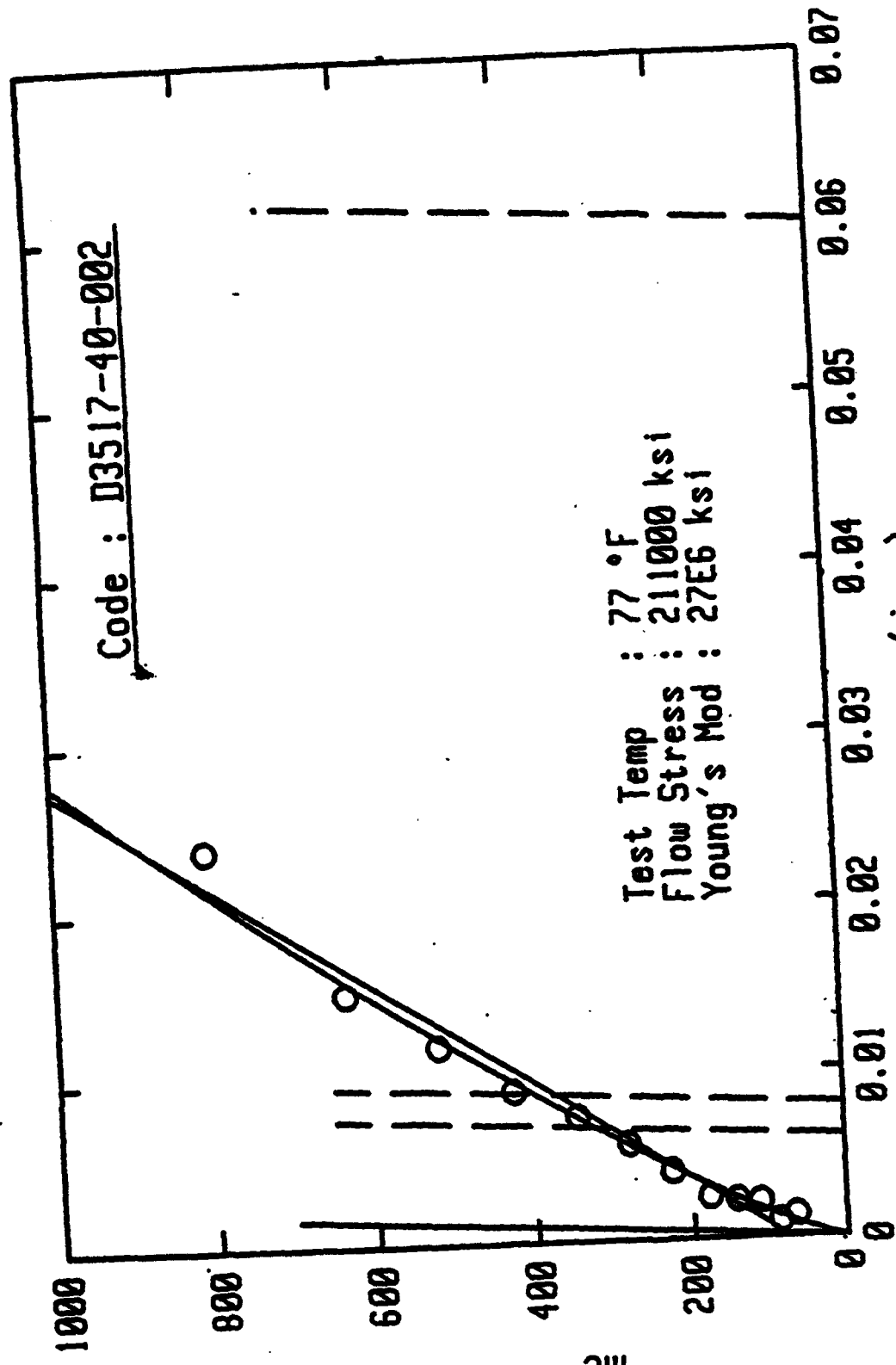
J_{pl} = 396.7 in-lb/in^2
K_{pl} = 103.3 ksi√in
r = 0.9836

Thickness : 0.093 in.
Initial a : 0.298 in.

J_{mc} (in-lb/in^2)

1000
800
600
400
200
0

0   0.01   0.02   0.03   0.04   0.05   0.06   0.07

Δa_p (in.)

C-82

Toughness J

Event	Load lbs	Jac in-lbs/in²	Jbt in-lbs/in²	J(Kr) in-lbs/in²	del-ap in.
1	.5262	63.4	41.4	120.2	0.0014
2	6229	85.5	60.2	159.6	0.0010
3	7161	109.6	83.8	203.4	0.0022
4	8101	139.8	113.7	254.0	0.0023
5	9022	175.9	149.6	310.4	0.0025
6	9921	223.5	195.1	374.9	0.0041
7	10790	277.9	248.9	447.0	0.0057
8	11644	342.7	314.9	530.1	0.0074
9	12487	423.3	397.0	628.1	0.0098
10	13274	515.5	491.4	737.1	0.0117
11	14016	631.3	611.4	867.8	0.0158
12	14602	803.4	789.8	1039.0	0.0237

Pmax = 14940 (lbs)
Net Stress = 218100 (psi)

Code : D3517-40-003

Test Temp   : 77 °F
Flow Stress   : 211000 ksi
Young's Mod   : 27E6 ksi
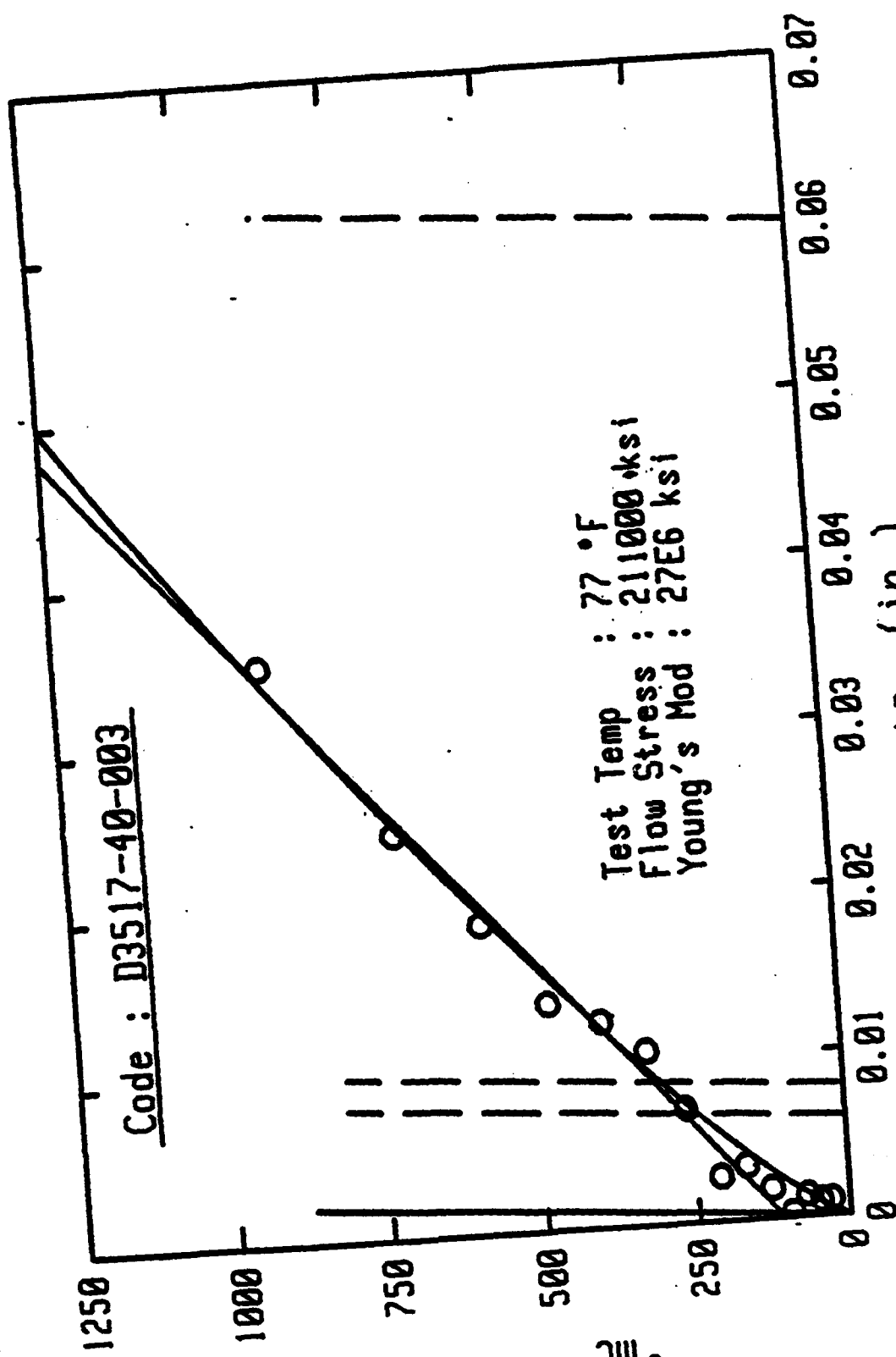
J_{pl} = 300.8 in-lb/in^2
K_{pl} = 90.1 ksi$\sqrt{in}$
r = 0.991

J_{Ic} = 115.5 in-lb/in^2
K_{Ic} = 55.8 ksi$\sqrt{in}$
r = 0.9913

Thickness : 0.093 in.
Initial a : 0.291 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

Toughness J

Event	Load lbs	Jac in-lbs/in²	Jbt in-lbs/in²	J(Kr) in-lbs/in²	del-ap in.
1	3586	28.7	18.4	61.5	0.0018
2	4547	46.4	26.8	88.2	0.0009
3	5470	67.7	39.3	118.3	0.0013
4	6373	93.4	56.8	152.8	0.0003
5	7253	125.1	79.3	191.7	0.0018
6	8135	165.3	107.8	236.4	0.0033
7	9062	208.3	145.4	290.7	0.0027
8	9958	260.6	192.0	352.5	0.0069
9	10791	320.6	245.1	419.4	0.0105
10	11580	392.8	310.0	495.7	0.0124
11	12421	477.5	390.7	589.4	0.0137
12	13164	578.8	486.5	693.8	0.0187
13	13865	710.6	607.2	820.1	0.0244
14	14328	912.1	816.0	1004.7	0.0349

Pmax = 14440 (lbs)
Net_Stress = 212910 (psi)

Code : D3517-40W-004

Test Temp : 77 °F
Flow Stress : 211000 ksi
Young's Mod : 27E6 ksi
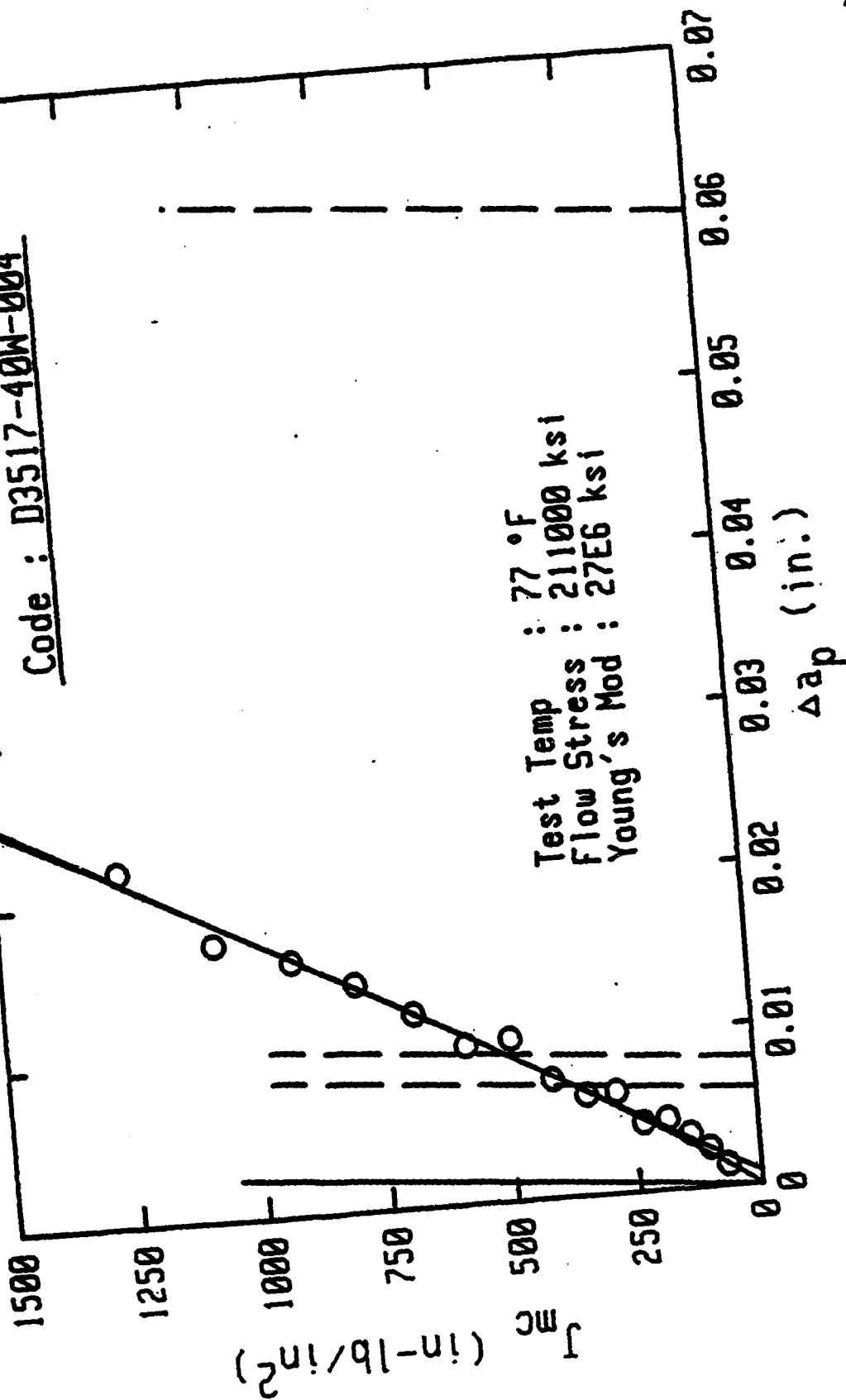
J_{pl} = 502.4 in-lb/in^2
K_{pl} = 116.5 ksi√in
r = 0.9857

J_{Ic} = -58.7 in-lb/in^2
K_{Ic} = 0 ksi√in
r = 0.9881

Thickness : 0.093 in.
Initial a : 0.289 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

Toughness J

Event	Load lbs	Jac in-lbs/in²	Jbt in-lbs/in²	J(Kr) in-lbs/in²	del-ap in.
1	2530	16.5	16.5	56.6	0.0000
2	3600	37.6	14.8	83.9	0.0000
3	4525	65.2	19.3	114.3	0.0013
4	5418	99.8	27.3	147.6	0.0024
5	6344	137.3	39.7	186.7	0.0034
6	7222	182.2	52.7	225.6	0.0044
7	8136	232.5	74.2	273.4	0.0043
8	8996	283.8	100.3	324.2	0.0063
9	9928	346.6	134.0	385.8	0.0062
10	10736	411.8	167.5	442.6	0.0073
11	11583	492.5	210.5	518.7	0.0100
12	12423	582.4	273.0	595.9	0.0098
13	13173	681.0	331.1	676.9	0.0120
14	13930	793.9	419.2	785.1	0.0140
15	14670	918.3	519.1	908.2	0.0157
16	15330	1070.8	644.9	1053.6	0.0177
17	15911	1253.3	793.5	1223.1	0.0219

Pmax = 16180 (lbs)
Net Stress = 228020 (psi)

Code : D3517-40W-005

Test Temp : 77 °F
Flow Stress : 211000 ksi
Young's Mod : 27E6 ksi
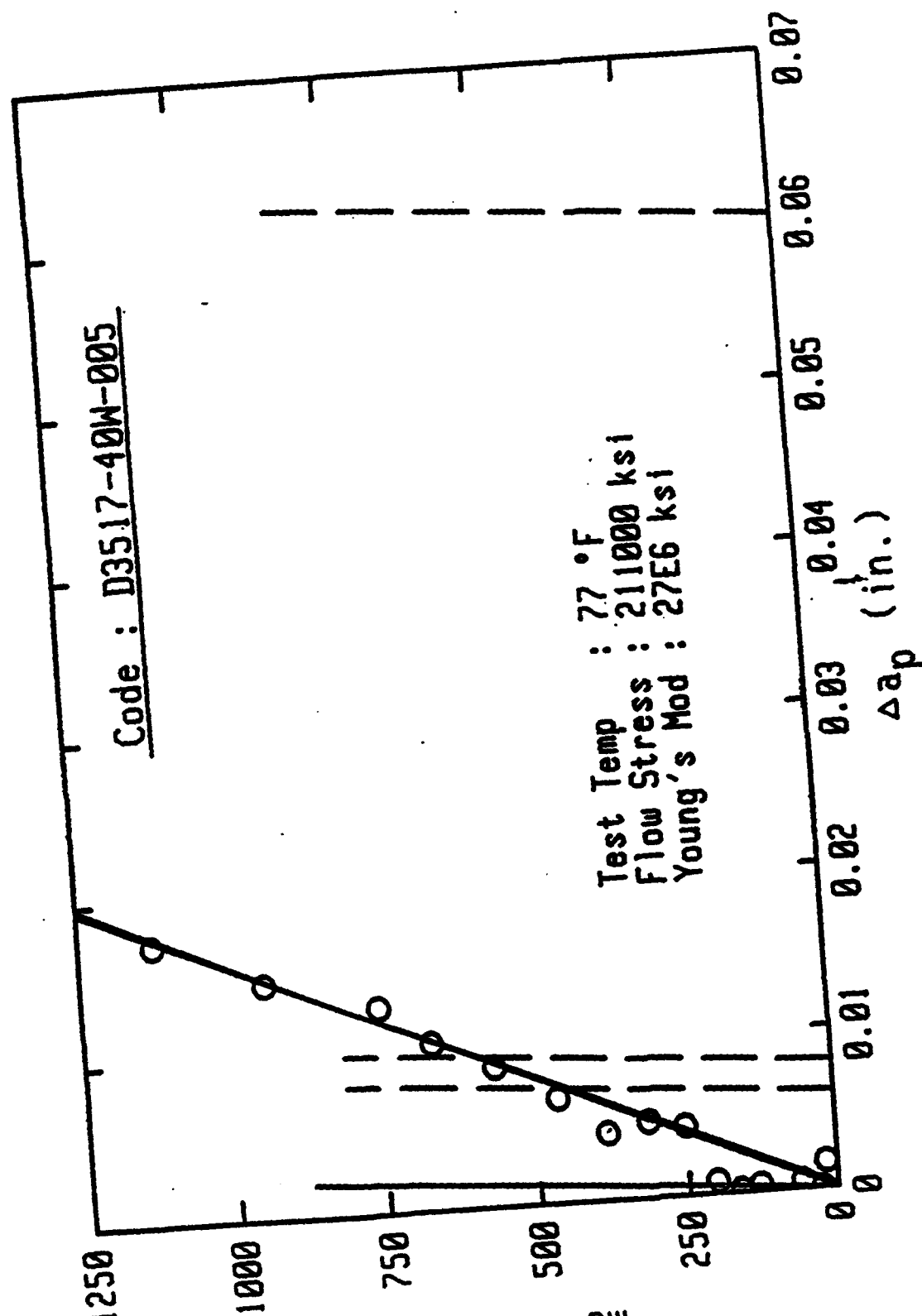
J_{pl} = 593.6 in-lb/in^2
K_{pl} = 126.6 ksi$\sqrt{in}$
r = 0.9871

J_{Ic} = -16.2 in-lb/in^2
K_{Ic} = 0 ksi$\sqrt{in}$
r = 0.988

Thickness : 0.093 in.
Initial a : 0.287 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

C-88

Toughness J

Event	Load lbs	Jac in-lbs/in²	Jbt in-lbs/in²	J(Kr) in-lbs/in²	del-ap in.
1	2530	16.3	16.3	39.3	0.0016
2	3470	24.0	18.0	59.6	0.0000
3	4353	41.1	24.1	83.1	0.0000
4	5270	57.3	35.1	112.2	0.0005
5	6215	74.6	51.6	147.3	0.0000
6	7119	97.9	72.7	186.2	0.0000
7	8051	128.0	100.2	232.0	0.0004
8	8968	160.8	132.6	282.7	0.0002
9	9863	201.4	172.6	339.9	0.0008
10	10729	258.5	219.1	402.8	0.0043
11	11624	311.6	279.5	479.1	0.0047
12	12453	380.6	344.4	559.2	0.0042
13	13250	461.8	425.9	652.8	0.0065
14	14035	563.8	525.2	763.1	0.0086
15	14690	664.8	622.6	870.2	0.0103
16	15113	747.9	701.5	953.6	0.0122
17	15657	937.5	895.0	1134.3	0.0145
18	16028	1122.1	1086.5	1313.3	0.0172

rmax = 16000 (lbs)
Net Stress = 222980 (psi)
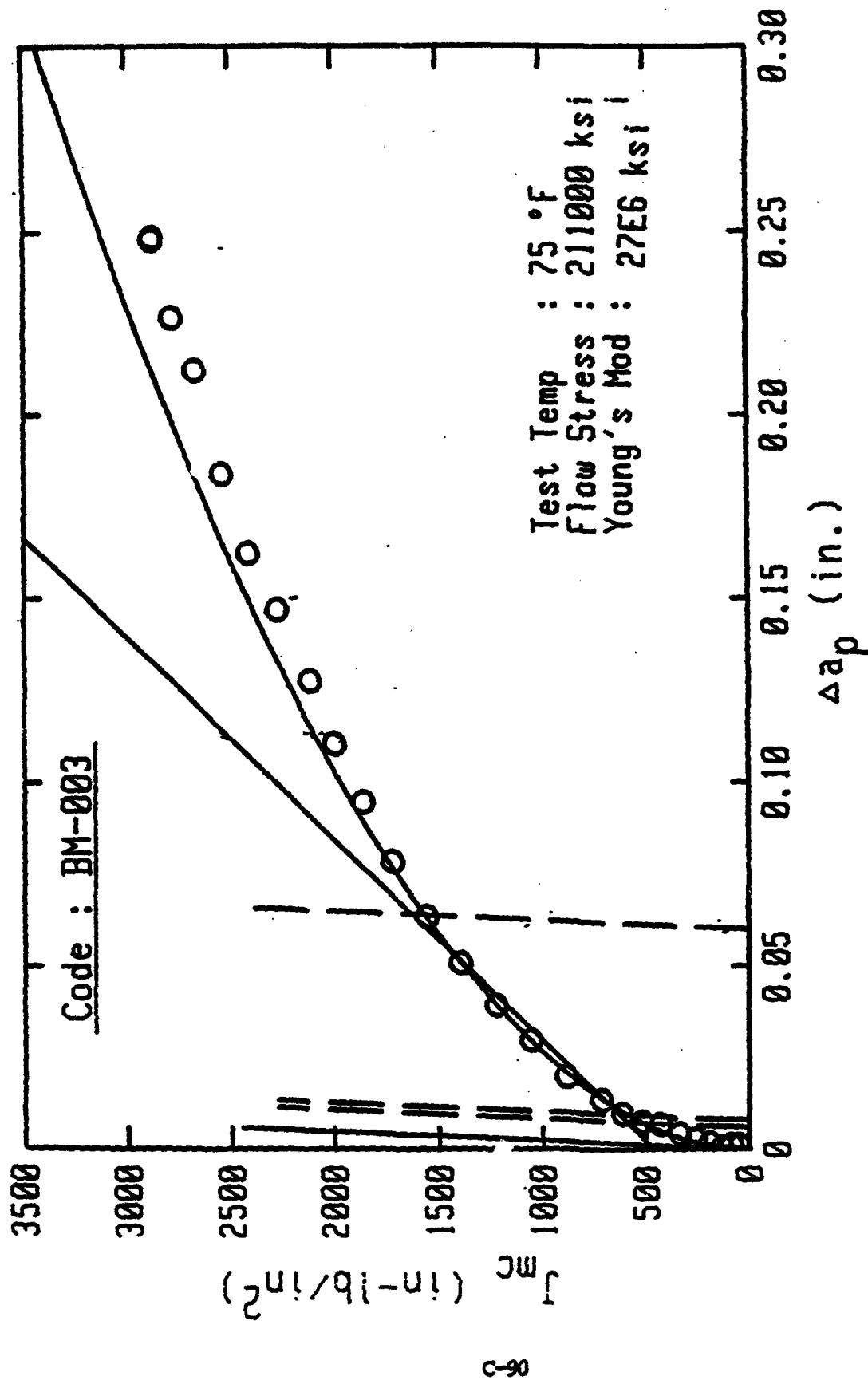
C-89

Code : BM-003

Test Temp   : 75 °F
Flow Stress   : 211000 ksi
Young's Mod   : 27E6 ksi

Δa_p (in.)

J_{mc} (in-lb/in^2)

Thickness : 0.09 in.
Initial a : 0.523 in.

$J_{pl} = 591.5$ in-lb/in^2
$K_{pl} = 132.9$ ksi$\sqrt{in}$
$r = 0.9991$

$J_{Ic} = 483.6$ in-lb/in^2
$K_{Ic} = 120.2$ ksi$\sqrt{in}$
$r = 0.9897$

C-90

Toughness J

Event	Load lb	Jac in-lb/in²	B in-lb/in²	Ja in-lb/in²	del-ap in.
1	295	38.8	43.3	43.7	0.0011
2	415	77.9	85.5	87.6	0.0013
3	517	123.7	132.5	139.0	0.0006
4	621	183.7	192.4	205.2	0.0018
5	712	251.6	255.0	279.5	0.0029
6	794	331.3	319.6	365.6	0.0043
7	865	426.0	385.9	465.6	0.0069
8	926	514.3	444.2	560.6	0.0075
9	980	613.9	504.6	665.0	0.0096
10	1022	715.2	562.1	760.1	0.0134
11	1047	885.1	639.5	939.1	0.0197
12	1005	1056.0	707.5	1103.4	0.0296
13	1079	1222.9	748.9	1263.3	0.0392
14	1063	1394.2	789.9	1425.1	0.0507
15	1014	1554.4	788.2	1572.2	0.0632
16	969	1715.0	807.0	1720.7	0.0781
17	891	1856.3	777.6	1843.6	0.0943
18	832	1992.0	775.4	1969.9	0.1103
19	777	2113.9	787.1	2081.6	0.1274
20	688	2271.6	738.6	2242.4	0.1466
21	634	2409.4	731.6	2397.8	0.1621
22	548	2537.6	684.6	2531.8	0.1837
23	463	2669.9	676.6	2671.5	0.2119
24	398	2782.0	597.5	2826.0	0.2262
25	338	2876.9	549.0	2948.0	0.2481
26	316	2879.0	502.9	2948.9	0.2479
27	315	2879.0	497.0	2950.0	0.2473

Pmax = 1096 lb

Code : BM-008

Test Temp   : 75 °F
Flow.Stress : 263000 ksi
Young's Mod :   27E6 ksi

$J_{pl} = 882.8$ in-lb/in^2
$K_{pl} = 162.3$ ksi$\sqrt{in}$
$r = 0.9977$

$J_{Ic} = 730.9$ in-lb/in^2
$K_{Ic} = 147.7$ ksi$\sqrt{in}$
$r = 0.9885$
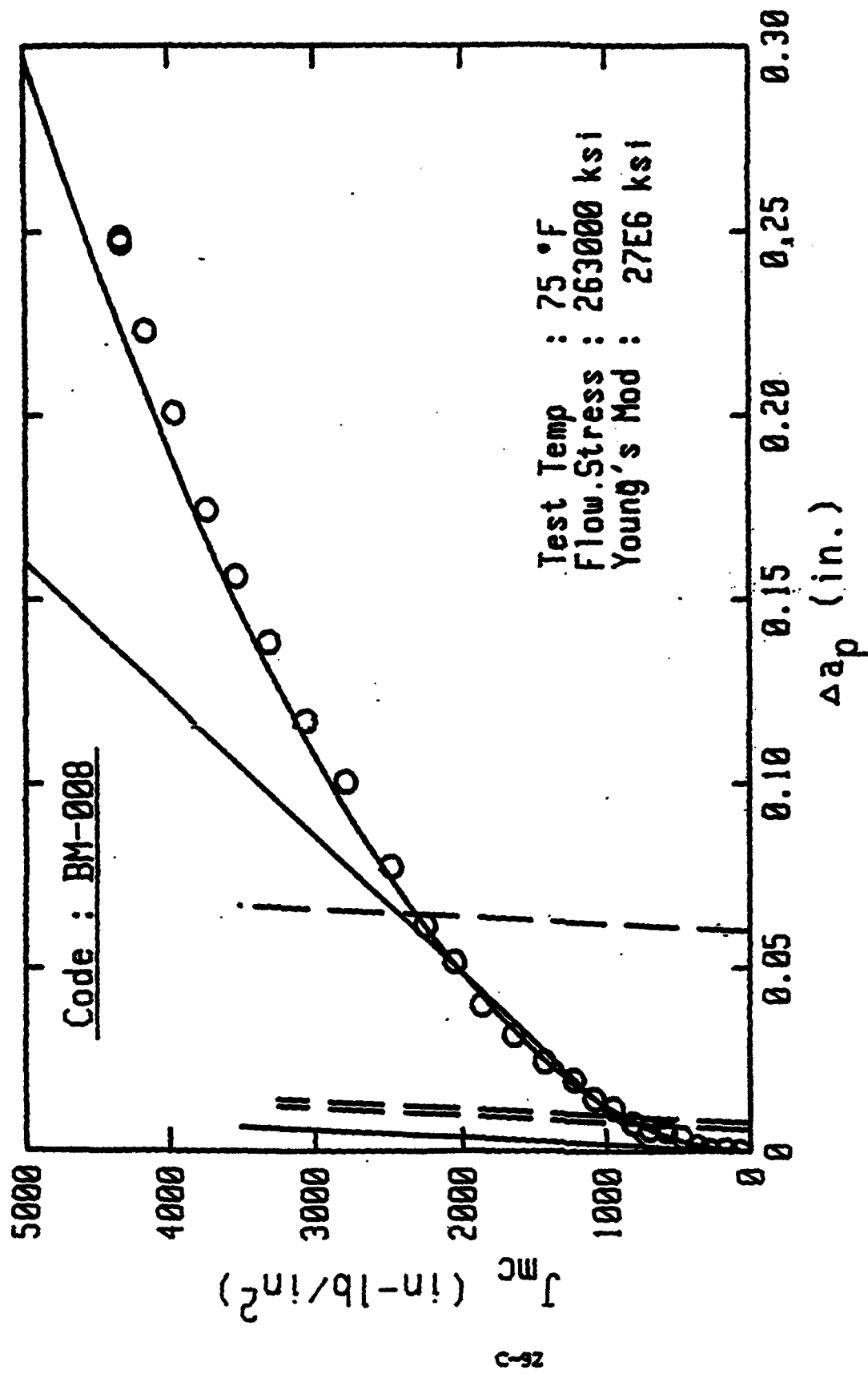
Thickness : 0.09 in.
Initial a : 0.5189 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

C-92

Toughness J

Event	Load lb	Jac in-lb/in²	G in-lb/in²	Ja in-lb/in²	del-ap in.
1	292	33.9	48.7	48.7	0.0000
2	396	63.1	75.3	75.6	0.0000
3	586	104.6	122.8	125.1	0.0000
4	619	158.9	185.0	189.5	0.0005
5	704	209.3	238.1	249.3	0.0000
6	797	274.5	305.4	325.5	0.0003
7	896	358.9	389.4	422.8	0.0014
8	992	467.3	485.2	544.3	0.0039
9	1074	576.8	574.7	666.9	0.0056
10	1141	696.6	658.4	799.5	0.0061
11	1199	811.5	725.5	925.1	0.0076
12	1252	945.1	812.0	1065.5	0.0116
13	1299	1077.1	888.9	1206.4	0.0142
14	1332	1216.5	967.1	1347.8	0.0194
15	1371	1421.2	1059.6	1540.7	0.0242
16	1384	1639.8	1133.4	1777.6	0.0315
17	1385	1861.0	1202.1	1996.2	0.0397
18	1331	2046.7	1200.1	2156.1	0.0514
19	1295	2244.1	1228.7	2342.8	0.0612
20	1221	2472.5	1231.9	2544.7	0.0772
21	1108	2776.9	1222.6	2822.1	0.1003
22	1020	3050.0	1190.0	3100.5	0.1167
23	905	3301.0	1134.0	3346.5	0.1381
24	820	3521.6	1103.1	3584.5	0.1560
25	722	3723.3	1028.9	3806.6	0.1741
26	599	3958.9	944.3	4078.5	0.2004
27	501	4168.8	861.5	4348.5	0.2228
28	413	4326.7	797.8	4563.6	0.2467
29	393	4331.9	736.7	4560.5	0.2482
30	391	4332.2	721.6	4561.7	0.2473

Pmax = 1386 lb

Test Temp   : 75 °F
Flow Stress : 198000 ksi
Young's Mod : 27E6 ksi

J_{Ic} = 294.3 $\frac{in\text{-}lb/in^2}{}$
K_{Ic} = 93.7 ksi$\sqrt{in}$
    r = 0.9823

Code : WM-11

Δa_p (in.)

J_{mc} (in-lb/in²)

5000
4000
3000
2000
1000

0   0.05   0.10   0.15   0.20   0.25   0.30

J_{pl} = 441 in-lb/in²
K_{pl} = 114.7 ksi$\sqrt{in}$
    r = 0.9822

Thickness : 0.09 in.
Initial a : 0.5219 in.

C-94

Toughness J

Event	Load lb	Jac in-lb/in²	S in-lb/in²	Ja in-lb/in²	del-ap in.
1	385	42.8	45.5	46.5	0.0000
2	399	73.7	77.9	81.3	0.0000
3	502	121.2	123.8	133.2	0.0000
4	591	179.6	173.5	195.5	0.0022
5	667	245.2	224.7	264.8	0.0049
6	738	319.5	274.2	342.5	0.0075
7	790	397.6	324.8	425.8	0.0090
8	844	481.3	372.8	513.9	0.0098
9	898	576.8	424.2	614.7	0.0109
10	955	729.8	491.2	771.3	0.0146
11	1002	876.5	557.5	921.8	0.0192
12	1031	1087.5	638.2	1130.8	0.0287
13	1022	1308.4	670.7	1346.9	0.0408
14	1006	1514.3	700.5	1550.8	0.0586
15	976	1723.8	717.4	1760.0	0.0650
16	947	1922.2	736.7	1961.9	0.0734
17	877	2111.5	721.8	2145.1	0.0901
18	796	2290.2	697.2	2319.2	0.1091
19	749	2485.8	684.5	2541.8	0.1212
20	661	2676.4	653.7	2746.8	0.1434
21	619	2844.6	665.3	2948.8	0.1585
22	565	2997.7	628.8	3143.5	0.1708
23	488	3135.9	572.8	3387.4	0.1924
24	394	3258.5	589.9	3445.2	0.2164
25	365	3348.6	514.5	3592.2	0.2293
26	338	3439.3	491.3	3741.5	0.2373
27	326	3442.6	453.3	3746.2	0.2369
28	325	3442.5	447.7	3746.4	0.2365

Pmax = 1035 lb

Code : WM-12

Test Temp   : 75 °F
Flow Stress   : 190000 ksi
Young's Mod   : 27E6 ksi

J_{pl} = 452 in-lb/in^2
K_{pl} = 116.2 ksi$\sqrt{in}$
    r = 0.9838

J_{Ic} = 290.1 in-lb/in^2
K_{Ic} = 93.1 ksi$\sqrt{in}$
    r = 0.9825

Thickness : 0.09 in.
Initial a : 0.5262 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

C-96

Toughness J

Event	Load lb	Jac in-lb/in²	B in-lb/in²	Ja in-lb/in²	del-ap in.
1	302	43.3	46.4	47.6	0.0011
2	387	72.4	75.4	79.5	0.0003
3	470	115.3	115.4	126.0	0.0005
4	572	174.0	167.7	189.2	0.0029
5	644	236.0	214.0	254.1	0.0043
6	711	311.1	267.4	332.3	0.0073
7	771	388.6	316.2	414.0	0.0084
8	822	473.2	361.4	503.1	0.0092
9	868	560.0	400.2	594.0	0.0111
10	909	654.6	452.3	691.6	0.0125
11	952	789.9	506.4	830.2	0.0157
12	997	962.2	576.0	1004.6	0.0212
13	1000	1114.8	616.8	1154.9	0.0277
14	1014	1270.4	655.2	1317.1	0.0347
15	1010	1439.7	693.0	1473.7	0.0437
16	986	1594.8	702.5	1625.7	0.0521
17	982	1750.8	727.7	1787.5	0.0580
18	968	1900.5	746.1	1950.3	0.0649
19	901	2059.7	733.7	2084.9	0.0811
20	877	2193.2	737.8	2226.8	0.0884
21	858	2335.7	745.8	2302.2	0.0952
22	809	2463.5	731.2	2510.4	0.1060
23	751	2706.9	723.8	2705.4	0.1224
24	714	2902.4	715.7	3020.9	0.1321
25	638	3080.8	670.2	3224.2	0.1489
26	585	3240.9	642.0	3422.4	0.1620
27	492	3386.5	576.6	3590.8	0.1843
28	421	3504.4	539.2	3733.9	0.2050
29	383	3608.4	522.7	3885.1	0.2185
30	323	3702.6	487.5	4011.1	0.2392
31	311	3705.2	451.5	4013.8	0.2393
32	310	3705.4	451.1	4012.9	0.2399

Pmax = 1024 lb

Code : WM-13A

Test Temp : 75 °F
Flow Stress : 230000 ksi
Young's Mod : 27E6 ksi

J_{pl} = 592.4 in-lb/in^2
K_{pl} = 133 ksi√in
r = 0.9951

J_{Ic} = 413.7 in-lb/in^2
K_{Ic} = 111.1 ksi√in
r = 0.9882

Thickness : 0.09 in.
Initial a : 0.5341 in.

J_{mc} (in-lb/in^2)

Δa_p (in.)

C-98
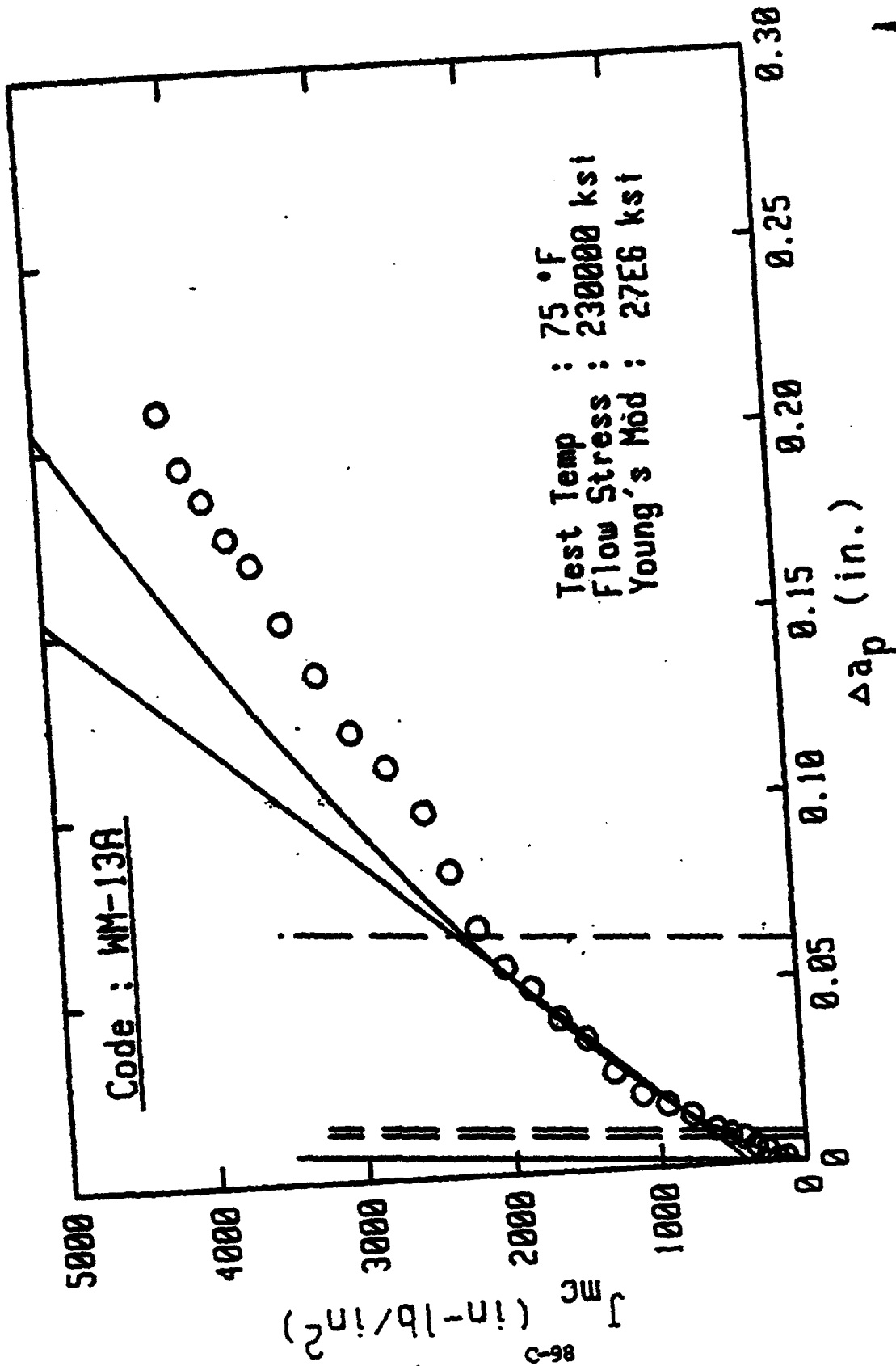
Toughness J

Event	Load lb	Jac in-lb/in^2	6 in-lb/in^2	Ja in-lb/in^2	del-ap in.
1	296	48.6	46.4	47.8	0.0000
2	400	75.5	84.9	87.4	0.0000
3	512	127.6	140.8	146.7	0.0010
4	606	185.9	195.9	213.1	0.0007
5	687	253.8	256.1	287.8	0.0033
6	766	333.2	320.8	375.6	0.0046
7	834	417.3	385.9	467.8	0.0069
8	896	509.0	449.2	567.8	0.0081
9	947	607.2	507.7	672.6	0.0096
10	1016	771.4	600.4	845.9	0.0137
11	1060	934.9	678.5	1010.4	0.0169
12	1100	1106.1	745.5	1190.1	0.0199
13	1120	1291.7	807.6	1384.8	0.0264
14	1127	1472.7	863.5	1559.6	0.0350
15	1125	1658.0	896.3	1739.7	0.0414
16	1101	1831.4	914.6	1916.6	0.0499
17	1077	2004.1	917.0	2091.5	0.0561
18	1040	2174.3	928.2	2254.6	0.0668
19	970	2348.9	914.9	2481.9	0.0823
20	915	2488.8	933.7	2533.5	0.0986
21	863	2727.5	927.0	2796.4	0.1112
22	819	2955.6	913.9	3061.7	0.1210
23	749	3166.9	888.4	3295.6	0.1369
24	683	3380.0	850.7	3558.4	0.1512
25	611	3565.5	805.1	3778.7	0.1672
26	581	3721.0	787.0	3984.5	0.1745
27	538	3871.9	762.0	4187.4	0.1852
28	505	4010.9	744.0	4384.9	0.1942
29	448	4143.7	708.3	4561.7	0.2097
30	435	4146.4	663.3	4562.8	0.2095
31	433	4147.7	660.7	4563.8	0.2099

Pmax = 1136 lb

Code : WM-14A

Test Temp : 75 °F
Flow Stress : 230000 ksi
Young's Mod : 27E6 ksi
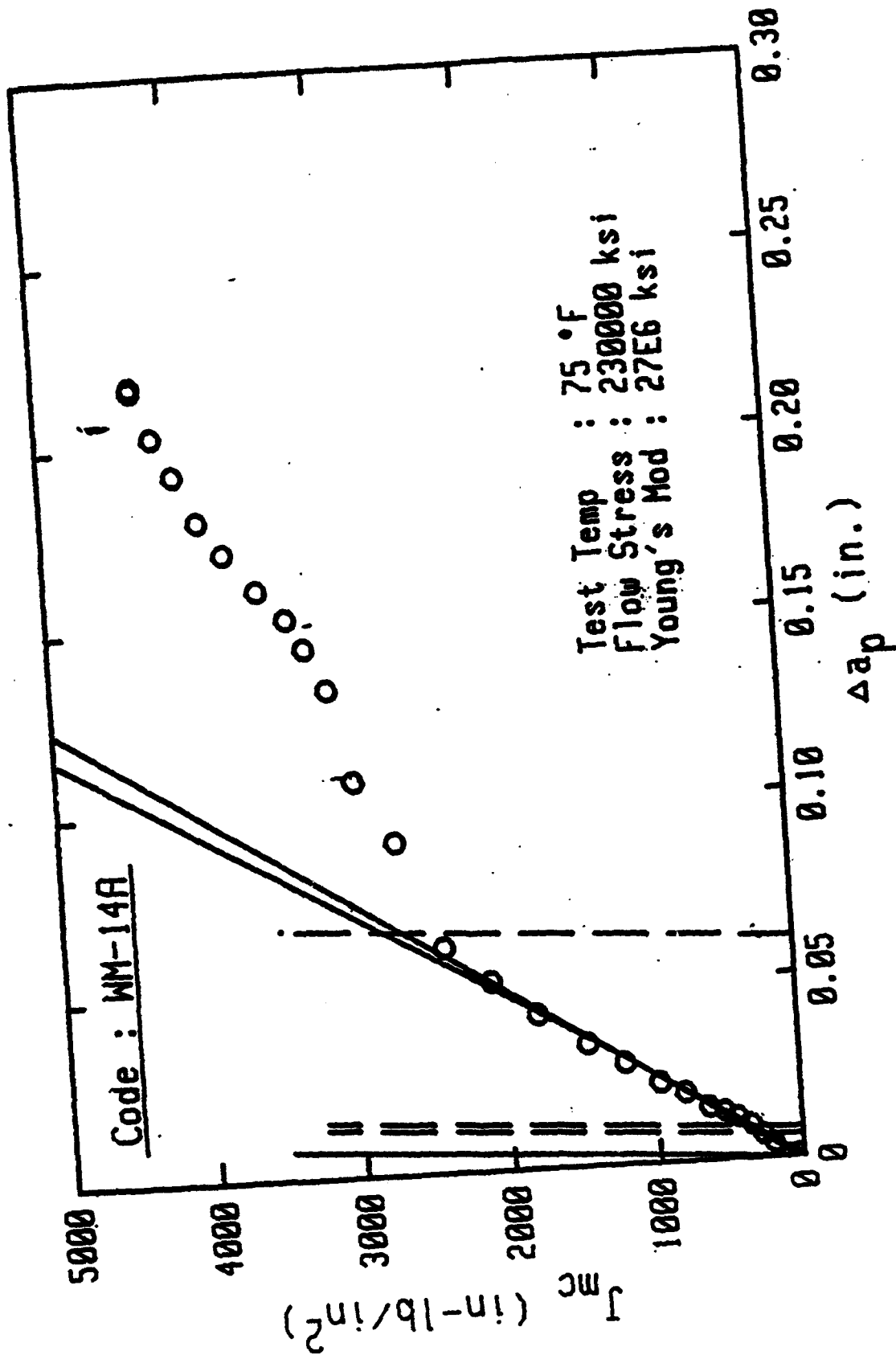
J_{pl} = 350.1 in-lb/in^2
K_{pl} = 102.2 ksi√in
r = 0.996

J_{Ic} = 47.1 in-lb/in^2
K_{Ic} = 37.5 ksi√in
r = 0.9962

Thickness : 0.09 in.
Initial a : 0.5206 in.

C-100

Toughness J

Event	Load lb	Jac in-lb/in²	G in-lb/in²	Ja in-lb/in²	del-ap in.
1	385	38.8	45.3	45.9	0.0006
2	438	81.6	93.5	96.4	0.0003
3	558	132.4	147.8	155.7	0.0008
4	648	194.3	209.4	225.2	0.0048
5	736	267.8	273.9	307.5	0.0064
6	814	347.6	341.7	396.8	0.0093
7	879	437.7	403.9	495.8	0.0113
8	943	529.3	470.2	596.3	0.0131
9	1082	633.8	535.9	710.5	0.0144
10	1072	796.4	638.7	865.5	0.0187
11	1122	966.7	704.9	1067.1	0.0217
12	1172	1205.8	799.8	1317.7	0.0274
13	1209	1451.9	885.8	1577.1	0.0331
14	1221	1788.3	959.8	1917.1	0.0417
15	1194	2887.4	982.3	2228.2	0.0513
16	1158	2392.4	988.8	2541.4	0.0611
17	1046	2683.8	1017.8	2796.8	0.0902
18	968	2940.6	985.8	3056.2	0.1071
19	989	3084.7	1102.7	3165.1	0.1323
20	777	3221.6	895.5	3291.1	0.1437
21	744	3337.4	889.8	3420.7	0.1520
22	787	3525.7	866.9	3670.5	0.1599
23	653	3741.8	823.5	3953.1	0.1703
24	612	3986.8	797.2	4175.5	0.1795
25	558	4058.5	748.2	4372.4	0.1922
26	511	4197.1	728.3	4567.3	0.2028
27	461	4321.3	693.9	4737.2	0.2171
28	447	4325.9	645.1	4741.4	0.2163
29	446	4326.9	648.8	4743.8	0.2159

Pmax = 1224 lb

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APPENDIX IV

EXAMPLE CALIBRATION INFORMATION

LVDT Size: *Clip Gage - MTS #77*
Conditioner Serial Number:
LVDT Serial number

excitation = 7.40 Volts

Secondary slope

Index	Volts	Displacement	Prediction	Difference
1	-1.510	.23500	.23502	.00002
2	-.960	.24000	.24007	.00007
3	-.415	.24500	.24509	.00009
4	.125	.25000	.25005	.00005
5	.671	.25500	.25507	.00007
6	1.215	.26000	.26008	.00008
7	1.751	.26500	.26509	.00009
8	2.305	.27000	.27010	.00010
9	2.847	.27500	.27509	.00009
10	3.387	.28000	.28005	.00005
11	3.926	.28500	.28501	.00001
12	4.462	.29000	.28994	-.00006
13	3.922	.28500	.28497	-.00003
14	3.377	.28000	.27996	-.00004
15	2.832	.27500	.27495	-.00005
16	2.286	.27000	.26993	-.00007
17	1.744	.26500	.26494	-.00006
18	1.200	.26000	.25994	-.00006
19	.655	.25500	.25493	-.00007
20	.109	.25000	.24991	-.00009
21	-.430	.24500	.24495	-.00005
22	-.975	.24000	.23994	-.00006
23	-1.520	.23500	.23492	-.00008

Displacement = .00919685 + volts + .24890380

Correlation Coefficient= .99999185

Standard deviation: .00000173   Standard error of estimate .00000000
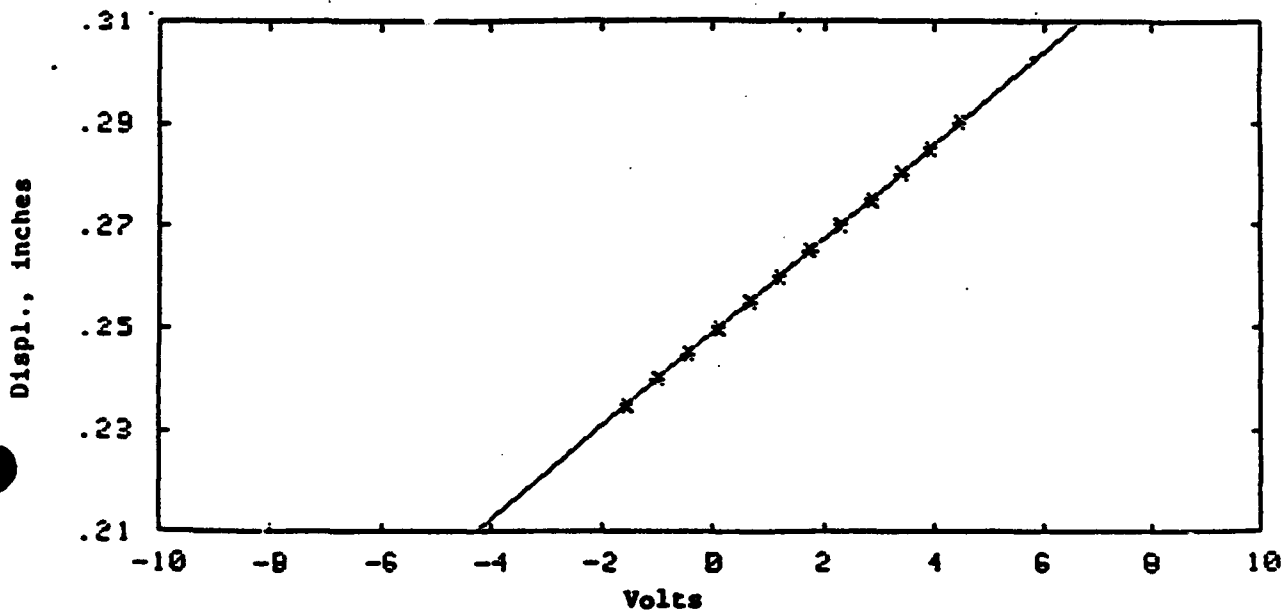95% Confidence limits--lower: .00919   Upper: .00920
Minimum difference=-.00009   Maximum difference= .00010
Percent minimum error=-1.01932   Percent maximum error= 1.06486

Avg = .009166

Index	Volts	Displacement	Prediction	Difference
1	-1.101	0.00000	-.00010	-.00010
2	-.560	.00500	.00499	-.00001
3	-.021	.01000	.01006	.00006
4	.509	.01500	.01504	.00004
5	1.040	.02000	.02003	.00003
6	1.570	.02500	.02501	.00001
7	2.100	.03000	.03000	-.00000
8	2.633	.03500	.03500	.00000
9	3.167	.04000	.04003	.00003
10	3.696	.04500	.04500	-.00000
11	4.220	.05000	.04993	-.00007

Displacement = .00940260 * volts + .01025245

Correlation Coefficient= .99999616

Standard deviation: .00000274   Standard error of estimate .00000000
95% Confidence limits--lower: .00939 Upper: .00941
Minimum difference=-.00010   Maximum difference= .00006
Percent minimum error=-1.01160   Percent maximum error= .63486

Mean Displacement = .00191798 * Volts + .01973719
Number of runs = 3
Standard deviation of Slope = .01032635
Standard deviation of Zero-intercept = .01865068
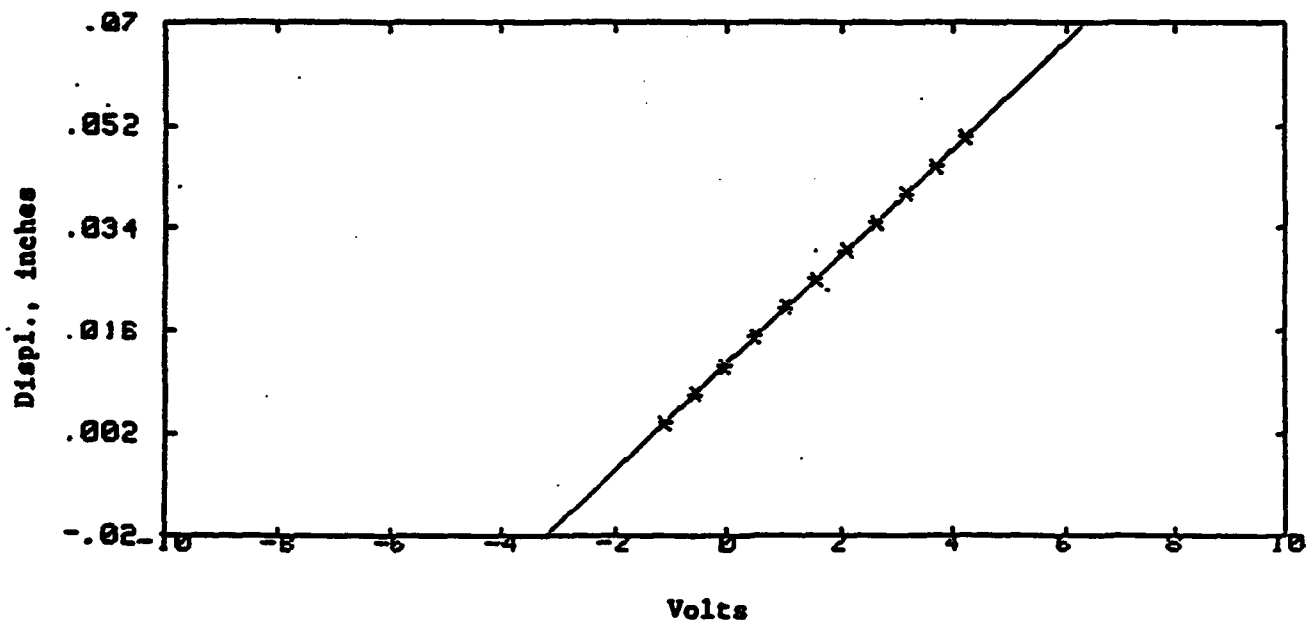
C-104

CLIP GAGE #MTS #810 USED FOR DATA ACQUISITION6/27/86

LOAD and DEFLECTION VALUES AS ACQUIRED
LOAD = SLOPE x DEFLECTION + CONSTANT

```
CORRESPONDING SLOPE ............ =  87.9911761991   INVERSE = .011364775915
ALTERNATE METHOD SLOPE ......... =  87.9910047431   INVERSE = .01136479806
THE Y INTERCEPT ................ = -16.3525088379
COEFFICIENT OF DETERMINATION R^2 =  .999998051446
CORRELATION COEFFICIENT R ...... =  .999999025722
STANDARD ERROR OF ESTIMATE ..... =  2.34753333333E-09
STANDARD DEVIATION OF SLOPE .... =  7.38066651691E-07
99% CONFIDENCE ON SLOPE IS ..... =  87.9760926572  < SLOPE <  88.0062649125
THE INVERSE SLOPE RANGE IS ..... =  1.13628274191E-02  < SLOPE <
   1.13667244111E-02
```

LOAD and DEFLECTION VALUES INTERCHANGED
(X) = SLOPE x (Y) + Constant

```
CORRESPONDING SLOPE ............ =  .01136479806   INVERSE = 87.9910047431
ALTERNATE METHOD SLOPE ......... =  .011364775915  INVERSE = 87.9911761991
THE Y INTERCEPT ................ =  .18584297856
COEFFICIENT OF DETERMINATION R^2 =  .999998051446
CORRELATION COEFFICIENT R ...... =  .999999025722
STANDARD ERROR OF ESTIMATE ..... =  1.81756190476E-05
STANDARD DEVIATION OF SLOPE .... =  5.71443115329E-03
99% CONFIDENCE ON SLOPE IS ..... =  1.13628498941E-02  < SLOPE <
   1.13667468939E-02
THE INVERSE SLOPE RANGE IS ..... =  87.9759186453  < SLOPE <  88.006090E417
```

```
POINT #   1    DVM =  5.637500    DEFL =  .250    DIFF = 0.000000    PD = .24991
POINT #   2    DVM =  5.199100    DEFL =  .245    DIFF = .438400    PD = .24493
POINT #   3    DVM =  4.761700    DEFL = ..240    DIFF = .437400    PD = .23996
POINT #   4    DVM =  4.323800    DEFL = .235    DIFF = .437900    PD = .23498
POINT #   5    DVM =  3.885300    DEFL =  .230    DIFF = .438500    PD = .23000
POINT #   6    DVM =  3.445800    DEFL =  .225    DIFF = .439500    PD = .22500
POINT #   7    DVM =  3.006800    DEFL =  .220    DIFF = .439000    PD = .22001
POINT #   8    DVM =  2.567930    DEFL =  .215    DIFF = .438870    PD = .21503
POINT #   9    DVM =  2.129180    DEFL =  .210    DIFF = .438750    PD = .21004
POINT #  10    DVM =  1.690300    DEFL = .205    DIFF = .438880    PD = .20505
POINT #  11    DVM =  1.249980    DEFL = .200    DIFF = .440320    PD = .20005
POINT #  12    DVM =  .810110     DEFL = .195    DIFF = .439870    PD = .19505
POINT #  13    DVM =  .370430     DEFL = .190    DIFF = .439680    PD = .19005
POINT #  14    DVM = -.069087     DEFL = .185    DIFF = .439517    PD = .18506
POINT #  15    DVM = -.510590     DEFL = .180    DIFF = .441503    PD = .18004
POINT #  16    DVM = -.951280     DEFL = .175    DIFF = .440690    PD = .17503
POINT #  17    DVM = -1.391850    DEFL = .170    DIFF = .440570    PD = .17002
POINT #  18    DVM = -1.833240    DEFL = .165    DIFF = .441390    PD = .16501
POINT #  19    DVM = -2.274620    DEFL = .160    DIFF = .441380    PD = .15999
POINT #  20    DVM = -2.716210    DEFL = .155    DIFF = .441590    PD = .15497
POINT #  21    DVM = -3.158000    DEFL = .150    DIFF = .441790    PD = .14995
POINT #  22    DVM = -3.599900    DEFL = .145    DIFF = .441900    PD = .14493
POINT #  23    DVM = -4.041200    DEFL = .140    DIFF = .441300    PD = .13992
```

5.2   APPENDIX C-II

C-106

LEAK-BEFORE-BURST CRITERIA APPLIED TO CRYOFORMED PRESSURANT TANKS

K. H. Cotter
Fracture Proof Design Corporation
St. Louis, MO

Abstract

A leak-before-burst (LBB) criteria, based on
linear-elastic fracture mechanics, was applied to
typical pressurant tanks fabricated from cryoformed
TP301 stainless steel. The LBB criteria included
consideration of sub-critical flaw growth via
fatigue and sustained load mechanisms. The
analytical results, developed using toughness data
obtained from coupons, were verified by full scale
pressure vessel tests of two designs. For the
verification tests, flaws were introduced into base
metal, weld metal and HAZ regions and subsequently
pressure cycled to leakage followed by
overpressure. It is shown that the margins of
safety attainable using a LBB criteria are
inversely proportional to the square root of the
wall thickness when other parameters are held
constant. Because of the method of fabrication,
consideration of weld residual stress effects and
bending stresses due to misalignment was not
necessary. Significant margins based on LBB
characteristics were demonstrated for effective
crack lengths that were in excess of those expected
for in-service conditions and in excess of flaw
sizes detectable by normal NDI methods.

Introduction

Background

During 1984 and 1985, the author participated
in the review of the integrity of cryoformed
stainless steel tanks. It became apparent during
those meetings that the true damage tolerance
capacity of such tanks and their likely "leak-
before-burst" (LBB) character had not been
demonstrated by test or by analysis. The lack of a
valid analysis stemmed from the fact that no
fracture toughness data existed for through-
thickness cracks. Accordingly, it was suggested
that fracture toughness data and crack growth
resistance curves be obtained from coupon tests and
a LBB analysis be performed. In view of the
potential significance of a LBB demonstration,
verification tests were planned in order to verify
the leak-before-burst character of typical tanks.
In order to obtain verification of the true
residual strength of vessels containing cracks, a
test program was begun. This paper details the
findings from the full scale tests of 11 and 23
inch diameter, cryoformed and aged TP301 stainless
steel spherical tanks.

Leak-Before-Burst Concepts

The current design philosophies for "high
energy" pressure vessels, in safety related
applications, include the consideration of the
integrity of the vessel based on fracture mechanics
in addition to margins against tensile failure. In
addition to providing a measure of the margin of
safety for a given detectable or postulated flaw

size, fracture mechanics principles can be used to
define inspection and material toughness
requirements.

To that end, the leak-before-burst (LBB)
concept is a useful measure of the tolerance of the
pressure vessel to defects, that is, its damage
tolerance. The simple concept begins with the
assumption that a crack-like defect exists in the
vessel (Figure 1a) and that the crack propagates by
a fatigue crack growth (or other) mechanism until
it penetrates the wall of the vessel (Figure 1b)
which results in a detectable leak (Figure 1c). At
break-through, the minimum size of the crack
causing the leak is assumed to have a length, 2c
of twice the wall thickness, 2t, or longer
Naturally, the larger the crack that can be
tolerated, the easier it is to detect the leak an-
the larger the margin against failure.

c) Assumed Length for Detectable Leak
and Stability Calculations (2c ≥ 2t)

b) At Breakthrough
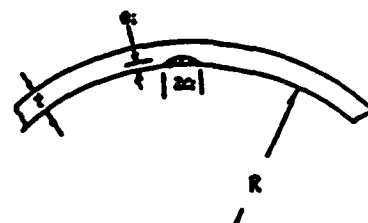
a) Assumed Initial defect

Figure 1 Crack Propagation for LBB

Fabrication, Metallurgy & Fracture Toughness

Fabrication

The procedure for the fabrication of the
spherical tanks consisted of hydroforming the
hemispheres, machining the hemispheres and then TI
welding. Each tank was next subjected to a detaile
inspection sequence followed by solution annealing
strengthening by cold work at -320
("cryoforming"), aging, and finally, proof-testing

The welds of the tank were not machined after welding which resulted in a slightly larger net section thickness in the weld region than in the base metal. As a result, a strain gradient exists in this region during the cryoforming procedure. Due to strain hardening effects, this thickness differential is less pronounced after the completion of the cryoforming process. Because of the plastic deformation that accompanies the cryoforming procedure, any bending stress component across the girth weld, that might be caused by misalignment during welding, is eliminated. This plastic straining, in addition to the solution anneal, insures that no weld residual stresses remain.

The results of more than 20 burst tests, conducted on similarly fabricated tanks were reviewed. All tanks exhibited fracture surfaces characteristic of tough materials. That is, the fracture surfaces exhibited some 30-40% shear rather than the flat fracture surface indicative of brittle behavior. Even though the running cracks crossed the girth weld, none of the burst test fractures tended to follow the weld metal or heat-affected zone. This behavior is indicative of high toughness at the weld metal and HAZ. The failures all appeared to initiate in the maximum effective stress region, that is, the region near to the transition from the sphere to the boss.

Metallurgy of Cryoformed TP301

The stainless steel alloy formulation used for the cryoforming, was developed in the 1960's as a closely controlled chemistry selected for reproducibility of process and maintainability of toughness and strength. It is a dual phase alloy composed of a very tough austenitic matrix with interlocking platelets of high strength martensite. The combination and distribution of phases results in a unique stainless steel alloy microstructure combining strength with high fracture toughness.

The thermal-mechanical processing technique used ("cryoforming") applies the metallurgical principal that an austenitic alloy, when strained, transforms to martensite. As the transformation to martensite occurs, the microstructure is locally hardened with no resultant local necking or thinning of the wall during the metallurgical transformation reaction. To accelerate the metallurgical reaction with minimum strain, the alloy is stretched at liquid nitrogen temperatures.

Forming of the hemispheres, machining of the bosses and the welding together of the vessel components are completed when the alloy is in the highly ductile austenitic phase. Room temperature deformation resulting from the fabrication leads to some work hardening of the vessel shell and welds. This is subsequently relieved by solution annealing.

Base Metal Microstructures. Straining the alloy at liquid nitrogen temperature significantly alters the initial austenitic microstructure by a shear transformation mechanism to martensite. The transformation occurs along the slip planes in the grains responding to the applied strain. The greater the strain the more complete the transformation. The structure can be visualized as platelets or laths of high strength material wedged in an orderly array to support the applied strain.

As the transformation is strain dependent, only those directions and areas in which (plastic) strain is applied are transformed. The remaining matrix is retained as a highly tough austenite. A typical microstructure at 500x magnification, using an electrolytic oxalic acid etchant, is shown in Figure 20.
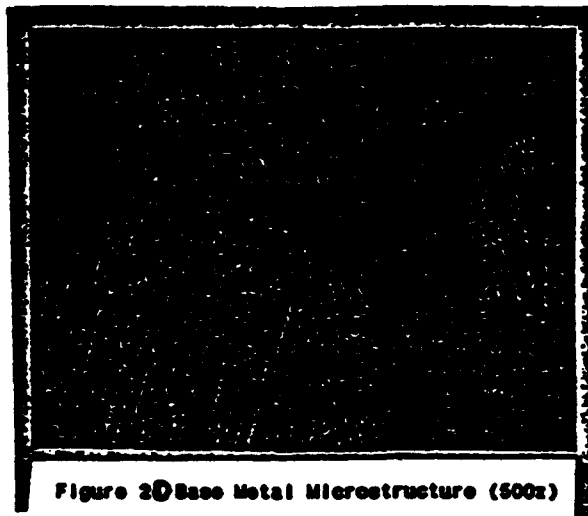

Figure 20 Base Metal Microstructure (500x)

Weld Metal Microstructure. The cast microstructure in the weldment is austenitic plus about a 5% delta ferrite phase principally located in the grain boundaries. The delta ferrite forms when the weld metal cools from the melting point through 1950F. The microstructure may, on occasion, be somewhat strained as the weld metal plastically deforms on cooling to release the thermal residual stresses.

The vessel, after welding, is solution heat treated and water quenched to assure that the microstructure is fully austenitic by redissolving all precipitated chromium carbides. This significantly alters the cast weldment as a major portion of the delta ferrite is converted to austenite. The residual delta ferrite grain boundary precipitates have also been significantly altered during the solution heat treatment and are observed in the microstructure as small isolated white or unetched spheres. The austenitic grain size formed during solution heat treatment is slightly larger that the adjacent wrought shell grain size. The small variations in chemical content inherent in the cast weld metal slightly modifies the amount of strain required to trigger the martensitic shear transformation. The cryostrained weld metal microstructure at 500x magnification is therefore somewhat mottled in appearance but otherwise equivalent to the wrought structure as shown in Figure 30.

Aging. The low temperature aging heat treatment of cryostretched material increases the ultimate tensile strength by 40 ksi and is accompanied by a small gain in fracture toughness. There is no apparent change in the aged microstructure as viewed optically. At very high magnifications a very fine precipitate is apparent at the martensite laths to austenite matrix boundary. The Cr rich precipitate is quite fine and of insufficient volume to be positively identified by presently available diagnostic techniques.

Figure 3. Weld Metal Microstructure (500x)

Comparison with a Quenched and Tempered Martensitic Structure. A typical medium carbon low alloy steel, such as type 4340, is heated into the austenite range and cooled rapidly to insure that all of the austenite is converted to martensite. After quenching, the material is at its maximum hardness and lowest toughness. This requires that the steel must be subsequently tempered at a lower temperature to increase ductility and toughness with a corresponding lowering of strength. The tempering leads to a fine needle shaped microstructure of a high strength martensite matrix with a identifiable precipitate of carbides and converts a portion of the martensite to ferrite. The longer the tempering cycle, the coarser the carbides and the lower the alloy's hardness and strength.

In contrast, the straining during the thermal-mechanical processing of TP301 stainless steel alloy induces the martensite to form in the areas of applied strain. The former austenitic grains end up as a series of platelets of untransformed austenite and martensite. Aging of the alloy increases its strength as a fine precipitate is formed at the martensite/austenite interface. The microstructure is quite different in appearance from low alloy carbon steels and is a composite of an austenitic matrix with interlocked platelets of high strength martensite.

The two microstructures react quite differently when strained in the presence of a sharp notch. In both microstructures the martensite fractures. The quenched and tempered steels have a long continuous path through the martensitic matrix while the austenite matrix of the cryoformed alloy blunts the fracture and redistributes the strain at the crack tip. This explains why the cryoformed alloy has higher fracture toughness values at equivalent strength levels.

Fracture Toughness

It was found that the majority of toughness values reported in the literature[3-8] for cryoformed TP301 stainless steel range from 85 to 105 ksi$\sqrt{in}$ for weld metal, HAZ and base metal alike. See Table 10. These values were computed from test specimens with part-through thickness crack shapes which are not strictly applicable to the demonstration of LBB characteristics. In order to determine whether LBB conditions exist, it is necessary to have data from specimens containing

through-thickness cracks and from material of similar thickness.

Fracture toughness tests were conducted by Beck and Schwartzberg[3] using part-through crack (PTC) specimens to determine the sustained load crack growth threshold, K_{th}. After sufficient hold times they cycled the specimens to produce center through-the-thickness crack specimen geometries (CTC) and then loaded the specimens to failure. Based on their data, the first applicable CTC data became available for LBB evaluations. Unfortunately, the material is not truly representative as there was not sufficient cryostraining and the alloy chemistry was not consistent with that currently in use.

The work of Bixler[8] resulted in the demonstration of the LBB character of tanks tested at -295F. He also demonstrated that the cracks were stable at 72F when the PTC's penetrated the thickness of the specimens to become through-the-thickness cracks (TC's). However, the results[8] relative to the toughness of TC's is qualitative rather than quantitative.

Recently, McCabe[2] tested cryoformed material in a number of conditions. He used the CTC specimen geometry for developing resistance curves for aged and unaged base metal and aged HAZ and weld metal. His results are compared with the results of prior studies in Table 10 where it is readily apparent that the cryoformed material exhibits excellent toughness. McCabe[2] also obtained estimates of the value of the toughness at which crack extension begins, the initiation toughness, K_{Ii}. He found that the values were in the range of 87-122 ksi$\sqrt{in}$. This range for K_{Ii} is consistent with the results of Forman[7], Bixler[8] and others.[3,4,5,6] Testing by McCabe[2] also provided data that conclusively showed some stable crack extension prior to instability as shown in the typical R-curve of Figure 4 for aged material.
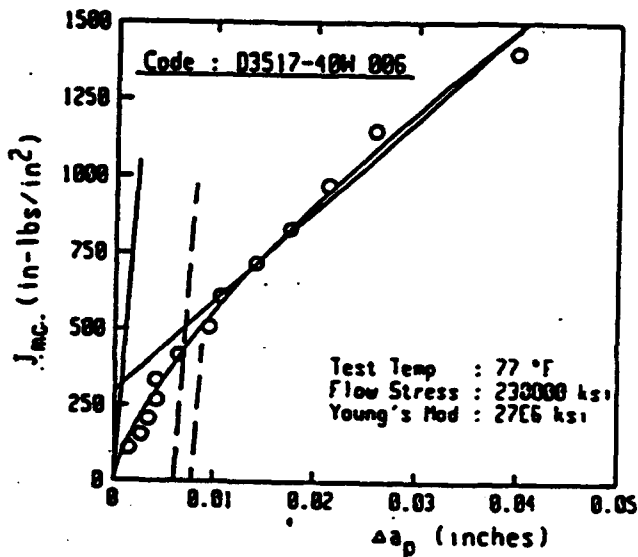

Figure 4. Typical Cryoformed Weld CTC R-Curve, 301 Base Metal/308L Weld Wire

Table 1X Room Temperature Fracture Toughness Data

Material (1)	Weld Wire	Specimen type (2)	Number of tests	Average Toughness (ksi√in)	σ_y (ksi)	σ_u (ksi)	t (in)	Source
BM/A		CTC	3	177.4	281	205	.004	Ref. 2
WM/A	308L	CTC	3	188.4	220	231	.004	
HAZ/A		CTC	3	188.4			.004	
WM/A	308L	CTC	3	183.2	220	231	.004	
BM/UA		CTC	3	188.0	207	215	.004	
BM/UA		PTC/TC	1	158	190	198	.125	Ref. 3
BM/UA		PTC	1	74	190	198	.125	
WM/UA	308L	PTC	1	85			.125	
WM/UA	308L	PTC	1	94			.125	
WM/UA	308L	PTC/TC	1	134			.125	
WM/UA	308L	PTC/TC	1	137			.125	
WM/UA	308L	PTC	1	87			.125	
BM/A		PTC(PV)	1	86.5	~200		.004	Ref. 5
BM/A		PTC	1	102.6	220		~.200	Ref. 6
BM/A		PTC	1	106.8	220		~.200	
WM/A	308L	PTC	1	103.6	219		~.200	
WM/UA	308L	PTC	3	86.5	175		.145	Ref. 7
HAZ/UA		PTC	3	86.8	~205		.145	
BM/UA		PTC	2	96.5	215		.145	
WM/A	308L	PTC	2	83.0	235		.145	
HAZ/A		PTC	2	87.3	~254		.145	
BM/A		PTC	2	102.8	256		.145	
BM/UA		PTC	10	116.5	174	210	(.100	Ref. 8
WM/UA	308L	PTC	7	82.3	181		&.025)	

Note:

.145 should be .063

1) BM= base metal; WM= weld metal; HAZ= heat-affected zone; /A= aged; and, /UA= unaged

2) CTC= center through-crack; PTC= part-through crack; PTC/TC= PTC became TC after penetrating thickness; and, CT= compact tension

LBB Analysis

Analytical Approach. The analysis of through-thickness cracks in the spherical tanks (Figure 1c) was based on that due to Sih and Sebroff[9] and Sih and Hagendorf.[10] For the computation of the stress-intensity factor, it is assumed that the crack is short compared with the radius of curvature of the shell and that the loading can be represented by a membrane force or stress, σ. For that condition, the stress intensity factor is given as follows:

$$K_t^o = F_s(\lambda c)\, \sigma \sqrt{\pi c} \qquad \text{(tension)} \qquad (1)$$

where the function F_s is given in Figure 5 in terms of $\lambda c = B_1 c/\sqrt{Rt}$, $B_1 = [12(1-\mu^2)]^{.25}$ and c, R, and t are as shown in Figure 1c. For the contribution due to the pressure of the fluid acting on the crack surface, the expression

$$K_p = p\sqrt{\pi c} \qquad \text{(crack surface pressure)} \qquad (2)$$

was used where p is the internal pressure (psi) in the sphere. Using the foregoing crack driving force parameters, the total K_{app} can be found by the use of superposition of Equations (1) and (2). The effects of the crack-tip plastic zone correction on K_{app} were included where significant.
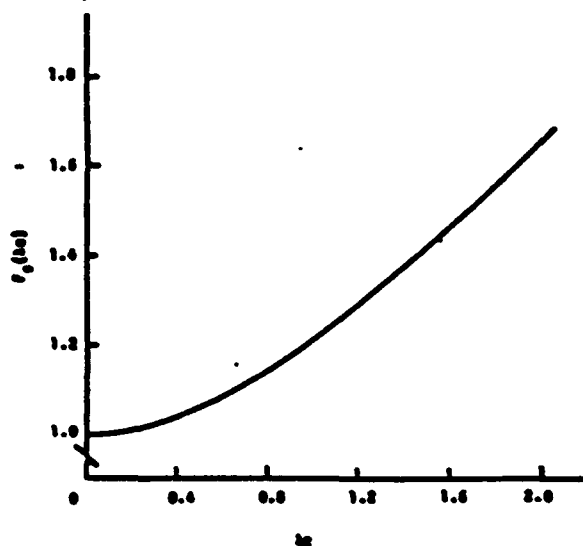
Figure 5. Spherical Shell Correction Factor, $F_s(\lambda c)$, Ref. 9 & 10

Crack Stability Calculations. Margins of safety for LBB computed using fracture mechanics methodology rely on the comparison of the crack driving force or stress-intensity factor, K_{app}, with the material's resistance to crack extension or R-curve. Alternately, a toughness criteria, $K_{app} < K_c$, can be used. The values of K_c used for the stability calculations were taken as the maximum values of the R-curves from Ref. 2 and shown in Table 1c.

Three 11 inch diameter spherical tanks and one 23 inch diameter spherical tank were selected for the LBB analyses. Tanks S/N 104 and S/N 105 were 11

inches in diameter with flaws located in the base metal (shell wall). The wall thickness at the flaw location, t_{eff}, was nominally 0.080 inches. Tank S/N 003 also had an 11 inch diameter, but had flaws located in the girth weld metal, $t_{eff} = 0.121$ inches. The final tank, S/N 113, was 23 inches in diameter with flaws in the girth weld metal, $t_{eff} = .314$.

To determine the LBB characteristics of the tanks, K_{app} was computed as a function of the through-thickness crack length, 2c, in multiples of wall thickness, t. K_{app} was computed for pressures equal to the operating pressure, P_{oper}, and for the overpressure, P_{max}. Because of the shape of the R-curves and the small amounts of crack extension, Δa, prior to failure ($\Delta a \leq .05$ in), it was possible to use the toughness criteria for stability computations. For reference, K_{app} was compared to both K_{II} and K_c.

The results for tank S/N 104 for $P_{oper} = 3,800$ psi and $P_{max} = 4,050$ psi are shown in Figure 6c. For flaw lengths 2c = 3t, $K_{app} < K_{II}$. It is apparent that this tank can tolerate flaws of 7t in length at P_{oper} and still maintain LBB conditions. The value of P_{oper} corresponds to liquid pressurant while that of P_{max} represents an overpressure condition with a gas pressurant. This tank exhibited LBB with large margin.

In tank S/N 105, the results at $P_{oper} = 3,850$ psi are similar to S/N 104 and appear in Figure 7c. At $P_{max} = 6,100$ psi, flaws of length 2c > 1.5t in the base metal have values of $K_{app} > K_{II}$. However, flaws as long as 5t are stable at P_{max} based on $K_{app} < K_c$. Again large margins were evident for LBB.

The flaws were located in the weld metal in tank S/N 003. For $P_{oper} = 4,050$ psi, flaws of length, 2c = 4t, have $K_{app} < K_{II}$. See Figure 8. This apparent improvement in tolerance to defects, compared with tanks S/N 104 & 105, is attributed to lower stresses in the weld than in the shell without any degradation in toughness. At $P_{max} = 6,800$ psi, $K_{app} < K_c$ for a flaw of length 2c = 5t. The margins for LBB were greater that those for flaws in base metal for the reasons noted.

The analysis of the 23 inch tank, S/N 113, also showed excellent margins of integrity based on a LBB criteria. At $P_{oper} = 4,000$ psi, $K_{app} < K_{II}$ for flaws 2c < 2.5t while no instability was apparent at $P_{max} = 4,050$ psi and 2c = 5t based on $K_{app} < K_c$. This tank showed slightly lower margins based on K_{II} than the 11 inch tanks due to the thicker shell and weld sections, but the margins for LBB remained excellent. The results appear in Figure 9.

This analysis was based on coupon data and was without the benefit of full scale verification tests. In the next section, the verification tests are presented and reviewed.

Verification Tests

Full scale demonstration tests were performed on the tanks analyzed in the previous section. The results are evaluated based on fracture mechanics principles. The tanks had 11 and 23 inch diameters with nominal base metal wall thicknesses of 0.080 and 0.220 inches respectively with their flaw locations summarized in Table 2c.
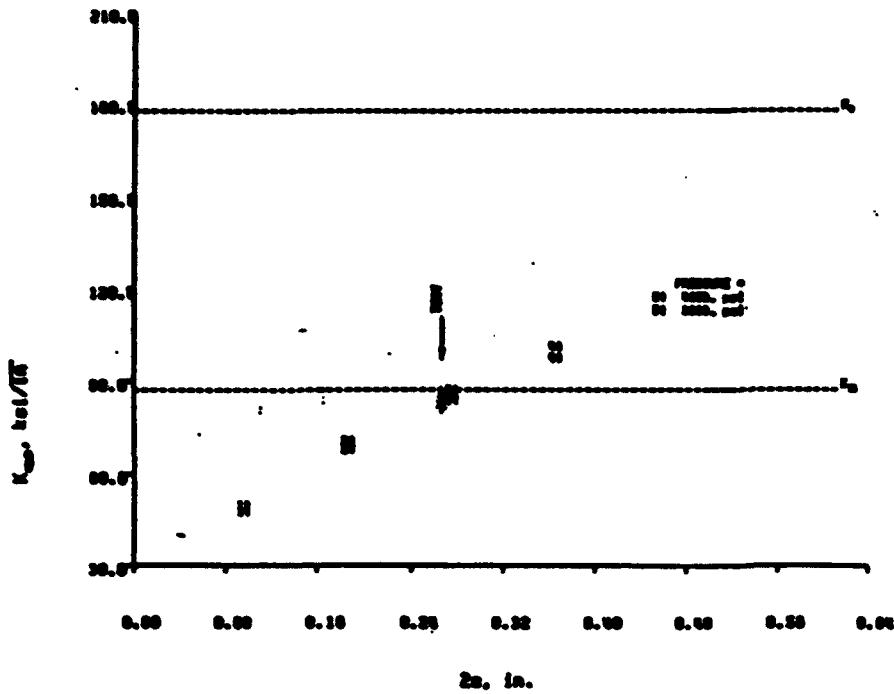
Figure 60 LBB Evaluation for Tank S/N 104,
D - 11 in., Flaw in Base Metal
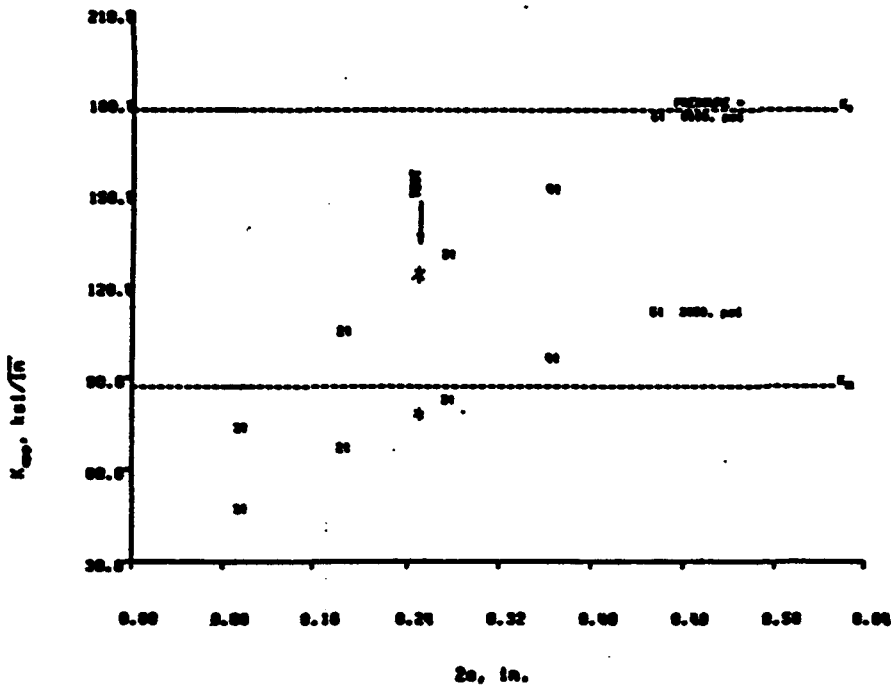
Figure 70 LBB Evaluation for Tank S/N 105,
D - 11 in., Flaw in Base Metal

Figure 8D LBB Evaluation for Tank S/N 003,
D = 11 in., Flaw in Weld Metal

Figure 9D LBB Evaluation for Tank S/N 113,
D = 23 in., Flaw in Weld Metal

Initial Defects. EDM notches were cut into the vessels in order to initiate fatigue cracks. These notches were all semi-elliptical having the initial aspect ratios, $(a/2c)_i$, given in Table 30. The aspect ratio was selected to produce fatigue cracks that would be conservative compared with that which might be expected to occur in practice. The notch cut into the 23 inch tank, S/N 113, is shown in Figure 10D.

Load Spectrum. For purposes of propagating the cracks introduced by the EDM notches, the vessels were subjected to pressure cycles $(0-P_{oper}-0)$ where P_{oper} is shown in Table 3D. After, the through-the-thickness crack had developed and a visible leak was noted, 2 of the vessels were subjected to the sustained loads for the durations and pressures, P_{oper}, shown in Table 4D. Finally, attempts to burst the tanks were made at the overpressures, P_{max}, shown in Table 5D. The load cycles to develop fatigue cracks were accomplished using an oil + water mixture to pressurize the tanks. The overpressure was similarly applied except to tank S/N 104 for which the overpressure was with gas.

Crack Stability. Specific computations were made for the effective crack lengths, $2c_{eff}$, for the 4 tanks. The associated values of K_{app} are shown in Figures 6-9D and identified as "TEST." The LBB characteristics of all tanks were verified as shown in Figures 6-9D. The pronounced leak in the 23 inch tank, S/N 113, due to the large crack size, is evident in Figure 11D at P_{max} = 4,850 psi. ➤
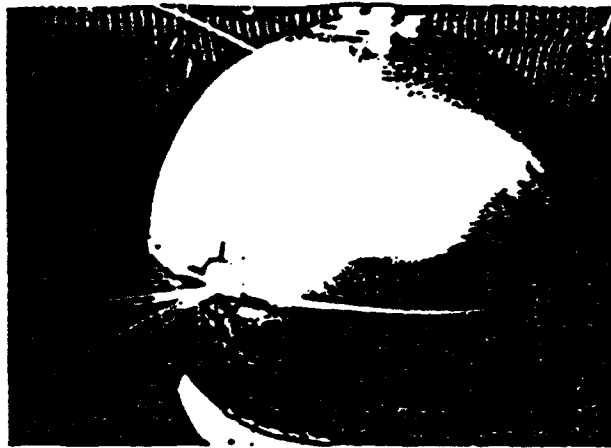

Figure 11D Fluid Leakage at P_{max} = 4,850 psi. Tank S/N 113

Sustained Load Crack Growth

The remaining concern in the evaluation of the integrity of the tanks is that of static or sustained-load crack growth. Two sustained-load crack growth tests were performed as a part of the test program. No crack growth was observed after 75 hours at operating pressure for tank S/N 105. Similarly, none was observed for the 48 hours at operating pressure during the test of tank S/N 003.

The literature[7] indicates that the value for the threshold for sustained load growth, K_{th}, should be between approximately 80% of the value of initiation toughness, K_{Ii}. K_{Ii} is the value of K_{app} at which crack extension begins, but not necessarily the point of instability. The values of K_{app} shown in Table 4D agree with those of Forman.[7]

Metallurgical Evaluation

After the completion of the tests, the vessels were subjected to a metallurgical examination. This consisted of taking SEM photomicrographs of the defect locations after exposing the crack surface. The penetration of the fatigue crack through the inside wall of tank S/N 113 is shown in Figure 12D. The fracture surface for tank S/N 113 is shown in Figure 13D. Note the EDM flaw, the fatigue crack growth and the shear lips, associated with a tough material, that were generated at breakthrough.
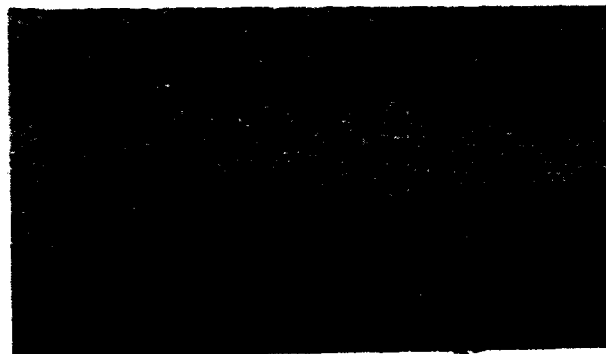

NOTCH SHAPE

°.825

.314 WELD

R

.J63

.102 .096

.002 R .001

°ACTUAL

Figure 10D EDM Crack Starter Notch in Tank S/N 113

Figure 12D Breakthrough of Crack on ID of Tank S/N 113

Table 2️⃣ Test Parameters

Tank S/N	Condition	Flaw Location	Nominal Diameter (in)
105	Aged	BM	11
003	Aged	WM	11
104	Aged	BM	11
113	Aged	WM	23

Table 3️⃣ Cycles to Leak

Tank S/N	P_{oper} (psi)	t_{eff} (in)	$(a/2c)_i$	a_i (in)	N (cycles)
105	4,200	-.090	.21	.041	2,590
003	4,000	.121	.24	.074	2,948
104	3,900	.090	.23	.044	2,338
113	4,000	.314	.20	.183	2,977

Table 4️⃣ Sustained Load Tests

Tank S/N	Duration (hr)	P_{oper} (psi)	K_{app} (ksi$\sqrt{in}$)
105	27	3,475 to 4,130	84.9
105	48	3,850 to 4,000	82.2
003	48	4,060	71.0

Table 5️⃣ LBB Verification

Tank S/N	$2c_{eff}$ (in)	$\dfrac{2c_{eff}}{t_{eff}}$	P_{max} (psi)	K_{app} (ksi$\sqrt{in}$)	K_{II} (ksi$\sqrt{in}$)	K_c (ksi$\sqrt{in}$)
105	.252	2.83	6,100	131.7	87.0	177.4
003	.363	3.00	6,800	119.2	87.0	177.4
104	.268	2.96	4,050	80.9	106.7	158.0
113	1.350	4.30	4,850	135.9	87.0	177.4

Figure 13() Fracture Surface of Leaking Crack,
Tank S/N 113, EDM Notch on OD

Conclusions

Based on the full scale tests performed, it was found that all of the tanks exhibited leak-before-burst (LBB) characteristics, with large margins, for defects located both in base and weld metal.

LBB characteristics were demonstrated by test for effective crack lengths, $2c_{eff}$, between 2.83 and 4.30 times the wall thickness. This is contrasted with an expected length at breakthrough, for in-service defects, of 2 times the wall thickness.

At the operating pressure selected for the 11 inch tanks, the value of K_{app} was less than K_{II} for cracks having lengths greater than 3t. Similar behavior was noted for the 23 inch tanks, but due to greater wall thickness, it was limited to cracks having lengths as long as 2.5t.

Based on coupon test data[2], no difference in tolerance to defects was noted between the weld metal, base metal or HAZ. It also appears that aged material, with its higher strength, has higher toughness than unaged material. This observation was substantiated by the full scale verification tests.

The analytical results showed that all tanks could tolerate defects having through-thickness lengths greater than 6t at operating pressure. Based on the values of overpressure considered, 4,050-6,800 psi, defects up to 5t in length would not cause failure of the tanks.

The low fatigue crack growth rate present in the full scale tests translates to additional margins when coupled with the fact that the flaw sizes used for the tests were much larger than that which would be expected in actual service.

From the review of the manufacturing procedures, it was determined that the combined weld procedures plus cryoforming result in weld residual stresses at or very near zero and have eliminated the possibility of local bending stresses at the weld.

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6. Tests conducted by Thiokol Chemical Corporation under NASA Contract NAS 8-11977.

7. Forman, R.G., "Environmental Crack Growth Behavior of High-Strength Pressure Vessel Alloys," NASA TN D-7952, April 1975.

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11. Escalona, A. "Leak Before Burst and Crack Growth Under Sustained Load Tests of D3912, S/N 105 HT. 88019," Ardé Report ARM No. 209, Oct. 4, 1985.

APPENDIX D - Fiber Wrapped Cylinder Pressure/Strain Tests

ARDE Report EG 42001-1, which describes 6" ϕ fiber wrapped cylinder experiments and test data correlation, is presented in this section.

PRELIMINARY MODEL VERIFICATION TESTS -
6 INCH DIAMETER KEVLAR -49 FIBER
WRAPPED CYLINDER PRESSURE/STRAIN TESTS

Prepared for:

PATRICK AIR FORCE BASE
FLORIDA, 32925

CONTRACT FO8606-84-C-0029

Prepared by:

D. Gleich

Approved by:

Engineering

Program Management

Submitted By:

ARDE, INC.
19 Industrial Avenue
Mahwah, N.J. 07430

CODE IDENT. NO. 05980

TABLE OF CONTENTS

LIST OF FIGURES

1. Introduction and Summary

This report describes the Preliminary Model Verification
Tests performed under Task I, "Develop Prediction Methods,"
of ARDE Contract FO8606-84-C-0029, "Kevlar Overwrap Study".
The purpose of the tests was to obtain fiber/resin materials
properties data that would aid in the composite vessel failure
modeling analysis task, using vessels constructed of the same
fiber/resin system. The tests were designed to determine fiber
less resin Young's modulus in the fiber directions, fiber ultimate
strain and to confirm the strain transformation relations.   The
testing was performed by Teledyne Engineering Services,
Waltham, Mass., under ARDE direction.

Two (2) 6" diameter Kevlar -49/resin fiber wrapped
cylinders (S/N 028 and 030) were pressure tested to
failure at room temperature using hydraulic oil as the
pressurizing fluid. Pressure versus fiber strains were
monitored by a pressure transducer and six (6) each
strain gages mounted on each vessel. The test pressures
and strains were recorded on strip chart recorders.

The test results confirmed fiber material properties
and ultimate strain values to be used in the failure
modeling analysis:

(1) Fiber (less resin) Young's Modulii values of
     19.5×10^3 ksi were obtained in the fiber
     direction for both the hoop and helical fibers.
     This result agrees closely with the 19×10^3 ksi
     value given by the manufacturer (DuPont),
     detailed by other investigators in the literature
     and used in the failure modeling.

(2)   The maximum fiber strain measured by a
strain gage at rupture was 1.91%, close to
the 2% ultimate strain value to be assumed
in the failure modeling study. Hoop fiber
stress was 372 ksi, compatible with the 1.91%
strain, 19.5×10^3 ksi Young's modulus and
the 3100 psig failure pressure.

(3)   Strain gage readings in the hoop, helical and
axial directions were consistent. The change
in fiber helical strain per change in pressure,
$\frac{\Delta \epsilon_x}{\Delta p}$, was found to be about .004 $(in/in)\big/ksi$
as directly measured, or as computed from
measured hoop and axial strains, ϵ_θ and ϵ_x,
together with the 24.75° helical fiber angle.
This result confirms the classical strain
transformation relations which will be utilized
in the failure modeling analysis.

Proper installation of strain gages is generally difficult
on uneven fiber wrapped surfaces. Although post yield strain
gages (3 to 5% ultimate strain) and compatible adhesives,
together with appropriate installation techniques were used
on the 6" diameter test cylinders, most strain gages failed
at strain levels much less than 2%. This result indicates
that there is a potential strain gage installation problem
with the full scale 16" diameter fiber overwrapped test
spheres whose outer fiber surfaces are significantly more

irregular than the outer hoop fiber wrapped surfaces
of the 6" diameter test cylinders discussed in this
report. It is suggested that consideration be given
to checking out the strain gage installation technique
by testing suitable fiber wrapped hardware prior to
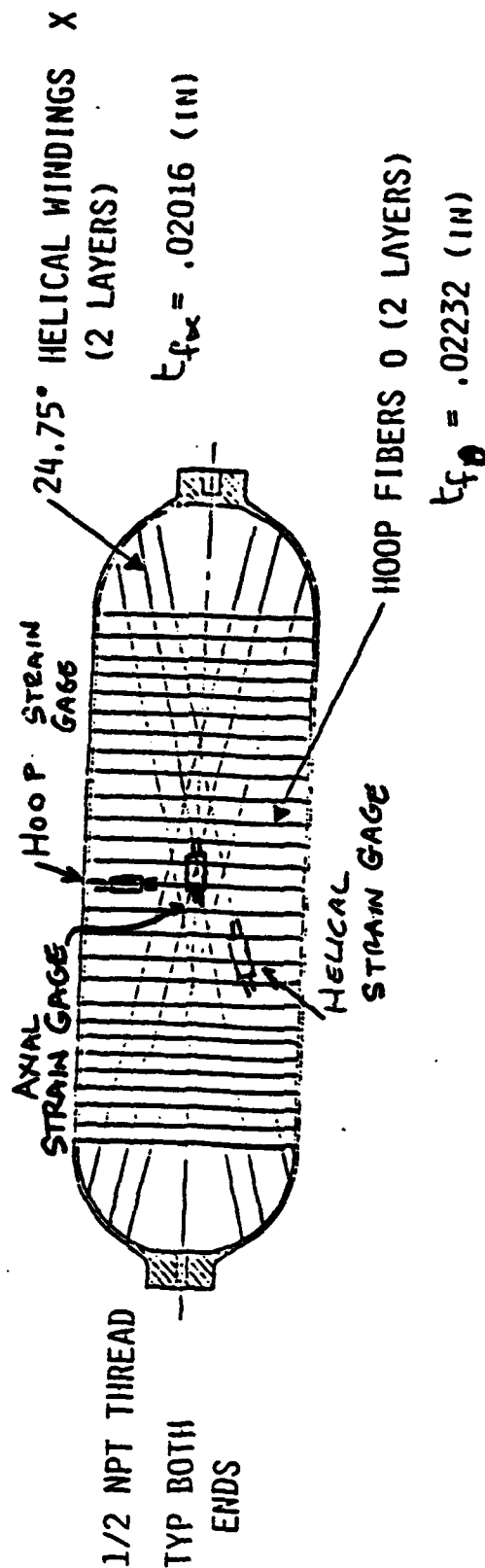testing the full scale 16" diameter composite spheres
at RPL.

2. **Test Description**

   2.1 **Test Specimen**

   The test specimen used is a 6" diameter Kevlar -49
   fiber wrapped cylinder as shown on the sketch of
   Figure 2-1E and the photographs of Figures 2-2E to
   2-6E. The fiber wrap pattern consists of two (2)
   each alternate layers of 24.75° helical and (90°)
   hoop fibers, with hoop fibers on the outer layer.
   The fibers are wrapped over a rubber liner supported
   by an aluminum mandrel. Port bosses and holes in
   the aluminum mandrel are provided for fiber cylinder
   fill, pressurization and draining. This construction
   assures that the fibers alone carry the internal
   pressure load. Hoop and helical Kevlar-49 fiber
   (less resin) thicknesses were .02232" and .02016",
   respectively, as given on Figure 2-1E. These
   test vessel fiber thicknesses were selected to
   give a hoop fiber failure mode. The resin system
   and cure temperature/time cycle for the 6" diameter
   cylindrical test specimen is the same as that which

VESSEL

· HERCULES ABL STANDARD 6" NOMINAL I.D. CYLINDRICAL
FILAMENT WOUND VESSELS WRAPPED OVER RUBBER COVERED
ALUMINUM MANDREL WITH TWO BOSSES ATTACHED

VESSEL DESIGNED TO FAIL IN HOOP SECTION

24.75° HELICAL WINDINGS X
(2 LAYERS)

$t_{f_{\alpha}} = .02016$ (IN)

HOOP FIBERS 0 (2 LAYERS)

$t_{f_{\theta}} = .02232$ (IN)

AXIAL
STRAIN GAGE

HOOP STRAIN GAGE

HELICAL
STRAIN GAGE

1/2 NPT THREAD
TYP BOTH ENDS

WRAP PATTERN X0X0

FIGURE 2-1

PHOTO 1 - TEST SET-UP
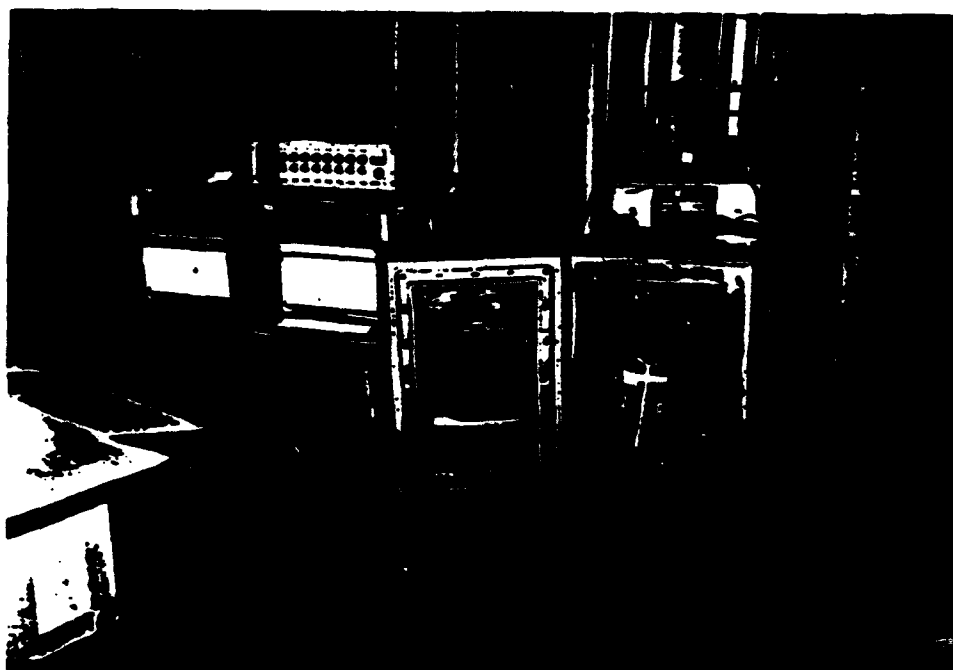
PHOTO 2 - TEST SET-UP

FIG. 2-2E

Arde, Inc.
6290-1

TELEDYNE
ENGINEERING SERVICES

PHOTO 3 - VESSEL 030 READY FOR TESTING

PHOTO 4 - VESSEL 030

FIG. 2-3E

▼▼ TELEDYNE
ENGINEERING SERVICES
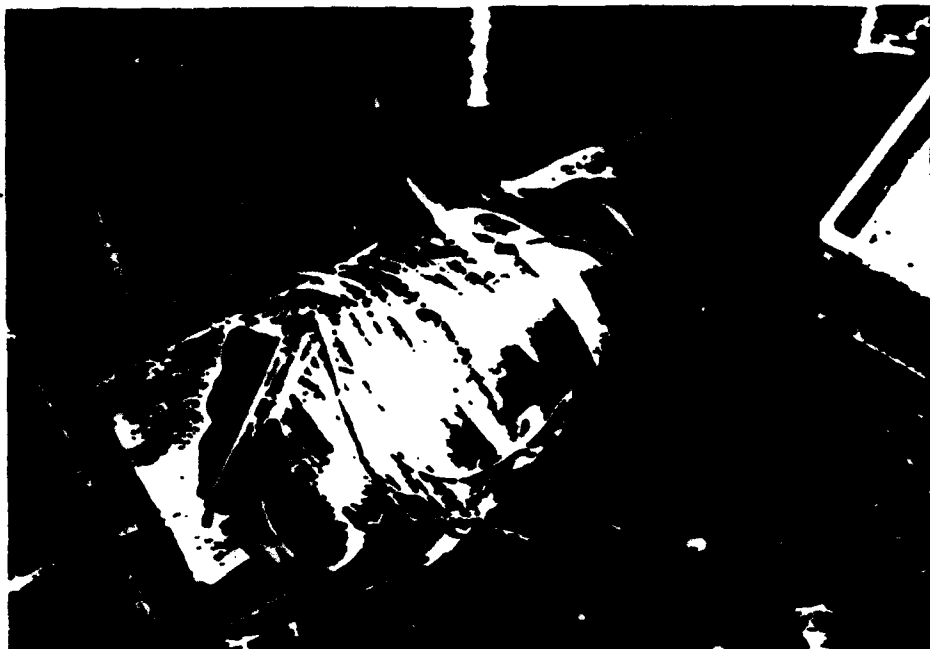
PHOTO 5 - VESSEL 030

PHOTO 6 - VESSEL 030

FIG. 2-4E
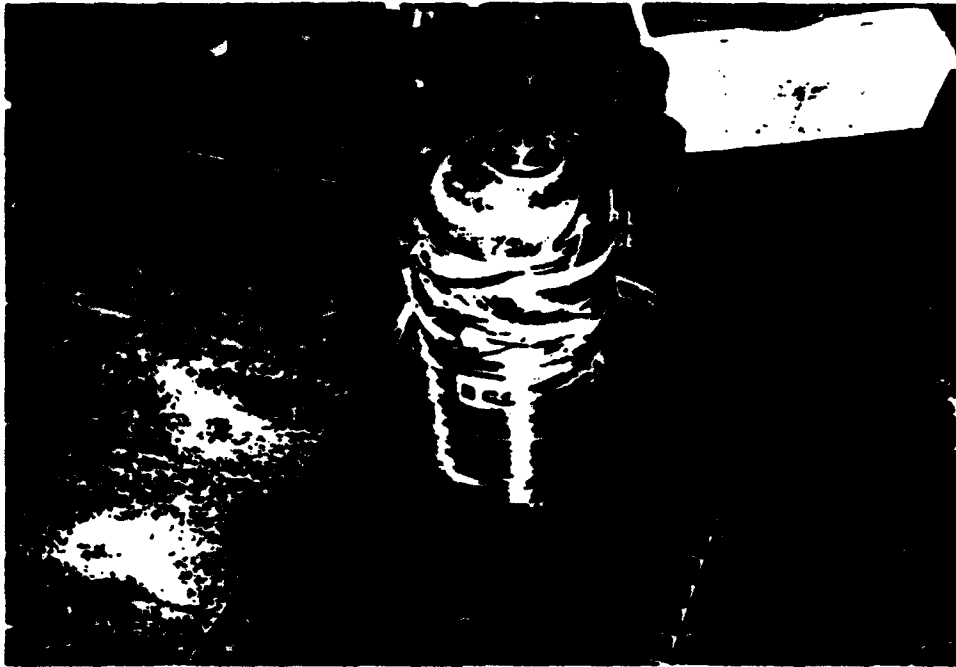
PHOTO 7 - VESSEL 028
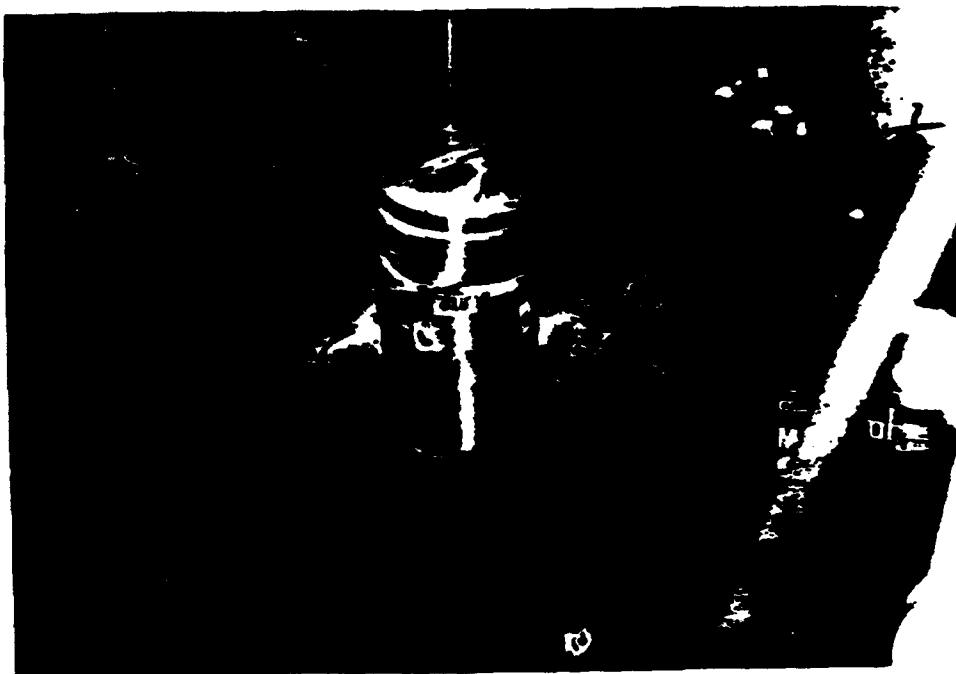
PHOTO 8 - VESSEL 028

FIG. 2-5E
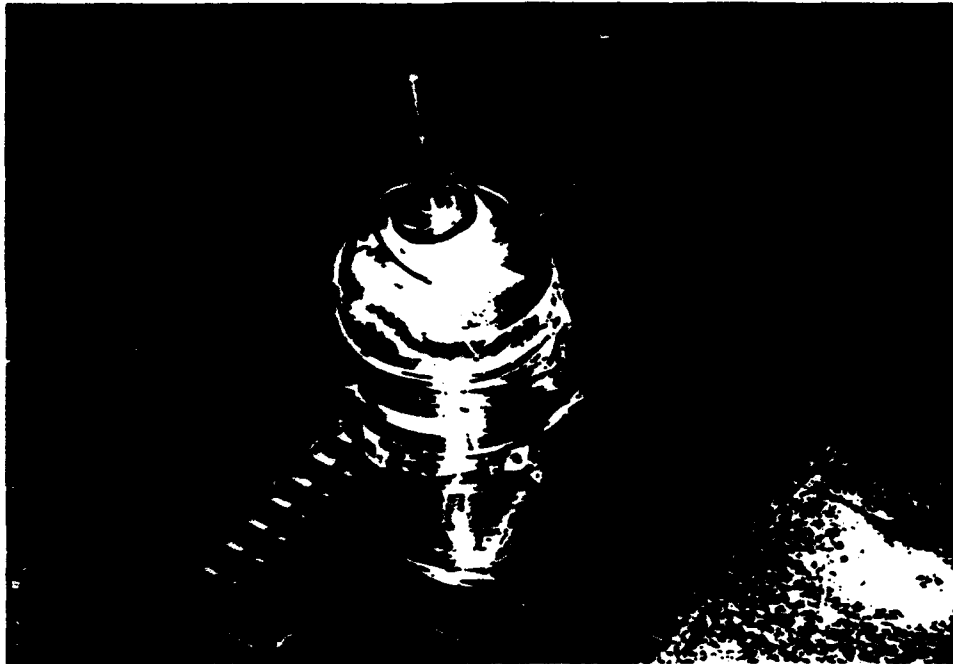
PHOTO 9 - VESSEL 028

FIG. 2-6E

will be used on the 16" diameter full scale composite test spheres. The resin is designated HARF 53 (DER 332/RD-2/TONOX 6040 with distribution in parts by weight of 100/25/29.3) cured 3 hours at 140°F followed by 4 hours at 248°F.

2.2 Test Set-Up

The test set-up is shown on the photographs of Figures 2-2, 2-3 and the schematic of Figure 2-7. The fiber wrapped cylindrical test specimen was instrumented at the cylinder center by hoop, helical and axial strain gages, 3 each at two locations 180° apart, as shown on the sketch of Figure 2-7. Pressure was monitored by a pressure transducer. Strain and pressure were recorded continuously on strip charts. The pressurizing fluid was hydraulic oil pressurized by an oil pump. The test specimen was housed in a metallic box for protection of personnel upon test vessel rupture.

3. Test Results

3.1 Fiber Material Properties and Strains

The actual test strain versus pressure traces for the two (2) test cylinders (S/N 028 and 030) are given on Figures 4-2 to 4-5 of Appendix 4.2. Details of the test data correlation are presented in Appendix 4.1. Figures 3-1 to 3-4 herein are graphs

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DATE_____

STRAIN GAGES

{ (1) HOOP
  (1) AXIAL
  (1) HELICAL
  2 PLACES
  180° APART

PRESSURE X-DUCER

PRESSURE GAGE

RECORDER
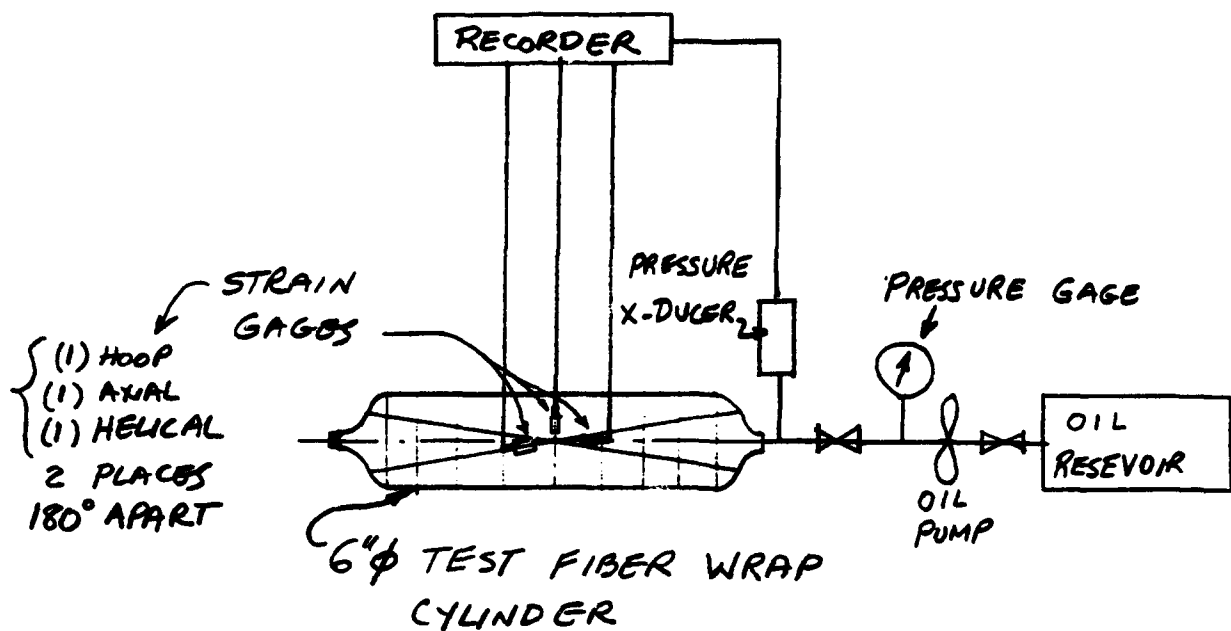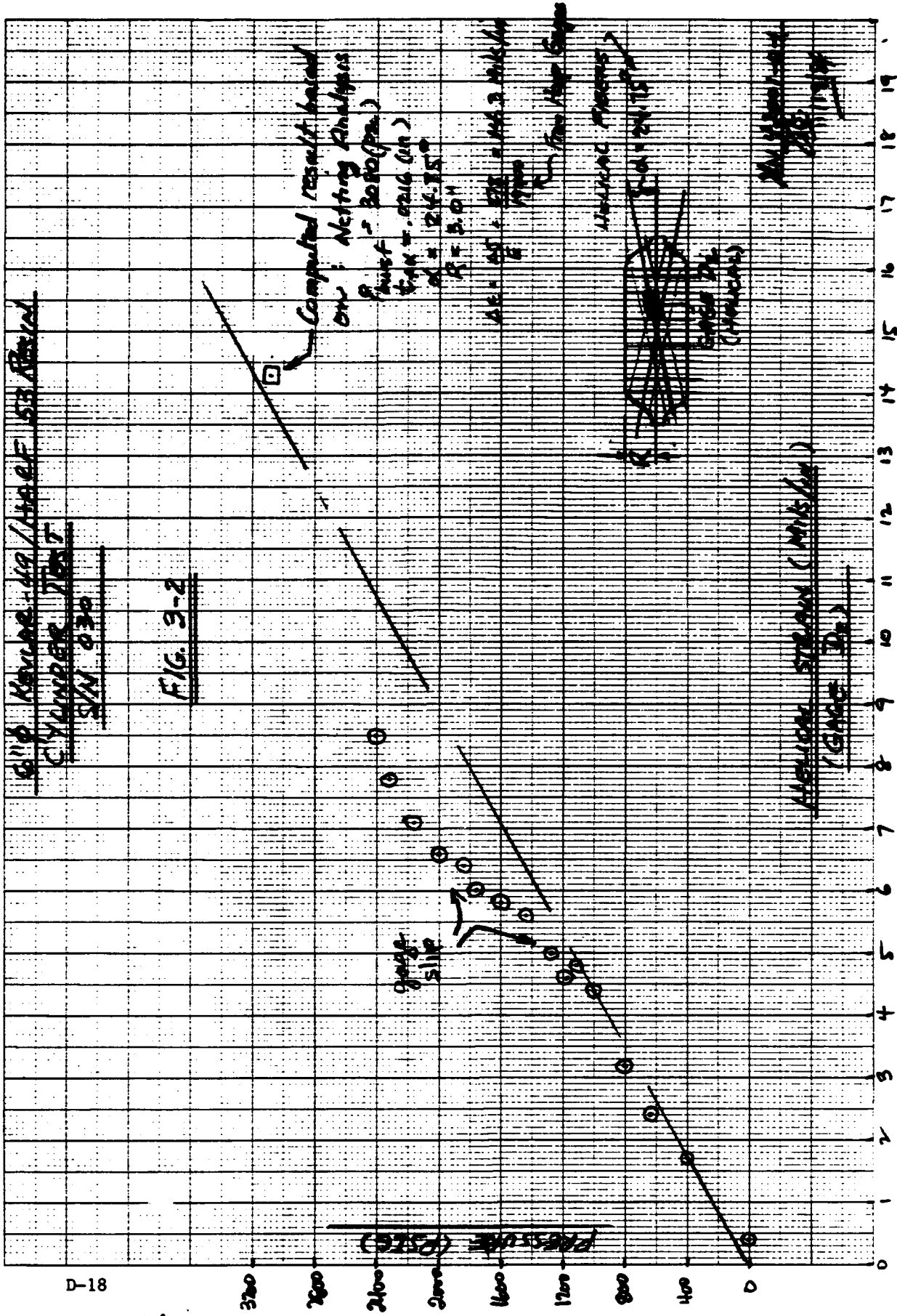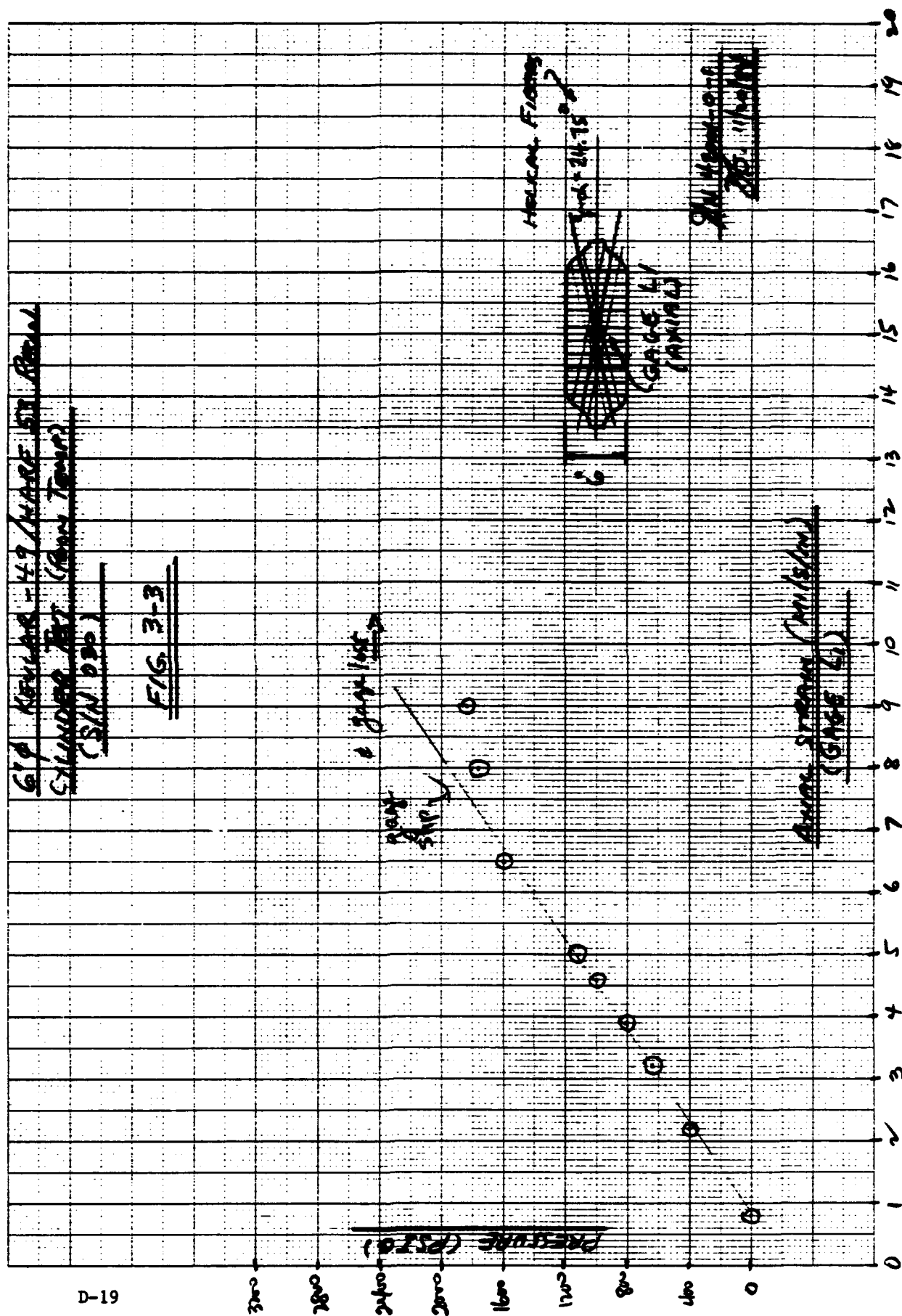
OIL RESEVOIR

OIL PUMP

6"⌀ TEST FIBER WRAP CYLINDER

FIG. 2-7 E

SCHEMATIC

6"⌀ CYLINDER TEST

SET UP

D-15

of pressure versus strain for selected strain

gages derived from the test traces. Figures 3-1 ε

to 3-3εgive hoop, helical and axial strain versus

pressure for test cylinder 030 and Figure 3-4 ε

presents hoop strain versus pressure for test

cylinder 028.

Test data correlation based on an equilibrium

netting analysis (fibers only resist load) and

measured strains, resulted in fiber less resin

Young's Modulus in the fiber directions (hoop

and helical) of 19.5 X 10^3 ksi which agrees closely

with the 19 X 10^3 ksi value given by DuPont and

reported in the literature by other investigators.

Fiber hoop strain at burst was measured as .0191 in/in

(See Figure 3-1ε)which is close to the 2% ultimate

strain assumed in the failure modeling analysis.

The vessel failure mode was hoop fiber failure,

as designed (See Figures 2-3$\varepsilon$to 2-6). Burst pressures

for the two test cylinders were very close; 3100/3080

psig for S/N 030 and 3040 psig for S/N 028 specimen.

Fiber stresses at rupture were 372 ksi hoop and

280 ksi helical for S/N 030 cylinder.

The measured hoop, helical and axial strain values

were found to be consistent. The change in fiber

6"∅ Kevlar-49 / Aramid 49 ??
CYLINDER ?? TEST (Room Temp)
S/N 030

FIG. 3-1

FAILURE

Helical Ply Failure

Glass C.I.
(Inner)

6"I

Hoop Strain (micro in)
Gage (?)

Longitudinal

PRESSURE (PSIG)

3200
2800
2400
2000
1600
1200
800
400
0

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

FIG. 9-2

46 1320

D-19

6'Ø Kevlar -49 /Wide Slit Round
Cylinder Test (Burr Tower)
(S/N 00)

FIG. 3-3

Helium Flames

Gage 4 (Amings)

Average Stresses (Amplitude) (Gage 20)

Right Skin

@ gain/ust

PRESSURE (PSIG)

6'Ø KEVLAR-49 / MORF STB RESIN
CYLINDER TEST (ROOM TEMP)

S/N 022

FIG 3-4

○ GAGE C1
x GAGE C2

FAILURE PRESSURE

HOOP GAGES C1, C2

ALL HOOP FIBERS

PRESSURE (PSIG)

HOOP STRAIN (MILS/IN)

helical strain per change in pressure, $\dfrac{\Delta \epsilon_\alpha}{\Delta P}$, was

determined to be about .004 (in/in)/ksi as

directly measured, or as calculated from measured

hoop and axial strains, ϵ_θ and ϵ_x, for the 24.75°

helical fiber angle. This result verifies the

classical strain transformations which will be used

in the failure modeling analysis. The effective vessel

fiber (less resin) Young's modulus in the non-fiber axial

direction derived from this data was 14.1×10^3 ksi.

3.2 Strain Gage Failures

Many strain gages failed well below rupture pressure

at strain levels much less than 2%. This is

illustrated on the Figures 4-2E through 4-5E pressure

traces of Appendix 4.2 and the graphs of Figures 3-2E, 3-3E.

The undulating, uneven surface of the fiber wound

vessel presents a difficult strain gage installation

problem. It is suggested that consideration be

given to verifying the adequacy of the strain gage

type and installation technique to be used on the

full scale 16" diameter composite spherical test

vessels by means of tests of suitable fiberwrapped

hardware prior to full scale testing at RPL.

4. APPENDICES

4.1 Test Data Correlation

4.1.1 S/N 030 Test Vessel

4.1.1.1 Notation

E = Youngs Modulus

p = Pressure

R = Radius

t = Thickness

α = angle of fiber with cylinder axis of rotation

Δ = Increment

ϵ = Normal Strain

γ = Shear Strain

ν = Poisson's Ratio

σ = Normal Stress

Subscripts

f = Fiber

α = Inclined   angle direction

θ = Hoop direction

x = Axial direction

D-22

4.1.1.2 Equilibrium Analysis

Figure 4-1 shows schematically the stresses, fiber directions, pressure load and radius of the test cylindrical vessel. Assuming that the resin does not resist load, hoop and axial equilibrium require that,

$$\sigma_{f\theta}\, t_{f\theta} + \sigma_{f\alpha}\, t_{f\alpha}\, \sin^2\alpha = pR \qquad \text{---(1)}$$

$$\sigma_{f\alpha}\, t_{f\alpha}\, \cos^2\alpha = \frac{pR}{2} \qquad \text{---(2)}$$

From (1) and (2) we have,

$$\sigma_{f\theta} = \frac{pR}{t_{f\theta}}\left(1 - \frac{1}{2}\tan^2\alpha\right) \qquad \text{---(3)}$$

For S/N 030 test results, Figures 2-1 & 3-1;
α = 24.75°, $t_{f\theta}$ = .02232, $t_{f\alpha}$ = .02016, P_b = 3100, R = 3.0, $\Delta\epsilon_{f\theta}$ = .0191

one obtains from (2) and (3) above the fiber less resin stresses and hoop Young's modulus,

$$\sigma_{f\theta} = \frac{3100 \times 3}{.02232}\left(1 - \frac{1}{2}\tan^2 24.75°\right) = 372 \; ksi$$

$$\sigma_{f\alpha} = \frac{3100 \times 3}{2 \times .02016 \cos^2 24.75°} = 280 \; ksi$$

$$E_\theta = \frac{\Delta\sigma_{f\theta}}{\Delta\epsilon_{f\theta}} = \frac{372}{.0191} = 19.5 \times 10^3 \; ksi$$

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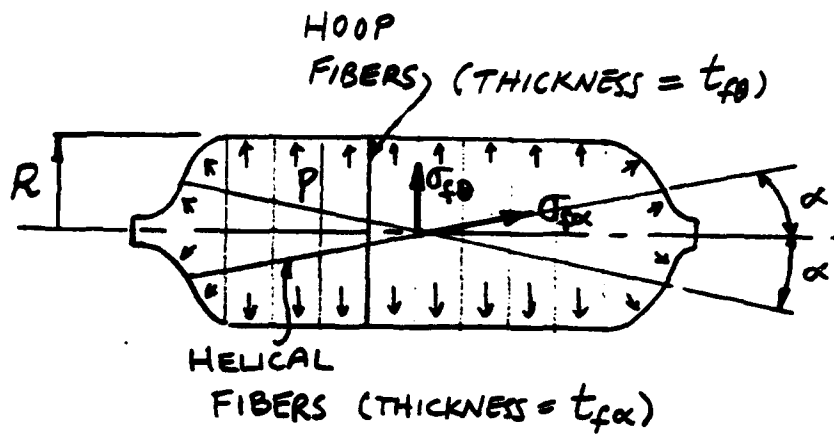
FIG. 4-1 E

CYLINDER

FIBER WRAP

STRESSES, CONFIGURATION

AND PRESSURE LOAD

D-24

4.1.1.3 Strain Transformation and Measured Strain Consistency

From Figures 3-1€to 3-3€, we obtain the measured slopes of the pressure versus fiber strain curves as,

$$-\frac{\Delta P}{\Delta \epsilon_\theta} = \frac{1.2}{.007} = 171.429 \ \frac{Ksi}{(in/in)} \ (Hoop)$$

$$\frac{\Delta P}{\Delta \epsilon_x} = \frac{1.4}{.0052} = 269.231 \ \frac{Ksi}{(in/in)} \ (Axial)$$

$$\frac{\Delta P}{\Delta \epsilon_\alpha} = \frac{1.8}{.008} = 225.0 \ \frac{Ksi}{(in/in)} \ (Helical)$$

Using the classical strain transformation relation,*

$$\epsilon_\alpha = \epsilon_x \cos^2\alpha + \epsilon_\theta \sin^2\alpha + \frac{\gamma_{\theta x}}{2} \sin 2\alpha \quad ---(4)$$

---

*Stavsky, Y. and Hoff, N.J., "Mechanics of Composite Structures," in "Composite Engineering Laminates," edited by A.G.H. Dietz, MIT Press, 1969.

we find with $\left(\gamma_{\theta x} = 0 \right.$ for hoop and axial principal directions $\left. \right)\ \alpha = 24.75°$ and the above numerical values that,

$$\epsilon_\alpha = \frac{\Delta p \cos^2(24.75°)}{269.231} + \frac{\Delta p \sin^2(24.75°)}{171.429}$$

or,

$$\frac{\epsilon_\alpha}{\Delta p} = .0041 \ (in/in)/_{psi}$$

This computed value using hoop and axial measured strains agrees very closely with the directly measured helical strain/pressure slope of

$$\frac{\epsilon_\alpha}{\Delta p} (measured) = \frac{1}{225} = .0044 \ (in/in)/_{psi}$$

The validity of the classical strain transformation and the consistency of the measured strains are therefore verified.

4.1.1.4 Helical Fiber Young's Modulus

We have from (2) and (3) with

$$\alpha = 24.75° , \ R = 3, \ t_{f\theta} = .02232, \ t_{fx} = .02016,$$

$$\sigma_{f\theta} = \frac{3p}{.02232}\left(1 - \frac{1}{2}\tan^2 24.75°\right) = 120.126\, p \ ---(5)$$

$$\sigma_{fx} = \frac{3p}{2 \times .02016 \times \cos^2 24.75°} = 90.218\, p \ ---(6)$$

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Taking principal directions as hoop

and axial, Hooke's Law for the fibers

becomes*

$$\epsilon_x = \frac{\sigma_{fx}}{E_x} - \frac{\nu_{\theta x}\,\sigma_{f\theta}}{E_\theta} \qquad \text{---(7)}$$

Substituting numerical values (5), (6)

in (7) gives with $\alpha = 24.75°$, $\nu_{\theta x} = .25$, $\sigma_{fx} = \sigma_x \cos^2\alpha$,

$$\epsilon_x = \frac{90.218\, p \cos^2(24.75°)}{E_x} - \frac{.25(120.126\,p)}{E_\theta}$$

or,

$$E_x = \frac{90.218 \cos^2(24.75°)\, p}{\epsilon_x + \frac{.25(120.126)p}{E_\theta}} \qquad \text{---(8)}$$

From Figure 3-3E, $\epsilon_x = .0052$ at $p = 1.4$ ksi

and taking $E_\theta \cong 19 \times 10^3$ ksi, we have from

(8) the axial direction Young's modulus,

$$E_x = \frac{90.218 \cos^2(24.75°) \times 1.4}{.0052 + \frac{.25(120.126) \times 1.4}{19 \times 10^3}} = 14.05 \text{ ksi}$$
(fiber less resin)

---

* See footnote on page D-25

For fiber volume ratio = 2/3, the composite

axial Young's modulus is,

$$E_x \text{(composite)} = 2/3 \times 14.05 \times 10^3 = 9.37 \times 10^3 \text{ ksi}$$

4.1.2 S/N 028 Test Vessel

Hoop Young's modulus is given by

$$E_\theta = \frac{\Delta \sigma_{f\theta}}{\Delta \epsilon_\theta} \quad \cdots \text{(9)}$$

Using (5) and noting from Figure 3-4 that

$$\frac{\Delta p}{\Delta \epsilon_\theta} = \frac{1.2}{.0074} \quad , \text{ we compute from (9)}$$

$$\frac{120.126 \; \Delta p}{\Delta p \left(\frac{.0074}{1.2} \right)} = 19.5 \times 10^3 \; \text{ksi} \quad \text{(fiber less resin)}$$

This value agrees with the prior determined

S/N 030 vessel result, demonstrating measurement

consistency.

4.2 Strain vs. Pressure Traces

Two (2) separate time-coordinated strip chart recorders
were used in the test and an individual pressure trace was
used on each recorder to maintain accurate pressure versus
strain recording.

APPENDIX E - 16" φ and 22"φ PSC Vessel Tests

This appendix gives detail descriptions of all the 16" φ and 22" φ full scale composite vessel tests. For ease of reference, the table of contents of this large appendix is given below.

E.1   <u>Full Scale Composite Vessel Tests -</u>

            <u>Instrumentation Requirements/Procedures</u>

This section of Appendix E contains ARDE document EG 42001-5 and ARDE letter 42001-KOS-084, which define Kevlar Overwrap Study Composite Vessel Tests Instrumentation Requirements/Procedures and near term experimental system checkout tests, respectively.

ARDÉ INC

SALES. ENG
19 INDUSTRIAL AVE
PHONE (201) 529-37(

February 3, 1986

Mr. Jim Miller
AFRPL/TOAE
Stop 24
Edwards AFB, CA 93523-5000

Reference: (1) Contract FO8606-84-C-0029

(2) ARDE Document EG42001-8, "Kevlar Overwrap Study Full
Scale Composite Sphere Testing Scope of Work"

(3) ARDE Document EG42001-5, "Kevlar Overwrap Study Full
Scale Composite Vessel Tests Instrumentation
Requirements/Procedures"

(4) AFRPL Document, AFRPL Project Number 573000RV, "Kevlar
Overwrap Study Full Scale Composite Vessel Experimental
Plan and Procedure", by Jim Miller, AFRPL/TOAE, Nov.
1985

(5) ARDE Letter 52001-KOS-080, "Transmittal of Meeting
Minutes for Kevlar Overwrap Study Test Planning Meeting
at AFRPL, EAFB, California, 12/10 to 12/12/85."

(6) Telephone Discussion, D. Gleich (ARDE) Sgt. J. Day
AFRPL, 1/22 and 1/27/86

(7) Telephone Discussion, S. Berko (ARDE) and M.
Dieckhoff (AFRPL) 1/23/86

(8) In Reply Refer to 42001-KOS-084

Gentlemen:

This letter defines revised test sequencing for near term tests to be per-
formed by AFRPL (ref. 1 to 5). The objective of this revised near term test
sequencing is to obtain Kevlar overwrap sphere brittle liner failure mode
test data and test facility/instrumentation verification at the earliest
possible date. The revised test sequencing, effective immediately, has been
coordinated with and approved by Mr. Pete Taddie, ESMC/SEM and discussed
verbally with AFRPL personnel, ref. 6,7.

An outline of test objectives and compatible test mode brief descriptions is
set forth below. Additional data are given on Figure 2 attached, which
defines the projected time phasing for the revised near term test
sequencing.

/

TEST OBJECTIVES/TEST MODES

1. ### TEST OBJECTIVES I

   1.1   Verify tank temperature/pressure control

   1.2   Verify strain gage installation/monitoring system

   1.3   Verify readiness of acoustic emission (AE) equipment

   ### TEST MODES I

   1.4   Mount 24 strain gages on 16"ϕ composite checkout vessel
              (P/N E4170 S/N 004) and hook up strain instrumentation to
              recorder(s). See Figure 16 for strain gage location and
              orientation. Check out AE equipment with pencil break.

   1.4.1   Pressure cycle test to check pressure/temperature control,
              strain monitoring system and AE equipment. Increase the
              pressure from 0 to 2000 ± 100 psig in a convenient "slow"
              time and then increase the pressure from 2000 psig to 5000
              psig ± 100 in 90 seconds or less and hold for $5 {}^{+1}_{-0}$ minutes.
              Vent pressure to $0 {}^{+100}_{-0}$ psig. Monitor pressure, tempera-
              ture, strain and AE instrumentation outputs. Maximum numnber
              of cycles is four (4).

   1.4.2   Remove P/N E4170 S/N 004 from test stand, retain strain gages
              and hold tank for later test.

2. ### TEST OBJECTIVE II

   2.1   Verify hydrogen embrittlement procedure

   2.2   Verify temperature/pressure/AE Equipment signals and strain
              monitoring system

   2.3   Perform brittle liner "dress rehearsal" test.

   ### TEST MODE II

   2.4   Same as 1.4

   2.5   Pressure cycle 0 to $5000 {}^{+100}_{-0}$ psig to $0 {}^{+100}_{-0}$ psig. Monitor
              pressure, temperature, strain and AE instrumentation to
              verify instrumentation/test set-up. Maximum number of cycles
              is two (2).

    2.6   **Disassemble tank from test stand and hydrogen embrittle per ARDE Procedure EG42001-6 Rev. A.**

    2.7   Re-install tank in test stand and hook up instrumentation.

    2.8   Fill vessel to operating GHe pressure (0 to $2000 \genfrac{}{}{0pt}{}{+100}{-0}$ psig in convenient "slow" time and from $2000 \genfrac{}{}{0pt}{}{+100}{-0}$ psig to $5000 \genfrac{}{}{0pt}{}{+100}{-0}$ psig in 90 seconds or less) and hold 5000 psig pressure level until liner rupture. Monitor instrumentation.

3.   TEST OBJECTIVE III

    3.1   Verify witness panel/overpressure instruments and failure strain monitoring.

TEST MODE III

    3.2   Re-install P/N E4170 S/N 004 in test set-up and perform gas burst test.

4.   TEST OBJECTIVE IV
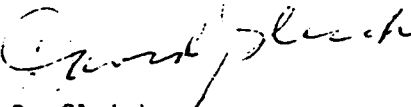
    4.1   Obtain brittle liner rupture test data on full up 16"ϕ tank (P/N E4168 S/N 001).

TEST MODE IV

    4.2   Assuming successful completion of Test Modes I to III, hydrogen embrittle P/N E4168 S/N 001 and perform brittle liner rupture test at operating pressure in accordance with the prior verified test procedures/test set-up.

Very truly yours,

ARDE, INC.

D. Gleich
Principal Investigator

DG:sr

FIG. 1G —
SKETCH, STRAIN GAGE MOUNTING
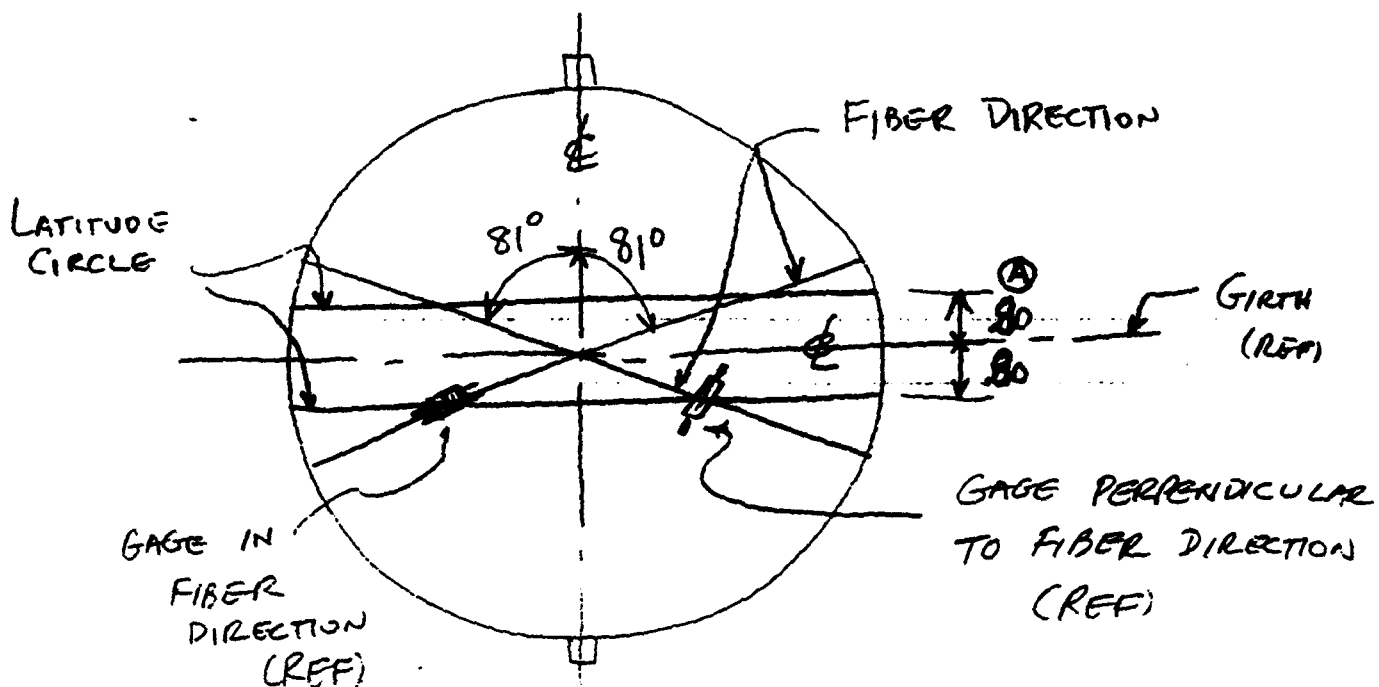
MOUNT 6 PAIRS OF GAGES (1 EA OF EACH PAIR IN THE
OUTER FIBER DIRECTION AND 1 EA PERPENDICULAR
TO THE OUTER FIBER DIRECTION ON EACH LATITUDE
CIRCLE) EQUALLY SPACED FOR A TOTAL OF
24 GAGES.

ARDE INC.
CONTRACT FO 8606-84-C-0029
J/N 42001-0-3
(REV A - .80 WAS .90)

ARDÉ, INC.

May 13, 1985

AFRPL/LKLH
Mr. John Marshall
Stop 24
Edwards AFB, CA 93523-5000

Subject: Transmittal of Arde Document EG 42001-5
          "Kevlar Overwrap Study Full Scale Composite Vessel
          Tests Instrumentation Requirements/Procedures"

Reference: 1. Contract F08608-84-C-0029

            2. Arde Letter 42001-KOS-036

            3. Telcon 5/6/85 and 5/7/85 John Marshall and
                Dick Grove (RPL) and D. Gleich (Arde)

            4. Telcon 5/7/85 D. Gleich (Arde) and Frank Davies (PI)

            5. Letter, John Marshall (RPL) to D. Gleich (Arde)
                5/3/85, "Transmittal of Technical Review Comments
                of Arde Document EG 42001-5, "Kevlar Overwrap
                Study Full Scale Composite Vessel Tests
                Instrumentation Requirements/Procedures"

            6. EG 42001-8, "Kevlar Overwrap Study, Full Scale
                Composite Sphere Testing Scope of Work

            7. In Reply Refer to 42001-KOS-042

Gentlemen:

Subject document has been formerly issued and is transmitted to
AFRPL for use in Their testing task defined by reference 6 Scope
of work.

The formal issue subject document reflects the comments of ESMC/SEM,
AFRPL, Aerospace Corp. and PI as finalized in discussions with Arde,
references 3, 4, 5.

                                 Very truly yours,

                                 ARDE, INC.

DG:sr   David Gleich
p.c. See separate distribution Principal Investigator
      list

KEVLAR OVERWRAP STUDY
FULL SCALE COMPOSITE VESSEL TESTS
INSTRUMENTATION REQUIREMENTS/PROCEDURES

PATRICK AIR FORCE BASE
Contract No. FO 8606-84-C-0029

Prepared By: Approved By:

_____   _____
D. Gleich   S. Berko

                                         _____
                                         A. Cozewith

ARDE, INC.
19 Industrial Avenue
Mahwah, N.J. 07430

TABLE OF CONTENTS

LIST OF FIGURES

1.0   SCOPE

This document defines the instrumentation requirements/procedures to be used in the testing of prestressed composite Kevlar 49 overwrapped cryoformed 301 CRES spheres (typified by 2.4, 2.5 & 2.6) under Patrick AFB Contract No F08606-84-C-0029. The testing is to be performed per 2.2 work scope and 2.3 test plan and procedures by AFRPL, who will furnish all necessary manpower, facilities, equipment and instrumentation.

2.0   APPLICABLE DOCUMENTS

2.1   Patrick Air Force Base Contract No. F08606-84-C-0029, "Kevlar Overwrap Study".

2.2   EG 42001-8, "Kevlar Overwrap Study, Full Scale Composite Sphere Testing Scope of Work".

2.3   EG 42001-4, "Kevlar Overwrap Study Full Scale Composite Vessel Test Plan and Procedure "TBD".

2.4   Arde Drawing E4168, "Pressurant Tank Composite"

2.5   Arde Drawing E4171, "Pressurant Tank Composite - Ductile Mode Wrap"

2.6   Arde Drawing E4170, "Test Set-Up Pressurant Tank Composite - Patrick AFB".

2.7   EG 42001-6, "Liner Hydrogen Embrittlement"

2.8   EG 42001-7, "Machining Defects in Metal Tank Wall by EDM Process"

2.9   MIL-STD-45662, 5 January 1983, "Calibration System Requirements"

3.0   TEST CONDITONS

3.1   Atmospheric Conditions

Unless otherwise specified in 2.3, testing shall be conducted at external ambient conditions existing at AFRPL. Sun shading shall be provided, wherever practical, to minimize the temperature rise in the test article, lines, plumbing and pressurant gas.

3.2 Test Measurement Tolerances

Unless otherwise specified, the maximum allowable tolerance of test conditions (exclusive of instrument accuracy) during the testing of the vessels (2.4, 2.5 & 2.6) shall be as follows:

a) current   5%
b) deflection   5%
c) flow rate   10%
d) frequency   2%
e) pressure, barametric   5%
f) pressure, fluid   2%
g) strain 500×10^{-6} (in/in)
h) temperature   5 degrees F
i) time   5%
j) velocity   10%
k) voltage   5%
l) weight   5%

3.3 Accuracy of Test Equipment

A calibration system conforming to MIL-STD-45662 (2.9) shall be utilized to control the accuracy of instruments and facility type test equipment used to monitor and control test parameters. The accuracy of special test equipment used to control and monitor test parameters shall be validated periodically and the validation period shall be less than the calibration period of any instrument contained with it. All instruments and test equipment used in conducting tests shall conform to laboratory standards whose calibration is traceable to the prime standards at U.S. Bureau of Standards. The instrumentation used to monitor pressure, strain, displacement, temperature, time and acoustic emission signals shall be calibrated immediately prior to the start of testing.

4.0 MEASUREMENTS REQUIRED

Measurements required are defined for each test mode, i.e., pre-test processing/checkout experiments and full up test modes (brittle liner failure and leak before burst ductile liner failure modes). Instrumentation details/requirements to obtain this measurement data are given in Section 5.0 herein.

4.1 Pre-Test Processing/Checkout Experiments Measurements

4.1.1 Hydrogen Embrittlement/Strain Gage Installation Check/Acoustic Emission Applicability (Ref. 2.2 and 2.7).

4.1.1.1 Pre-Pressurization

a) acid solution composition
b) depth and volume of acid solution fill
c) charging current and voltage
d) time versus events (charging and hold)
e) photographic coverage

4.1.1.2   Pressurization Mode
As function of time with common time base:

a) pressure (gas)
b) fiber strain
c) temperatures (gas, tank, strain gages)
d) acoustic emission signals
e) fragment velocity and overpressure (if fibers rupture)
f) ambient conditions (pressure, temperature, humidity)
g) photographic coverage

4.1.1.3   Post Test

a) post test inspection
   1) visual inspection of outside and inside surfaces (boroscope, if applicable) and note condition of specimen and type of failure; describe fragments (if applicable).

   2) pack and ship test specimen (all parts) to Arde for further inspection/evaluation

b) data documentation

   1) document post test inspection results (including sketches and photos)

   2) review and update test logs and data

   3) transmit test reports and data to Arde (see 2.2 Scope of Work)

c) photographic coverage

   1) sufficient 3" X 5" or larger black and white photographs to adequately describe post test specimen condition; three (3) photographs minimum

   2) Provide title/legend as part of photograph

4.1.2   System Checkout Tests (Ref. 2.2)
As function of time with common time base:

a) GN2 parameters (pressure, temperature and flow for system and tank)
b) heat exchanger characteristics (temperature and pressure drop, flow)
c) tank (fiber strain, metal, strain gage and fiber temperature, GN2 parameters)

d) valve and pressure regulator settings/sequencing

e) ambient conditions (temperature, pressure, humidity)

f) photographic coverage

4.2   Full Up Composite Sphere Tests Measurements

4.2.1   Hydrogen Embrittled Liner Test Mode
           As function of time with common time base:

           a)   Tank Input Parameters
                1. GN2 internal pressure, temperature
                2. metal, fiber and strain gage temperatures
                3. ambient (temperature, pressure, humidity)

           b)   Tank Response Parameters
                1. fiber strain
                2. fiber displacement
                3. acoustic emission signals (if applicable)
                4. fragment velocity and overpressure (if fibers rupture).

           c)   System Parameters
                1. GN2 pressure, temperature, flow rate
                2. heat exchanger characteristics (temperature and pressure
                    drop, flow rate)
                3. valve and pressure regulator settings/sequencing

           d)   Post Test
                1. post test inspection
                2. data/documentation

           e)   Photographic Coverage
                Still and motion picture coverage as applicable, from pre-
                test through post test modes.

4.2.2   Leak Before Burst (LBB) Liner Test Mode
           Same as 4.2.1 except:

           a)   valving, plumbing and tank pressure measuring instrumentation
                shall facilitate isolating the tank from the rest of the
                system and permit the monitoring, during hold at operating
                pressure, of any pressure decay to indicate a tank leak, as
                set forth in detail in 2.3 test plan and procedure.

           b)   the pressure cycling spectrum, including holds at operating
                pressure, shall be as defined in 2.3.

4.3   Data Recording

           All measured data as applicable during pre-test, calibration and
           test modes shall be recorded with a common time base. The
           recorded data, together with test logs, shall be presented in a
           form convenient for analysis by PISCES 2D ELK computer program.

5.0   INSTRUMENTATION DETAILS/REQUIREMENTS

5.1   Overview

A schematic of test tank instrumentation indicating the type of tank measurements required is sketched on Figure 1**F**. Recording instruments, acoustic emission monitoring equipment, blast overpressure and fragment velocity monitoring devices are not shown on Figure 1**F**. Specific instrumentation details/requirements are discussed in 5.2 following:

5.2   Instrumentation Details

5.2.1   Kevlar 49 Fiber Strain Monitoring (See Figures 1, 2, 3, 4)
Requirements: F   F   **F**   F
    Maximum Strain   2%
    Bandwidth   80 KHZ

Instrumentation System:
a)   Sensor:
    1)   Micromeasurement (Type EA06)
    2)   Four element bridge; dummy gage mounted close to active element

b)   Cables:
    1)   RG 58/RG 62 coaxial cable to tape machine and Twinax to preamplifier

c)   Signal Conditioning:
    1)   Pre-amplifier 100/80 KHZ
    2)   Calibration System: Relay switching system to provide end to end calibration by insertion of appropriate resistors.

d)   Recording System:
    Wideband Group II FM tape recorder or
    Wideband Group I direct record tape recorder
    Wideband Group I FM (80 KHZ)

e)   Temperature measurement at active and dummy elements

Number of Channels:
    Brittle liner failure   24 channels.
    Twelve (12) bi-axial gages equispaced on two (2) great
    circles ten degrees from equator.

    Ductile liner failure   8 channels.
    Four (4) bi-axial gages, 1/2" from flaw, spaced 90 degrees
    apart.

Data Processing:
    Strain-time history plots. Digitized data on a VAX
    compatible tape (1600 BPI, 9 track ASCII character set with
    record length block set and number of files specified).

    NOTE: AFRPL to send PI tape with signal on it for PI
    comment.

Strain Gage Procurement: Gages from one (1) lot

Strain Gage Mounting Requirements:
    Use separate support posts for connectors to isolate them
    from shock and vibration (See Figure 1).

KEY

C = connector

Strain
SGB = strain gage (brittle failure) - (12) bi-axial gauges - equispaced on 10° great circles
SGD = strain gage (ductile failure) - (4) ea - @ 90°, ½" from flaw
DSG = dummy strain gage close to active gages

Shell Displacement
FOS = Fiber Optic Sensor - 4 ea equispaced on girth (Brittle Failure) - 1 ea above flaw (Ductile Failure)
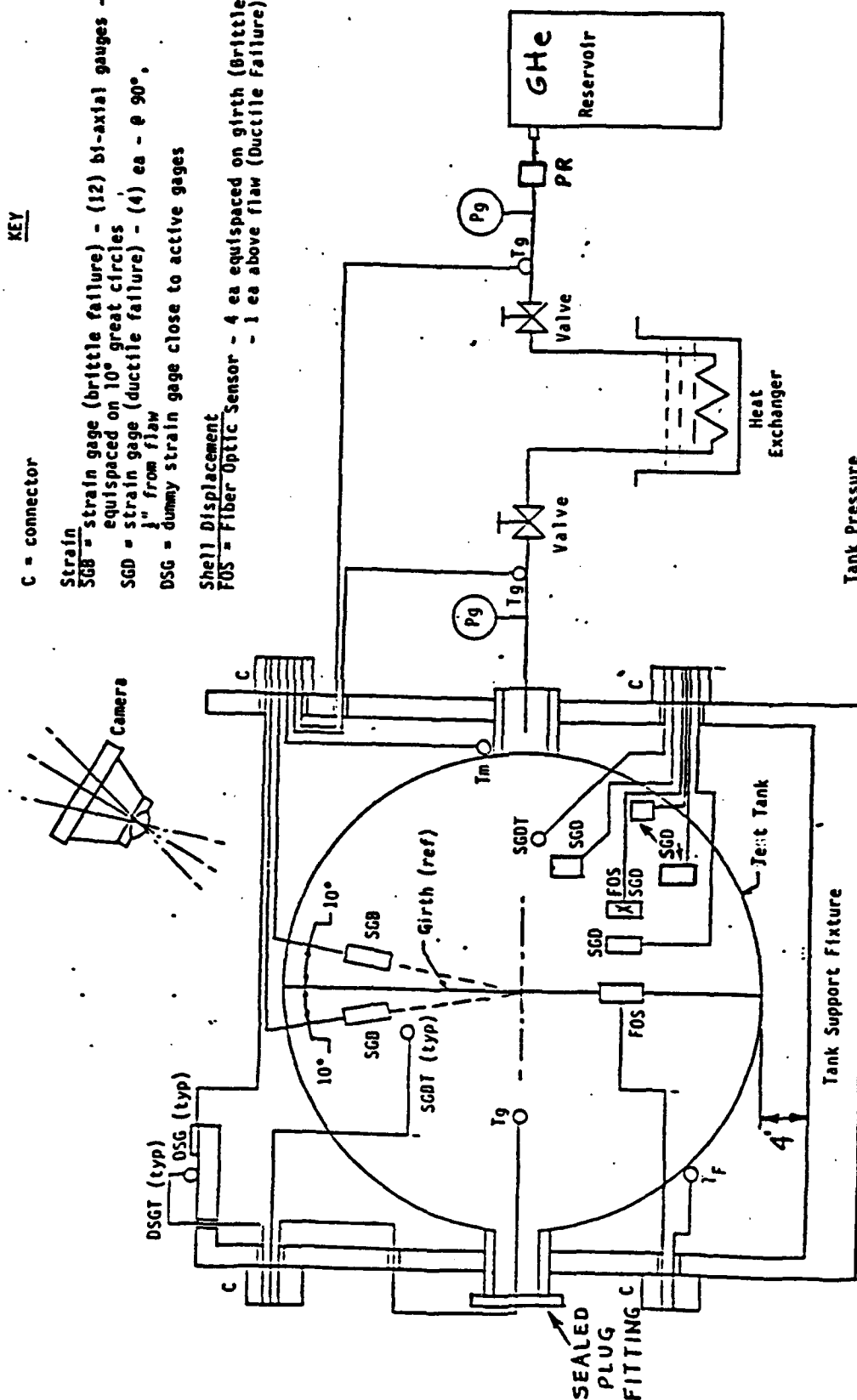
Tank Pressure
Pg = Pressure gauge (Piezo - resistive)
PR = Pressure Regulator

Temperatures (Thermocouples)
Tg = gas temp
Tm = tank metal temp
T_f = fiber temperature

SGBT = strain gage (brittle failure) temp
SGDT = strain gage (ductile failure) temp
DSGT = dummy strain gage temp

Valves
Valve closures identified and sensed (microswitches)

GHe Reservoir

PR
Pg
Tg
Valve
Heat Exchanger
Valve
Pg
Tg

Camera

C
Tm
SGDT
SGD
SGD
FOS
SGD
SGB
Girth (ref)
10°
10°
SGD
SGDT (typ)
Tg
Test Tank
Tank Support Fixture
4'
T_f
FOS
DSGT (typ)
DSG (typ)
C
C

SEALED PLUG FITTING

FIG. 1F
SCHEMATIC
TEST TANK INSTRUMENTATION

Data Processing:
Strain-time history plots. Digitized data on a VAX
compatible tape (1600 BPI, 9 track ASCII character set with
record length block set and number of files specified).

NOTE: AFRPL to send PI tape with signal on it for PI
comment.

- Strain Gage Procurement: Gages from one (1) lot

Strain Gage Mounting Requirements:
Use separate support posts for connectors to isolate them
from shock and vibration (See Figure 1).

Strain Gauge Mounting Requirements

TWISTED CONNECTING WIRES

ACTIVE GAUGES

DUMMY PAD

CABLE CLAMPS

GIRTH BANDS

RED
(+EXCIT)

ACTIVE GAGES

GRN
(+SIGNAL)

BLK
(-EXCIT)

WHT
(-SIGNAL)

- One mil Kapton tape under all lead runs and wire crossovers
- Care must be taken with isolation if coaxial cable is used for strain gauges. Best solution is probably to float power supply and ground one side of signal.
- TCs required on active and dummy pads

SIA
SIB

SIAD
SIBD

ALL INTERNAL BRIDGE WIRING 40 AWG. ALL SAME LENGTH. WIRES TO BE TWISTED TO MINIMIZE INDUCTANCE.

DUMMY PADS

CABLES CLAMPED TO GIRTH BANDS. CABLES WITH CONNECTORS ABOUT 18 in. LONG

SI

LEAD WIRE LENGTH:
$A_4 = BD_4$
$A_1 = AD_1$
$B_2 = AD_2$
$B_3 = BD_3$

65-02-113

Strain Gauge Bonding Requirements

Strain gauge bonding procedures:

- Bond under pressure using room temperature cured epoxies

  — Instruction Bulletin B-129-2, surface preparation for strain gauge bonding

  — Instruction Bulletin B-137-8, strain gauge applications with M Bond AE-10/18 and M Bond and GA-2 adhesive systems

  — Instruction Bulletin B-141-2, application of M coat G and GL protective coatings

- Must minimize mass of solder connection and lead wire

  — Manufacturer applied solder dot only

  — 40 AWG Belden magnet wire (type 8046)

85 02 104

E-20

FIGURE 3 F

Basic Strain Gauge Recording System
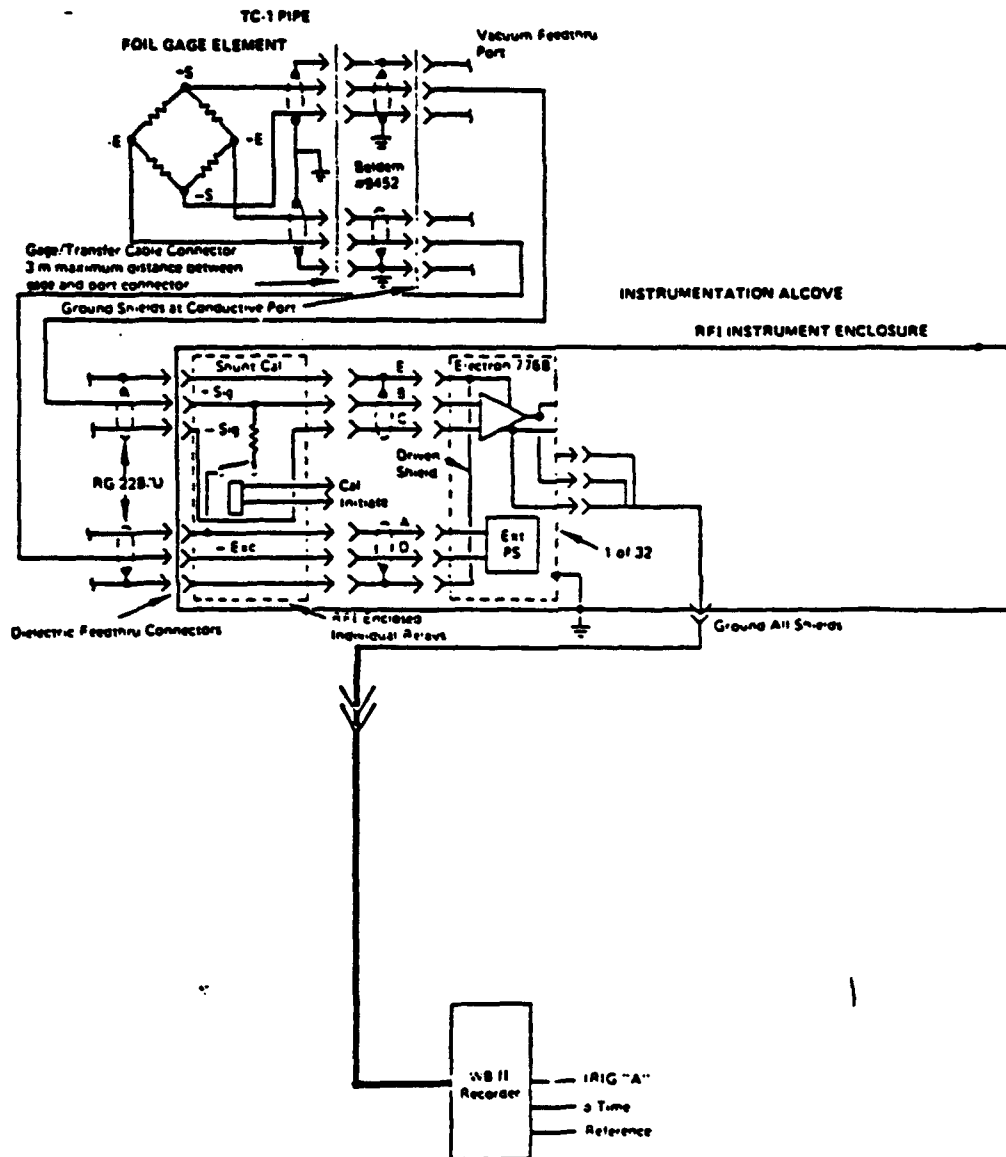
FIGURE 4 F

Mechanical Measurement Instrumentation System
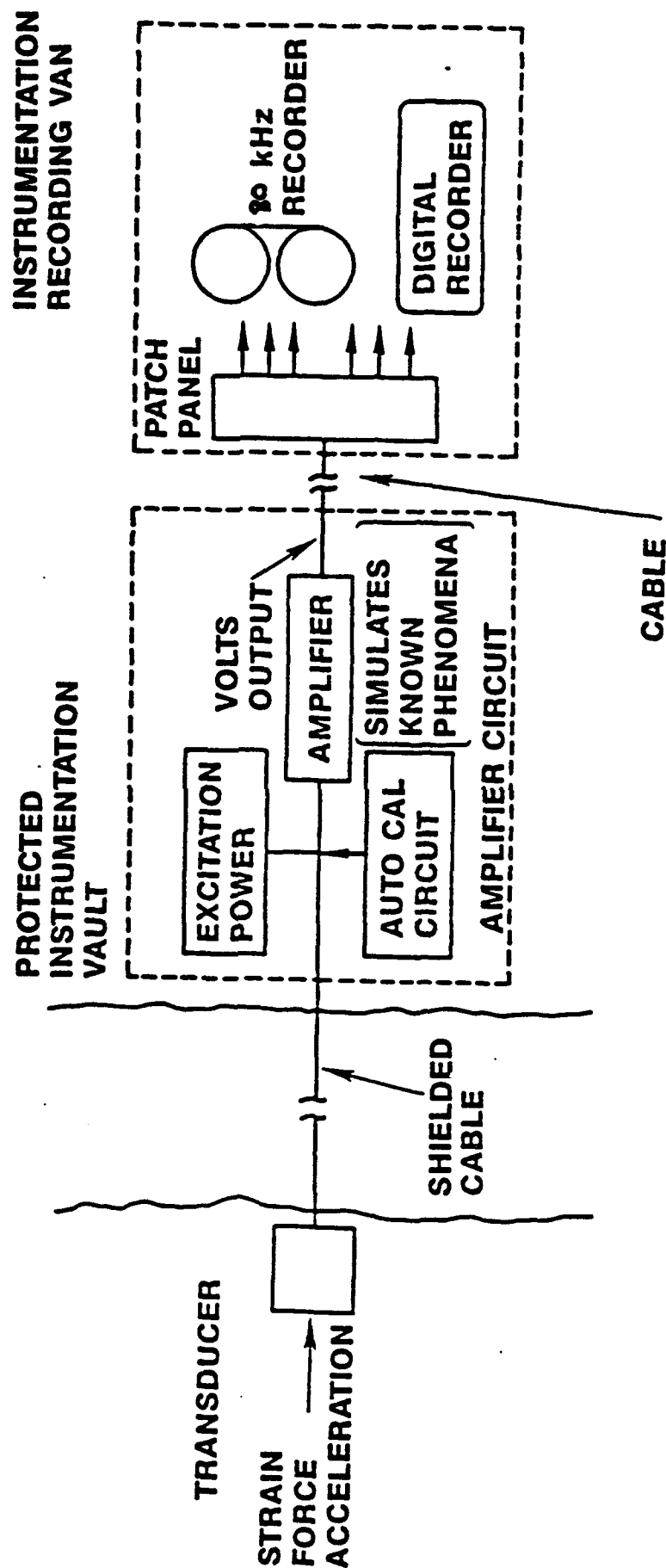
Shell Displacement
Measurement Requirements (See Figure 1, 5)

Mounting:

Rigidly mount sensor heads to define their reference positions

Requirements:

Maximum displacement - ~ $\frac{1}{2}$ cms.

Resolution - 0.05 cms, 10 μsec.

Bandwidth - 70 KHz

Instrumentation System:

a) Sensor

i) Fatonic KDC4SL/KT-245HF. Fiberoptic noncontact sensor.

b) Cables

(i) RG 213 coaxial cable or Twinax.

e) Signal conditioning

i) KD-245 signal conditioner located in forward bunker. Fiber optic cable from KD-245 to sensor head.

d) Recording System

Wideband Group I FM tape recorder or equivalent.

Number of Channels:

Brittle Liner Failure: Four sensors equispaced around the equator.

Ductile Liner Failure: Single sensor located immediately above flaw.

Data Processing:

Plotted displacement time histories, digital data print outs, digitized data on VAX compatible tape.

85-02-094

FIGURE 5 F

Fotonic Fiberoptic Noncontact Sensor

- Bifurcated fiberoptic probe transmits and receives light

Typical Probe Tip
o Transmit   • Receive

Hemispherical Fiber Distribution (H)

Concentric Transmit Inside (CTI)

Random Fiber Distribution (R)

OUTPUT IN VOLTS D.C.
(Proportional to intensity of reflected light)

OPTICAL PEAK   (CTI)   (H)   BACK SLOPE   FRONT SLOPE   (R)

GAP   (Distance from Probe to Target Surface)
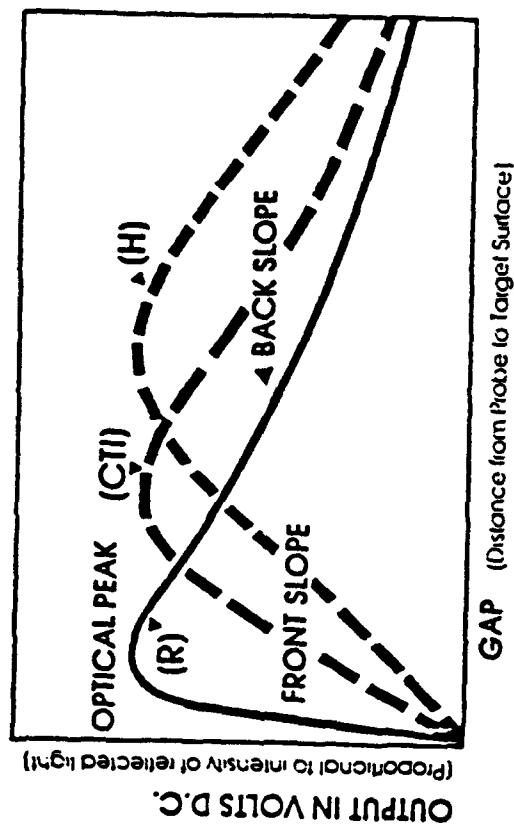
Plug-In Cartridge	Probe Model KDP—	Probe Tip Diameter Total	Probe Tip Diameter Active	Frequency Response (-3db)	Output Signal Ripple (Mv-p-p)	FRONT SLOPE CHARACTERISTICS					BACK SLOPE CHARACTERISTICS					Optical Peak (mils)	
						Dynamic Resolu- tion' (μin)	Static Resolu- tion' (μin)	Sensi- tivity $(\mu in /mv)$	Linear Range' (mils)	Standoff Ctr. of Range (mils)	Dynamic Resolu- tion' (μin)	Static Resolu- tion' (μin)	Sensi- tivity $(\mu in /mv)$	Linear Range' (mils)	Standoff Ctr of Range (mils)	Mid Point	Range' $\pm5\%$
KT	245 HF	0.245"	0.230"	750 kHz	8	320	1000	40	70	35	2400	6000	300	300	300	150	100

85-02-136

Temperature Measurement Requirements

(See Figures 1, 6)

Requirements:

       150°F

       Bandwidth > 1 KHz

Instrumentation System:

    a)   Sensor

           Chromel/Alumel thermocouples with reference junction.

    b)   Cables

           Twisted Shielded Pairs

    c)   Signal Conditioning

        i)   Preamplifier

        ii) Calibration (end to end) by use of known voltage sources.

    d)   Recording System

           Datalogger.

Number of Channels:

Brittle Liner Failures

Strain gauge temperatures	24
Gas temperatures	4

Ductile Liner Failure

Strain gauge temperature	16
Gas temperatures	4

Thermocouples used to detect gas temperatures must have fast response, i.e., low thermal capacity.

Data Processing:

Temperature time history plots, digitized data print out, VAX compatible magnetic tape file.

85-02-097

FIGURE 6F

Temperature Measurement System
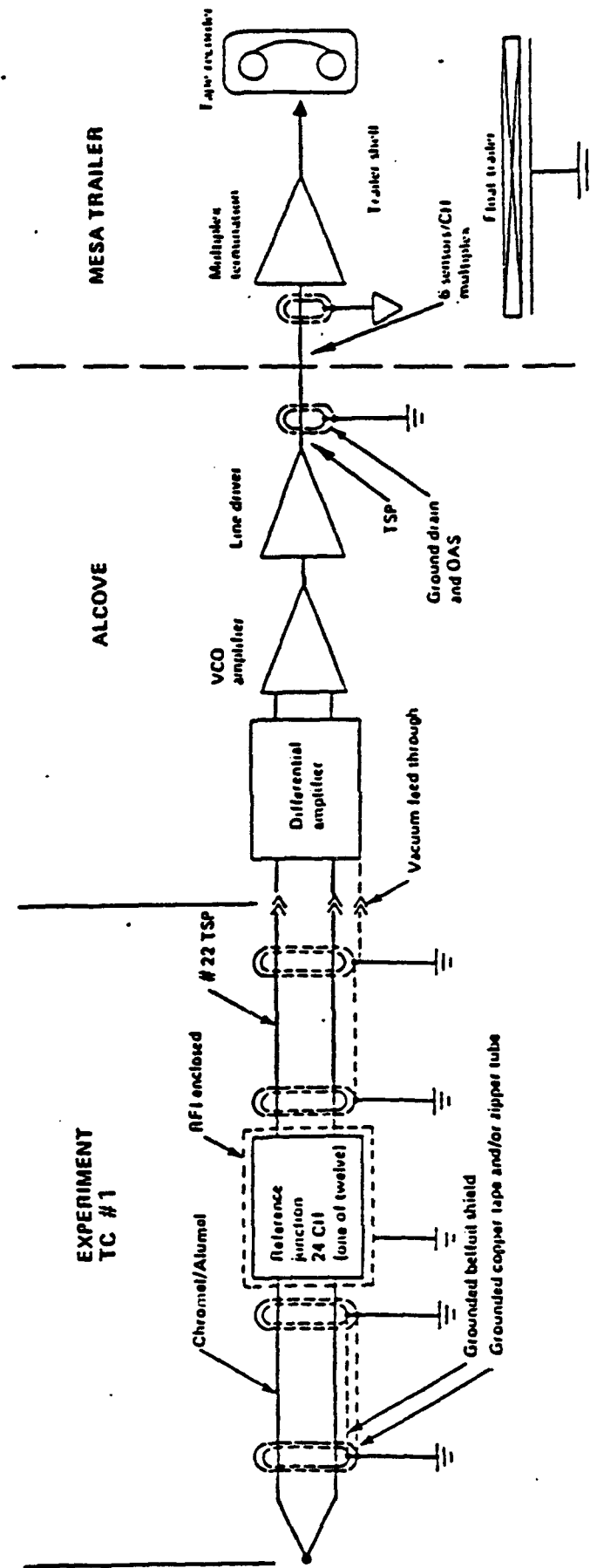
Tank Pressure Measurement Requirements

(See Figures 1,7)
F F

Requirements:

   5000 psi

   Bandwidth - > 1KHz.

Instrumentation System:

   a)   Sensor

            Piezo-resistive pressure gauges.

   b)   Cables

            Twisted Shielded Pair

   c)   Signal Conditioning

        i)   Preamplifier

        ii) Calibration system

   d)   Recording system

            Datalogger

Number of Channels: 4

   Monitor pressures at vessel and reserviors.

Data Processing:

   Plots of pressure time histories and digitized data print out.

85-02-096

FIGURE 7F

Piezoelectric Pressure Measurement System
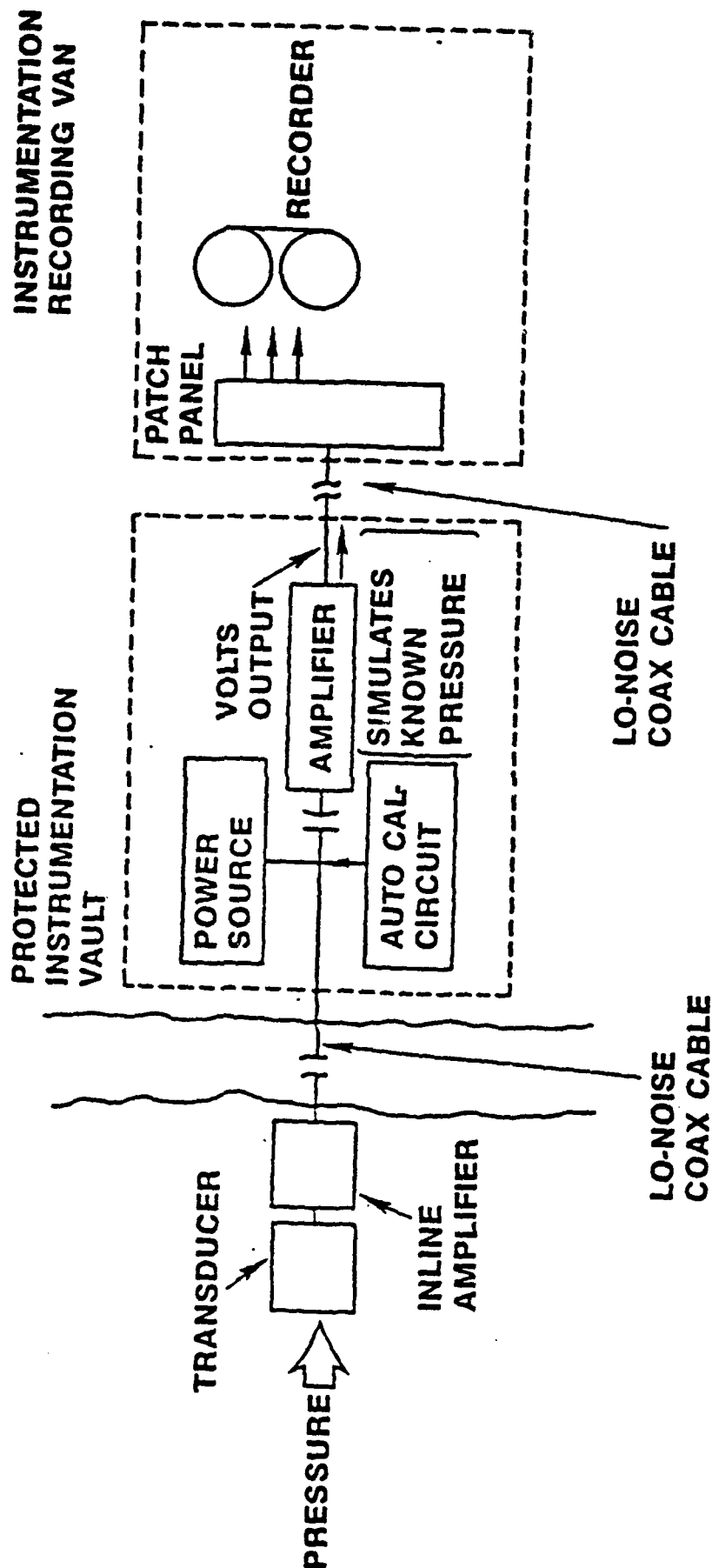
Valve Closure Requirements

Requirements:

    Valve positions unambiguously identified.

    Bandwidth - > 1 KHz

Instrumentation System:

    a)   Sensor: Microswitches

    b)   Cables: Twisted Shielded Pairs

    c)   Signal Conditioning

    d)   Recording System: Datalogger.

Number of Channels: 5

Data Processing:

    Print out defining times of valve position changes.

85-02-091

Timing, Firing and Monitor Requirements

Requirements:

   Time correlation of all measurements

Instrumentation System:

   IRIG time on all tape recorders and data loggers.

Data Processing:

   History of time of all events such as tape starts and camera activation.

85-02-099

Airblast Measurement Requirements

REQUIREMENTS:

1—10 psi overpressure and stagnation pressure
80 kHz bandwidth

INSTRUMENTATION SYSTEM:

(a) Sensor   (X-DUCER)   Piezoelectric pressure gauges (1-50 PSI)
(b) Cables   RG 213 coaxial cable
(c) Signal conditioning   Liner drivers
(d) Recording system   Wide-band group one FM tape (80 KHz)
(E) TANK 4' ABOVE GROUND (POINT X-DUCERS TO TANK CENTER)

NUMBERS OF CHANNELS:

Three radials with overpressure measurements at four ranges (2',6',10',14')
i.e., total of 12 plus stagnation pressures at closest and
mid-range (6 measurements)

Radials spaced 120 degrees apart

DATA PROCESSING:

Plots of pressure time histories, digit..ed data printout,
digitized data on VAX compatible tape

85-02-112

Fragment Velocity Measurement Requirements

Requirements:

    Maximum velocity - 20 meters/sec.

    360° coverage

Instrumentation System:

    a)   Sensors

        i)   High speed cameras - $\frac{2000}{5000}$ fps Hycam or Fastex 1 Kc Timing

        ii) Witness panels - (foam, plywood or celetex)

Number of channels:

        i)   Cameras - 2 split image.

        ii) Witness panels - 8 ranges on 4 radials. Provide 360 degree coverage on a single range for brittle rupture. For LBB only need local zone in region of flaw

Data Processing:

    Developed film.

    Photographic documentation of witness panels before recovery.

E.2   <u>16" φ and 22" φ PSC Vessel Test Matrix</u>

Table E-1 herein contains the 16" φ and 22" φ
PSC Vessel Test Matrix and brief descriptions of
test specimens employed, test objectives and key
test results. Additional details for each test
are given in following sections E.3 to E.12.

TABLE E-1 16" φ AND 22" PSC VESSEL TEST MATRIX

TEST TYPE	OBJECTIVE	TEST SPECIMEN DESCRIPTION	TEST RESULTS
(RV-4, 4A) high pressure GHe test 5600/5000 psig (16" φ PSC)	Demonstrate "fail safe" mode and define structural response	16 " φ sphere Olympus configuration Kevlar overwrapped 301 cryo CRES Global embrittlement (100% fiber thickness)	Demonstrated "fail safe" mode at operating pressure. "Static" structural response behavior observed. Need for increased hydrogen concentration at tip of cracks for enhanced brittle liner failure indicated.
(RV-5) high pressure GHe test 4900 psig (16" φ PSC)	Demonstrate "fail safe" mode and define structural response. Determine effect of increased H_2 charging time, pickling and $N_As O_2$ additive on brittle failure	Same as RV-4, 4A except increased H_2 charge time liner I.D. pickle and $N_As O_2$ solution additive.	Demonstrated "fail safe" mode at operating pressure with "static structural response. Enhanced brittle liner failure observed: Broke in short time at 4900 psig on way up to 5000 psig.
(RV-7) high pressure GHe test 3800 psig (16" φ PSC)	Demonstrate "fail safe" mode for local girth embrittlement (worst case structural) (model Define structural response.	Same as RV-5 except local girth embrittlement and increased H_2 charge current density.	Demonstrated "fail safe" mode. Large dynamic fiber strain spikes observed. Liner broke in short time on way up to pressure (effect of increased charge current density). Liner separated in two halves at girth simulating worst case structural model. Fiber shell intact.

TABLE E-1 16" φ AND 22" PSC VESSEL TEST MATRIX

(CONTINUED)

Test	Objective	Description	Results
RV-9 high pressure GHe test 3700 psig (16" φ PSC)	Demonstrate fail safe mode for local girth embrittlement. Define structural response. Get higher metal liner operating stress at failure.	Same as RV-7 except H_2 charge current density reduced by 50%.	Repeat of RV-7. Demonstrated fail safe mode; observed large dynamic fiber strains; liner separated in two halves as intended. Did not achieve higher liner failure stress. Need still lower H_2 charge current density.
RV-10 high pressure GHe test 3260 psig (sure fail test) (16" φ PSC)	Demonstrate brittle liner & fiber both fail mode for local girth embrittled liner. Determine structural response. Get higher metal liner operating stress at failure. Obtain fragment & over pressure data	Same as RV-7 except (fiber thickness reduced 50%) and H_2 charge current density reduced still further to RV-4 & RV-5 test level.	All test objectives achieved. Demonstrated as designed intended "catastrophic" brittle liner & fiber both fail mode. Predicted liner separation/fragments & large fiber strain spikes observed. Obtained desired magnitude of metal liner operating stress at failure. Obtained fragmentation and over pressure data.
RV-11 high pressure GHe test 3600 psig margin test (16" φ PSC)	Demonstrate fail safe mode margin for local girth embrittlement. Define structural response.	Same as RV-10 except fiber thickness was nominally 83% of baseline.	Both fibers and embrittled liner liner failed very close to predicted pressure. Anticipated large fiber strain spikes observed. Over pressure and fragmentation data obtained. Strain gage data indicates fibers came very close to remaining intact per no failure prediction.

	Demonstrate fail safe mode and define structural response for local boss/head weld embrittlement	22" φ Shuttle Centaur PSC sphere Kevlar overwrapped 301 cryo CRES. Local boss/head weld embrittlement (100% design fiber thickness, .192")	Demonstrated "fail safe mode" at low (2500 psig) liner failure pressure. Too much hydrogen at tip of crack (effect of new tank geometry). Need for decrease in hydrogen embrittlement charging current indicated to raise liner failure pressure.
RV-12 high pressure GHe test 2500 psig (22" φ PSC)			
RV-12A high pressure GHe test 3750 psig (22" φ PSC)	Demonstrate fail safe mode and define structural response for local boss/head weld embrittlement	22" φ Shuttle Centaur PSC sphere Kevlar overwrapped 301 Cryo CRES. Local boss/head weld embrittlement 100% design fiber thickness, .192	Demonstrated "fail safe" mode at operating pressure. Reduced hydrogen embrittlement charging current density raised liner operating failure pressure to 3750 psig. No boss separation, boss still attached to liner head.
RV-14 pressure GHe test 3914/3788 psig (16" φ PSC)	Demonstrate fail safe mode margin for local girth weld embrittlement	Same as RV-10 except Kevlar fiber thickness was nominally 90% of baseline	No liner failure at operating high pressure ≈ 3900 psig. Test aborted after FM tape ran out. Too little hydrogen at tip of crack. Need to increase hydrogen embrittlement charging current density indicated in order to achieve desired liner failure at operating pressure.
RV-14A high pressure GHe test 3112 psig (16" φ PSC)	Demonstrate fail safe mode for local girth weld embrittlement	Same tank as RV-14 except hydrogen embrittlement charging current increased by 10% and hold time decreased to 3 hours instead of 3-1/2 hours compared to RV-14 test.	Fail Safe mode demonstrated by benign leak mode.

E.3   <u>RV-4, RV-4A Tests (16" ϕ PSC)</u>

There was no liner failure in test RV-4. The vessel was then re-embrittled and repressurized in test RV-4A.

E.3.1   <u>Test Vessel Description</u>

- P/N E4170, S/N 002 (Kevlar Overwrapped 301 Cryo CRES Composite Sphere)

- Kevlar Fiber (less resin) thickness = .154" (100% Baseline Thickness)

- Metal Thickness = .05 nominal

- Inside Radius = 7.66"

- Hydrogen Embrittlement Mode = Global

- Electrolyte Solution =

$$\frac{20 \text{ cc } H_2SO_4 + 980 \text{ cc Tap } H_2O}{1000 \text{ cc solution}}$$

- Solution Additive = none

- Sensitize liner inside surface = No

- Charging Current Density = .005 amps/in^2 of surface to be embrittled

- Charging Time = 60 hours (RV-4), 72 hours (RV-4A)

- Hold Time Before Test = 12 hour (RV-4), 2-1/2 hours (RV-4A)

- Adcoat AC818T liquid maskant on areas not to be embrittled

E.3.2

INSTRUMENTATION OBSERVATIONS. (By AFAL Instrumentation Eng) T/k 4200)
E.3.2.1
KEVLAR TEST 004, 25FEB86. Project number 573000RV.

EXPERIMENTAL PROCEDURE. The vessel was pressurized from 2000
psig to 5000 psig in slightly less than 60 seconds, and pressure
was maintained for about another 8 minutes.   Pressurization was
preceeded by a 150 second purge for cool down from the initial
ambient condition: the tank vent was closed, and pressure was
increased to 2000 psig for a 30 second hold before starting the
final pressure increase to 5000 psig.   No leak was observed.
Frost appeared on the vessel and remained for at least 30
minutes.   The vessel did not rupture.   Reembrittlement and
retesting were scheduled.   Vessel S/N 002, which was hydrogen
embrittled, was tested in a horizontal configuration.

IMPRESSIONS FROM THE DIGITIZED FM DATA.

Data analyst's comments.   The ITT data analyst's comments follow:
"SG5/7105, SG6/7106, SG18/7118, SG19/7119, SG22/7122 were not
amplified - (or) recorded;   SG9/7109, SG13/7113, SG21/7121 bad -
not able to calibrate; SG20/7120 goes bad at 267 seconds."

Delta strain measurement.   The data graphs from the FM do not
show the initial condition strain because the pressurization was
started prior to starting the FM tape.   Measuring the initial
strain level is a contractor requirement because delta strain
measurement is a key parameter.   This is an action item requiring
a modification to future testing procedures.

IRIG time code.   IRIG time code format was satisfactory.

Graphs.   Three copies of data were made for TOA.   The initial
graphs were filtered at 100 Hz, and the digitized sample rate was
1024 samples per second; data were plotted at one point every 400
milliseconds.   The graphs contained a few spikes.   Time expansion
of some of the spikes revealed their shapes are similiar; the
strain drops rapidly in a single dip from the initial condition
at an abrupt inflection, reverses direction rapidly at the bottom
of the dip and rapidly ascends to a point slightly past the
initial condition where it changes direction in a single slow
overshoot that recovers in an overdamped profile that settles
without major oscillation at the initial condition.   Additional
analysis of the spikes at a much higher sample rate may uncover
their true shapes without the filter distortion present on the
initial graphs, which were required to identify the spikes exact
time locations for subsequent analysis.   The spikes may represent
fiber snapping, debonding, or crack noise; on this test 18 gages
had completely debonded, and the remaining 6 were partially
debonded after the test; a decision was made to improve the
mounting technique by sanding, etc.   Visual inspection of the
Kevlar surface after the test revealed small fractures in the

1

moisture barrier. Trace identifiers are periodic and are also automatically generated on excessively large data excursions.

QUALITY CONTROL CHECK. A quality control check of the strain parameter was done; the resistance RCAL in the bridge completion circuit indicated a plus 2.3mv shift; physically placing the RCAL resistor across the active gage also caused a similiar shift, which confirms the established arbitrary polarity convention for compression is plus and for tension is minus.

IMPRESSIONS FROM THE QUICK-LOOK AND DIGITAL DATA ACQUISITION SYSTEM DATA. Immediately after the test, three quick-look plots were compared: item 1901, Tank Pressure; item 7123, Strain Gage #23; and item 2208, Vessel Temperature #12. Comparing graphs indicate better correlation probably exists between the strain gage and tank pressure than between the strain gage and tank temperature. This was determined by laying down the strain gage graph face up on a light box and turning over the tank pressure graph and laying it face down over the strain gage graph (to correct for the opposite polarity); if the major points of inflection are observed, an impressive correlation is apparent; note how most of the inflection events occur slightly ahead in time on the strain gage graph, which is consistent with the strain gage channel's higher frequency response; also note how the small tank pressure variations, which are caused by cycling the pressurization valve during the steady-state condition, are reflected in the strain channel. Later it was confirmed that the tank temperature #12 had a polarity reversal, and this data is not correct; it is similiar to the family of curves generated by adjacent thermocouples, however; but, it just can't be flipped over to correct for the reversal because of nonlinearities in the mv-to-F transform; we will not request that this problem be resolved by the data analyst unless it is established that the work would be worth the effort. Strain gage #11 can be used in place of strain gage #12, for strain gage #11 is only 4 inches away from strain gage #12.

REQUEST FOR CORRELATION ANALYSIS. A rigorous step-wise regression correlation analysis has been requested, and this will be provided by the data analyst. Briefly, the strain gage will be correlated with the tank pressure to find the residuals; the residuals will be correlated with the temperature, and the results will be evaluated by a mathematician and discussed in a short report.

ACOUSTIC EMISSION IMPRESSIONS. Supplied to ARDE directly by AET.

AIR PRESSURE SENSORS did not produce any significant data because the tank did not rupture.

SUMMARY. As the tank was pressurized to about 5000 psig, the strain gages responded with a tension strain of about 4800

microinches/inch. During pressurization, all of the tank temperatures decreased; the temperatures near the strain gages started out between 95 to 130 degrees F, rose about 5 F degrees above the initial condition, and then dropped rapidly 25 to 35 F degrees below the initial condition during steady pressurization before settling out to their final smooth behavior profiles after steady-state tank pressure was reached. Boss and gas temperatures behaved similiarly except prominent undershoots are evident just prior to steady pressurization; the undershoots are consistent with the rapid vessel cooling experienced during the purging associated with the cool down phase and the location of the sensors.

REVISION RECORD. Initial issue: 4MAR86. Filename: testrv4. Revision A: 18MAR86; added paragraph on impressions from the digitized FM data. Revision B: 7APR86; added text to the summary and consolidated the quick-look impressions. Added text to the digitized FM data to clarify sample rate, etc. Revision C: 8APR86; corrected S/N from 004 to 002. Experimental procedure paragraph expanded. Improved spike description in digitized FM data. Acoustic emission impressions and air pressure paragraphs added.

DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE. The embrittlement procedure was started at 1130 PST 15FEB86. Arde procedure EG 42001-6 Rev A was followed. Sixty hours of embrittlement was completed at 2330 on 17FEB86; the tank was drained, flushed and purged. The tank was placed in Bldg 9665 for a 12 hour hold; at 0900 the tank was placed on the test stand, and instrumentation was hooked up; at 1120 on 18FEB86 the test was started.

DISTRIBUTION: ITT, ARDE, AFRPL.

INSTRUMENTATION OBSERVATIONS. (By AFAL Instrumentation Eng.)

KEVLAR TEST 004A, 17MAR86.   Project number 573000RV.

EXPERIMENTAL PROCEDURE.

Cool Down and Initial Pressurization Cycle. Pressurization was
preceeded by a 60 second purge for cool down from the initial
ambient condition; the tank vent was closed, and pressure was
increased to 2000 psig for a short hold before starting the final
pressure increase to 5000 psig.   No leak was observed during the
hold period.

Final Pressurization Ramp. The vessel was pressurized with a
steady ramp from 2000 psig to 5000 psig in about 27 seconds, and
pressure was maintained near 5100 psig for a 150 second hold
period with some minor pressure readjustments.   There were no
major leaks. Following the hold period, pressure was maintained
within a 5000 to 5600 psig bandwidth by the following three
distinctly separate pressurization adjustments.

First Repressurization Cycle. The pressure was raised from about
5100 psig to 5500 psig and the vessel started to   leak.
Pressurization was stopped. The pressure loss profile that
followed was smooth and almost linear.   The loss rate was small,
1.5 psi/sec.

Second Repressurization Cycle. Repressurization continued when
the pressure dropped to 5300 psig, and it was stopped at 5540
psig.   The vessel continued to leak.   The pressure loss profile
that followed was smooth and almost linear.   The loss rate
increased slightly to 1.7 psi/sec.

Third Repressurization Cycle. Repressurization continued when
the pressure dropped to 5450 psig, and it was stopped at 5640
psig.   The vessel continued to leak.   The pressure loss profile
that followed was again smooth and almost linear.   The loss rate
increased slightly again to 2.5 psi/sec.

Pressure Decay Cycle. As pressure decay continued, the rate of
decay remained almost linear; when the pressure reached 4940
psig, the tank was vented in one step to zero psig.

Post Test Observations. The vessel retained its shape; no pieces
separated from the vessel.   The vessel was checked (before/after
borescoping) for leaks at 2000 psig with yellow sea dye and tap
water, which readily oozed through many pinholes in the Kevlar
overwrap.

Other Details. Vessel S/N 002, which was hydrogen embritled, was
tested in a vertical configuration.   Because the vessel leaked,
reembrittlement and retesting was not done.   The vessel was
borescoped and hair line cracks were detected.

1

The vessel was returned to ARDE by AFRPL where it was cut in half and a large crack, approximately two-thirds around the girth, was noted along with numerous hair line cracks.

IMPRESSIONS FROM THE QUICK-LOOK DATA. No quick-look data was generated for immediate post-run evaluation.

IMPRESSIONS FROM THE DIGITAL DATA ACQUISITION SYSTEM. To conserve record time, the data systems were started after the 2000 psig point was reached, and the initial condition data values are missing from the data cut but are available from the calibration zero cut. This condition will be corrected on subsequent tests.

Chamber Pressure Graphs. The PC1/1901 and PVSOUT/1904 graphs were essentially identical. The PC1/1901 graph indicates after the pressure was stabilized at 2000 psig, it remained steady with less than a 5 psig drop for 2 minutes. Then the pressure was adjusted upward three times followed by three periods of pressure loss; the slopes of the loss rates progressively increased after each pressure readjustment. Similiar loss slopes exist on the TBALL gas temperature thermocouple. Speculation as to the cause is reserved, except to note the ball started to leak at 5500 psig.

Strain Gage Graph. The only S/G on the DACS, SG2143/7124, operated satisfactorily. The S/G profile was almost an exact duplicate of the PC1 profile, except for scaling and polarity differences. No major spikes appeared.

Temperature Graphs. All of the T/Cs worked satisfactorily.

Strain Gage T/Cs: During pressurization, after the 2000 psig point, all S/G T/Cs increased about 15 to 25 F degrees above their 53 to 70 degrees F initial condition. Each S/G T/C was within a family of curves with a reasonably smooth increasing tendency modulated with explainable inflections, moderate magnitude excursions and slopes consistent with system time constants, sensor locations and heating rates.

Other T/Cs: The behavior of the boss, ball and heat exchanger temperatures was within normal limits. While probably not of importance, it is noted the boss outlet temperature was lower than the boss inlet temperature, and this is the reverse of what was observed on the first test; the boss outlet temperature was more sensitive to temperature changes caused by the tank pressure adjustments than the inlet temperature, which doesn't reflect the adjustments or, for that matter, temperature decays as it had a consistent slow rate of climb; the differences may be related to the following facts: This vessel had thicker bosses than the first vessel; more cool gas was used than in the first test because the vessel leaked. The test configuration was vertical with the inlet at the top and exposed to the sun while the outlet was shaded by the vessel.

2

IRIG Time Code Format. The IRIG data was within normal limits. It was not decoded, but the code was of sufficient quality to allow decoding.

DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE. ARDE embrittlement procedure dated 7-15-85 was followed; embrittlement was started at 0700 hours on 4APR86. Seventy-two hours of embrittlement were completed at 0815 hours on 7APR86; the tank was immediately moved from the shop embrittlement area to the test site, instrumented, hooked up and tested at 1045 hours on 17MAR86.

IMPRESSIONS FROM THE DIGITIZED FM DATA.

Data analyst's comments, first data pass. "SG14/7114 goes out at 29.0 seconds."

Graphs. The initial graphs were filtered at 100 Hz, and the digitized sample rate was 1024 samples per second; data were plotted at one point every 400 milliseconds. A couple of spikes appeared on the S/G graphs; these spikes will be analyzed at a higher sample rate.

Data analyst's comments, second data pass. "(data) rerun with correct time reference and cal cuts for zero strain to determine delta strain."

Graphs. The graphs on the second data pass confirms the magnitudes of strain on the graphs from the first data pass are correctly referenced to the initial strain conditions; to verify this, the time axis was started at -150 seconds; the initial conditions are shown near this time. The graphs from both passes are identical except for the differences already noted.

ACOUSTIC EMISSION IMPRESSIONS. Acoustic emission data were not taken.

AIR PRESSURE SENSORS did not produce any significant data because the tank did not rupture in a catastrophic failure mode.

REVISION RECORD. Initial issue: 9APR86. Filename: TESTRV4A. Revision A: 16APR86; major text corrections, and additions. Revision B: 17APR86; major text additions, time & date corrections in embrittlement paragraph. Revision C: 25APR86; corrected acoustic emission impressions text. Revision D: 12May86; FM S/G data rerun to include initial condition values so strain deltas can be confirmed; comments added to impressions from the digitized FM data.

E.3.3   Pressure and Strain Versus Time Plots

Figures E-1 to E-12 give pressure versus time and fiber strain versus time plots for tests RV-4 and RV-4A. Tensile strain is negative. A total of twenty four (24) strain gages were installed on the fiber outer surface, twelve (12) each above and below the girth at $\pm$ .80 height on the outer last 81° fiber wrap, as sketched on Figure 1G. Even numbered gages are parallel to the fibers and odd numbered gages are perpendicular to the fibers.

Fig. E-1

KEVLAR VESSEL TEST RV-4 - P/N E4170, S/N 002   25 FEB 1986

PC1/1901 (PSID) x10'

Time (Seconds)

E-45
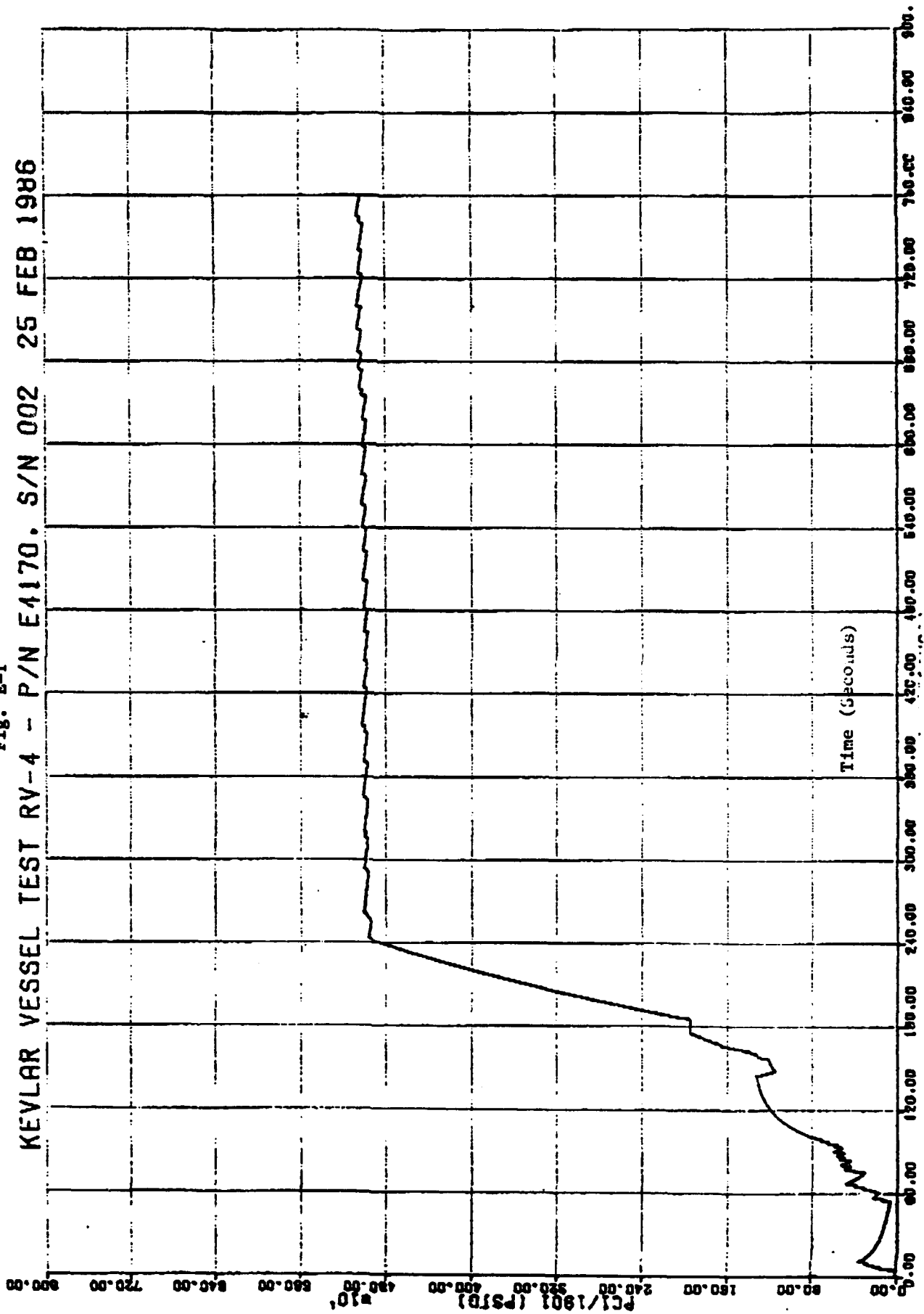
Fig. E-2

KEVLAR VESSEL TEST RV-4 - P/N E4170, S/N 002   25 FEB 1986

Fig. E-3
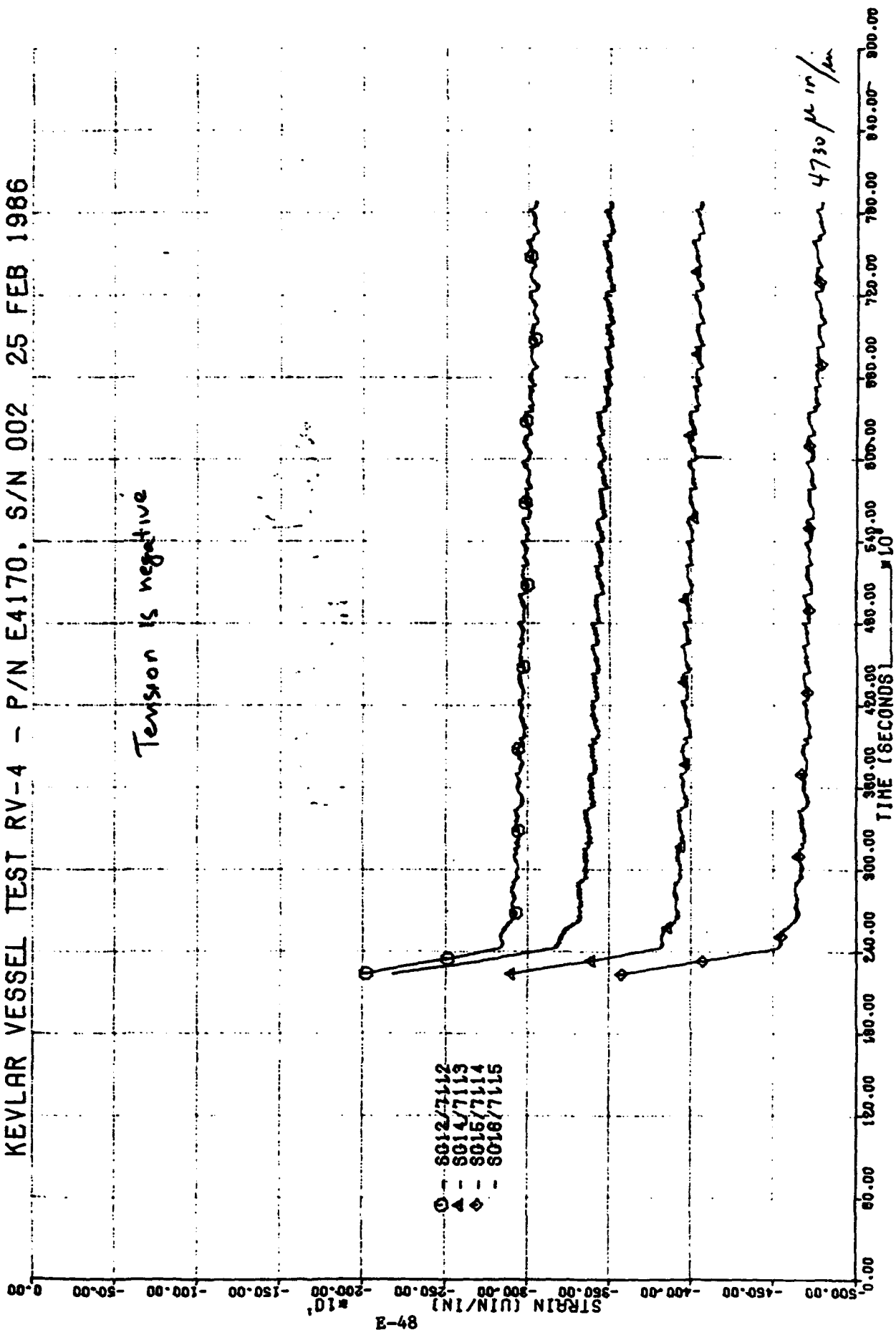
KEVLAR VESSEL TEST RV-4 - P/N E4170, S/N 002   25 FEB 1986

KEVLAR VESSEL TEST RV-4 - P/N E4170, S/N 002   25 FEB 1986

Tension is negative

4730 μ in/in

Legend:
- ⊙ - 8012/7112
- ▲ - 8014/7113
- ◆ - 8015/7114
- ◇ - 8016/7115

STRAIN (UIN/IN) *10¹

TIME (SECONDS)

Fig. B-5

KEVLAR VESSEL TEST RV-4 – P/N E4170, S/N 002   25 FEB,1986

E-49
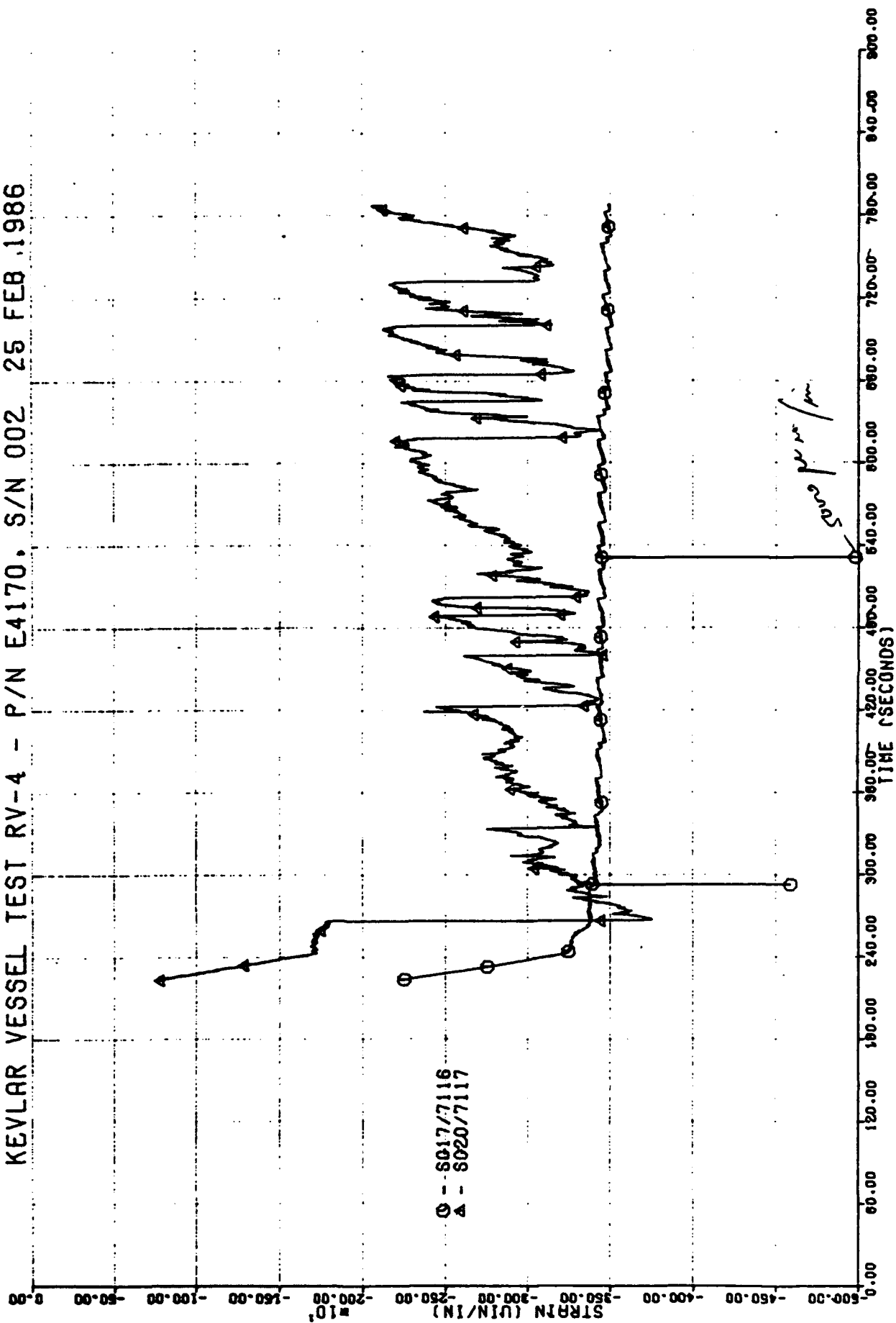
KEVLAR VESSEL TEST RV-4A – P/N E4170, S/N 004   17 MAR 1986

Fig. E-6
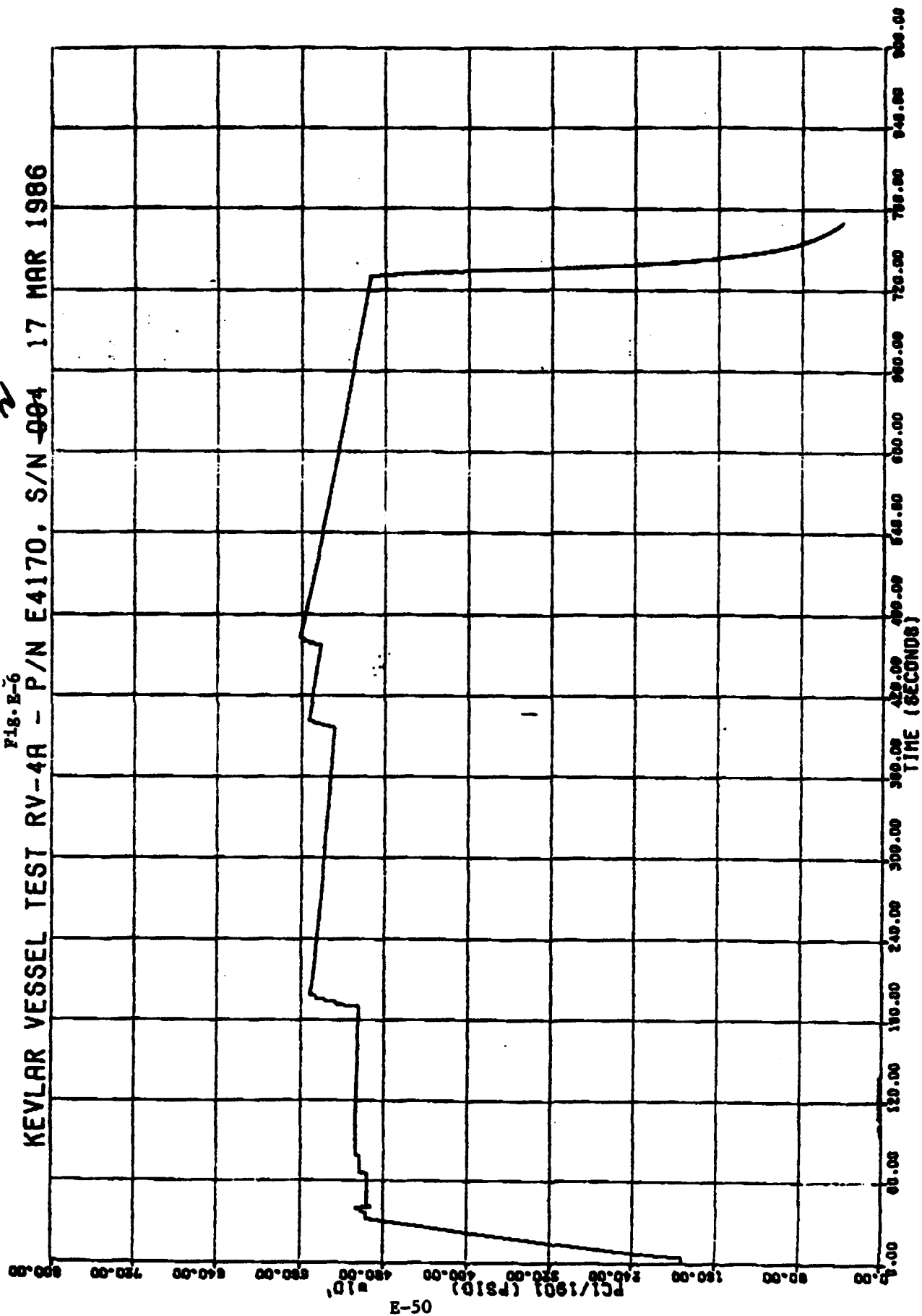
E-50

Data from 2ND H_2 Embrittlement Experiment on this tank
Note: 100 Hz Filtering/1024 samples/sec digitized Data plot every 400 ms.

Fig. E-7

KEVLAR VESSEL TEST RV-4A – P/N E4170, S/N 004   17 MAR 1986

CO_2

$\left\{ \begin{array}{l} 2^{nd} \ GHe \ pressure \ Test \\ 2^{nd} \ GH_2 \ Liner \ embrittlement \end{array} \right.$

Note: Tension is negative!

significant phenomenon

P=5800

Test GHe Pressure

p = 5800 psy

p = 5550 psy

⊕ – SO1/7101
△ – SO2/7102
◇ – SO3/7103
    – SO4/7104

E-51

Fig. E-8

KEVLAR VESSEL TEST RV-4A – P/N E4170, S/N 004   17 MAR 1986

CO2

E-52

KEVLAR VESSEL TEST RV-4A - P/N E4170, S/N 004   17 MAR 1986

Fig. E-9

□ - SG9/7109
△ - SG10/7110
◇ - SG11/7111

STRAIN (UIN/IN) x10²

TIME (SECONDS)

E-53

Fig. E-10

KEVLAR VESSEL TEST RV-4A - P/N E4170, S/N 004   17 MAR 1986

CO2

Significant
Pressure
Decay

$\dot{P} = Slow$

$\dot{P} = 155 \text{ °/}$

$\dot{P} = 500 \text{ °/sec}$

250

Note: Tension is negative

$7800 \quad \left(\Delta \epsilon = 200 + 7800 = 8000 \left(\dfrac{\mu \text{ in}}{\text{in}} \right) \right)$

⊕ — SG12/7112
△ — SG13/7113
◇ — SG14/7114
▽ — SG15/7115

TIME (SECONDS) ×10

STRAIN (UIN/IN) ×10²

E-54

E-3

Fig. E-11

KEVLAR VESSEL TEST RV-4A - P/N E4170, S/N 004   17 MAR 1986

002

Fig. E-12

KEVLAR VESSEL TEST RV-4A - P/N E4170, S/N 004   17 MAR 1986

002

← This channel used
low bandpass filter
yielding relatively
lower frequency response.

⊙ — 6020/7120
△ — 6021/7121
◇ — 6022/7122
  — 6023/7123

E-3
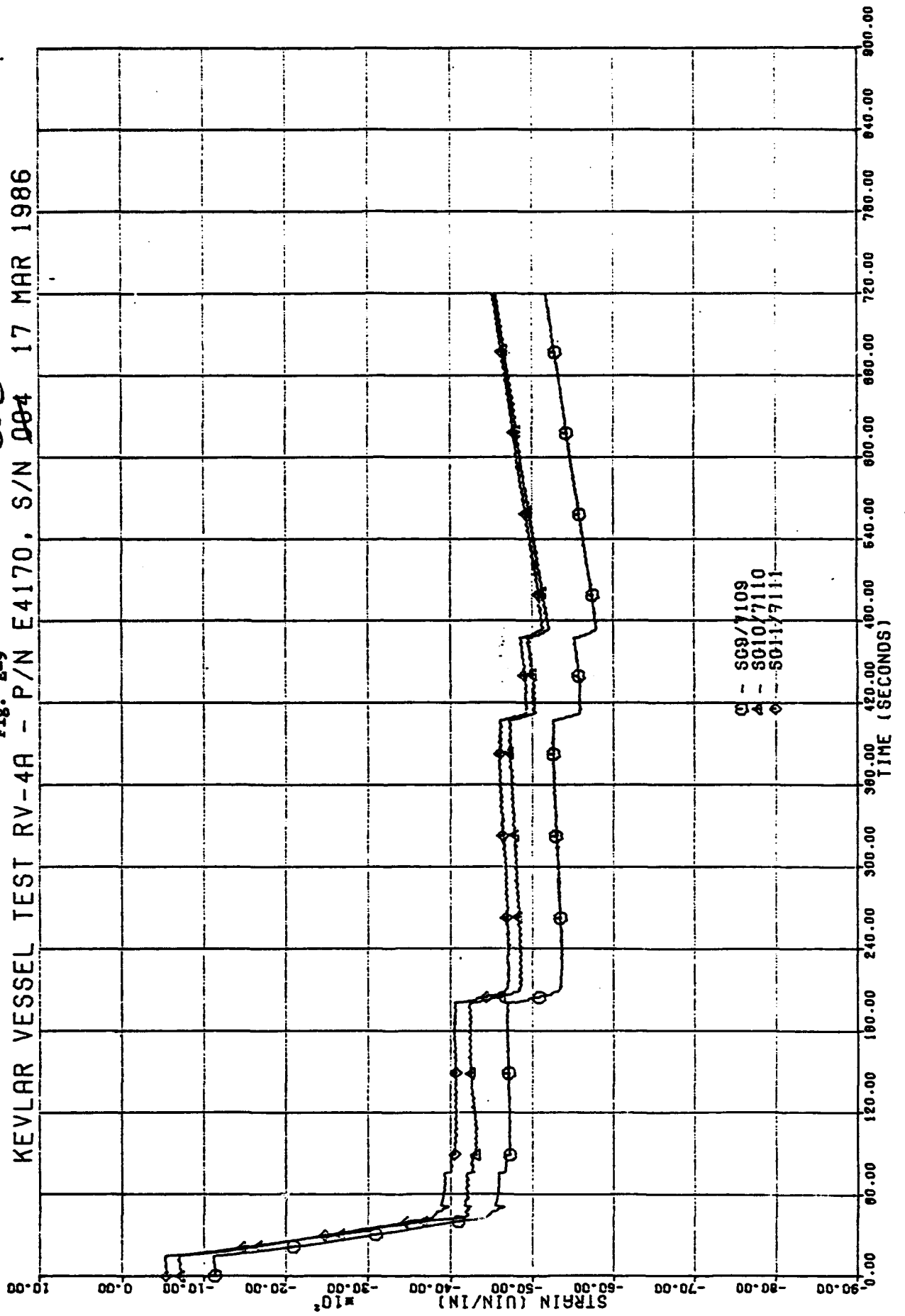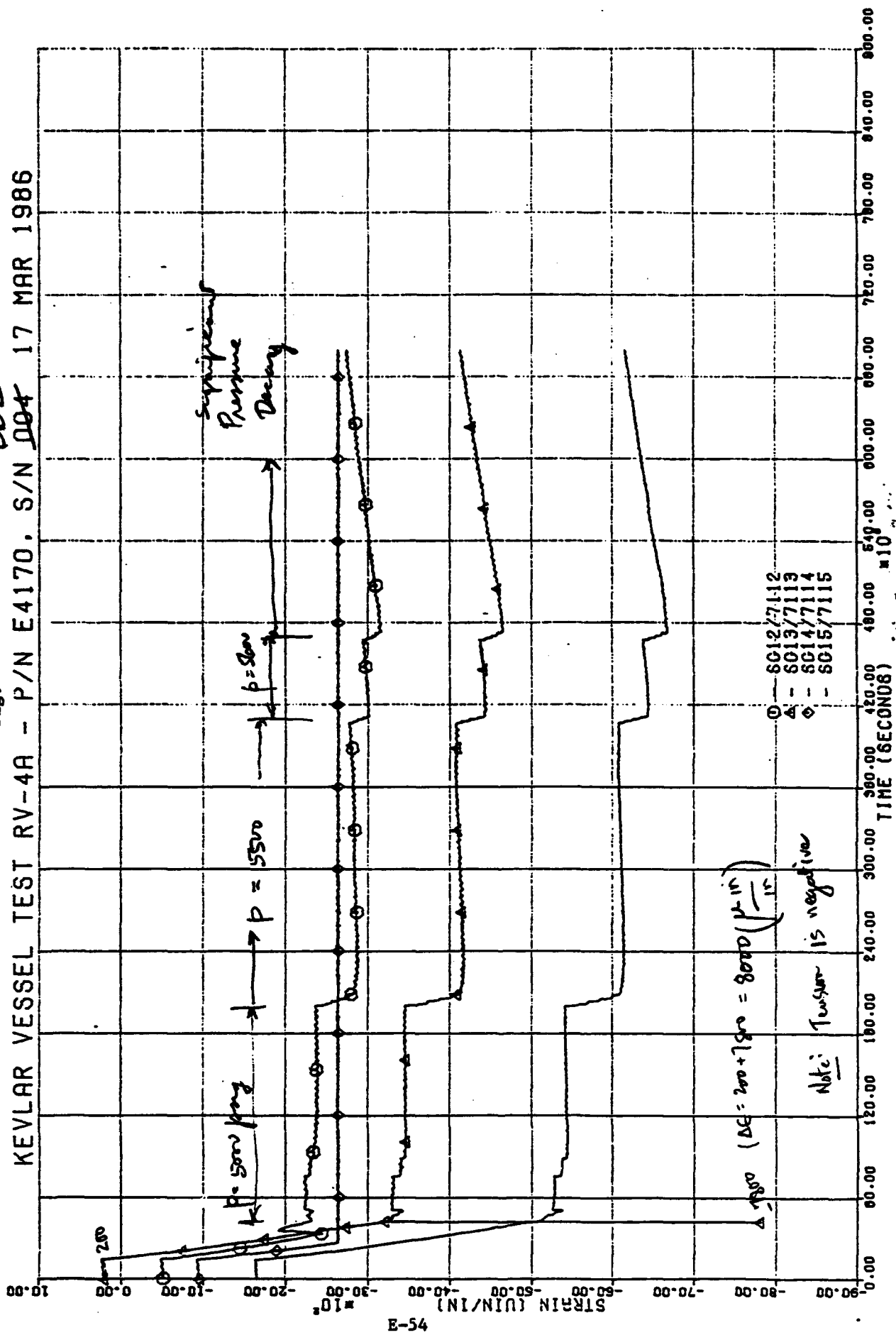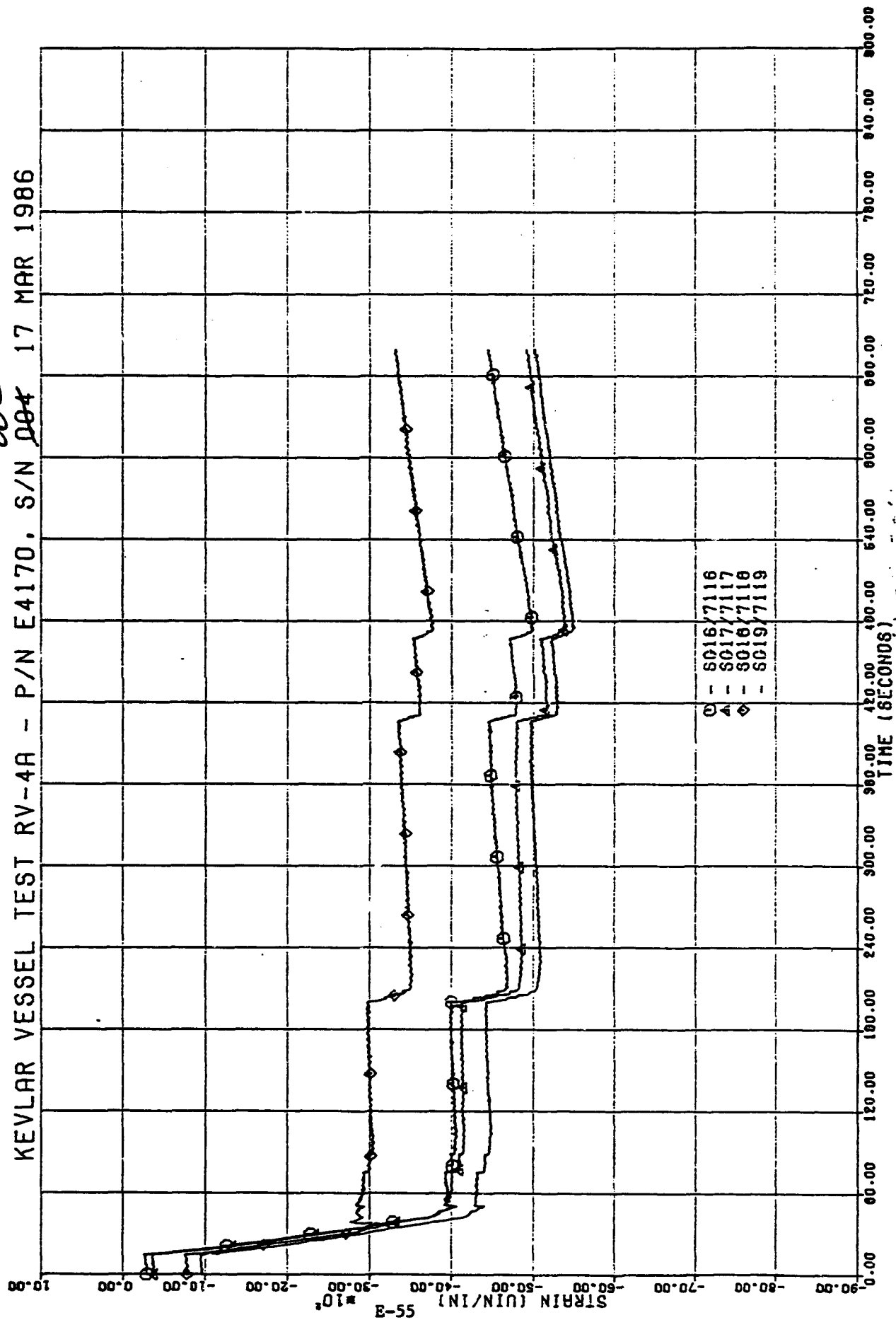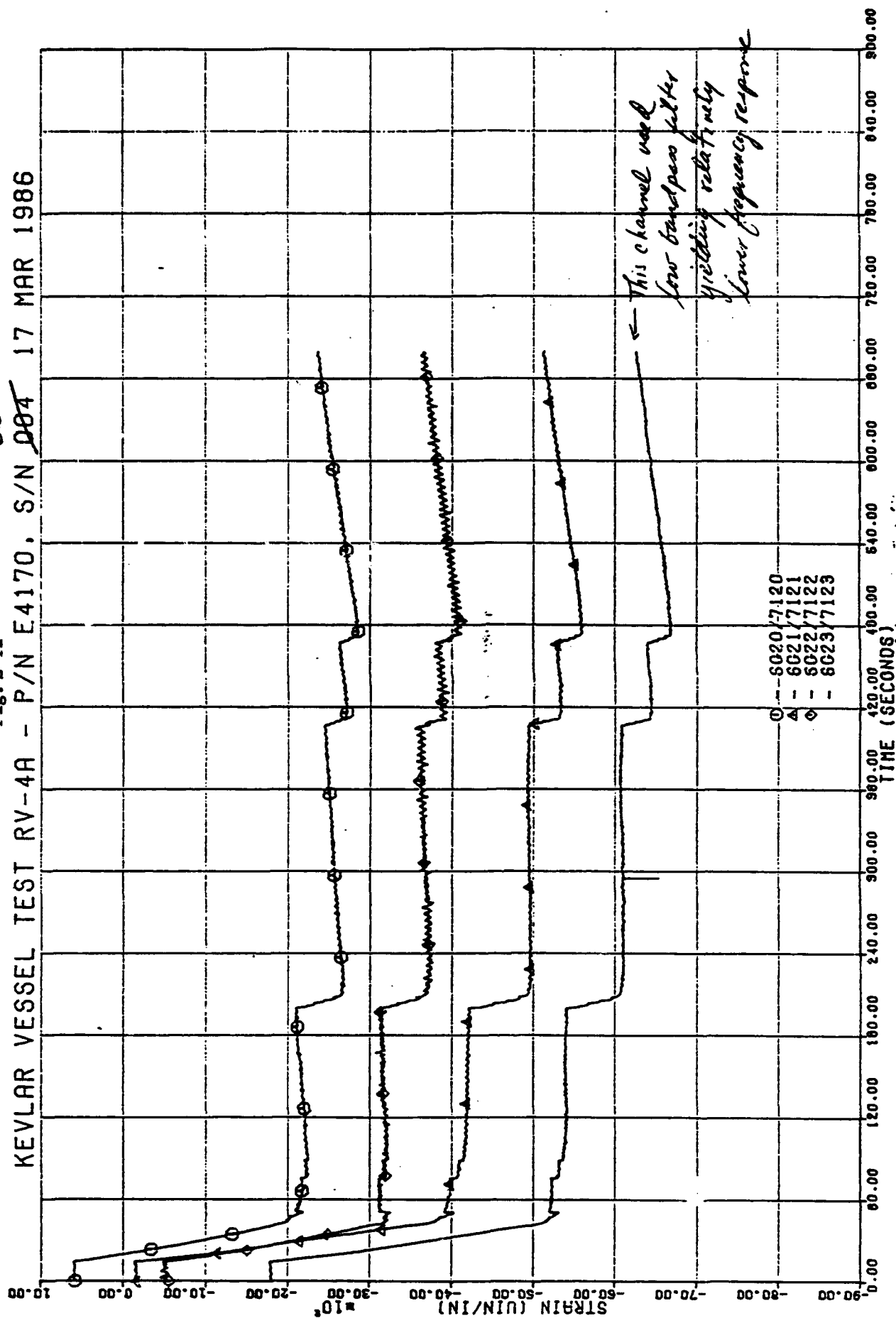
E.3.4   Acoustic Emission Monitoring

Acoustic emission (AE) probes were mounted on each metal boss for the RV-4 test. During testing, the AE signals were masked by high noise level coming from the tank outlet boss region which indicated a leaking fitting. No AE data was taken for RV-4A experiment.

E.3.5   Post Test Inspection

E.3.5.1   RV-4 Test

Borescopic examination of the pre-compressed intact vessel liner inside surface at AFAL revealed many hairline type cracks in the metal, indicating that the GH_2 embrittlement process was working. A tank leak check verified a leaky outlet fitting (bad seal). This demonstrated the effectiveness of the AE monitoring.

E.3.5.2   RV-4A Test

A post-test elevated pressure water/yellow die leak check performed on the vessel at AFAL showed pronounced leakage. Additional post test examination of the tank was performed at ARDE. The composite vessel was parted at the girth for viewing/die penetrant of the tank's metal liner to assess the extent and type of liner cracking.

A fine network of matrix-type cracking was observed in the liner's inside surface and a large, fairly wide continuous crack was also seen. This large crack traversed approximately 28 surface inches and had some branching. Figure 2-4 is a photograph of the die penetrant-enhanced cracked liner inside surface.

E.4   <u>RV-5 Test (16" φ PSC)</u>

E.4.1   <u>Test Vessel Description</u>

- P/N E4170, S/N 004 (Kevlar Overwrapped Cryo Cres Composite Sphere)

- Kevlar Fiber (less resin) Average Thickness - .154" (100% Baseline Thickness)

- Metal Thickness - .05" nominal

- Inside Radius - 7.66"

- Hydrogen Embrittlement Mode - Global

- Electrolyte Solution -

$$\frac{20 \text{ cc } H_2SO_4 + 980 \text{ cc Tap } H_2O}{1000 \text{ cc Solution}}$$

- Solution Additive - 500 mg Sodium Arsenite

- Sensitize liner inside surface (cold pickle, 70°F-90°F)

    a. Nitric acid A.C.S Technical Grade, 70 weight percent, 22% by volume.

    b. Hydrofluoric acid A.C.S. Technical Grade, 55 weight percent, 2% by volume.

    c. Potable tap water - remainder. The same solution used on all applicable test tanks.

- Charging Current Density - .005 amps/in^2 of surface to be embrittled

E-59

● Charging Time - 72 hours

● Hold Time Before Test - 2-1/2 hours

● Adcoat AC818T liquid maskant on areas
not to be embrittled.

The photographs of Figures E-13 and E-14 show the entrance to the AFAL test area with the camera tower in the background and an upper view of the test stand and tower showing the motion picture camera installations. Figures E-15 to E-17 are photographs of the tank in the test fixture and closeups of strain gages on the test tank. Installation and checkout of Acoustic Emission (AE) probes on the test tank metal bosses is shown in the photograph of Figure E-18. A view of the tank mounted in the test stand together with pole mounted Bikini blast over pressure gages and fragment catching witness panels in the background is given on Figure E-19.
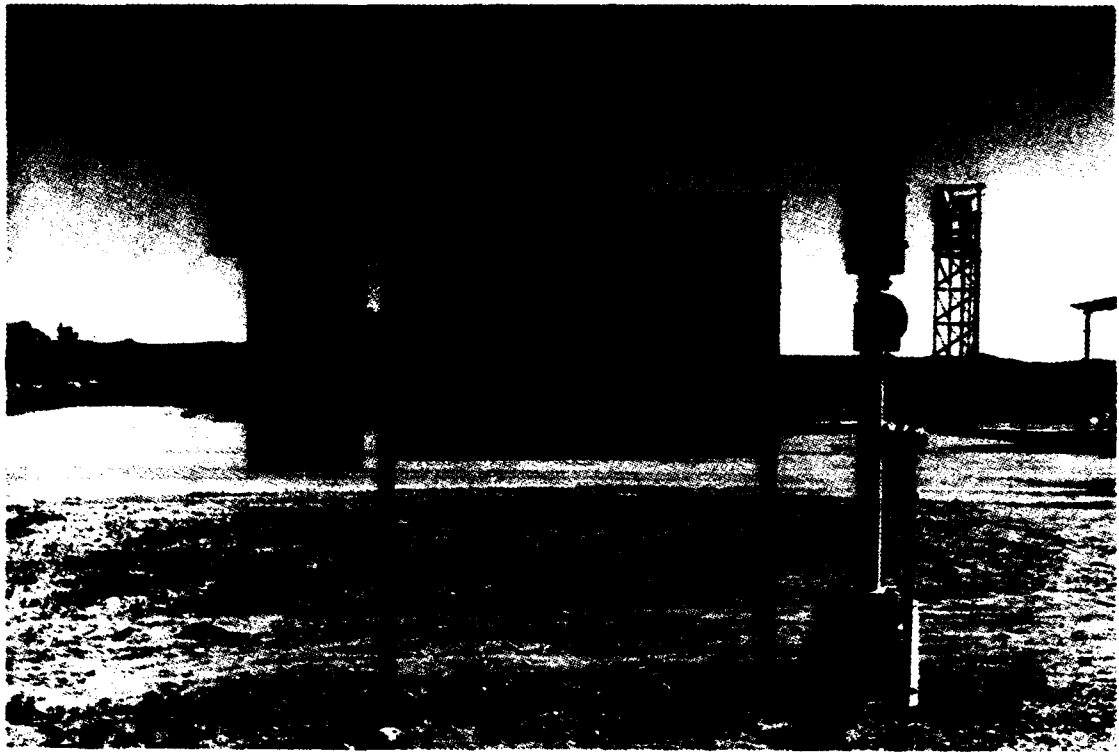
Fig. E-13   AFAL TEST AREA 1-52

Fig. E-14   TEST TOWER CAMERA INSTALLATION

Fig. E-15   TANK MOUNTED IN TEST FIXTURE

Fig. E-16   TEST TANK STRAIN GAGE INSTRUMENTATION

Fig. E-17

STRAIN GAGE CLOSE UP VIEW

Fig. E-18

ACOUSTIC EMISSION PROBE INSTALLATION AND

CHECK OUT
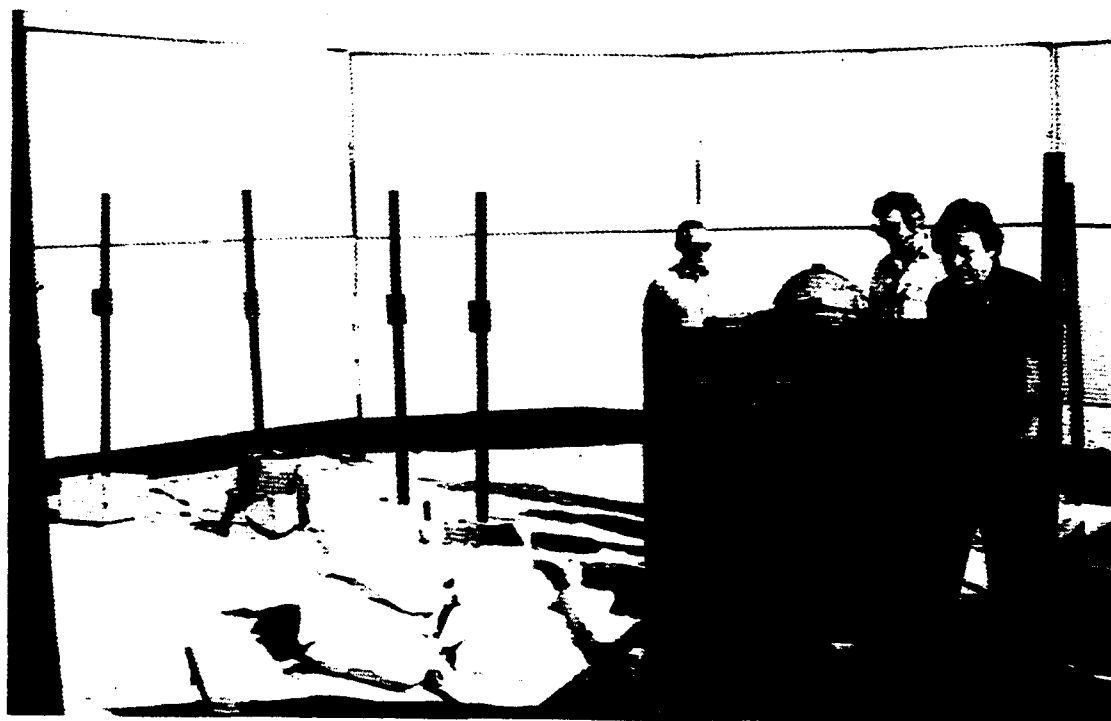
Fig. E-19   VIEW OF TEST TANK, BIKINI GAGES AND WITNESS PANELS

INSTRUMENTATION OBSERVATIONS (by AFAL Instrumentation Engineer)

KEVLAR TEST 005, 7APR86.   Project number 573000RV.

EXPERIMENTAL PROCEDURE.

Cool Down and Initial Pressurization Cycle. Pressurization was preceeded by a 150 second purge for cool down from the initial ambient condition; the tank vent was closed, and pressure was increased to 2000 psig for a 15 second hold before starting the final pressure increase to 5000 psig.   No leak was observed during the hold period.

Final Pressurization Ramp. The vessel was pressurized with a steady ramp from 2005 psig to 5000 psig in 32 seconds, but pressure could not be maintained; pressure loss started as soon as pressurization was stopped at 5000 psig; the pressure loss was sharply demarcated and followed a profile that was smooth, nonlinear and rapid.   The loss rate was 13.2 psi/sec.

First Repressurization Cycle. Repressurization was requested by ARDE when the tank pressure failed to hold at 5000 psig and drooped to 3500 psig.   Pressurization was attempted but it couldn't be maintained much past 4730 psig and was stopped; the pressure loss profile that followed remained smooth and nonlinear but was much more rapid than the loss following the final pressurization ramp.   The loss rate increased to 86.9 psi/sec.

Second Repressurization Cycle. Repressurization continued when the pressure dropped to 4300 psig, but it couldn't be maintained past 4600 psig and was stopped; the pressure loss profile that followed was again smooth and nonlinear but had a changing slope magnitude that started at 125 psi/sec and ended up approaching zero before the pressure decay cycle was started.   Frost started to appear during this cycle and remained for at least 30 minutes.

Pressure Decay Cycle. As pressure decay continued, the rate of decay decreased; when the pressure started to level out near 1000 psig, the tank was intentionally vented in one step to zero psig. PC1 shows a two step vent profile, but this is due to pressure lockup caused by line icing, and the graph in this region isn't correct; PVSOUT displays the correct pressure-time history.

Post Test Observations. The vessel retained its shape; no pieces separated from the vessel.   The source of the leaks was not obvious until the vessel was separated at its girth weld by an AFRPL machinist.   A cleaner, dye penetrant and developer were used to enhance the apparent fine cracks, pits and bumps, which were moderately spaced and randomly concentrated in a wide field between the girth weld and end bosses.

Other Details. Vessel S/N 004, which was hydrogen embrittled, was tested in a vertical configuration.   Because the vessel leaked, reembrittlement and retesting was not done.   The vessel's halfs were returned to ARDE by ARDE via air freight.

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IMPRESSIONS FROM THE DIGITIZED FM DATA.

Data Analyst's Comments. Richard Thomsen, ITT, noted "SG1/7101 and SG7/37103 (is bad and) SG7/7107 is (noisy)." Also, he continues, "several data anomalies were noted: SG1/7101 zero and 50% cal were the same. SG3/7103 too noisy to calibrate. SG4/7104 three shifts and return on two of these. SG6/7106 shows the smallest tension delta strain. SG7/7107 extremely noisy. SG14/7114 shows a step at 70 seconds. SG16/7116 has alot of what I would call noise spikes. SG20/7120 shows a prominate step at 205 seconds. SG22/7122 low frequency noise."

Additional data passes were made for the purpose of evaluating the spikes, and the analyst's comments continue with the following:

"4AUG86. Plots of RV-5 (70PR86) strain gage 16, digitized FM at 80,000 SPS (10,000 Hz filter). (This set of graphs shows) data from 7-98 seconds (which) was first plotted at 10,000 SPS to detect spikes. These show many barely detectable spikes ((150 microstrain), some bigger ones (150 to 300 microstrain) and a few large ones ($\geq$300 microstrain). The frequency (of distribution, or histogram,) of spikes of all sizes, for time intervals of ten seconds, are shown (below).

```
            8
 number     7                                          *
   of      ·6                                         | | |
 spikes     5                                         | | |        *
            4                                         | | |      | | |
            3      *    | | |         | | |      | | | | | |    | | |
            2    | | |  | | |         | | |      | | | | | |    | | |
            1    | | |  | | |  | | |  | | |  | | | | | | | | |  | | |

               10    20    30    40    50    60    70    80    90
                            time (seconds)
```
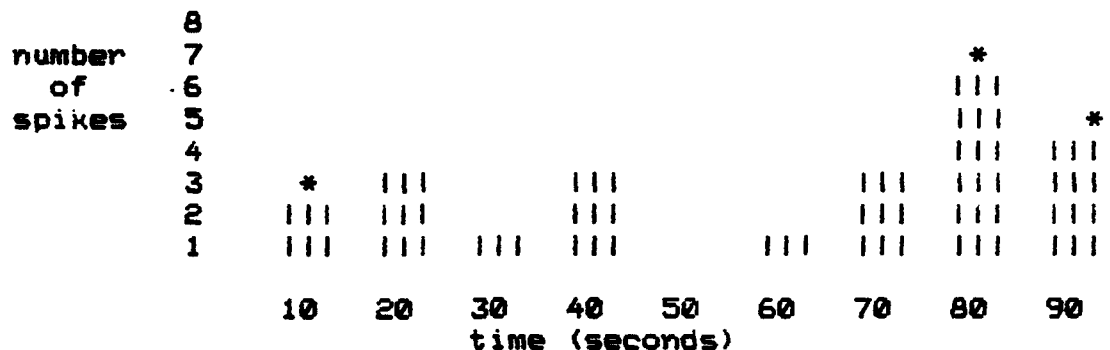
The regions with large spikes are marked with a *. To be selected, a spike had to be an abrupt increase and decrease in tension, above the noise bands. This eliminated possible data drop outs that show up as a single spike in one direction only. This method did not select all of the spikes as there are some within the noise band."

The comments for the second set of graphs follow:

"Several spikes (on SG16) were plotted at the full 80,000 SPS rate to study their shape. At 75.371 seconds is an example of (a) single downward pointing spike. Many of these spikes showed up on the 1024 SPS pass, but only a few (showed up) at this high (80,000 SPS) sample rate. Also, the rise time is the minimum allowable by the filter, in this case 50 microseconds. For these reasons, I would consider them noise (generated during data

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reduction).

Spikes at 67.354, 71.211, 72.988, 76.699, 77.300, 82.054, 83.206, 83.734 and 92.460 seconds were also plotted. These show a consistent pulse shape with a gradual increase in tension, a quick release and then a gradual return to the same level as before. The rise time of the release averages 250 microseconds, well within the limits of the 10K Hz filter. I suggest these are due to resin cracking, the Kevlar wrap snapping, or liner cracking.

Plots at full sample rate were also made for 300 milliseconds during the maximum tension strain, but no new spikes were noted.

Plots of the 1024 SPS SG16 data are also included for comparison purposes.

These (two) sets of plots (SG16/711 SPIKE ANALYSIS, sample rate 80,000 SPS, filter frequency 10,0000 Hz, full sample rate plot from 75.36 to 77.010 seconds; and SG16/7116 Spike Analysis, 10K SPS plots) should be used rather than those (plots) previously sent, due to a (small) time reference error on those (plots) first sent (to the agencies listed on the distribution list)."

Spike theory #1 speculates the spikes represent the natural resonant frequency of the composite structure; the resonance is alleged to be 10,000 Hz, which would have a period of 100 microseconds and a rise time of 33 microseconds (using rt=1/3(f) method). The frequency seen at the 72.98800 second spike is about 2440 Hz (period=72.98885-72.98844 seconds=410 microseconds); the other spikes have similiar periods. Recognizing that the error in estimating the period from the graphs is considerable, and, in practice, acknowledging the disrupting influence of the broken liner on the composite resonance, it would be expected to have a resonant frequency, particularly a lower resonance frequency, other than that which was predicted. In fact, half an order of magnitude isn't too bad considering the complications. However, note the damping characteristic of the spike; it is close to being critically damped, for there is no major overshoot or evident period of resonance, characteristic of underdamping, or prominent slow approach to the peak, characteristic of overdamping. In nature and with artifacts, critical damping is rare and is usually obtained through modification or design not pure circumstance. For this reason, suspicion is cast on this theory; and it should be more thoroughly explored.

Graphs. The initial graphs were filtered at 100 Hz, and the digitized sample rate was 1024 samples per second; data were plotted at one point every 400 milliseconds. Several spikes appeared on the S/G graphs; these spikes will be analyzed at a higher sample rate. Except as noted elsewhere, the parameters' noise floors did not include major transverse or common-mode minus L(di/dt) transients, artifacts, crosstalk, atmospherics,

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noticeable RFI, intermodulation, spurious parasites, or sibilants. However, latent noise or data manifestations may be obscured in some parameters, and digital signal processing may be needed for signal enhancement. In general, the data appeared to be unbiased, precise and accurate.

Strain Gage Graphs. Except for the problems already mentioned, the strain data from the 20 good strain gages were within normal limits.

Fourteen (70%) of the strain gages had final values slightly higher than their initial conditions; the remaining six (30%) had values slightly lower than their initial conditions. At the end of the test, ninety percent (18) of all the gages (20) were within about 300 uin/in of their initial conditions.

Speculation as to the cause of this general trend of higher final strain values on a very large percentage of the gages is important particularly if it shows temperature is involved. Temperature induced apparent strain error is an unwanted data contributor in this experiment, and the investigators remain alert for any data that would confirm its expected influence or for any data that would overwhelm and distort valid data. Unfortunately, the reason for the differences in static strain levels before and after the test is not immediately obvious.

It may be an erroneous oversimplification to assume the general trend for higher final strain values is a simple intrinsic erratic experimental error caused only by vessel frosting and how it influences the gages, Kevlar fiber, metal liner and resin. As temperature decreases, the -08 STC gages generate a tension (expansion) correction, the Kevlar fiber expands, the metal liner contracts and the resin contracts. The gages parallel to the fiber and the fiber respond synergistically with one another and this is probably the major contributor; the liner may be out of the picture at this point (it is broken or weakened, has a complicated preload characteristic and may not necessarily be touching the overwrap uniformally although the gages track the pressure rather well, which may contradict this theory!); the potential for compliant resin behavior in the parallel direction is overpowered by the stiffer, more influential fiber (In other special Kevlar sample tests, as the sample heated to equilibrium, the total absolute strain change in the perpendicular direction was about 37% of the total absolute strain change in the parallel direction; the polarity wasn't the same, however. The strain parallel to the fibers went into an obvious compression, and the perpendicular direction went into a general tension trend. For cooling, it is assumed, the strain parallel to the fibers would go into significant tension and the perpendicular direction would go into not so significant compression). Anyway, the strain graphs that end up with the most amount of deviation from their initial condition have the least amount of temperature change over the same time period, and this information would appear to be exciting, except that the strain directions have opposite

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polarity.

IMPRESSIONS FROM THE QUICK-LOOK AND DIGITAL DATA ACQUISITION
SYSTEM DATA. Immediately after the test, the tank pressure
graph, 1901, and the strain gage graph, 7124, were generated and
compared. Both data parameters were satisfactory and were
practically identical except for known scaling differences,
expected opposite polarity and two interesting locations on the
strain gage graph that exhibited unexpected behavior profiles.
Remaining unexplained, after reviewing the digital data graphs,
is a small but very obvious dip in the strain gage graph at 65
seconds, which occurs between 64 to 76% of the final
pressurization ramp duration; surprisingly, the dip doesn't show
in either tank pressure graph; and the dip doesn't appear to be a
clear function of the temperatures; although most T/Cs are
changing only slightly during this period, suspicion could start
with TT9/2205, TT10/2206 or TBSIN/2209 because they exhibit small
but conspicuous inflections as they undergo noticeable rates of
change near this time period. Also, there remains an unexplained
slow strain inflection during the pressure decay following the
second repressurization cycle, at 400 to 500 seconds; the
inflection isn't an obvious function of the tank pressure or tank
gas temperature, TBALL; temperature relationships again are under
suspicion, as TT1, 2, 4, 8, 9, 10, & 12, continue to exhibit
small but conspicuous inflections as they undergo noticeable
rates of change at the onset of this slow strain inflection.
Implicated also in this manifestation may be the other tank
pressure transducer, PVSOUT, which shows some unexplained trace
widening between 400 and 450 seconds; this transducer is in the
valve box and is subject to less icing risk than PC1. The trace
widening is consistent with undesirable noise or may represent
valid data.

ACOUSTIC EMISSION IMPRESSIONS. From Jim Leaird, AET: "...I
believe that the onset of AE activity at time 47 seconds (my test
time) represents the onset of catastrophic cracking/failure.
This is well indicated on the 2nd pass. AE data where I
filtererd on the basis of AE to valid had to be)2RDC)4000
(eliminates electronic signals & 90% leak type noise) & greater
than 47 dB peak amplitude to indicate fracture type AE. Please
note that this is first pass at AE analysis." A number of graphs
indicate the AE events vs time that were recorded. RDC = ring
down counts, which are acoustic emissions or sound pulses that
travel from a discontinuity or an origin and correspond to a
microscopic deformation event such as the sudden forward movement
of a crack.

AIR PRESSURE SENSORS did not produce any significant data because
the tank did not rupture in a catastrophic failure mode.

DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE. ARDE embrittlement
procedure dated 3-27-86 was followed; embrittlement was started a
0815 hours on 4APR86. Seventy-two hours of embrittlement were
completed at 0815 hours on 7APR86; the tank was immediately moved

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E-68

from the shop embrittlement area to the test site, instrumented, hooked up and tested a 1045 hours on 7APR86. The electrolyte was sulphuric acid; sodium arsenite was added as an enhancer. The liner inside surface was pickled for 10 minutes immediately prior to the embrittlement.

ADMINISTRATIVE INFORMATION.

Revision Record. Initial issue: 7APR86. Filename: Testrv5. Revision A: 17APR86; text updated and corrected; made minor text revisions. Revision B: 23APR86; grammatical errors corrected; FM impressions added; data analyst comments added. Revision C: 23May86; pickling procedure added to embrittlement discussion; 32 second ramp was 45 seconds in second paragraph. Revision D: 14AUG86; data analyst comments expanded to include comments on spike anaylsis; administrative paragraph clarified. Revision E: ; clarified text in IMPRESSIONS FROM THE DIGITIZED FM DATA paragraph.

Filename. testrv5.

Distribution.   ARDE, Steve Berko, Dave Gleich
                       PI, Dr. Pius Chih Hsu Chao
                       Aerospace Corp., Dr. Yen Pan
                       AFRPL, Jim Miller, Mike Dieckhoff, Dick Grove,
                             MSgt Jim Day, John Marshall
                       ITT, Richard Thomsen
                       PAFB, Pete Taddie

Office of Primary Responsibility.   USAF/AFRPL/TOAE/Edwards CA 93523.

6

E.4.3   <u>Pressure and Strain Versus Time Plots</u>

Figures E-20 to E-26 give measured test tank pressure versus time and fiber strain versus time plots. Data anomalies were noted for strain gages 4, 6, 14, 16, 20, 22. Tensile strain is negative. Location of strain gages is given on Figure E-27.
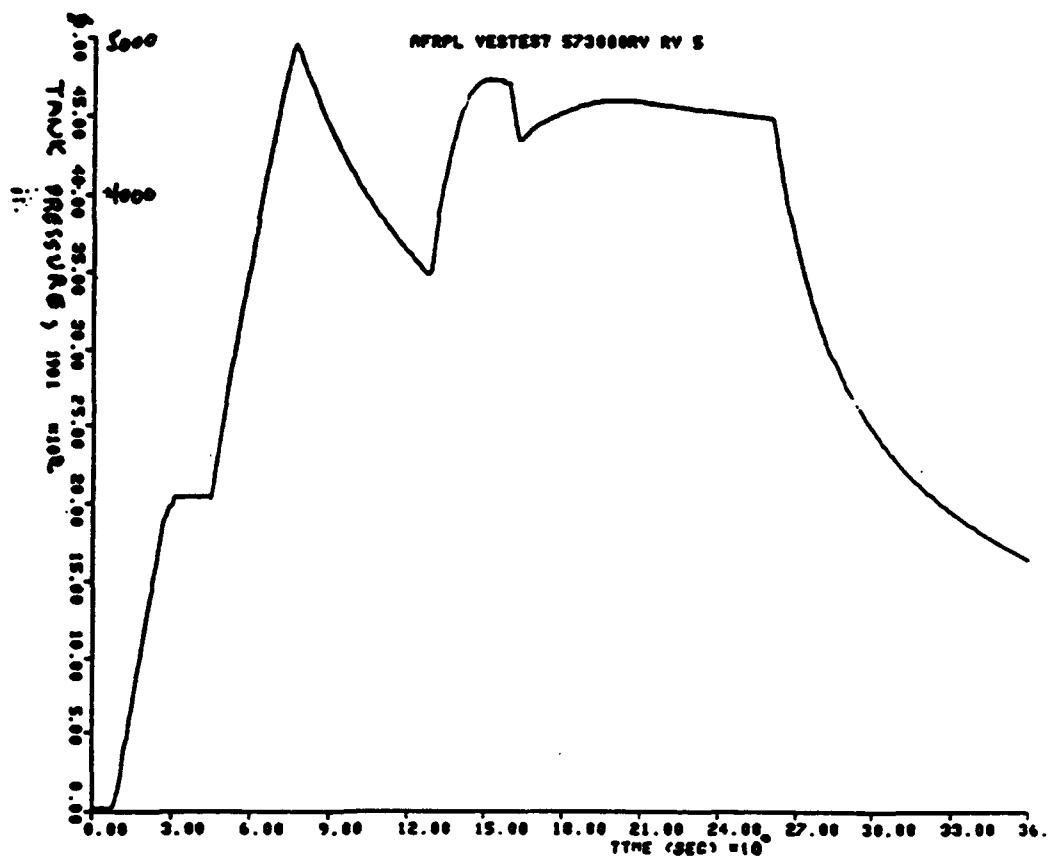
Fig. E-20

E-71

Fig. E-21

KEVLAR VESSEL TEST RV-5 —:P/N E4170, S/N 004   7 APR 1986
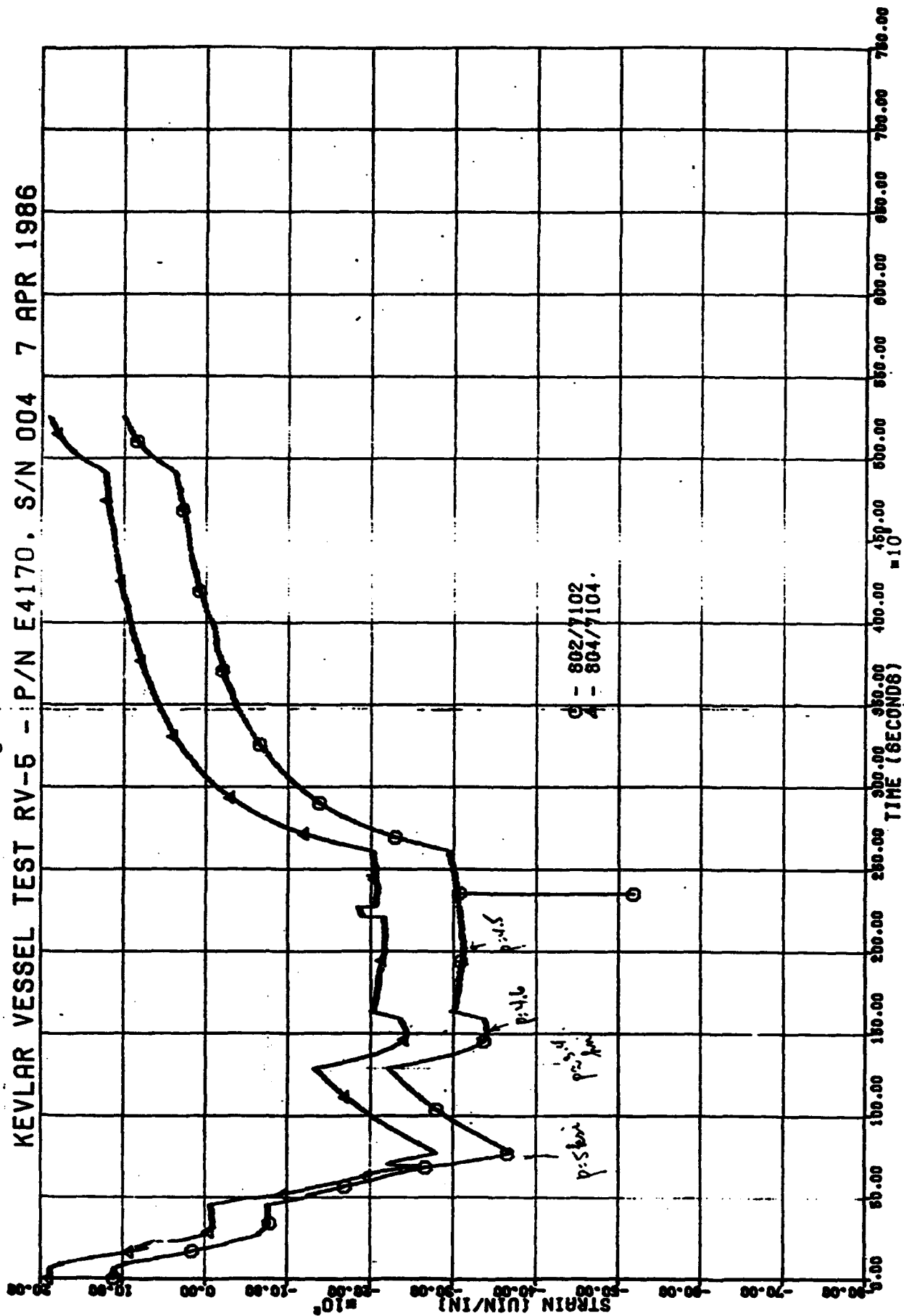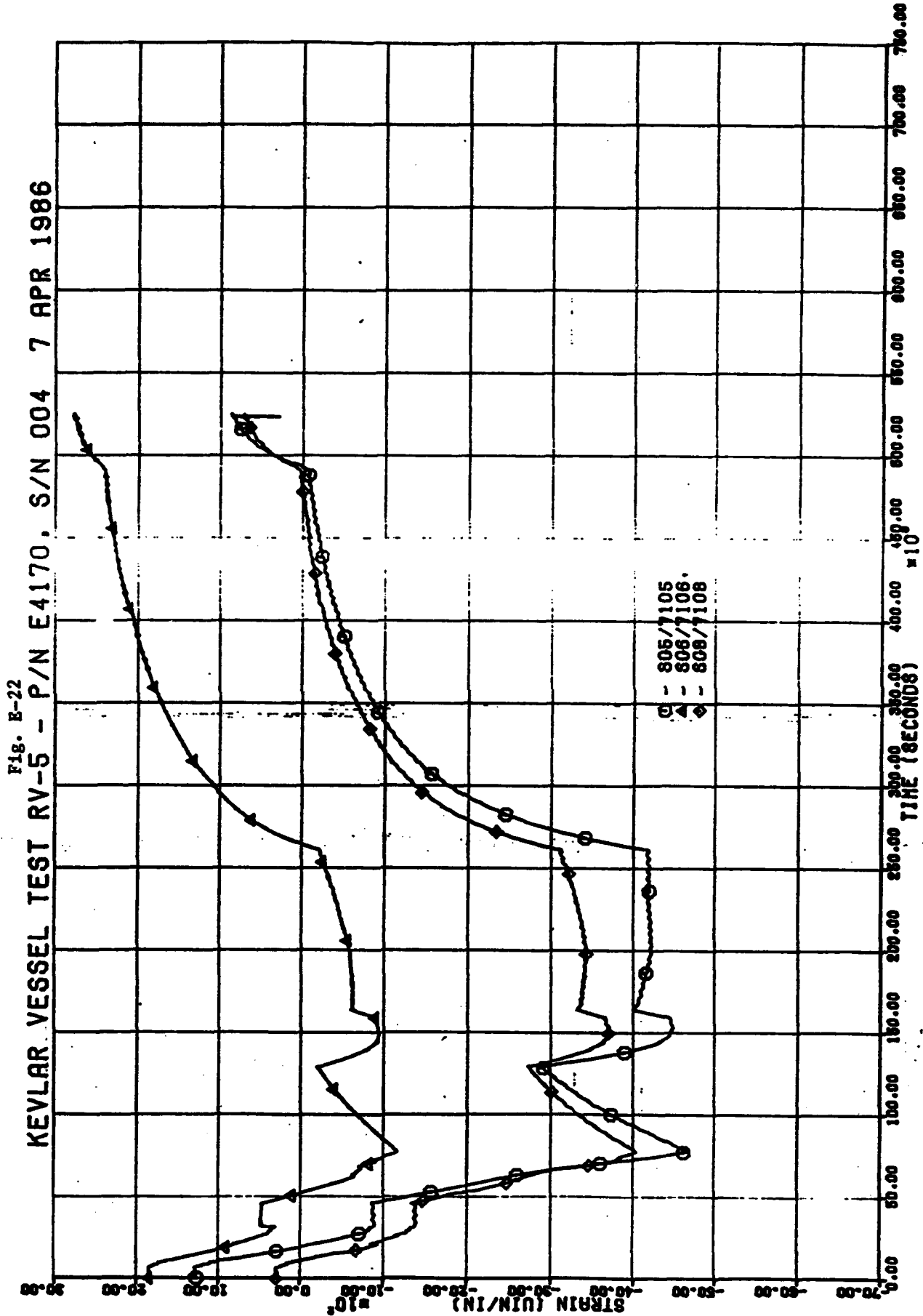
Fig. E-22

KEVLAR VESSEL TEST RV-5 − P/N E4170, S/N 004 7 APR 1986

KEVLAR VESSEL TEST RV-5 P/N E4170, S/N 004   7 APR 1986

Fig. E-23

800/7109
8010/7110
8011/7111

STRAIN (UIN/IN) x10⁶

TIME (SECONDS)
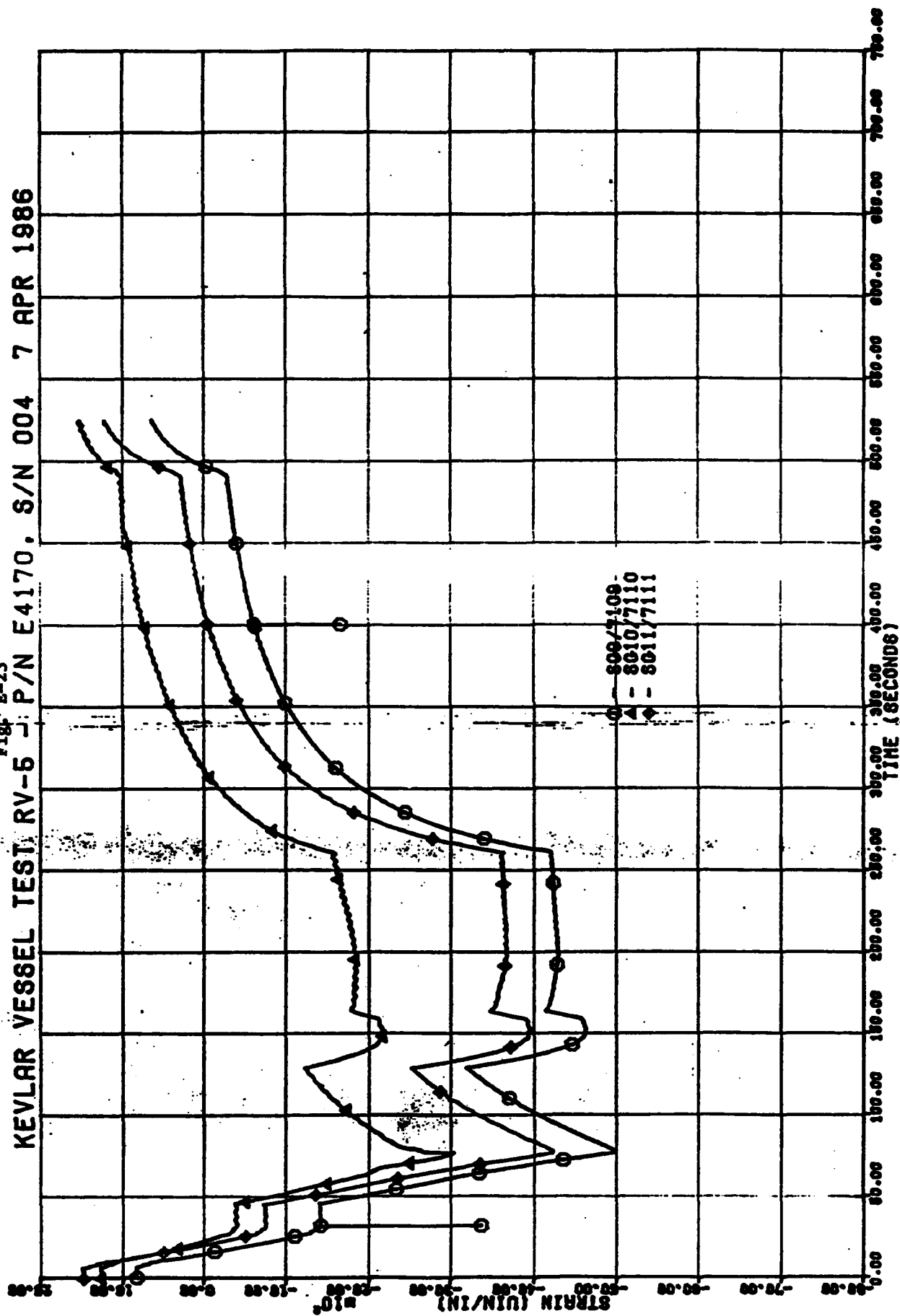
Fig. E-24

KEVLAR VESSEL TEST RV-5 - P/N E4170, S/N 004   7 APR 1986
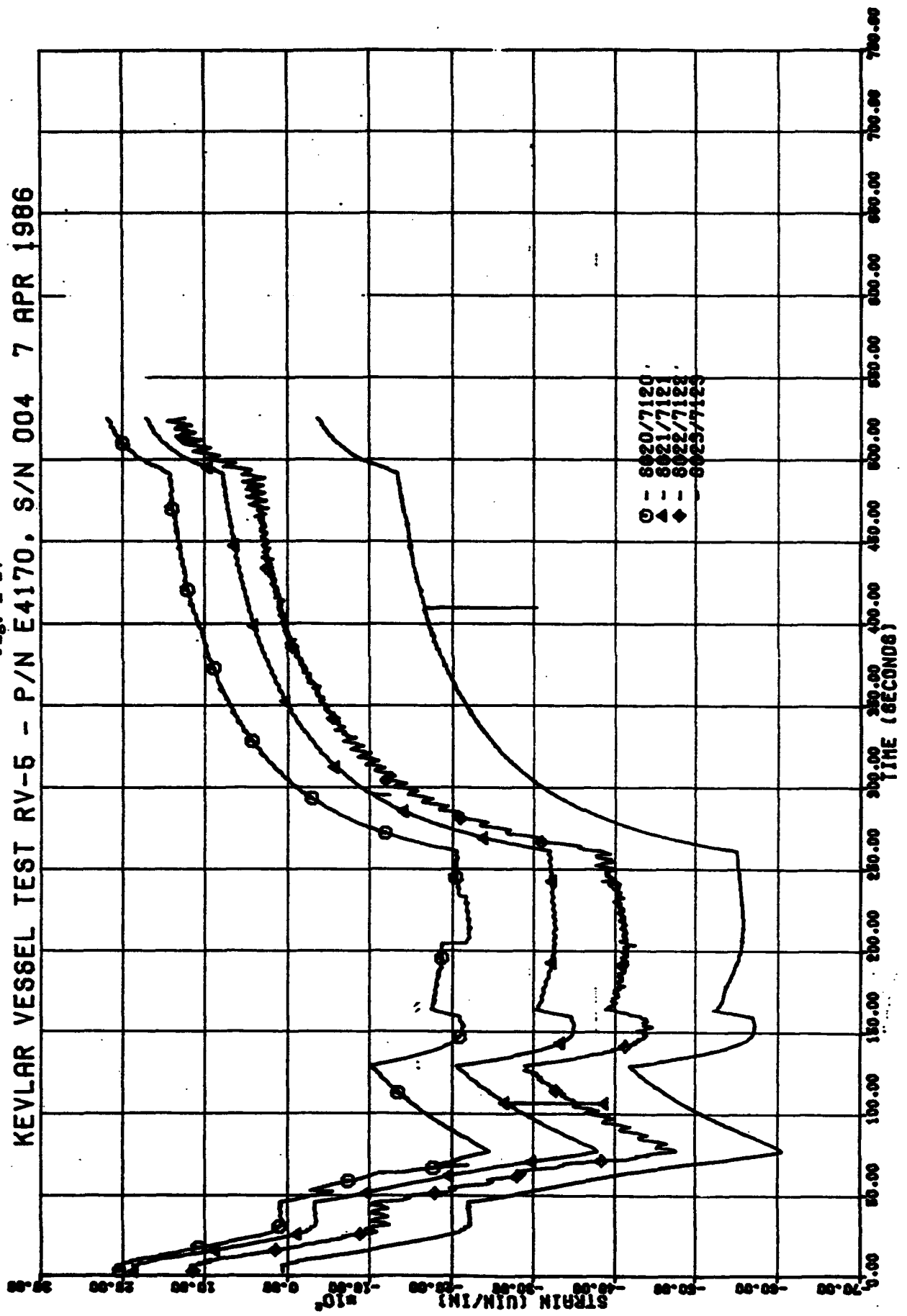
KEVLAR VESSEL TEST RV-5 - P/N E4170, S/N 004   7 APR 1986
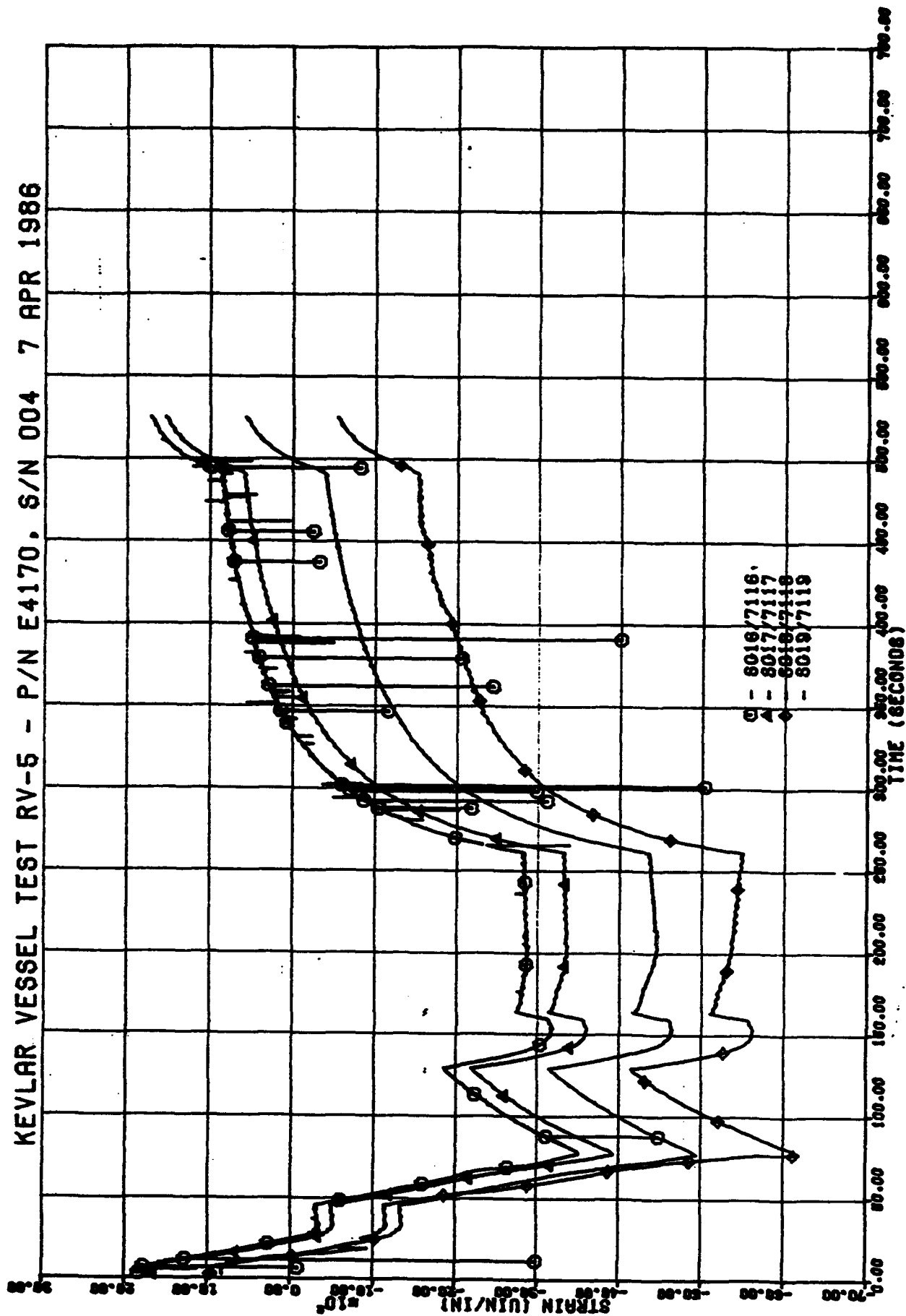
Fig. E-26

KEVLAR VESSEL TEST RV-5 - P/N E4170, S/N 004   7 APR 1986
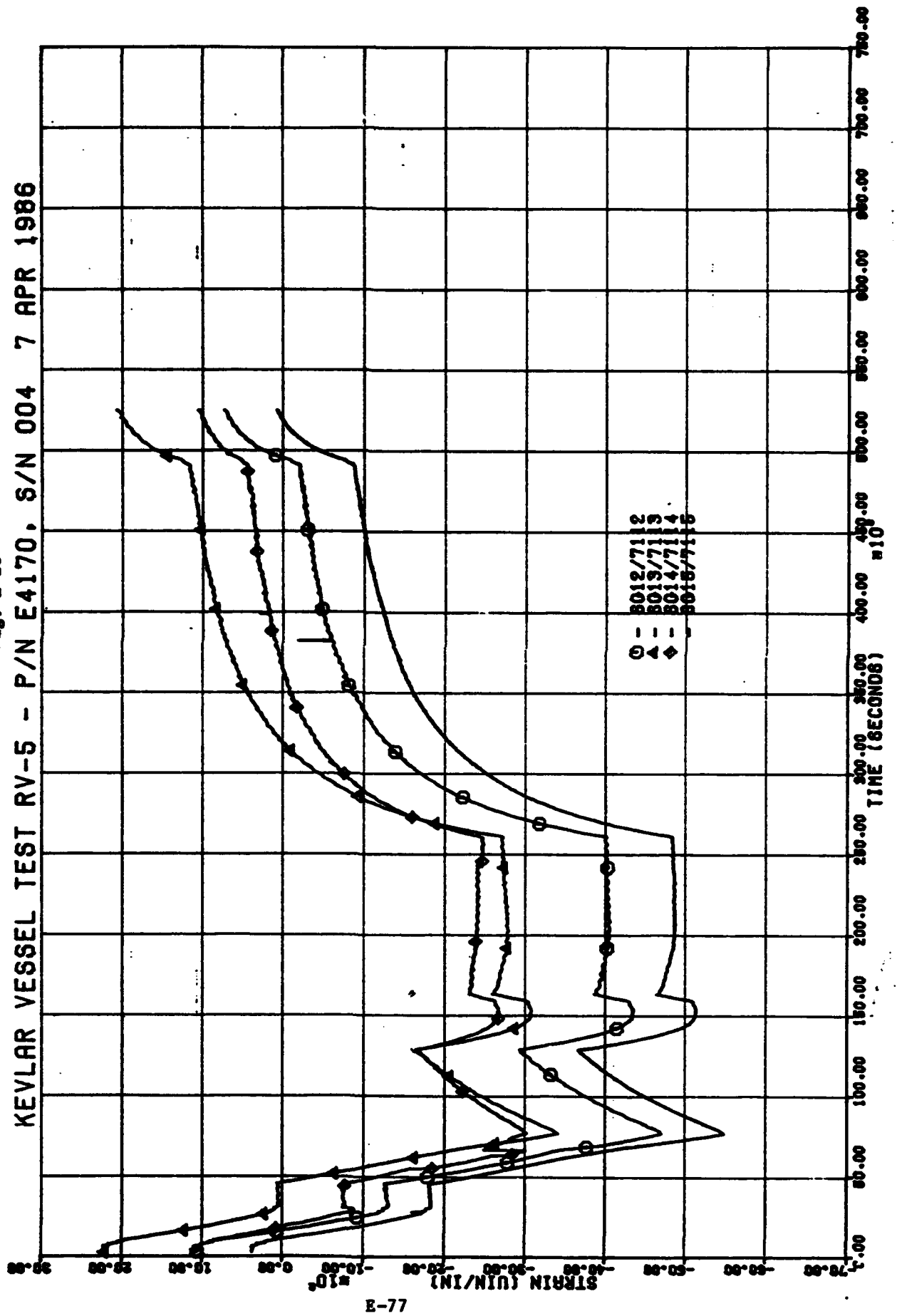
FIG. E-27
SKETCH, STRAIN GAGE MOUNTING
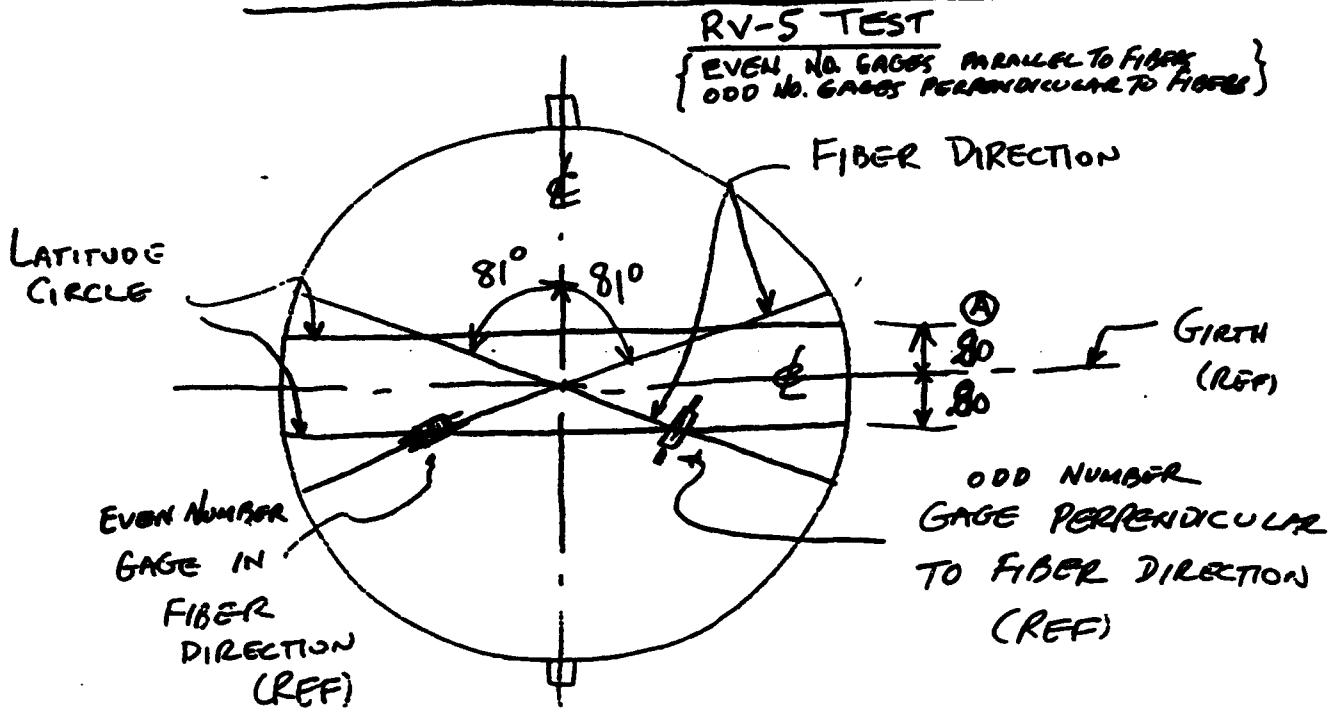
RV-5 TEST
{ EVEN No. GAGES PARALLEL TO FIBERS
ODD No. GAGES PERPENDICULAR TO FIBERS }

MOUNT 6 PAIRS OF GAGES (1 EA OF EACH PAIR IN THE
OUTER FIBER DIRECTION AND 1 EA PERPENDICULAR
TO THE OUTER FIBER DIRECTION ON EACH LATITUDE
CIRCLE) EQUALLY SPACED FOR A TOTAL OF
24 GAGES.

ARDE INC.
CONTRACT FO 8606-84-C-0029
J/N 42001-0-3
(REV A - .80 WAS .90)

E.4.4 **Post Test Inspection**

The post test tank was intact in its spherical shape with no visible exterior fiber damage. The vessel was cut at the girth and die check was applied to the liner inside surface. Multitudes of interconnected radial and tangential cracks outlining the grain boundaries were visible in the hydrogen embreittled zone between the girth and the boss region as shown on the photographs of Figures E-28 and E-29.

E-79
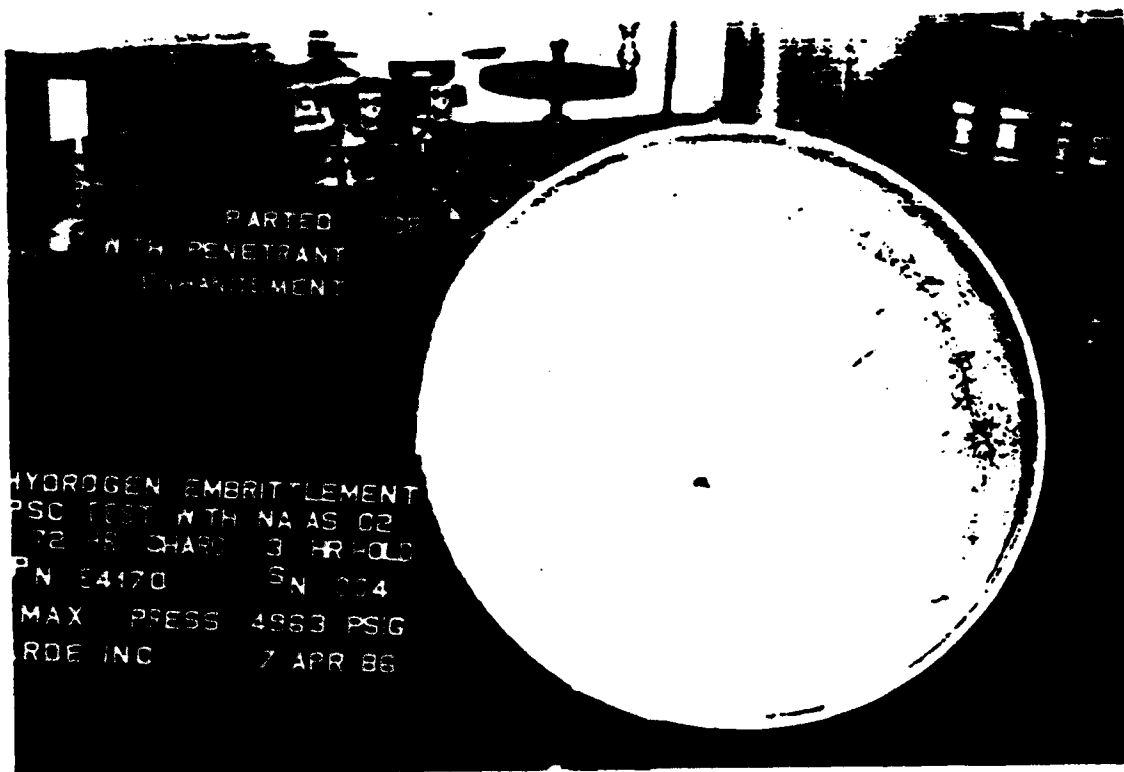
Fig. E-28

TEST RV-5, POST TEST HYDROGEN EMBRITTLED LINER
. CRACKS, DIE PENETRANT ENHANCED
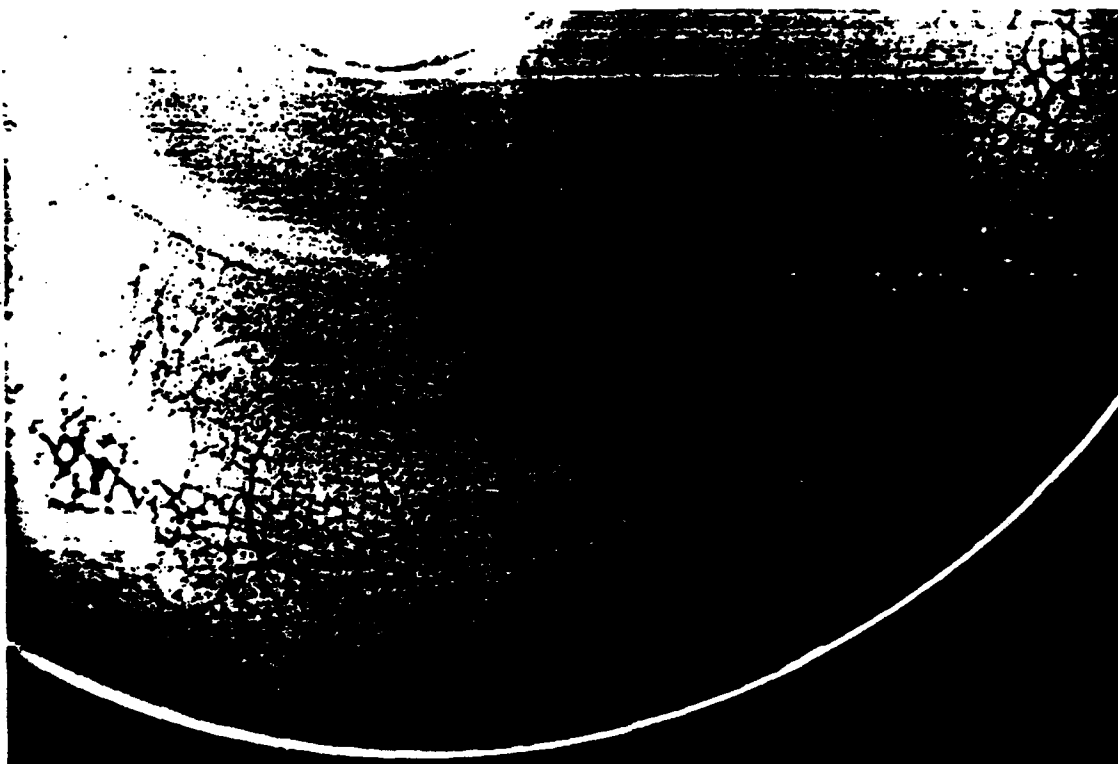
Fig. E-29

TEST RV-5, CLOSE UP OF POST TEST LINER DIE

E.5   <u>RV-7 Test (16" φ PSC</u>

E.5.1   <u>Test Vessel Description</u>

- P/N E4168, S/N 001 Kevlar Overwrapped 301 Cryo CRES (Composite Sphere)

- Kevlar Fiber (less resin) Average Thickness - .154" (100% Baseline Thickness)

- Metal Thickness - .054/.048"

- Inside Radius - 7.66"

- Hydrogen Embrittlement Mode - Local Girth Weld Region

- Electrolyte Solution -

$$\frac{20 \text{ cc } H_2SO_4 + 980 \text{ cc Tap } H_2O}{1000 \text{ cc Solution}}$$

- Solution Additive ~ 500 mg Sodium Arsenite

- Sensitize liner inside surface (cold pickle)

- Charging Current Density - .042 amps/in^2 of surface to be embrittled.

- Charging Time - 72 hours

- Hold Time Before Test - 3-1/2 hours

- Adcoat AC818T liquid maskant on areas not to be embrittled.

A photograph of the instrumented tank on the test stand at AFAL is shown on Figure E-30 herein.

E-81

Fig.   E-30

TEST RV-7, INSTRUMENTED TANK MOUNTED IN TEST STAND

E.5.2

INSTRUMENTATION OBSERVATIONS (by AFAL Instrumentation Engineer) *list to DG all originals incl digital data*

KEVLAR TEST 007, 26JUN86. Project number 573000RV.

EXPERIMENTAL OBSERVATIONS.

Introduction. Vessel S/N 004 was tested. It was a 16 inch diameter stainless steel sphere and had a Kevlar overwrap. The vessel was hydrogen embrittled about the girth for about a 1 inch width. This vessel was the first vessel in the test matrix with a girth embrittlement; all previous embrittlements were global. It was tested in a vertical configuration. Briefly, the tank pressure was increased with pressure pulses and ramps until liner cracking occurred. More specifically, the tank pressure graph displays a locus consisting of the polarization and depolarization components representing the moderately complex pressurization and depressurization histories, which are discussed elsewhere. Furthermore, the pressure locus morphology is impressively reflected in the strain gage loci, and the similarities are emphasized in the text.

Pressurization Ramp. The vessel was pressurized with cool helium gas. Initially, the pressure was increased from ambient pressure to about 640 psig (most figures were estimated from the graphs) during a cool-down period, which took about 2 minutes. During the next 24.5 seconds (28.0-3.5 seconds), pressure was increased with a salvo of 17 small pulses and steps to a plateau, which stabilized at 2080 psig during a 17 second (45-28 seconds) pause. After a rapid but small 120 psig pressure increase, pressurization continued in a classical linear ramp from 2200 psig to 3850 psig in 20.3 seconds (65.3-45.0 seconds), which is a *liner* pressurization rate of 189.7 psig/sec. The vessel cracked *should be ≈ 65 sec* following 20.3 seconds of ramp time at (63.3) seconds. The crack generated a sharply demarcated depressurization profile. The profile followed an exponential decay, which was distorted by a failed repressurization episode at 76 seconds, and ended in an asymptotic approach to zero pressure. Total pressurization time above 640 psig was 61.8 seconds (24.5+17.0+20.3 seconds). Initially, the depressurization rate was 7700 psig/second [(3850-0 psig)/(65.8-65.3 seconds)], from the graph, or 1,275.6 psig/second [(3804-2529 psig)/(64999.836-65999.352 milliseconds)], from the tabular data.

Catastrophic Burst. *Should be ≈ 65 sec* The vessel *liner* cracked at the end of the 20.3 second ramp time at (63.3) seconds with subsequent rapid pressure loss; during depressurization, a repressurization attempt failed. and depressurization continued to zero pressure; as zero pressure was approached, prominent Kevlar fiber pinging, within the audio spectrum, became noticeable and continued for about 6 minutes. The Kevlar fiber remained intact, in general; but some fiber fraying was concentrated on the ends of the vessel near the bosses. In particular, fiber wrap 1 had no fraying; wraps 2-8 had moderate fraying; and wrap 9-to-the-girth had no fraying.

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Post-run Inspection. After the test, the vessel was cut open by
AFRPL; the cut was made away from the girth weld; seen was the
location of one small (3/8") missing triangular metal piece,
which was probably lost through one of the fittings, and the
fractures outlining another small, potentially loose, metal
piece. At ARDE, another cut was made creating a ring of liner
and overwrap; the overwrap was severed, and the ring separated
into two rings at a continuous, circumferential crack adjacent to
the girth weld; there were accompaning fractures.

Other Details. After the Post-run Inspection, the parts were
shipped to ARDE. Acoustic emission and overpressure data were
not taken.

IMPRESSIONS FROM THE DIGITIZED FM DATA.

Strain Gages. The gages were mounted on the 81 degree wrap angle,
which is the last fiber layer; they were equally distributed and
were 8 degrees off the girth. The polarity convention for
increasing strain is negative. Except where indicated, the
following comments are based on the initial data pass, which
generated graphs with a sample rate of 1024 SPS, filter frequency
of 100 Hz and plot rate of 80 SPS.

Data Anayst's Comments. ITT, Richard M. Thomsen, states

"Strain gauges: 1,2,7,10 and 19-21 were bad. SG6 went out when
the vessel burst. SG14 did not detect the burst and has no data
under -5000 microstrain.

Two ranges were calculated for the good strain gauges. The
difference between zero and the hold at 2000 psig, and that
between the strain just before the spike at rupture and the
minimum value of the spike. These follow:

Strain Gage #	Microstrain 0 to 2000 psig	Microstrain Burst Spike size
3	-1540	-2700
4	-1470	-7100
5	-1510	-3500
6	-1450	-8300
8	-1950	-2000
9	-1570	-3400
11	-1554	-3400
12	-1820	-8100
13	-1540	-2500
14	-1360	-----
15	-1580	-3600
16	-1730	-5500
17	-1490	-2400
18	-1510	-2200
22	-1350	-4000
23	-1580	-3000" (End of ITT text)

2

Observations. Strain gages parallel to the fibers have odd numbers, and strain gages perpendicular to the fibers have even numbers. The arithmetic mean (average) for the eight odd gages parallel to the fiber is 3060 microinches/inch; the average for the seven gages perpendicular to the fiber is 5314 microinches/inch. This 2254 microinches/inch differential is consistent with the characteristic stiffness parallel to the fiber and the excessive compliancy perpendicular to the fiber. Noteworthy are the irregularities seen during the pressurization ramp on the even gages perpendicular to the fibers. In most cases, there are no spikes; major distortions present as slope changes at inflection points, transient offsets, and complex nonlinear transitions, etc. Such distortions are conspicuously absent in the gages parallel to the fibers; the ramp on these gages is linear and smooth except for a few spikes. Some of the distortions continue into the decay portion of the profile in several of the perpendicular gages. The parallel gages remain distortion free during the decay, except for the repressurization attempt discussed elsewhere. The observed dynamic strain performance (increasing strain) is not the same as the predicted model (implosion — decreasing strain prior to increasing strain).

Speculations. Changes in slope represent changes in stiffness.

General Comments.

Except for the bad gages discussed above, and item 7114, the strain gage data appeared to be unbiased, precise and accurate. Item 7114 exhibited bizarre behavior. The noise floors were within normal limits, except for item 7123.

Item 7123.

Item 7123 had excessive noise randomly modulating the strain data; the rate of occurrence was particularly high near the beginning and end of the test period where it is directly proportional to the lower dynamic conditions — a very unusual performance characteristic. The alleged noise was predominantly unipolar, clearly nonperiodic and contained random magnitudes. The etiology shows the following: The zero and calibration cuts were satisfactory. The noise can probably be blamed on a bad connection somewhere in the strain gage circuit. Strain gage crazing cannot be ruled out.

Item 7114.

Item 7114 had a bizarre response to the Kevlar strain. The channel saturated during the ramp; it stayed saturated during and for a short time after the rupture. The data are probably not valid. Channel overload has been eliminated as a cause. The probable cause is gage debonding or an amplifier problem. The calibration information follows:

3

	Counts	MV	microstrain
0 cal	1380	-2.7	-1205
50 cal	3802	----	-----
75 cal	5023	0.9	402
data limit	-7186	-11.2	-5000

The FM input was set for 1 volt full scale input, which was adequate to capture the -11.2 mv (X 50 = 0.55V after the amplifier) signal and the -2.7 mv (X 50 = 0.135V after the amplifier) offset without overload.

Spikes.

Occasional legitimate spikes on the remaining strain parameters are consistent with Kevlar fiber noises created by breaking, stretching and settling. Note the polarity direction trend (same direction as increasing strain), magnitude (usually 1/3 to 1/2 of total strain seen on the channel), phase (not unique, unless time disparities can be related to location by subsequent spike analysis), and frequency of occurrence (not too often). On the initial 80 SPS plot rate graphs, no discernible spike time differences were noted, or expected.

Correlations.

In general, the strain gage profiles were directly proportional to the tank pressure profile, and excellent correlation exists between the strain gages and tank pressure. The systemic inflections, modulations, plateaus, slopes and decays are impressively similiar. The only major exception is the large, single spike paroxysm, at rupture, seen on each strain gage parameter; the spike is not on the tank pressure parameter.

Theory #1: This theory speculates the spike represents the natural resonant frequency of the composite structure; the resonance is alleged to be 10,000 Hz, which would have a period of 100 microseconds and a rise time of 33 microseconds (using rt=1/3(f) method). This theory is discussed in more detail in file TESTRV5.

Theory #2: The spike may be due to the metal tank halfs slamming into the fiber overwrap at rupture. Of course, this is an oversimplification, for the metal is probably touching the overwrap many places at the higher pressures seen prior to rupture.

Theory #3: This speculation admits the spike may represent the energy released at rupture, and the two rapidly separating halfs cause the spike by just pushing very quickly against the overwrap they already are contacting whe⋅ the integrity of the metal liner is lost.

Theory #4: Much less probable as a possible cause is the pressurization of the Kevlar overwrap: the overwrap has open ends

and cannot hold much pressure, and this theory isn't much of a
contender.

IMPRESSIONS FROM THE QUICK-LOOK AND DIGITAL DATA ACQUISITION
SYSTEM DATA. All data appeared to be unbiased. precise and
accurate. The noise floors were within normal limits.

Tank Pressure. The tank pressure functioned as described under
the Pressurizatiion Ramp paragraph. All the pressure parameters
were within normal limits.

Temperatures.

Tank Temperatures. The tank temperatures, TT1-TT12, were within
normal limits. The graphs were clean and smooth; in general,
they formed a family of broadly separated curves representing
valid behavior profiles. The graphs started with stable initial
conditions, around 86.3-91.6 degrees F (@ 60 seconds); the curves
continue with a very small (about 2 F degrees) increase
immediately following rupture. Following the small increase, the
graphs plunge smoothly, at different rates, to their lowest
values where they reverse direction and heat, at different rates,
to about half their initial conditions, or they remain almost
level or return to near the initial condition; some modulate
slowly after they.plunge to their lowest values. The lowest
temperatures ranged from -1.0 degrees F (TT4) to -105.2 degrees F
(TT5). Intentionally remaining unexplained are the causes of the
modulations, inflections and rates of changes not already
discussed, and the final values; for the values and variations
seen are considered normal and consistent with sensor locations,
depressurization, and sensor specifications, etc. However, these
behavior variations and profiles may be important in subsequent
analyses.

Temperatures. Other. The remaining temperatures, TBSIN, TBSOUT,
TBALL, THXIN and THXO were within normal limits. The trend
performances, however, were not evaluated, and speculations on
the behavior of these parameters are reserved.

IMPRESSIONS CONCERNING THE DISPLACEMENT SENSORS.

Displacement Sensors. The ITT data analyst, Richard Thomsen
reports in his "DATA ANALYST COMMENTS 20JUN85 TEST RV-7 26JUN86
(AN) OSCILLOGRAPH TRACE OF SG15, SG17, SG23, DP1(-), DP2(+) AND
IRIG B (was made.)

The strip chart shows the upper band edge, the center frequency
and the lower band edge. The cal cuts from the analog tape are
next. Immediately the signal from DP2 becomes very noisy and
remains so for the rest of the data. DP1 shows a good zero cal,
but shifts to the upper band edge for the RC1 and RC2 cals. On
the digital output this shows up as noise (possibly 60 Hz) making
this channel impossible to calibrate.

5

Suprizingly (sic) DP1 again appears at the beginning of the run.
It is modulated by a 60 Hz signal, but well below the band edges.
(The numbers penciled in on the edge of the strip chart are the
approximate time in seconds.) At 65.5 seconds the burst occurs
as shown by the strain gauges. DP1 records this event well. Why
this channel should show up as noise on the digital output is not
known.

In reference to the strain gauge spikes, the ones that show up on
the strip chart for SG15 also show up on the plots of the
digitized data.   It is not known why the many spikes that show up
on the plots for SG23 do not show up on the strip chart..."

**DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE. ARDE embrittlement
procedure dated 18JUN86 was followed; only the girth area for a
width of about 1 inch was embrittled.   Embrittlement was
inhibited, where required, with a maskant.   Embrittlement was
started at 0800 hours on 23JUN86.   Seventy-two hours of
embrittlement were completed at 0800 hours on 26JUN86; the tank
was immediately moved from the shop embrittlement area to the
test site, instrumented, hooked up and tested at 1130 hours on
26JUN86.   The electrolyte was sulphuric acid; sodium arsenite was
added as an enhancer.**

ADMINISTRATIVE INFORMATION.

Revision Record.   Initial Issue: 23JUL86.   Revision B: 19UG86;
changed text in item 7114 and 7123 paragraphs.   Milliseconds was
seconds in Pressurization Ramp paragraph.   Added text to Strain
Gage paragraph.   Added Displacement Sensor paragraph.   Revision
C: 17SEP86; expanded Displacement Sensor paragraph. Revision D:
17OCT86; `S/N corrected from 007 to 004; added text to
Catastrophic Burst paragraph; many was mamy in Displacement
Sensors paragraph; expanded distribution list; added text to
Introduction paragraph.   Revision E: 6NOV86; added text to
Introduction paragraph.

Filename: testrv7.

Distribution.   ARDE, Steve Berko, Dave Gleich
                       PI, Dr. Pius Chih Hsu Chao
                       Aerospace Corp., Dr. Yen Pan
                       AFRPL, Jim Miller, Mike Dieckhoff, Dick Grove,
                            MSgt Jim Day, John Marshall, Capt
                            Seidemann
                       ITT, Richard Thomsen, Dr. Tae-Woo Park
                       PAFB, Pete Taddie

Office of Primary Responsibility.   USAF/AFRPL/TOAE/Edwards CA
93523.

E

E.5.3   <u>Pressure and Strain Versus Time Plots</u>

Measured test GHe tank pressure vs. time and fiber strain vs. time plots for key strain gages are given on Figures E-31 to E-43. Data for both 100 Hz filter frequency, 1024 samples/scc (SPS) and 20,000 Hz, 160,000 SPS are given for each strain gage. The higher filter frequency and sample rates (20,000 Hz and 160,000 SPS, respectively) show greater detail on the strain spike amplitudes at liner failure.

Tensile strain is negative and even numbered strain gages are perpendicular to the fibers and odd numbered strain gages are parallel to the fibers. The strain gages were evenly distributed and were mounted at .80" height above and below the girth on the outer last 810 fiber wrap. Figure E-44 is a sketch of the strain gage locations.

VESTEST 57300RV TEST 7

Fig. E-31

E-90

Fig. E-32
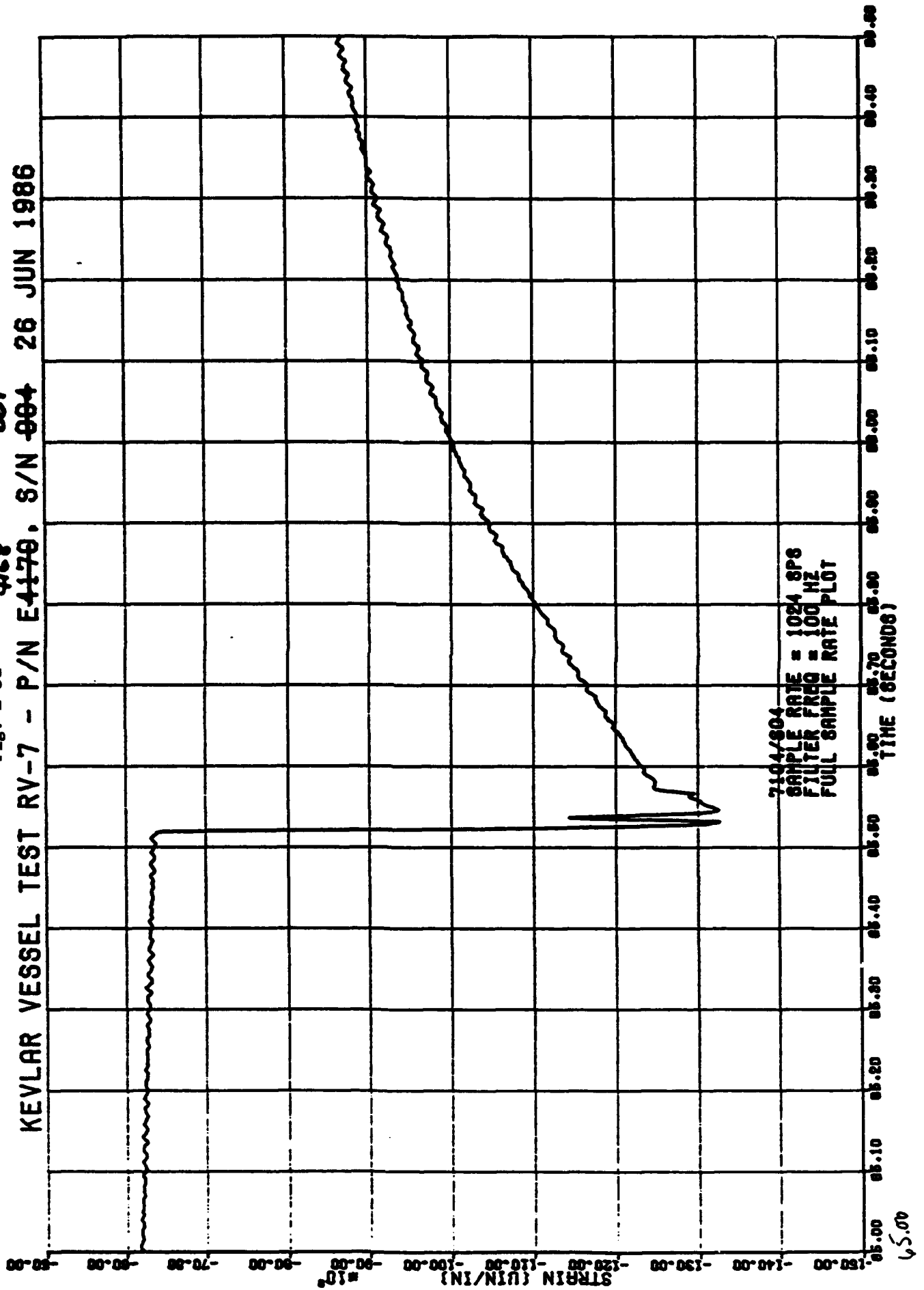
KEVLAR VESSEL TEST RV-7 - P/N E4470, S/N 004   26 JUN 1986

7404/804
SAMPLE RATE = 1024 SPS
FILTER FREQ = 100 HZ
FULL SAMPLE RATE PLOT

TIME (SECONDS)

STRAIN (UIN/IN)

$\#10^6$

Fig. E-33

KEVLAR VESSEL TEST RV-7 P/N 4170, S/N 004, 26 JUN 86
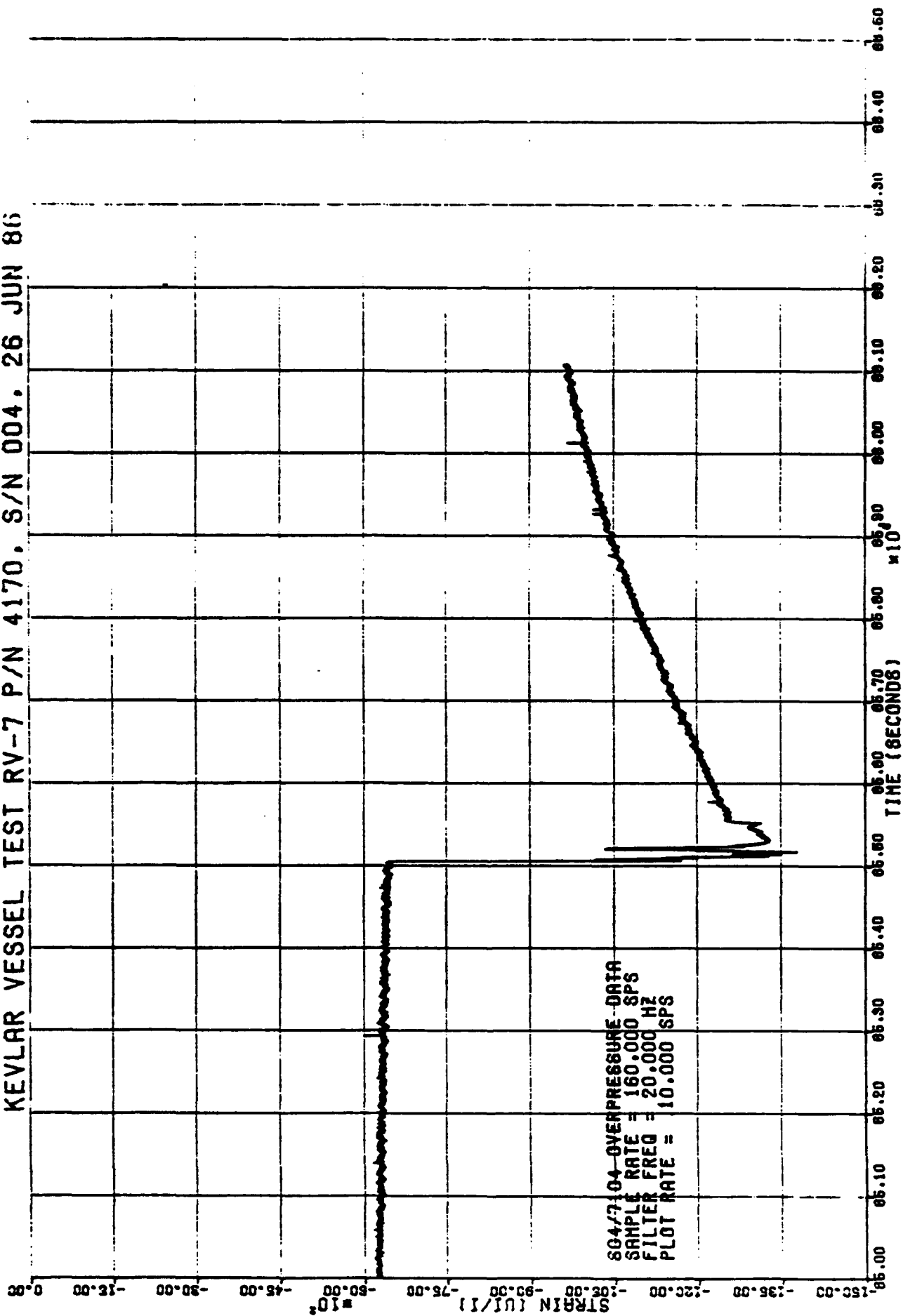
604/7:04 OVERPRESSURE DATA
SAMPLE RATE = 160.000 SPS
FILTER FREQ = 20.000 HZ
PLOT RATE = 10.000 SPS

TIME (SECONDS)

STRAIN (U1/1) ×10²

Fig. E-34

KEVLAR VESSEL TEST RV-7 P/N 4170, S/N 004, 26 JUN 86

004/7104 OVERPRESSURE DATA
SAMPLE RATE = 160,000 SPS
FILTER FREQ = 20,000 HZ
PLOT RATE = 160,000 SPS

KEVLAR VESSEL TEST RV-7 – P/N E4476, S/N 004   26 JUN 1986

Fig. E-35

7106/806
SAMPLE RATE = 1024 SPS
FILTER FREQ = 100 HZ
FULL-SAMPLE-RATE PLOT

STRAIN (UIN/IN)   ×10²

TIME (SECONDS)

Fig. E-36

KEVLAR VESSEL TEST RV-7 P/N 4170, S/N 004, 26 JUN 86

S06/7108 OVERPRESSURE DATA
SAMPLE RATE = 160,000 8PS
FILTER-FREQ = 20,000 HZ
PLOT RATE = 10.000 6PS

STRAIN (UI/I)

TIME (SECONDS)

Fig. E-37

KEVLAR VESSEL TEST RV-7 P/N 4170, S/N 004, 26 JUN 86

806/7106 OVERPRESSURE DATA
SAMPLE RATE = 160,000 SPS
FILTER FREQ = 20,000 HZ
PLOT RATE = 160,000 SPS
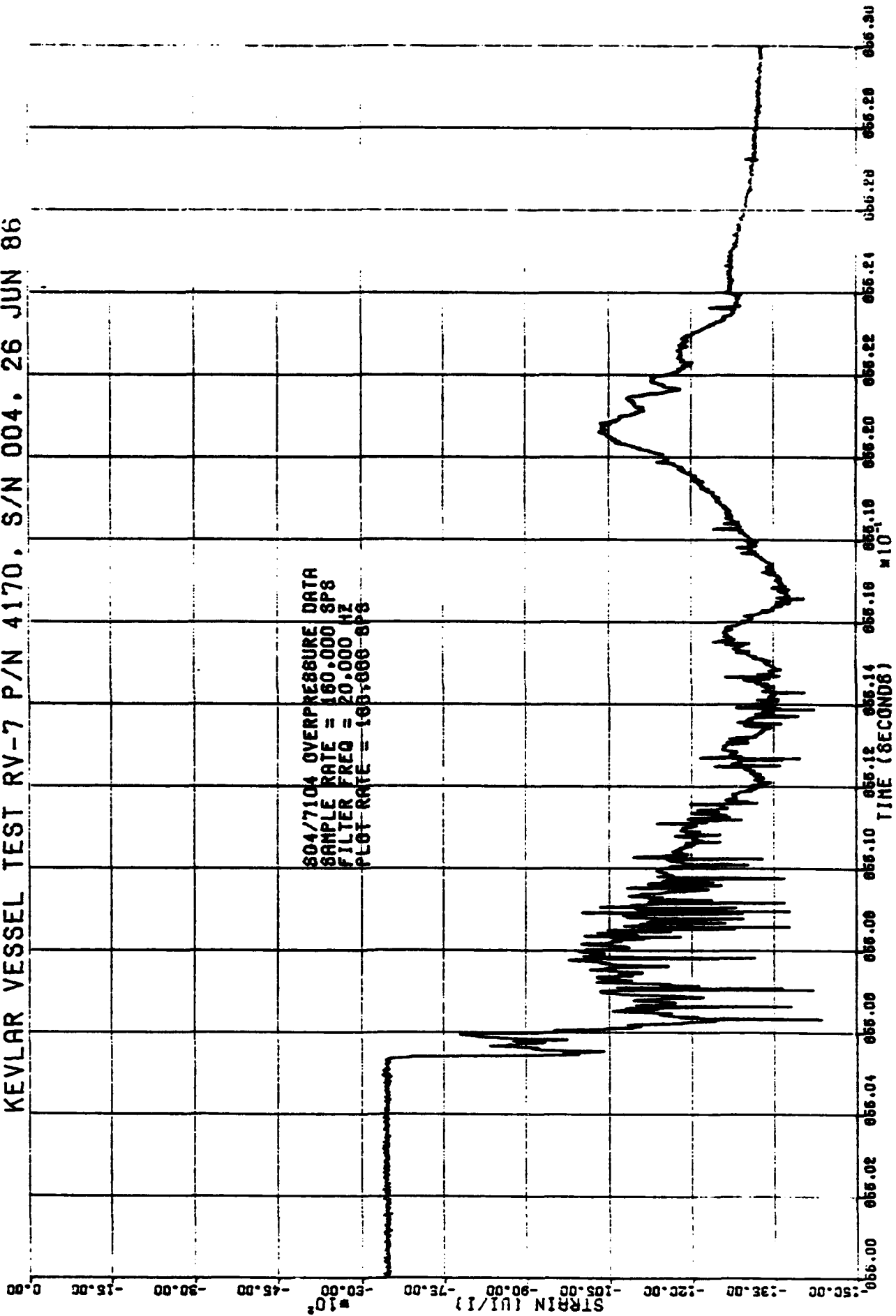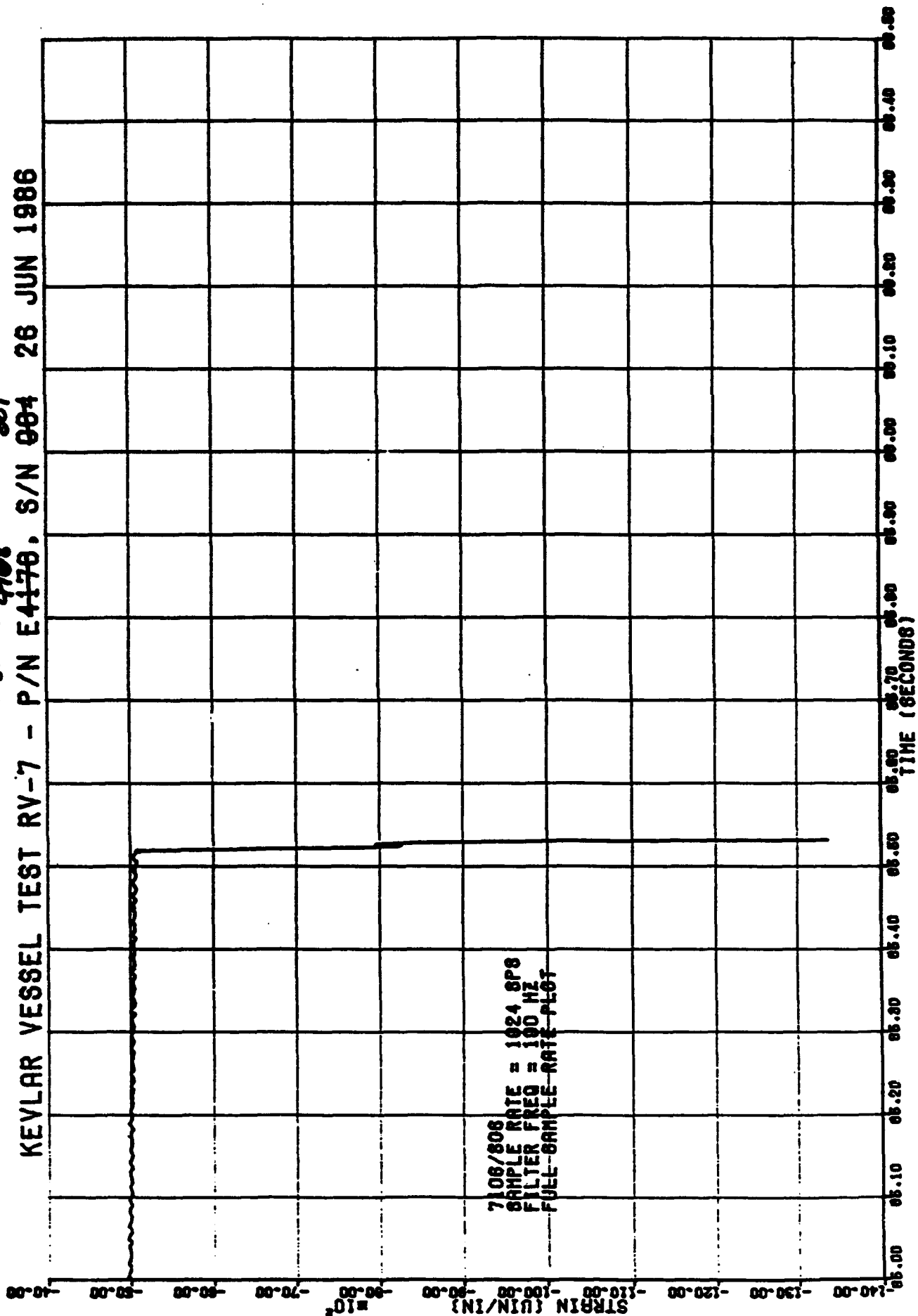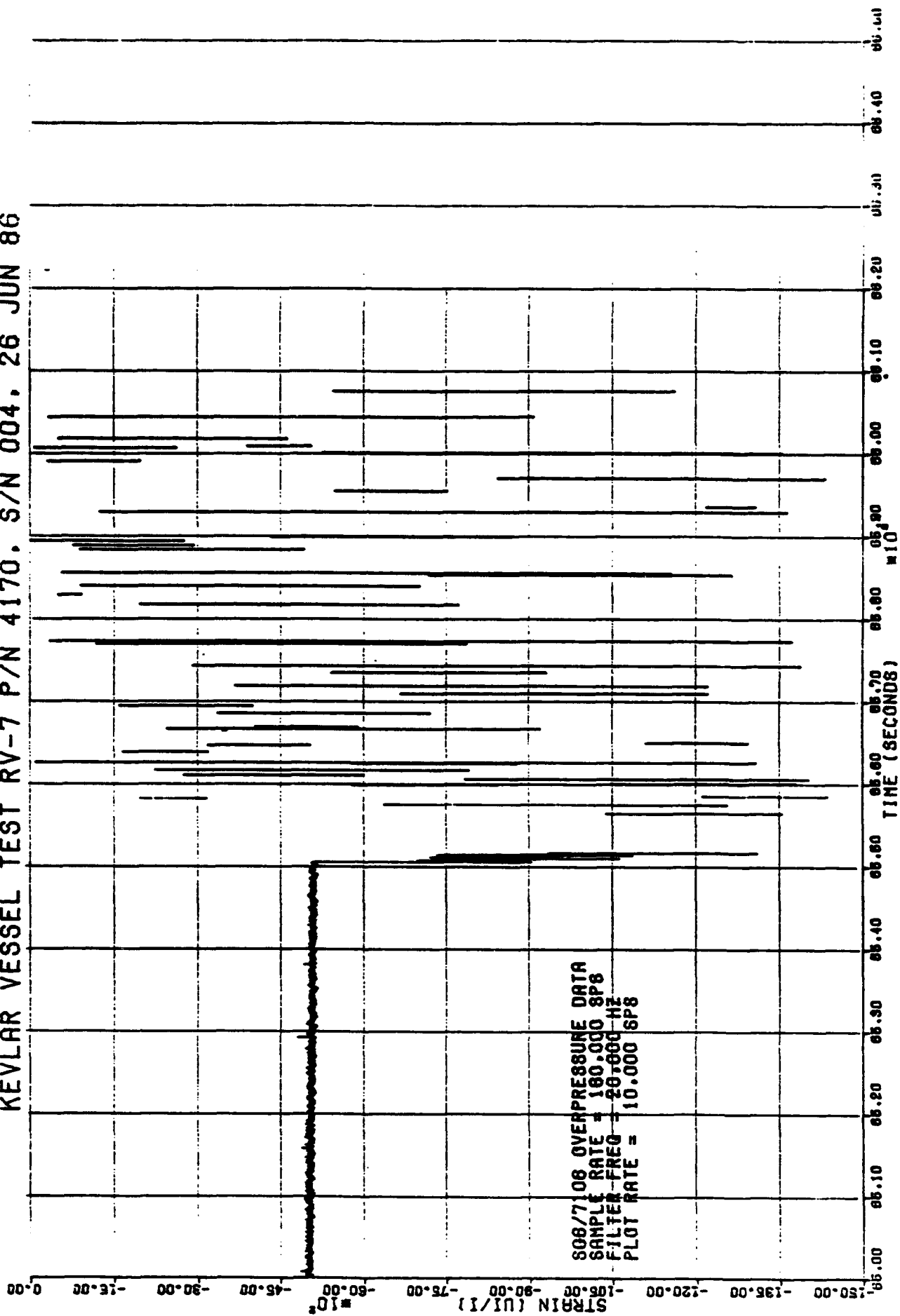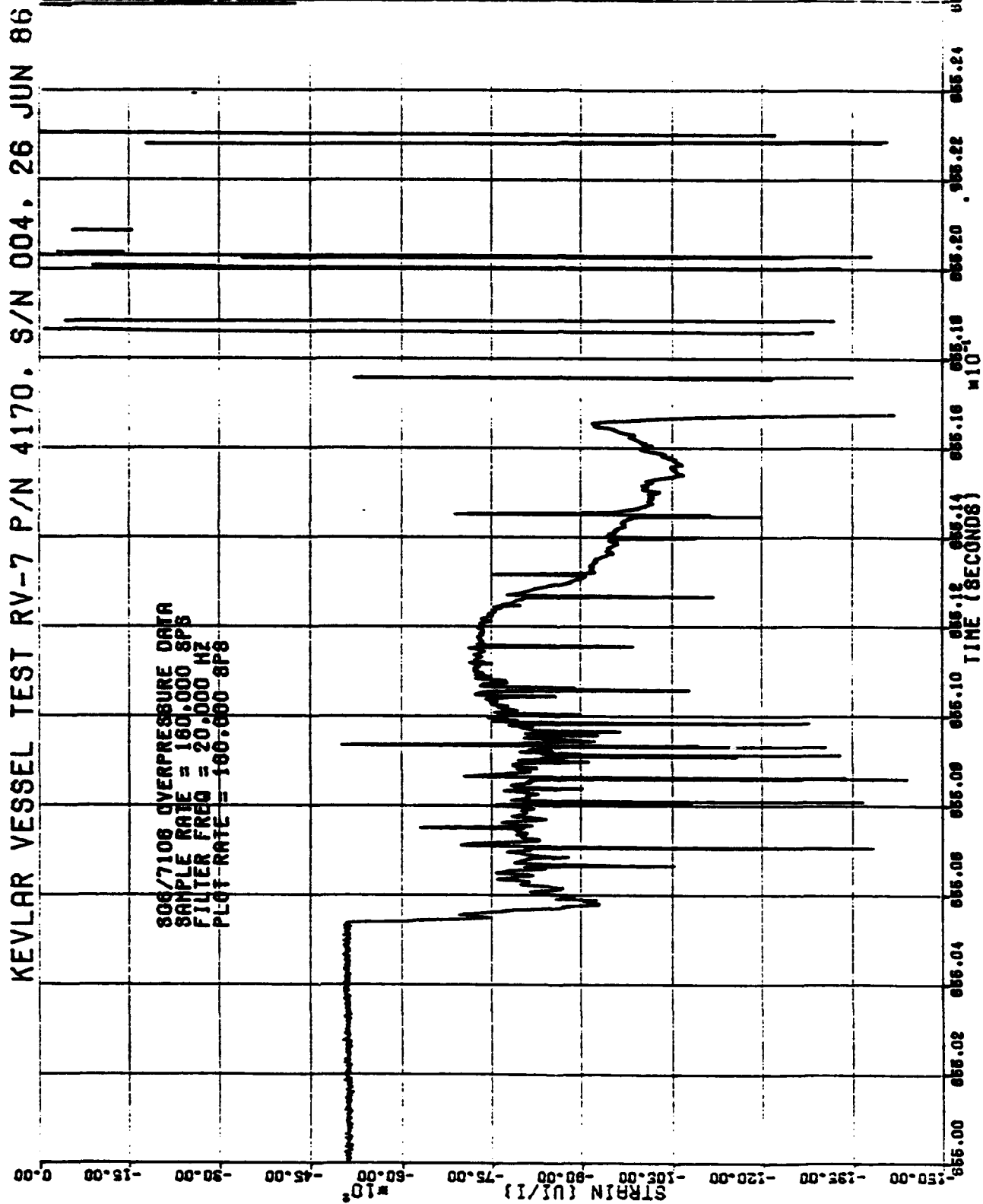
Fig. E-38

KEVLAR VESSEL TEST RV-7 - P/N E4470, S/N 004   26 JUN 1986

Fig. E-39

KEVLAR VESSEL TEST RV-7 P/N 4170, S/N 004, 26 JUN 86

SG12/7112 OVERPRESSURE DATA
SAMPLE RATE = 160.000 SPS
FILTER FREQ = 20.000 HZ
PLOT RATE = 10.000 SPS

E-98

Fig. E-40

KEVLAR VESSEL TEST RV-7 P/N 4170, S/N 004, 26 JUN 86

Fig. B-41441469

KEVLAR VESSEL TEST RV-7 — P/N E4470, S/N 004   26 JUN 1986

7118/8016
SAMPLE RATE = 1024 SPS
FILTER FREQ = 100 HZ
FULL SAMPLE RATE PLOT

E-100

Fig. E-42

KEVLAR VESSEL TEST RV-7 P/N 4170, S/N 004, 26 JUN 86

SO16/7116 OVERPRESSURE DATA
SAMPLE RATE = 160,000 SPS
FILTER FREQ = 20,000 HZ
PLOT RATE = 10,000 SPS
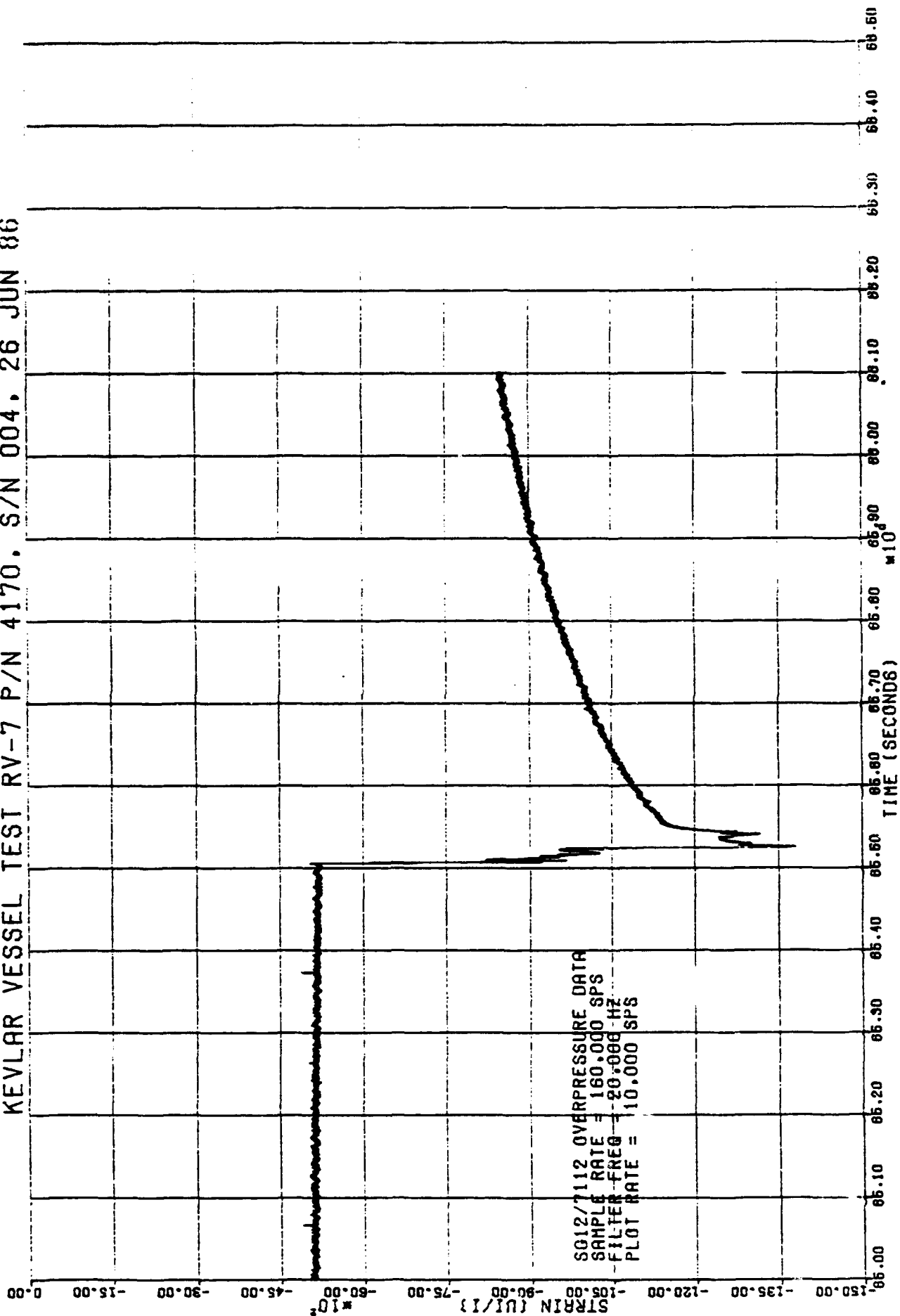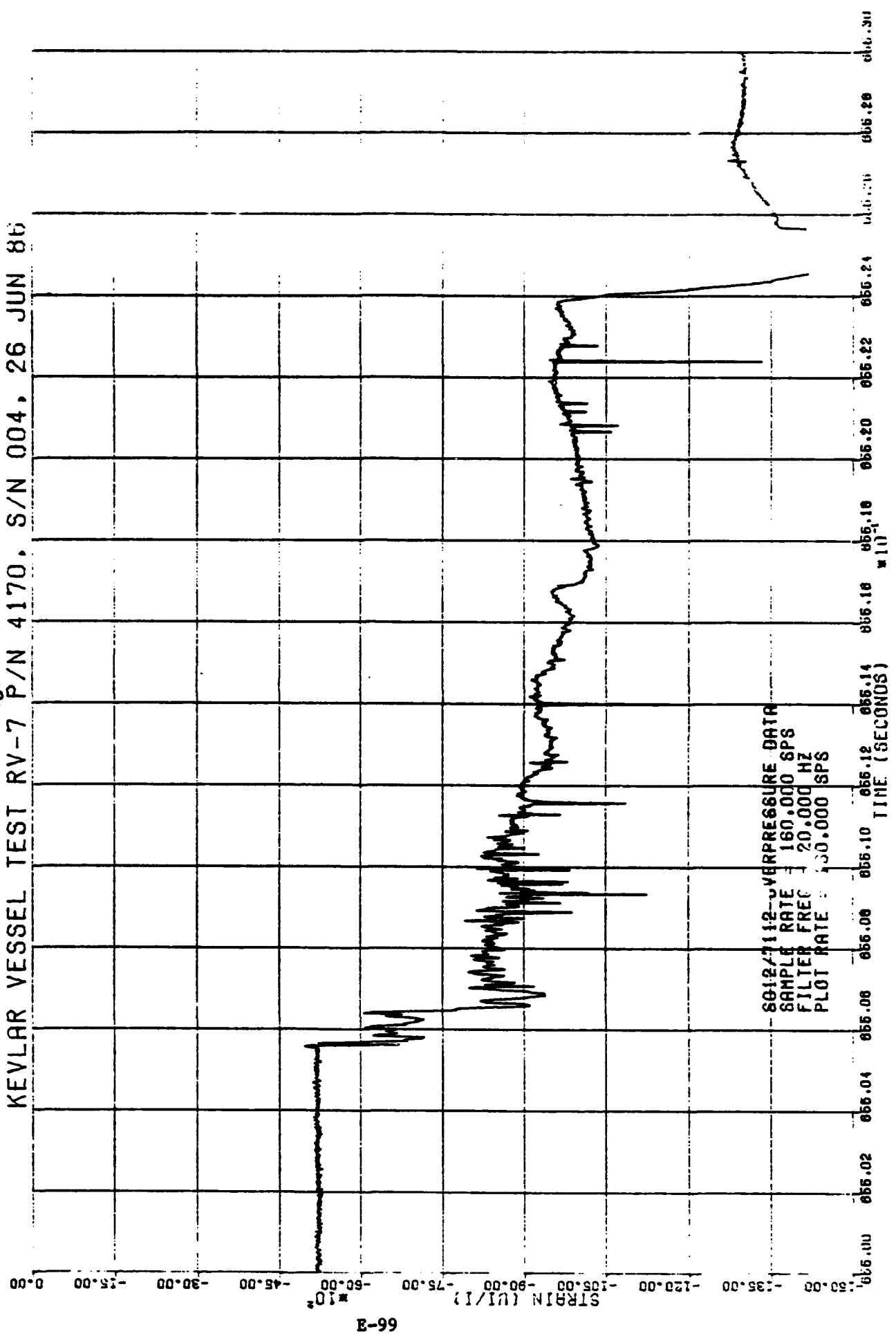
E-101

KEVLAR VESSEL TEST RV-7 P/N 4170, S/N 004, 26 JUN 86

Fig. B-43

SO16/7116 OVERPRESSURE DATA
SAMPLE RATE = 160,000 SPS
FILTER-FREQ = 20,000 HZ
PLOT RATE = 160,000 SPS

STRAIN (UI/1)

TIME (SECONDS)

E-102
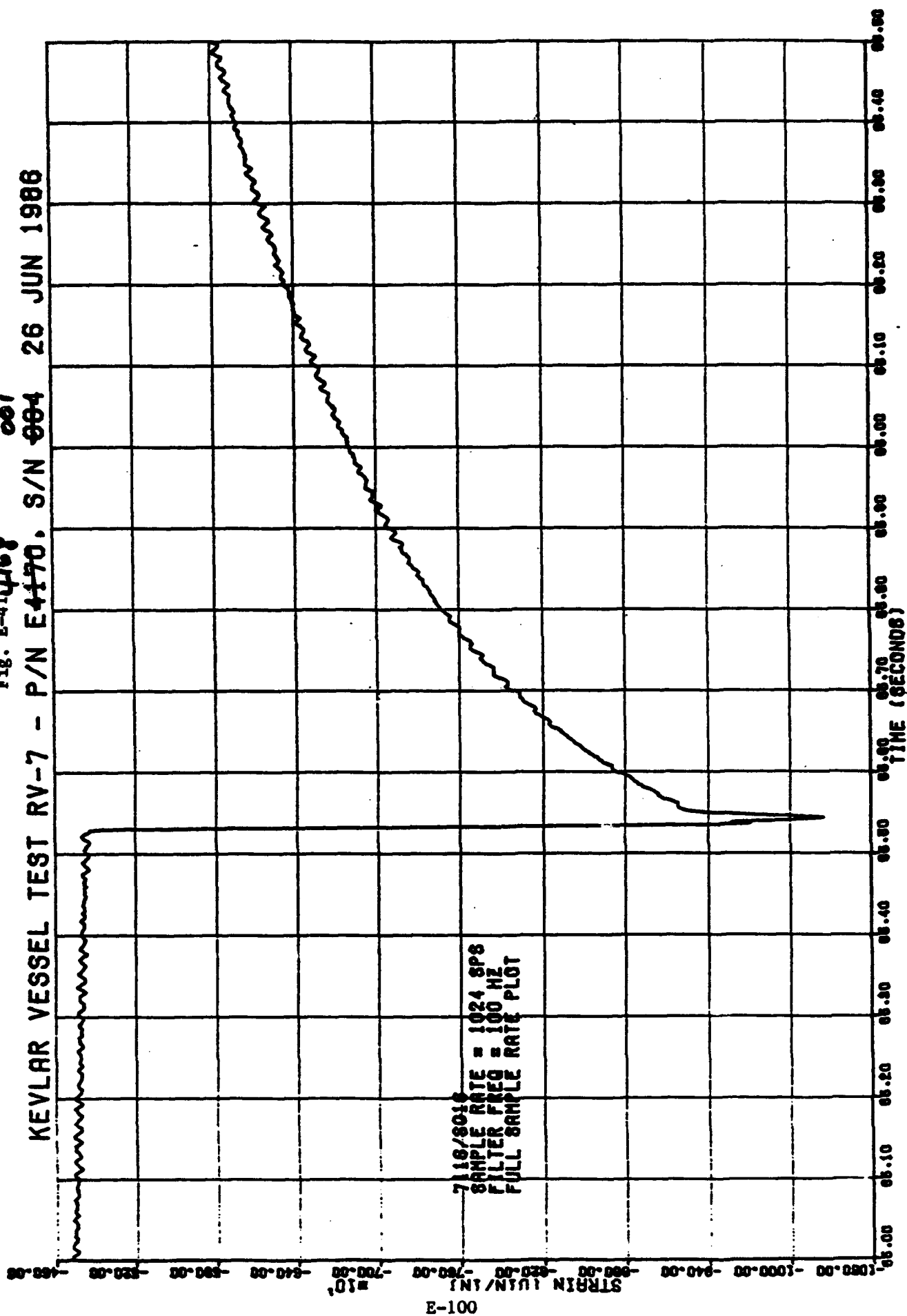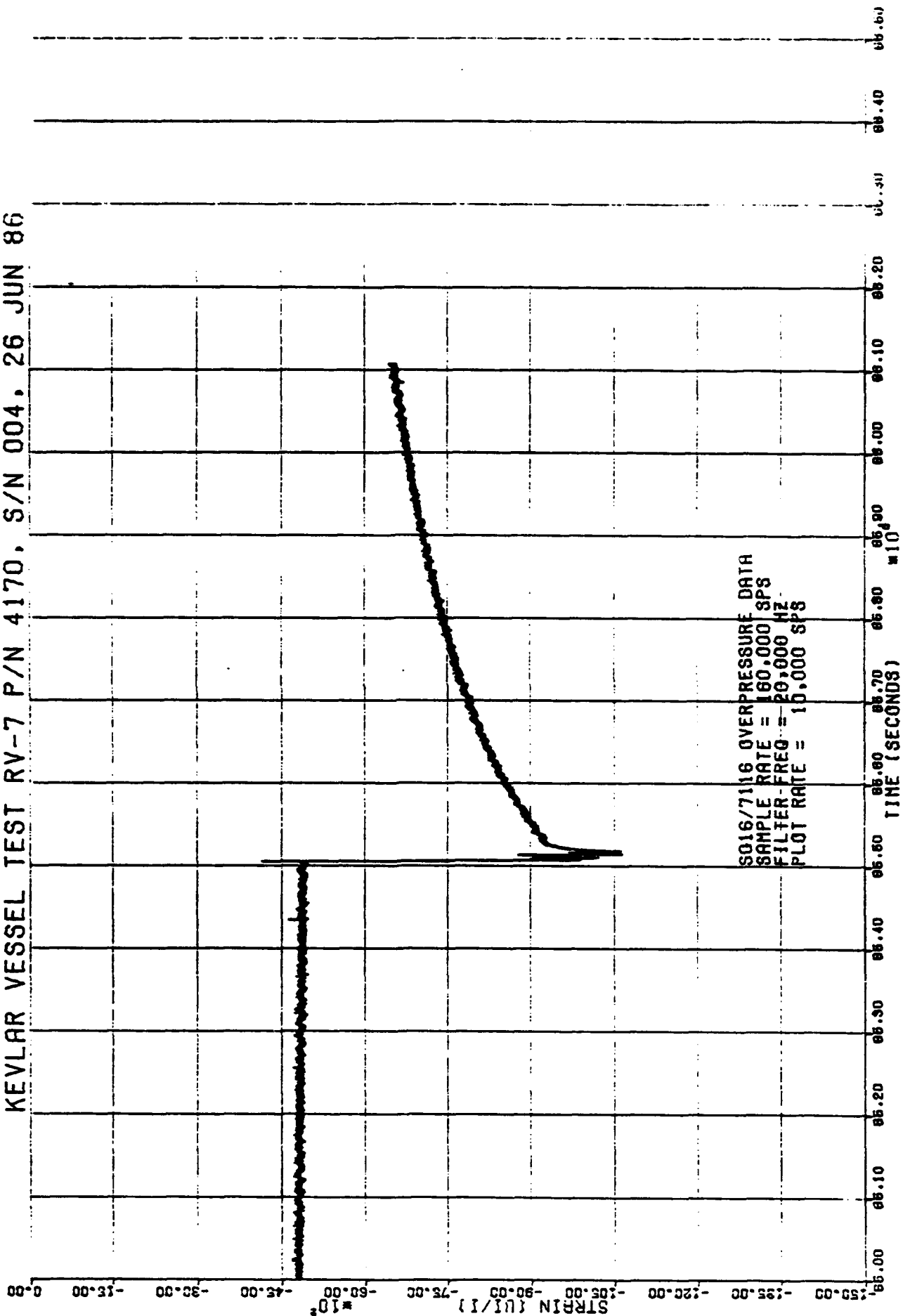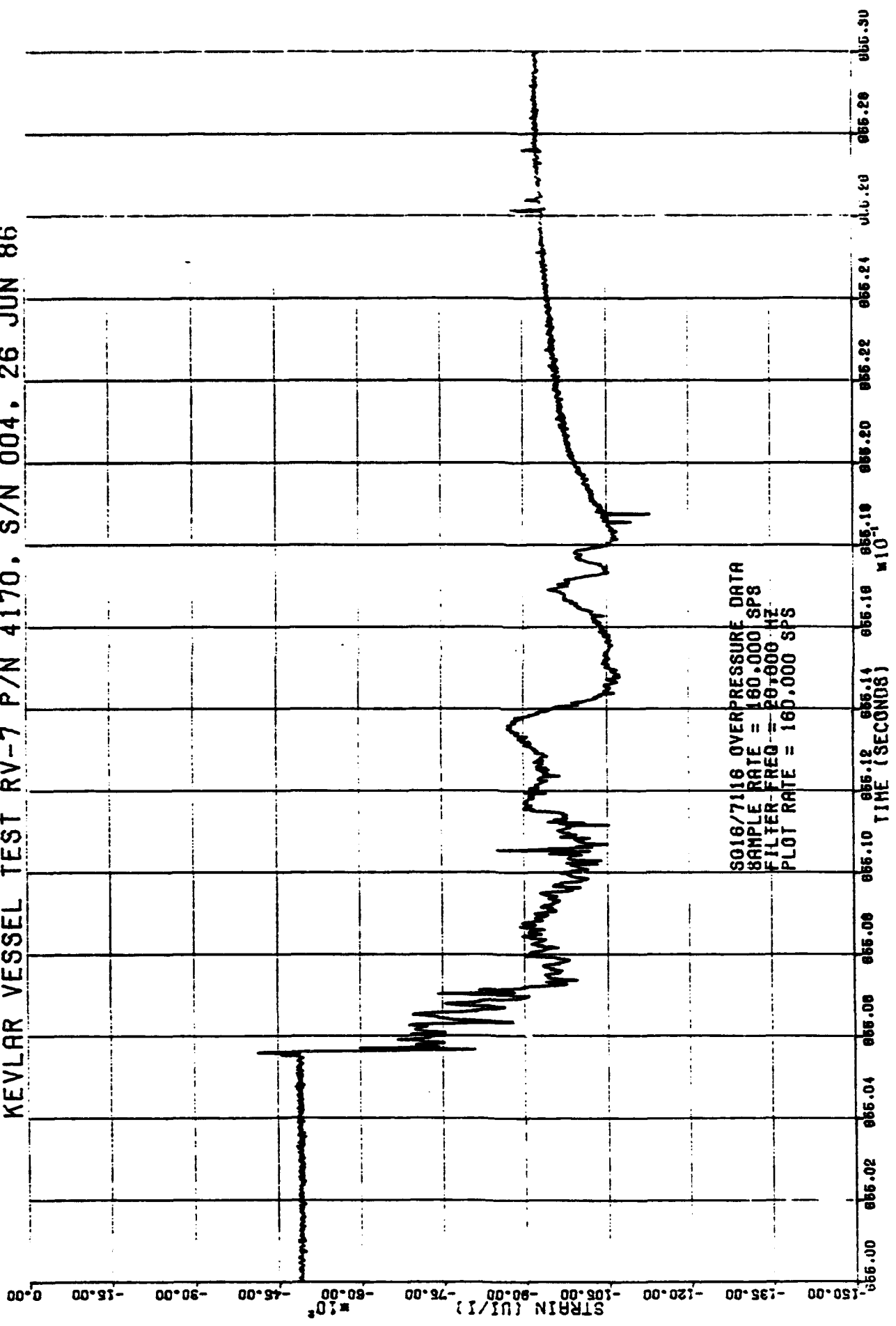
FIG. E-44
SKETCH, STRAIN GAGE MOUNTING
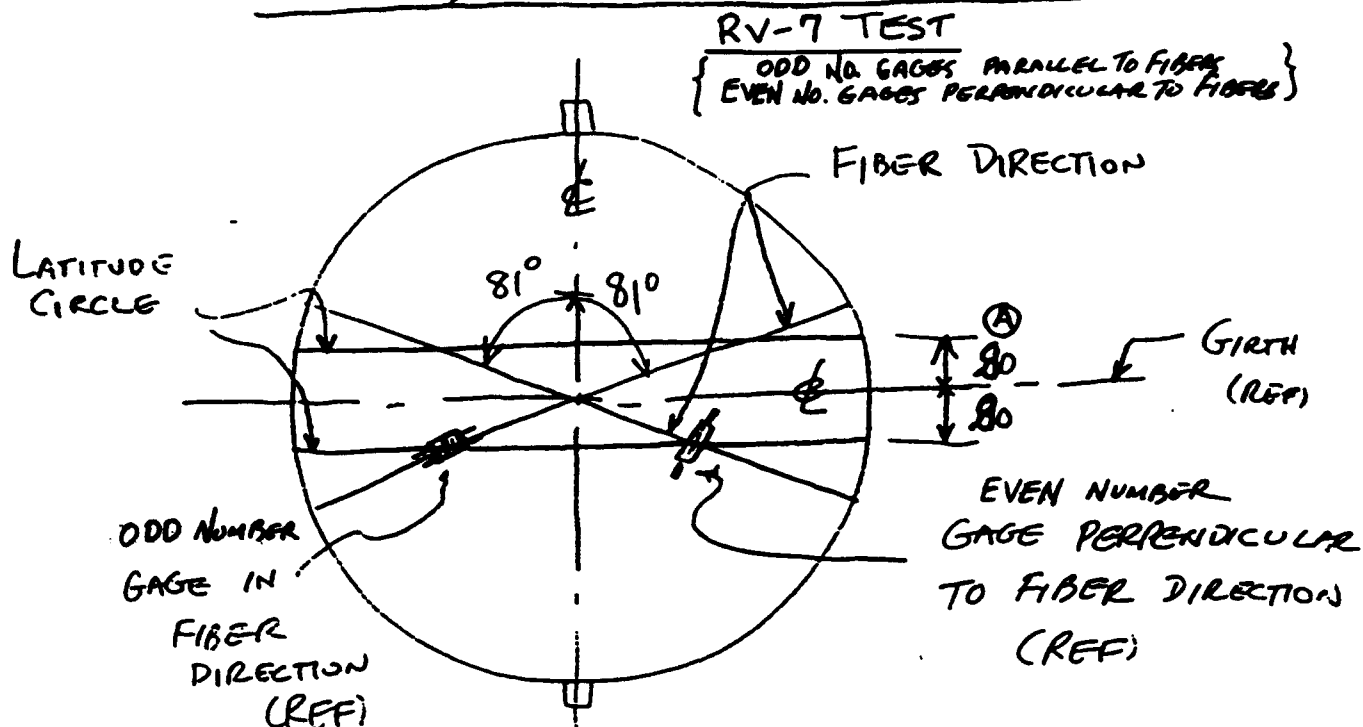
RV-7 TEST
{ ODD No. GAGES PARALLEL TO FIBERS
EVEN No. GAGES PERPENDICULAR TO FIBERS }

FIBER DIRECTION

LATITUDE CIRCLE

81° 81°

Ⓐ
.80
.80

GIRTH (REF)

EVEN NUMBER GAGE PERPENDICULAR TO FIBER DIRECTION (REF)

ODD NUMBER GAGE IN FIBER DIRECTION (REF)

MOUNT 6 PAIRS OF GAGES (1 EA OF EACH PAIR IN THE OUTER FIBER DIRECTION AND 1 EA PERPENDICULAR TO THE OUTER FIBER DIRECTION ON EACH LATITUDE CIRCLE) EQUALLY SPACED FOR A TOTAL OF 24 GAGES.

ARDE INC.
CONTRACT F0 8606-84-C-0029
J/N 42001-0-3
(REV A - .80 WAS .90)

E.5.4   Post Test Inspection

          After the test, the tank was first

inspected when it was still attached to the test

stand/instrumentation. The outer fiber shell of

the tank was completely intact with no evidence

of any metal liner pieces exterior to the tank.

Some outer surface fiber damage was observed as

seen in the post test photo of Figure E-45. The

vessel was removed from the test stand and cut

open away from and parallel to the girth weld by

AFAL. Continuous liner fracture around the girth

weld region was noted and one small (3/8")

triangular metal piece was missing, probably lost

through one of the fittings during the cutting

operation. The test tank was shipped to ARDE for

further inspection, where the liner inside

surface was die checked and another girth region

cut made parallel to the girth, producing a ring

of liner and fiber overwrap. The ring overwrap

was then severed, releasing its hoop restraint

and the metal liner ring separated into two rings

at the continuous circumferential crack adjacent
to the girth weld. The remaining portions of the
liner heads were then readily removed from the
fiber overwrap. The liner and fiber overwrap
pieces were photographed in detail.
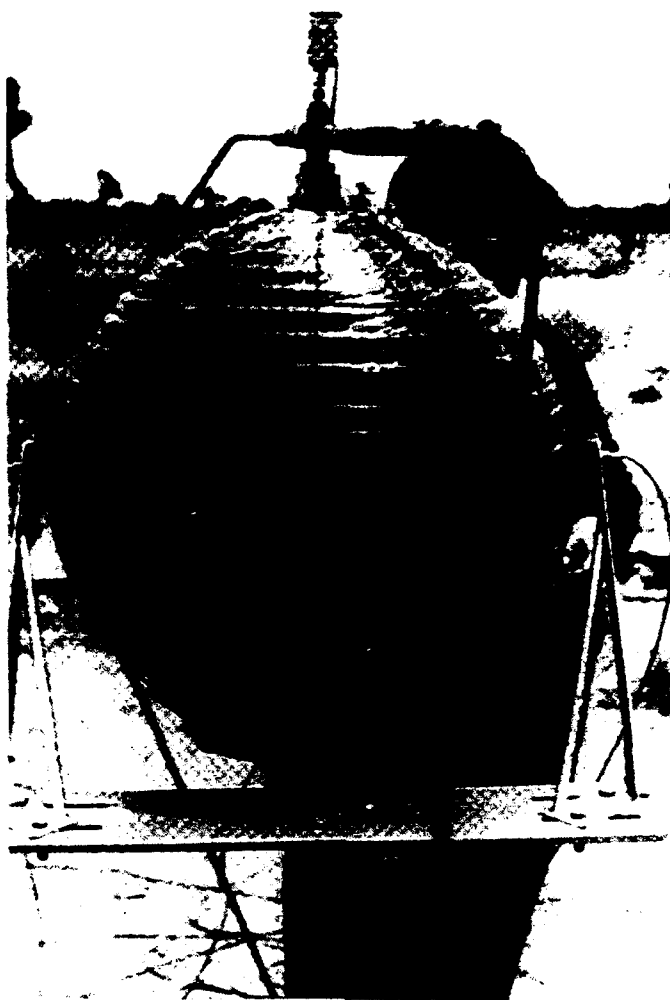
TEST RV-7, POST TEST VIEW OF TANK ON TEST STAND

Fig. E-45

Figures E-46 and E-47 show views of the continuous through girth cracks highlighted by die check of the cut tank inner liner surface as received from AFAL, prior to additional ring cut and fiber removal. Details of the continuously girth cracked liner ring and a view of the separated metal liner ring and heads are given on the photographs E-48, E-49, E-50 and E-51, respectively. The liner failure mode included a small loose girth ring fragment in addition to the two halves split at the girth. Views of the small fragment are shown on Figure E-55. Photographs of the removed fiber ring and head pieces are shown on Figures E-52 and E-53 which provide overall views of fiber damage. Whatever bonding that existed on the liner fiber interface was broken when the intentionally embrittled liner broke into two pieces, as evidenced by the ready removal of the overwrap and the photograph of the fiber wrap pieces inside surfaces as shown in E-54, as well as the smooth outer surfaces of the metal heads and ring (Figures E-49 to E-51).
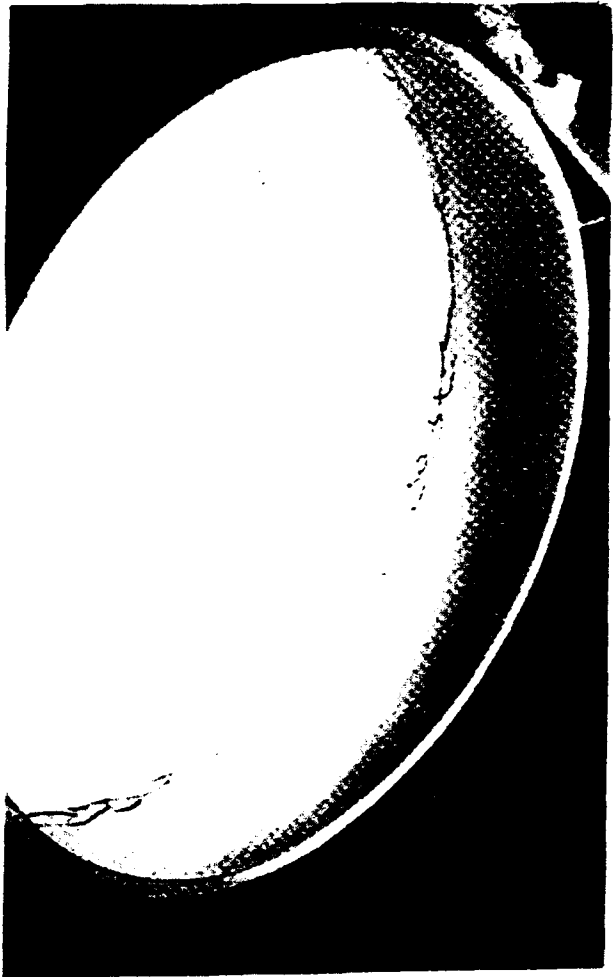
FIG. E-46 TEST RV-7, CONTINUOUS GIRTH CRACKS HIGHLIGHTED
BY DIE CHECK

FIG. E-48 TEST RV-7, CONTINUOUSLY CRACKED PERMITTED
GIRTH RING
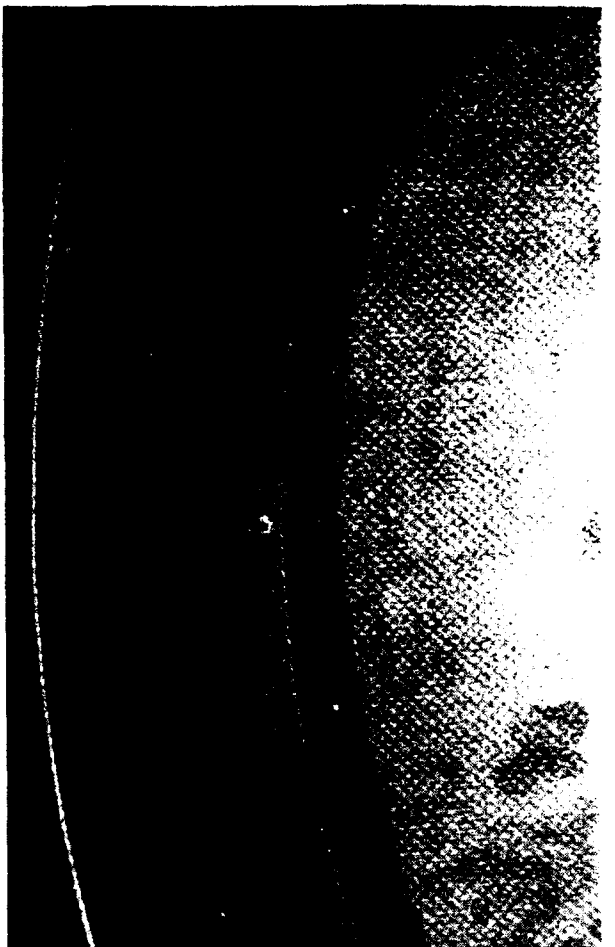
FIG. E-47 TEST RV-7, CLOSE UP OF CONTINUOUS GIRTH CRACKS
HIGHLIGHED BY DIE CHECK
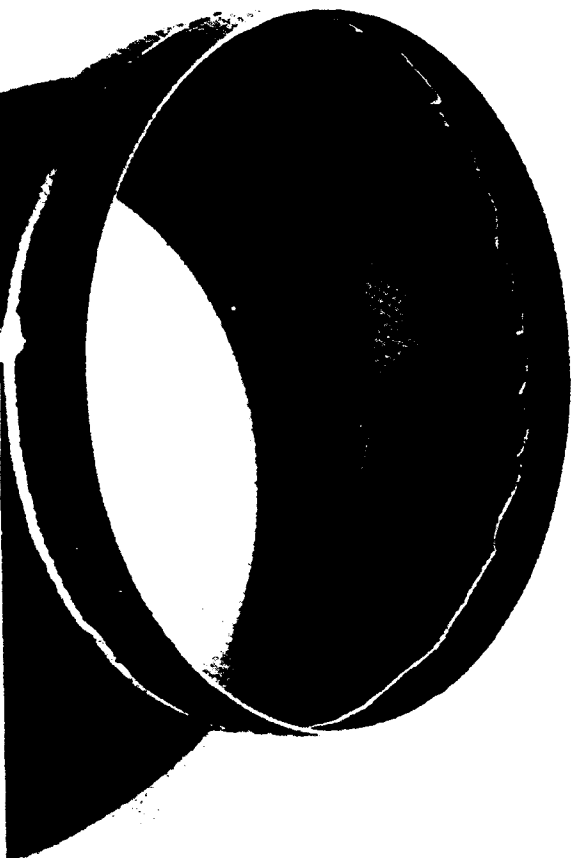
FIG. E-49 TEST RV-7, CONTINUOUSLY CRACKED PERMITTED
GIRTH RING

E-108

FIG. E-51 TEST RV-7, SEPARATED METAL RING AND HEADS

FIG. E-53 FIBER HEAD PIECES TEST RV-7, REMOVED FIBER HEADS

FIG. E-50 TEST RV-7 SEPARATED METAL RING

FIG. E-52 TEST RV-7, REMOVED FIBER GIRTH RING AND

E-109
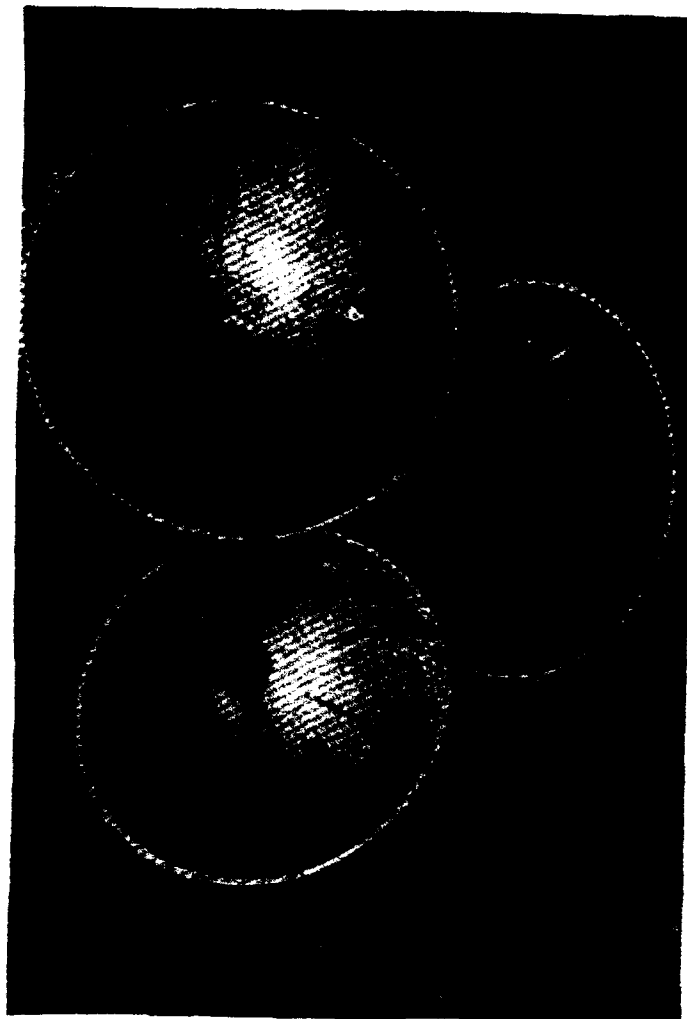
Fig. E-54 TEST RV-7, INSIDE VIEW, REMOVED FIBER HEADS
AND GIRTH RING
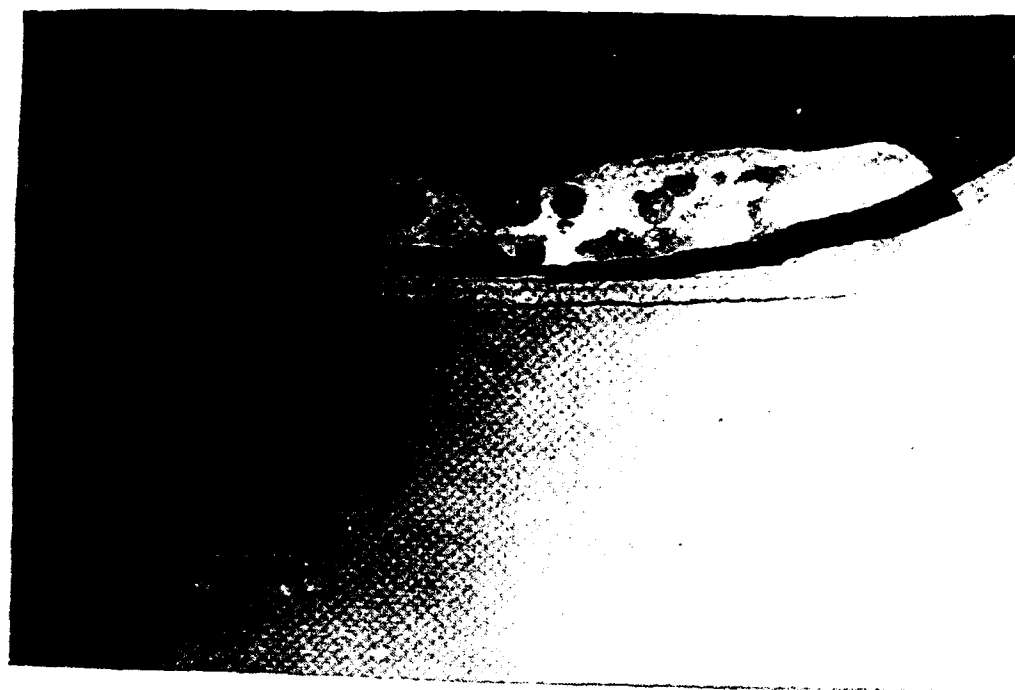
Fig. E-55 SMALL LOOSE LINER FRAGMENT

E.6   **RV-9 Test (16" ϕ PSC)**

E.6.1   **Test Vessel Description**

- P/N E4171, S/N 002 (Kevlar Overwrapped 301 CRYO
  CRES Composite Spheres)

- Kevlar Fiber (less resin) Average thickness —
  .154 (100% baseline thickness)

- Metal Thickness — .057/.050

- Inside Radius — 7.64

- Hydrogen Embrittlement Mode — Local Girth Weld
  Region

- Electrolyte Solution —

  $$\frac{20 \text{ cc } H_2S)_4 + 980 \text{ cc Tap } H_2O}{1000 \text{ cc Solution}}$$

- Solution Additive — 500 mg Sodium Arsenite

- Sensitize Liner Inside Surface (cold pickle)

- Charging Current Density — .021 amps/in^2 of
  surface to be embrittled

- Charging Time — 72 hours

- Hold Time Before Test — 3 hours

- Adcoat AC818T liquid maskant on areas not to be
  embrittled.

    Prior test photographs of the instrumented
tank in the wooden handling stand and a close up
of strain gages 11, 12, 13, 14 are shown on
Figures E-56 and E-57 of this section

Fig. E-56

TEST RV-9, INSTRUMENTED TANK IN WOODEN HANDLING

STAND

Fig. E-57

E-113   TEST RV-9, CLOSE UP OF STRAIN GAUGES 12 TO 14

E.6.2

INSTRUMENTATION OBSERVATIONS *(by AFAL Instr. Eng)*

KEVLAR TEST 009, 9OCT86. Project number 573000RV.

EXPERIMENTAL OBSERVATIONS.

Introduction. Vessel S/N 002, P/N E4171, was tested. It was a
16 inch diameter stainless steel sphere and · had a Kevlar
overwrap. The vessel was hydrogen embrittled about the girth for
about a 1 inch width. It was tested in a vertical configuration.
The tank pressure was increased with pressure pulses and ramps
until liner cracking occurred.

Pressurization Ramp. The vessel was pressurized with cool helium
gas. Initially, the pressure was increased from ambient pressure
to about 200 psig during a cool-down period, which took about 2
minutes.   During the next 32.3 seconds, pressure was increased
with a salvo of 19 small pulses and steps to a plateau, with an
average value of 1956 psig.   The plateau pressure was not
maintained; it started at 1973 psig and decayed slightly to 1940
psig over a period of 33 seconds.   After a 1.099 second long
pressure tansient, pressurization continued in a classical linear
ramp from 2244 psig to 3752 psig in 17.6 seconds (89.699226-
72.099138 seconds), which is a pressurization rate of 85.7
psig/second.   The vessel cracked following 17.6 seconds of ramp
time at 89.7 seconds.   The crack generated a sharply demarcated
depressurization profile.   The profile followed an exponential
decay, which was not distorted until one repressurization episode
was attempted at 23.2699452 seconds; repressurization failed, and
pressure could not be maintained above 1951 psig.   Total cool-
down and pressurization time was 203.999 seconds (120.000 +
32.300 + 33.000 +1.099 + 17.600 seconds).   Initial
depressurization rate was 1515 psig/second [|(2236-3752
psig)/(90.699720-89.699226 seconds)|].

Catastrophic Burst.   The vessel cracked at the end of the 17.6
second ramp time at 89.7 seconds with subsequent rapid pressure
loss; during depressurization, one repressurzation episode was
attempted.   During depressurization, prominent Kevlar fiber
pinging, within the audio spectrum, became noticeable, but the
pinging only lasted for about 2 minutes.   The Kevlar fiber
remained intact,   in general;   but some fiber fraying was
concentrated on the ends of the vesel near the bosses.

Post-run Inspection. After the test, the vessel was cut open by
AFRPL; the cut was made 3 inches away from the girth weld; seen
was a jagged, cirumferential crack near the girth weld.   Dye
penetration was not done at this time to identify any accompaning
fractures.   A more detailed examination was done in DEC86 at
ARDE.

Other Details.   After the post-run inspection, the parts were
shipped to ARDE. Acoustic emission was not used.

IMPRESSIONS FROM THE DIGITIZED FM DATA.

Strain Gages.

Location. The strain gages were located IAW ARDE drawing dated 29AUG86. The locations were concentrated near the bosses and the 4th wrap, although some were near the girth and the 13th wrap.

Evaluation of the Graphs.

Of the 23 strain gages recorded, the activities before, during and after the burst for 21 gages were compared; not compared were SG7, which opened immediately following burst and SG10, which was noisy. All 21 graphs started from reasonable noise floors (SG3 and SG23 were the slightly noisy), and each of 10 graphs (SG1, 2, 8, 9, 13, 15, 16, 17, 18, 21) progressed into a steady but short period of prominent oscillation, without offset, before making the transition to tension strain activity. The remaining 11 graphs made almost immediate transitions to tension strain, but some did so abruptly (SG4, 6, 14, 20, 22); and some did so with a little oscillatory activity modulating a noticeable slope (SG3, 5, 11, 12, 23) or smooth curve (SG19). The distribution of the nominal differential strain magnitudes is interesting; twelve of the 21 gages are close together between 2100 (SG12) and 3300 (SG2) microinches/inch; the other 9 gages are much more widely distributed between 3860 (SG17) and 7800 (SG9) microinches/inch; the 7800 value for SG9 is isolated and considerably higher than the other gages. These categories are subjective calls, and exhibit considerable variance because of interpretation; the trends, however, are apparent. Of unknown significance is the observation of just how the 10 oscillatory graphs started their oscillations; seven of the 10 started in the positive (compression) direction, and 3 of the 10 started in the negative (tension) direction. The oscillation is most clear on SG16, and the frequency is about 7000 Hz [7 cycles/(89.782-89.781 second)], which is close to the estimated 10,000 Hz resonance frequency of the composite structure discussed in test 5, Spike Theory #1.

The distribution of the 9 gages (SG 1, 4, 6, 9, 14, 15, 16, 17, 22) with the higher nominal differential strain values is biased as to location. Seven of the 9 gages are on the half of the vessel containing sections 1, 2, 3, 4, which are outlined by the grid lines used to locate the positions of the sensors. Also, out of 6 girth gages (SG4, 6, 12, 14, 20, 22) mounted perpendicular to the fiber (the weakest direction), 4 gages (SG4, 6, 14, 22) are in the high strain category; out of 6 boss gages (SG1, 7, 9, 15, 17, 23) mounted parallel to the fiber (the strongest direction), 4 gages (SG1, 9, 15, 17) are in the high strain category. Simply stated, the exiting gas at the girth failure could provide uniform stress to the girth area resulting in more strain in the weak direction, and the two vessel halves slamming into the wrap near the end bosses could provide nonuniform strain in the Kevlar with more strain in the fibers

2

trying to keep the end bosses together. Other speculations exist.

The activity on all channels starts betwen 44% to 66% of the time between 89.780 and 89.782 seconds. After activity following burst, 3 of the functioning graphs (SG2, 16, 18) return to above the initial condition, and the remaining 10 graphs (SG3, 5, 8, 9, 12, 13, 15, 17, 19, 21) stay below the initial condition.

An interesting paroxysm, appearing most prominent on SG18 between 89.788 and 89.790 seconds, may be related to inflection activity in the same time period on SG6, 8, 12, 16, 17, 20, 23. The phase shifts in time are probably related to gage location. The width relationships remain undefined and vague, and there may not be a correlation.

All gages had spikes.

Displacement Sensors.

Both displacement sensors worked. They remained noise free. DP1/8001 shows a displacement of about 87 mils and DP2/8002 shows a displacement of 127 mils. The start of activity correlated well with the strain gages. The 7000 Hz oscillation seen on the strain gages was not seen on the displacment gages. Much lower frequencies were seen on the displacement sensors, and the frequencies were not the same; DP1 had about 300 Hz and DP2 was noticeably lower – about 200 Hz. Good correlation exists between both graphs for the first 0.015 seconds following vessel fracture. After that, the frequencies are not the same, but the nominal trends are similiar. Only a couple of spikes were noticed on DP1.

Data Analyst's Comments. ITT, Richard M. Thomsen, 20NOV86, states:

DATUM ANOMALIES

Item PC1/1901 shows pressure spiking unlike previous tests. Item PVSOUT/1904 may show a better pressure trace.

Item SG24/7124 has four strain shifts during the pressrue ramp prior to burst.

FM ANOMALIES

No IRIG-B was recorded on the analog tape. The burst pulse recorded on SG1/7101 was used to synchronize the times of these gauges with the burst pulse recorded by the datum system for SG24/7124.

The recording started 42 seconds into the test.

3

SG7/7107 was noisey (sic). SG23/7123 looks bad until 72 seconds.
SG13, 14 and 16/7113, 14 and 16 show a spike at approximately 89
seconds. Several strain gauges showed strain level shifts during
the pressure ramp prior to burst.   SG 1,4,6,10,20,22 and
23/7101,04,06,10,20,22 and 23 went out completely at the burst.
SG2 and 14/7102 and 14 went out after the burst. SG8 and 11/7108
and 11 overranged during the burst spike."

FM HIGH FREQUENCY PROCESSING. ITT continues with comments dated
17DEC86.

"DIGITIZING PROCESS

Digitizing was done at 160,000 samples per second using a 20,000
Hz filter.   SG1 was recorded with each of the other items and
used as the time reference to sync the FM time scales. This time
scale was referenced to that recorded by the DATUM system,
synchronizing the burts recoreded (sic) for SG1 on the FM and
SG24 on the DATUM (89.78301).

DATA ANOMALIES

Most of the strain gauges show spiking at the burst. Some of the
spikes occur at the same time on different gauges.   Note the
spikes at 89.7861 and 89.7892 seconds for SG1 and 2   SG3 has
periodic noise spikes every millisecond. SG7 has a complex noise
signal with a frequency of 120 Hz.   SG8 overrages at the burst.
The following items go out at [following] the burst: SG1, 4, 6,
10, 11, 14, 20, 22 and 23." End of ITT text.

IMPRESSIONS FROM THE QUICK-LOOK AND DIGITAL DATA ACQUISITION
SYSTEM DATA.

Tank Pressure. The tank pressure functioned as described under
the Pressurization Ramp paragraph.

PVSOUT/1904 is the vessel output pressure, but it is located near
the vent valve about 15 feet from the vessel.   This parameter's
behavior is smoother than 1901, which is subject to interference
from the line pressurization activity as discussed in TESTRV8.
Note the differences between 1904 and 1901; the pulses do not
reach 1904, the 1.099 second long transient at 70.999866 seconds
on 1901 doesn't appear on 1904, and neither does the transient at
the beginning of the repressurization effort at 232.699452
seconds.   In some respects, 1904 may be more interesting than
1901 because it is 94 psig higher than 1901 at rupture, although
some of this difference is probably due to transducer error; 1901
could be in error by 37.5 psig (.5%X7500 psig) and 1904 could be
in error by 60 psig (0.5%X12000 psig), but it is unlikely both
errors would compound one another in the opposite direction at
the same time.

DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE. An undated ARDE embrittlement procedure was followed; only the girth area for a width of about 1 inch was embrittled. Embrittlement was inhibited, where required, with a maskant. Embrittlement was started at 0915 hours on 6OCT86. The current level was 0.65 amperes. Seventy-two hours of embrittlement were completed at 0915 hours on 9OCT86; the tank was immediately moved from the shop embrittlement area to the test site, instrumented, hooked up and tested at 1210 hours on 9OCT86. The electrolyte was sulphuric acid; sodium arsenite was added as an enhancer.

ADMINISTRATIVE INFORMATION.

Revision Record. Initial Issue: 17SEP86. Revision A: 2DEC86; Pressurization ramp description and embrittlement procedure completed. Revision B: 14JAN87; text added: Evaluation of the Graphs, Displacement Sensors, Data Analyst's Comments.

Filename: testrv9.

Distribution.   ARDE, Steve Berko, Dave Gleich
                           PI, Dr. Pius Chih Hsu Chao
                           Aerospace Corp., Dr. Yen Pan
                           AFRPL, Jim Miller, Mike Dieckhoff, Dick Grove
                                   MSgt Jim Day, John Marshall, Capt
                                   Seidemann
                           ITT, Richard Thomsen, Dr. Tae-Woo Park
                           PAFB, Pete Tadie

Office of Primary Responsibility. USAF/AFRPL/TOAE/Edwards CA 93523.

6

E.6.3   <u>Pressure and Strain Versus Time Plots</u>

Figures E-58 and E-59 give test pressure versus time graphs. Key strain versus time plots are given on Figures E-60 to E-69 for sample rates of 1000 and 160,000 SPS, filter frequencies of 100 and 160,000 Hz and plot rates of 1000, 80,000 and 160,000 SPS. Strain gages were located in the apex and girth regions on the 23° and 81° fiber wraps as detailed in Figures E-70 and E-71. Odd number gages were parallel to the fibers and even numbered gages were perpendicular to the fibers.

E-120

RUN RV 9

Fig. E-58

TTME (SEC) min

1901 #10⁴

AFRPL VESTEST 573000RV RUN RV 9

Fig. E-59

E-122

Fig. E-60

KEVLAR VESSEL TEST RV-9 - P/N E4171, S/N 002   9 OCT 1986

801/7101
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 1000 SPS

TIME (SECONDS)
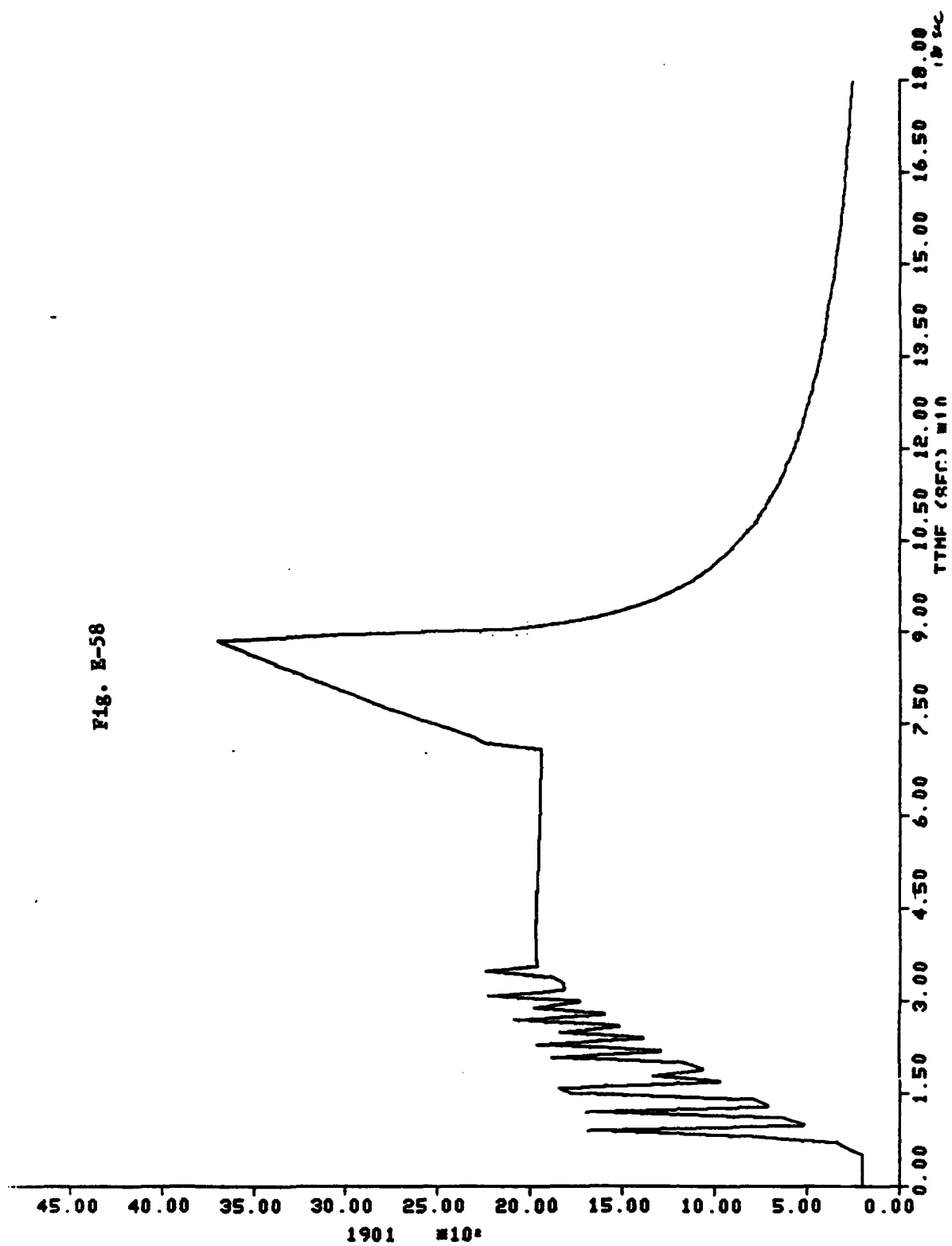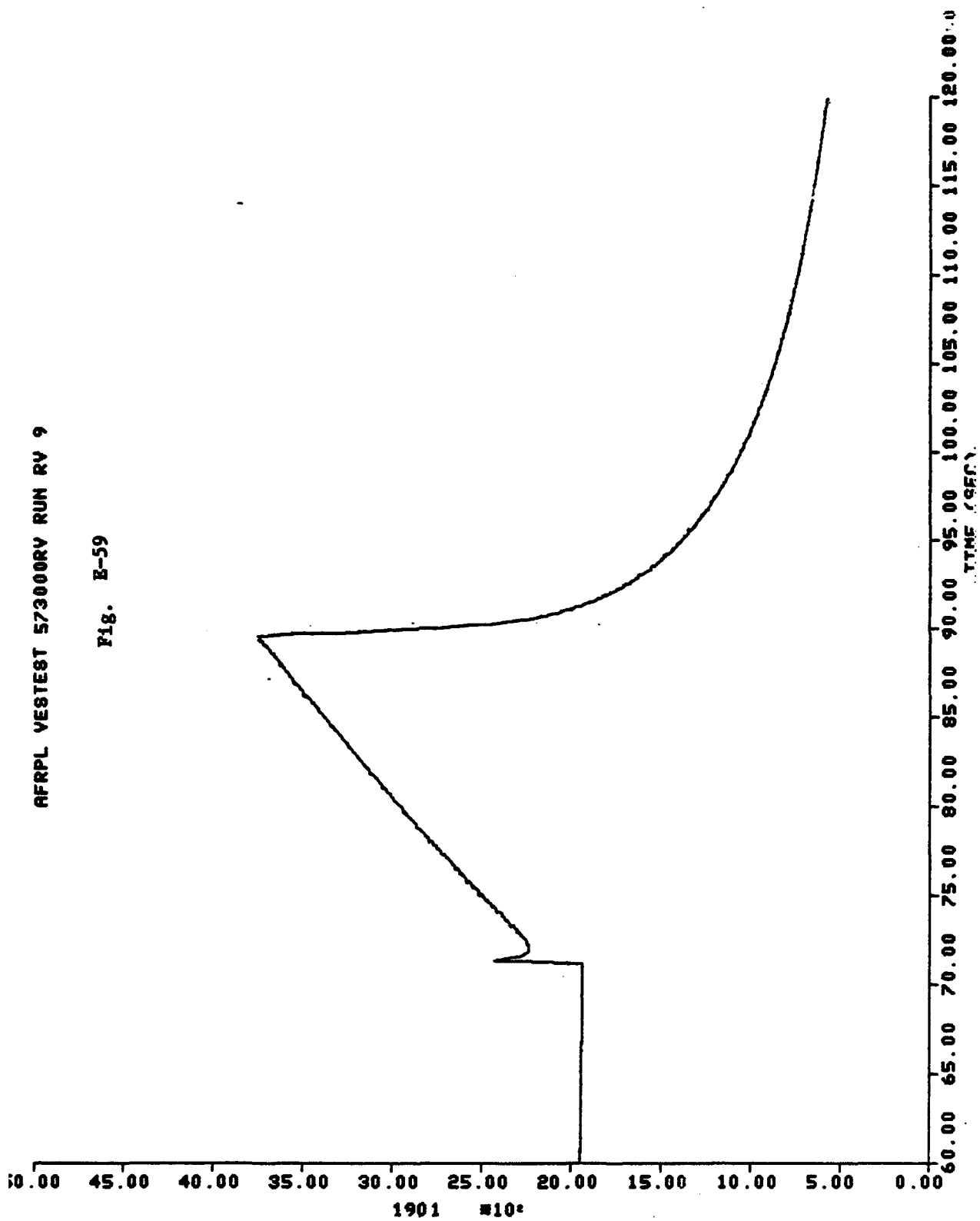
STRAIN (UIN/IN) $\times 10^6$

Fig. E-61

KEVLAR VESSEL TEST RV-9 — P/N E4171, S/N 002   9 OCT 1986
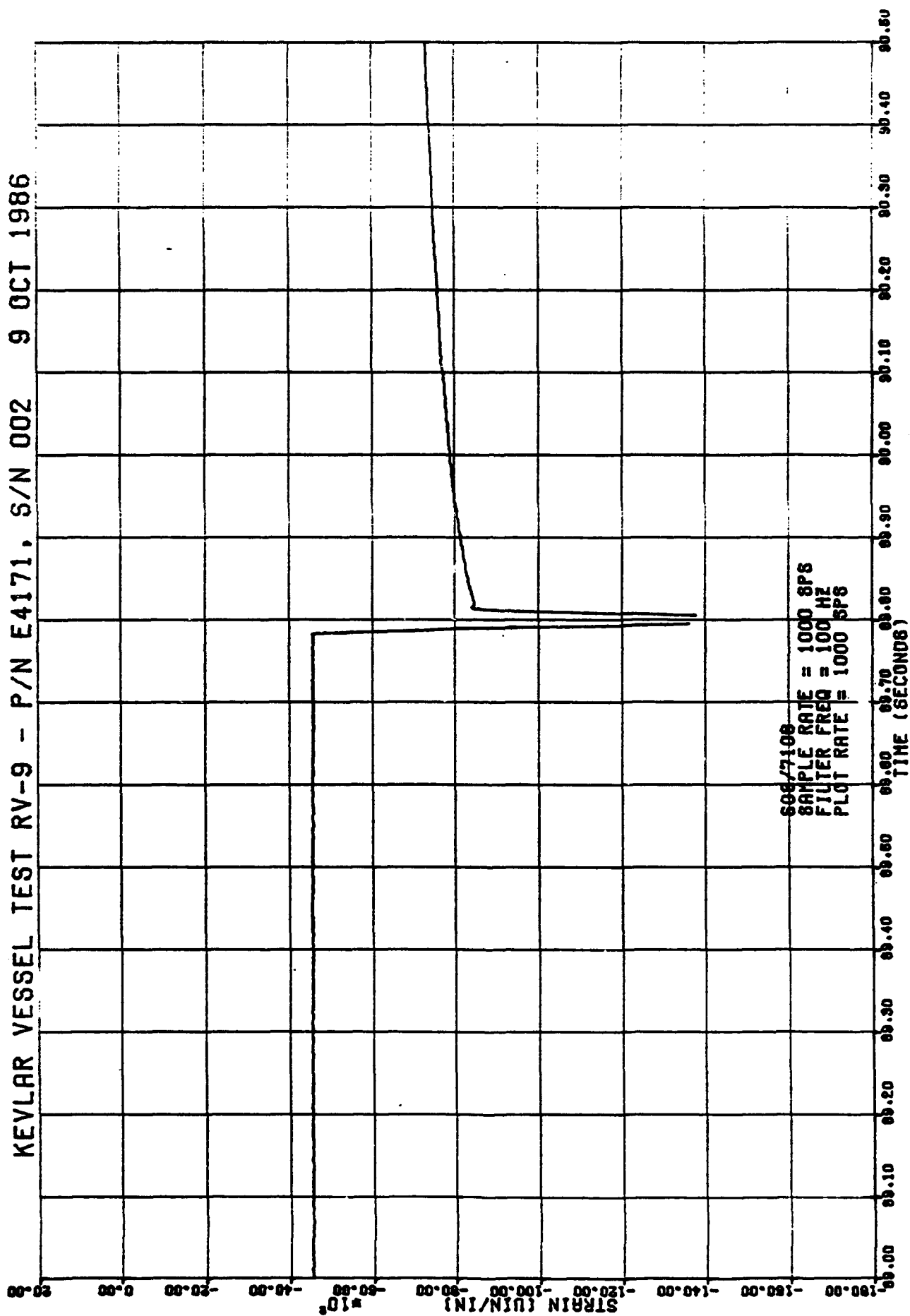
606/7106
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 1000 SPS

TIME (SECONDS)

STRAIN (UIN/IN) $\times 10^3$

Fig. E-62

KEVLAR VESSEL TEST RV-9, P/N 4171, S/N 002, 9 OCT 86

SO8/7108
SAMPLE RATE = 160,000 SPS
FILTER FREQ = 20,000 HZ
PLOT RATE = 80,000 SPS

E-125

Fig. B-63

KEVLAR VESSEL TEST RV-9, P/N 4171, S/N 002, 9 OCT 86

809/7108
SAMPLE RATE = 160.000 SPS
FILTER FREQ = 20.000 HZ
PLOT RATE = 160.000 SPS

STRAIN (U)/I

TIME (SECONDS)
x10⁻¹

E-126

Fig. E-64

KEVLAR VESSEL TEST RV-9 – P/N E4171, S/N 002   9 OCT 1986

E-127

Fig. E-65

KEVLAR VESSEL TEST RV-9, P/N 4171, S/N 002, 9 OCT 86

809/7109
SAMPLE RATE = 160.000 SPS
FILTER FREQ = 20.000 HZ
PLOT RATE = 80.000 SPS

TIME (SECONDS)

STRAIN (UI/I)

E-128

Fig. E-66

KEVLAR VESSEL TEST RV-9, P/N 4171, S/N 002, 9 OCT 86

808/7109
SAMPLE RATE = 160.000 SPS
FILTER FREQ = 20.000 HZ
PLOT RATE = 160.000 SPS

TIME (SECONDS)

STRAIN (UI/1)

Fig. E-67

KEVLAR VESSEL TEST RV-9 — P/N E4171, S/N 002   9 OCT 1986

8010/?110
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 1000 SPS

TIME (SECONDS)

STRAIN (UIN/IN) =10⁴
E-130

Fig. E-68

KEVLAR VESSEL TEST RV-9, P/N 4171, S/N 002, 9 OCT 86

8010/7110
SAMPLE RATE = 160,000 SPS
FILTER FREQ = 20,000 HZ
PLOT RATE = 80,000 SPS

STRAIN (UI/1) ×10²

TIME (SECONDS)

E-131

Fig. E-69

KEVLAR VESSEL TEST RV-9, P/N 4171, S/N 002, 9 OCT 86

ARDE INC. RV9

PAGE 1 of 2
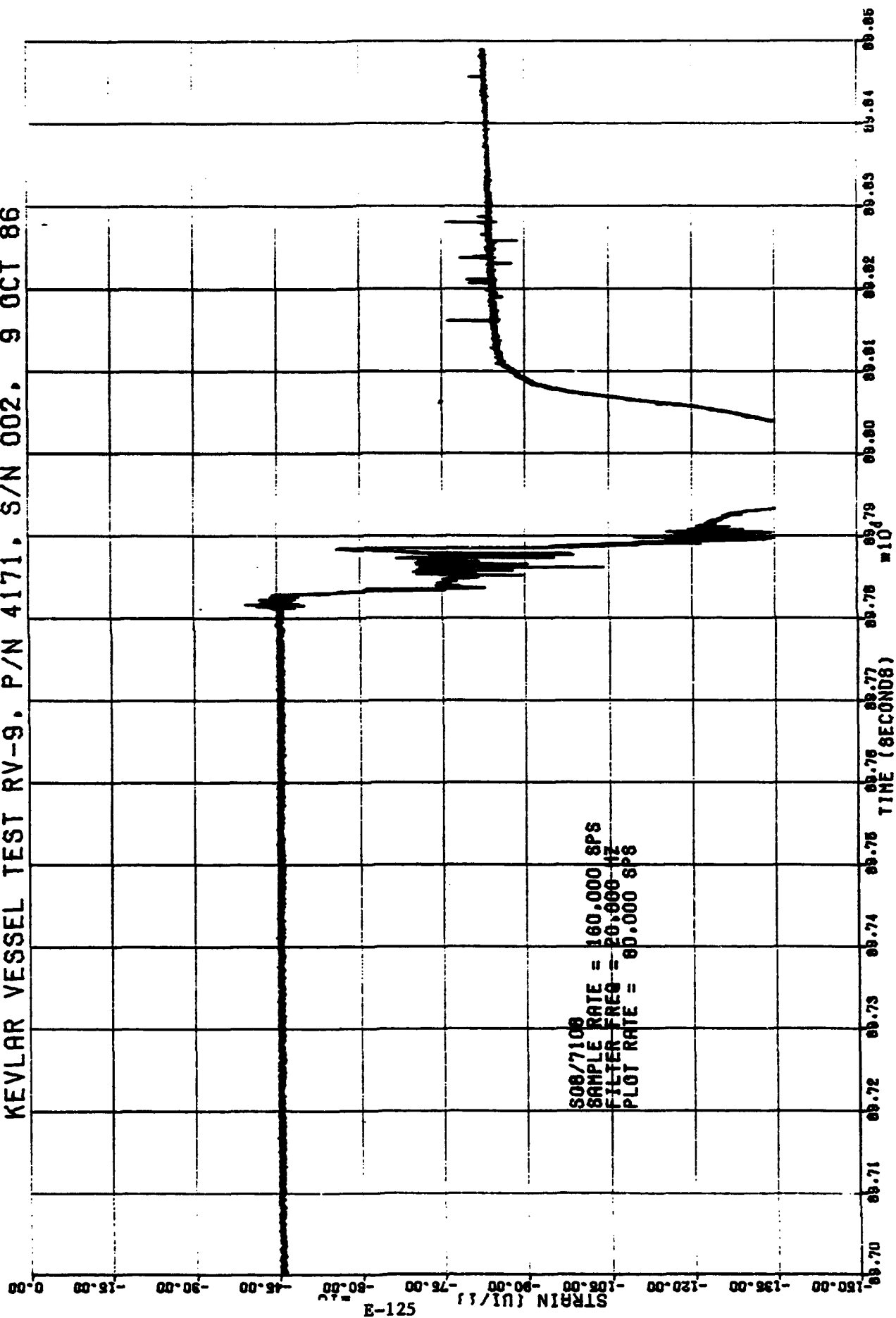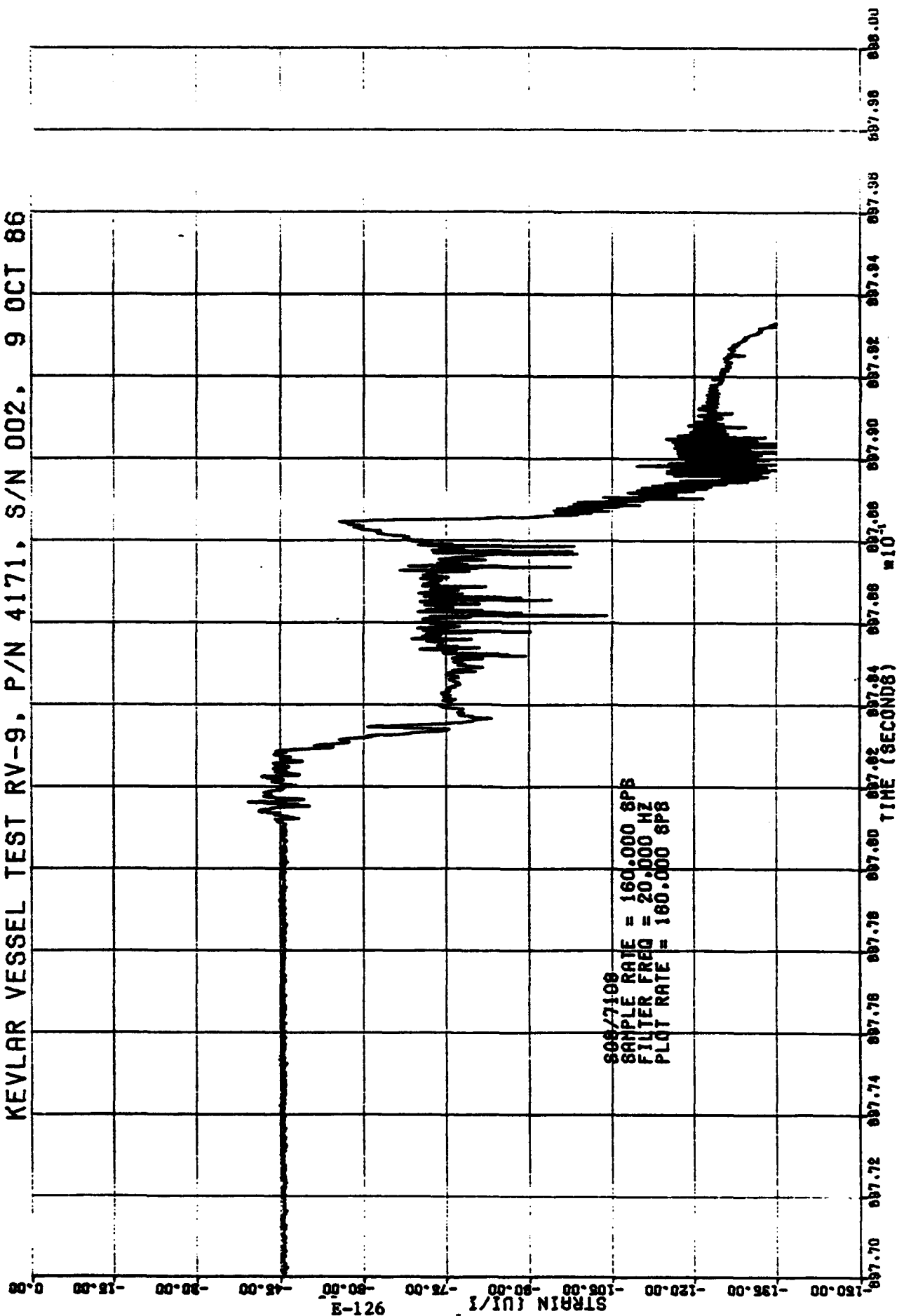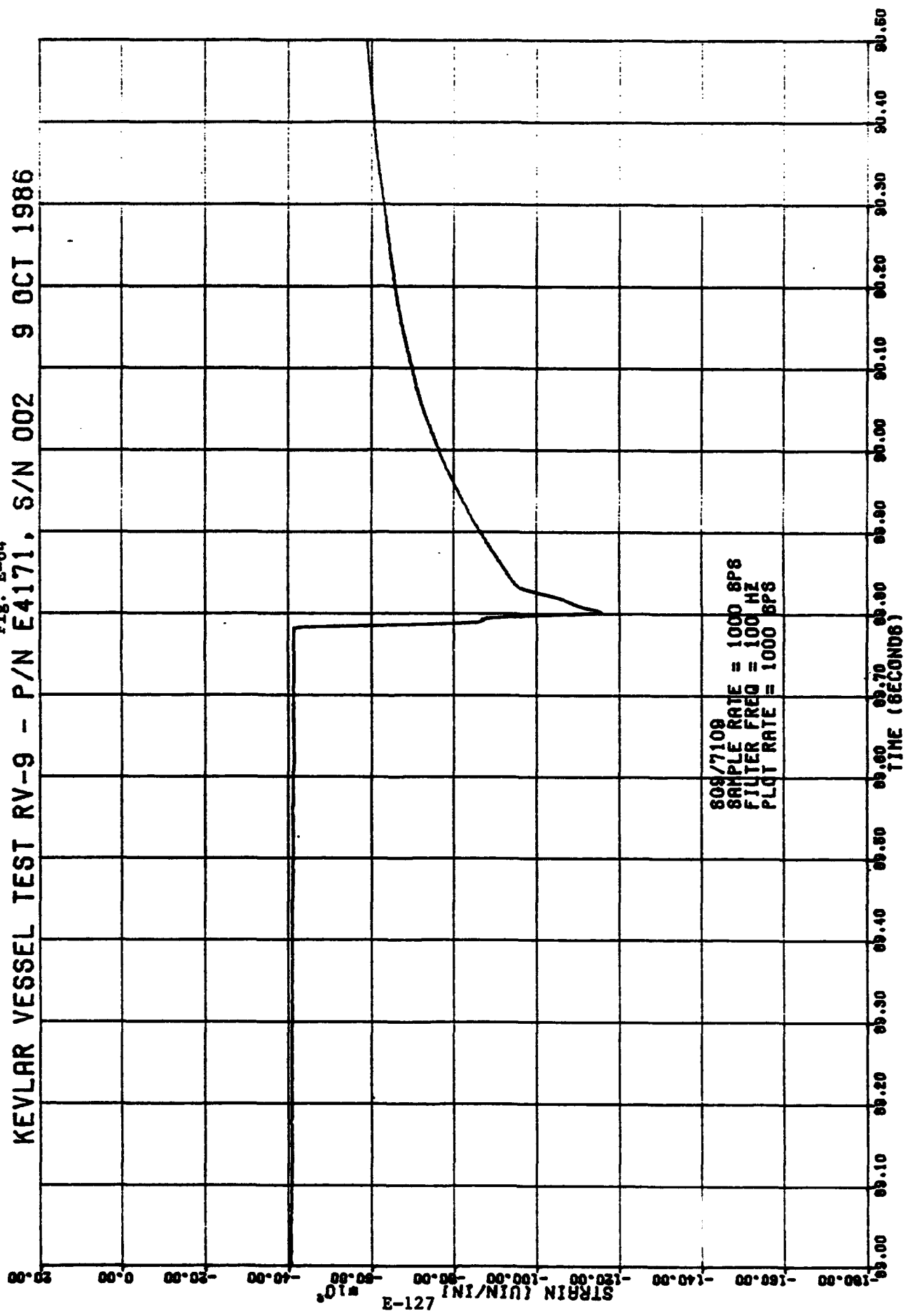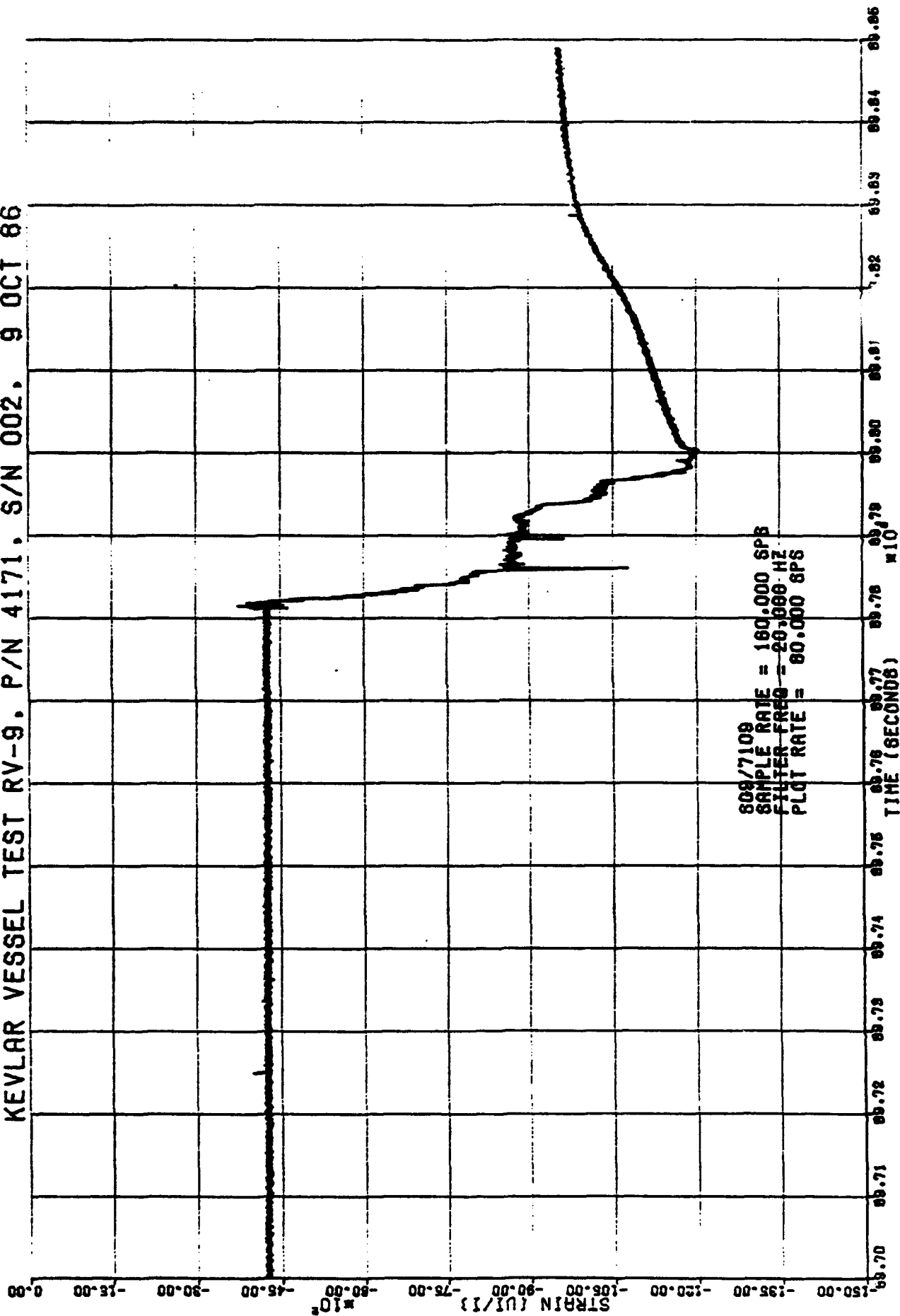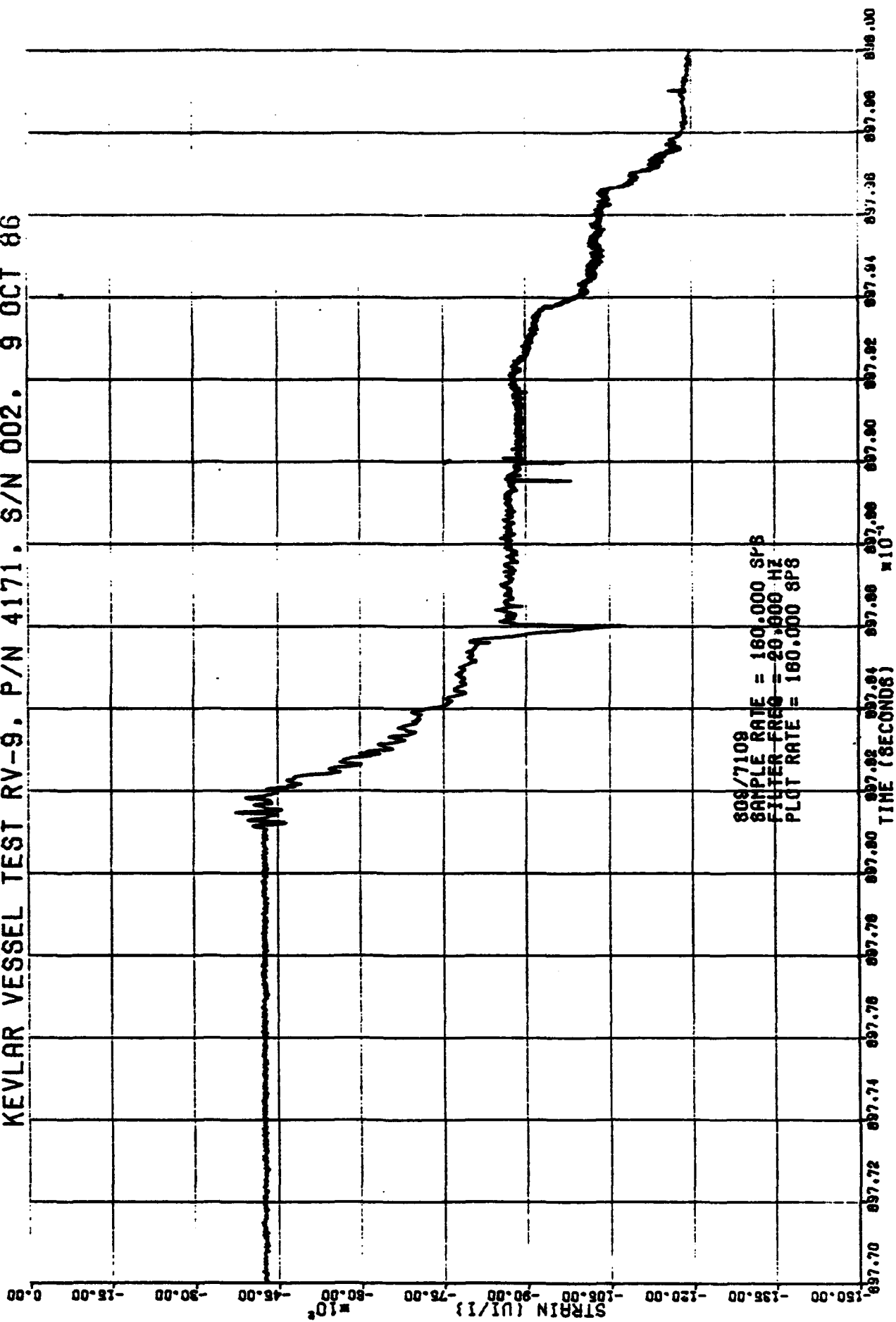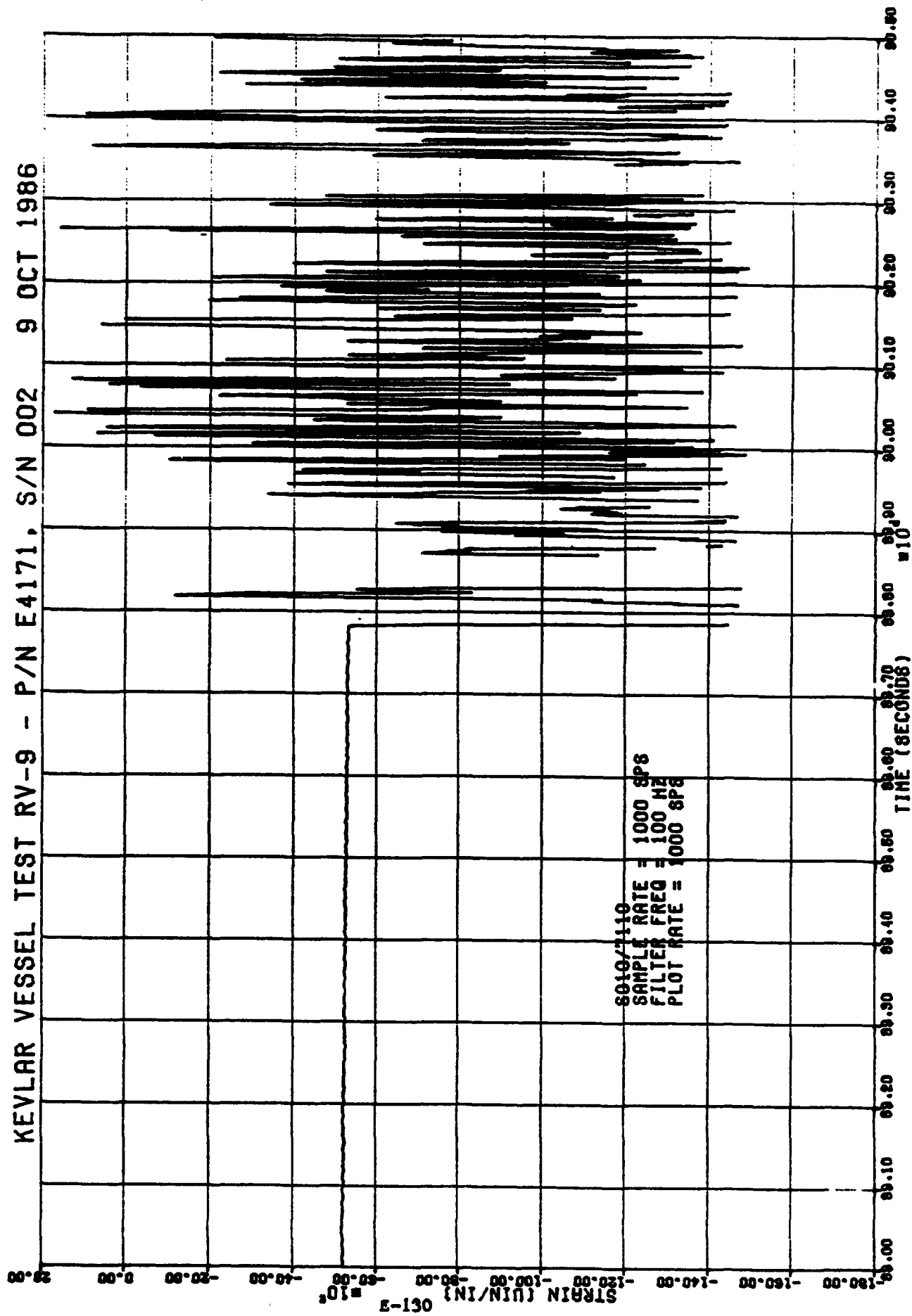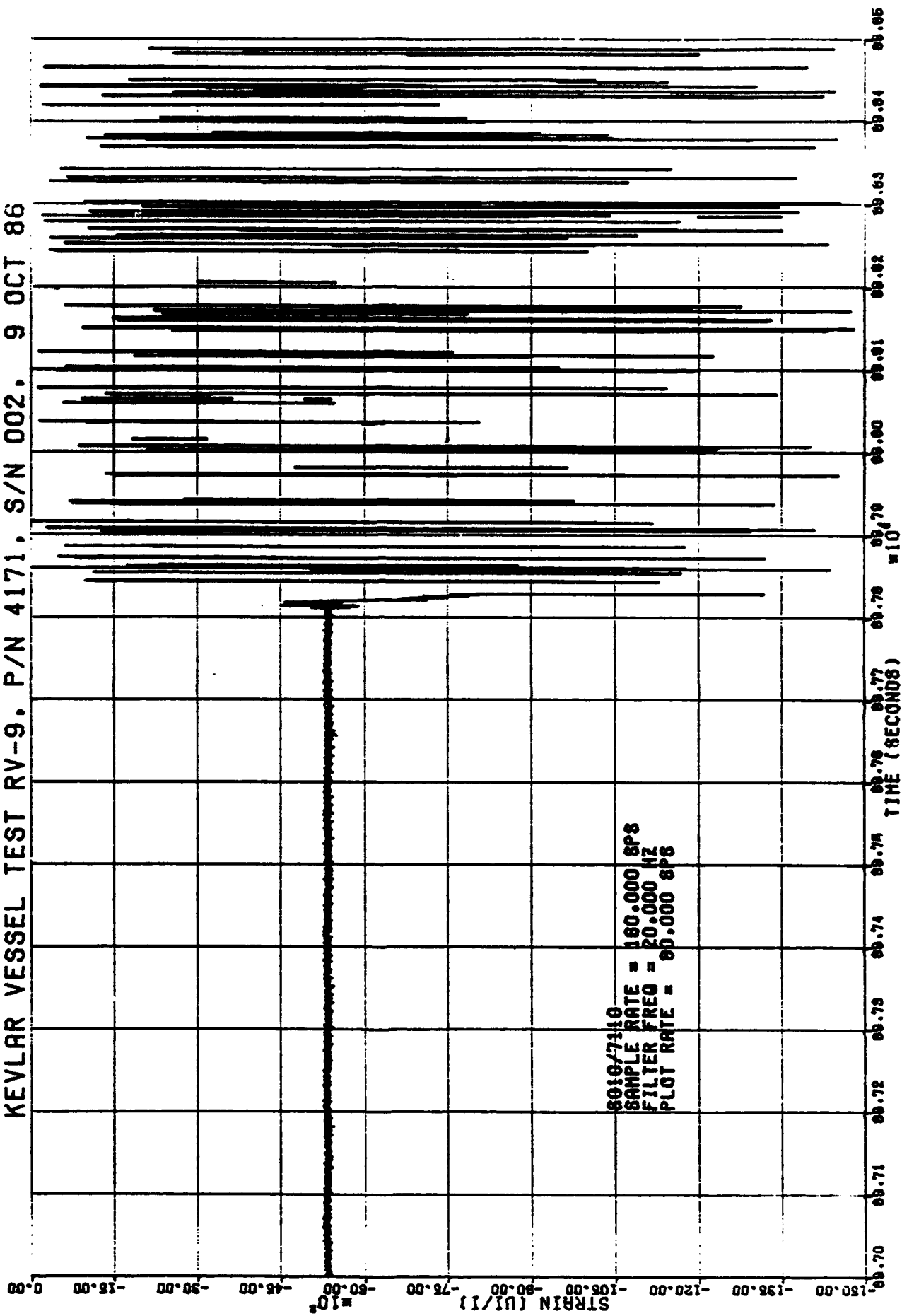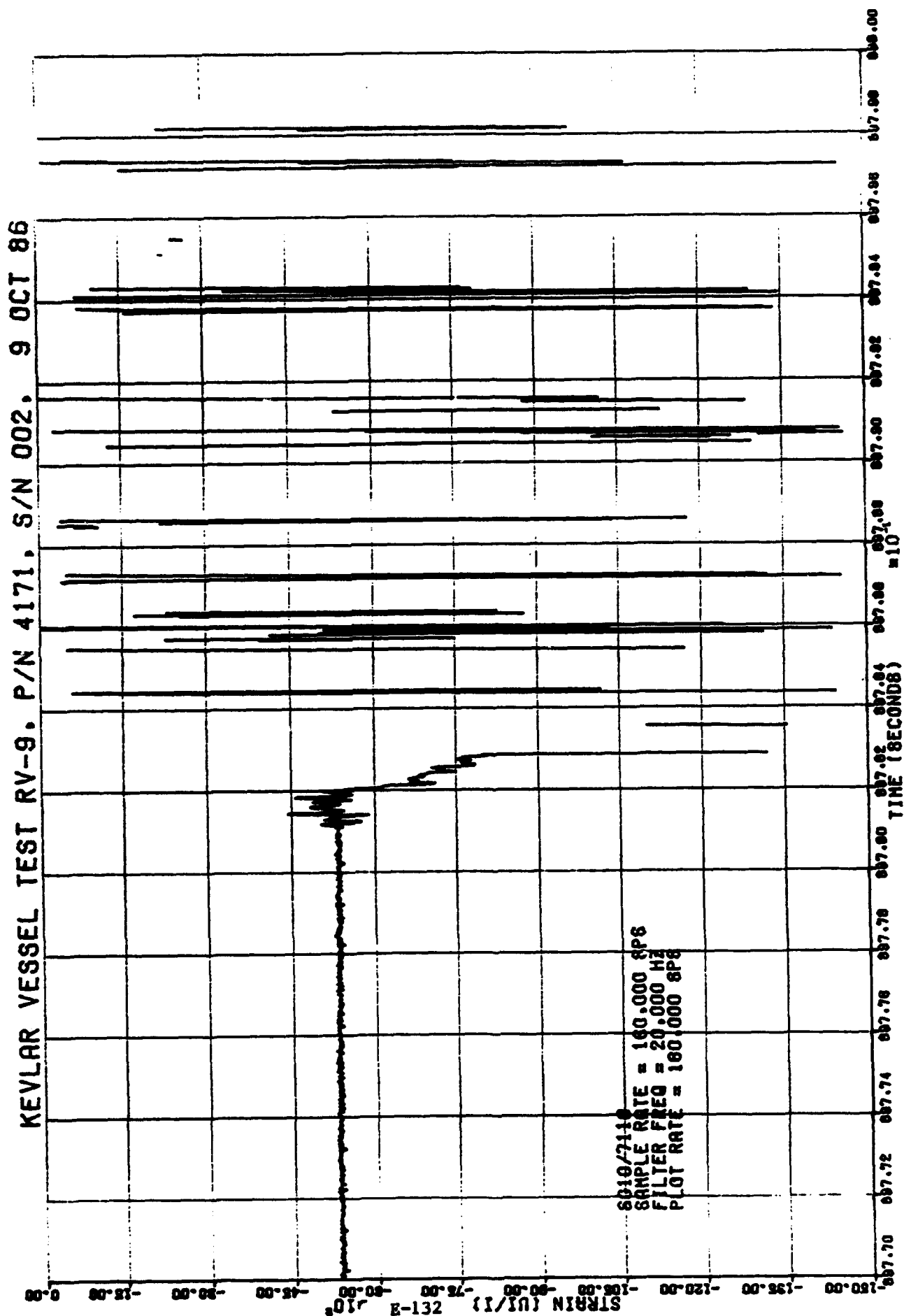
REPORT NO.

JOB NO. 42001

PREPARED BY SmB

DATE 29 Aug 86

P/N E4171 S/N 002 STRAIN GAGE LOCATIONS

ODD GAUGE N^os = PARALLEL TO SURFACE FIBER DIRECTION

EVEN = PERPENDICULAR

MS 33649-8 SIDE

GRID LINES

SECTION N^os
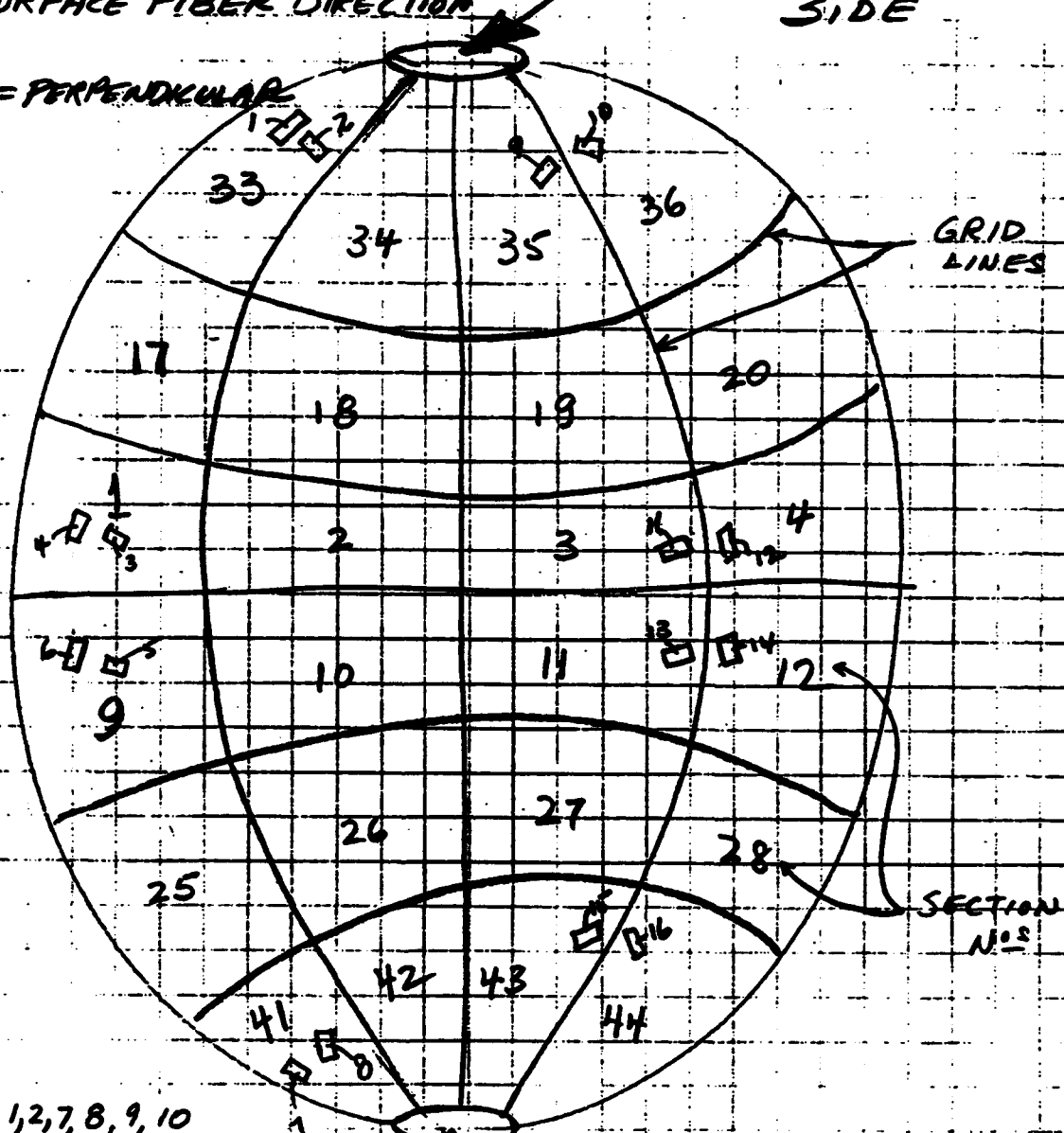
GAUGES 1, 2, 7, 8, 9, 10
15, 16, 17, 18, 23, 24
ON 4TH WRAP (23.55° ⌀)

GAUGES 3, 4, 5, 6, 11, 12
13, 14, 19, 20, 21, 22 ON 13TH (FINAL) GIRTH WRAP NEAR EDGES
(81° ⌀)

MS 33649-6 SIDE

FIGURE E-70

P/N E4171 S/N 002 STRAIN GAGE LOCATIONS

ODD GAGE No's PARALLEL TO FIBERS
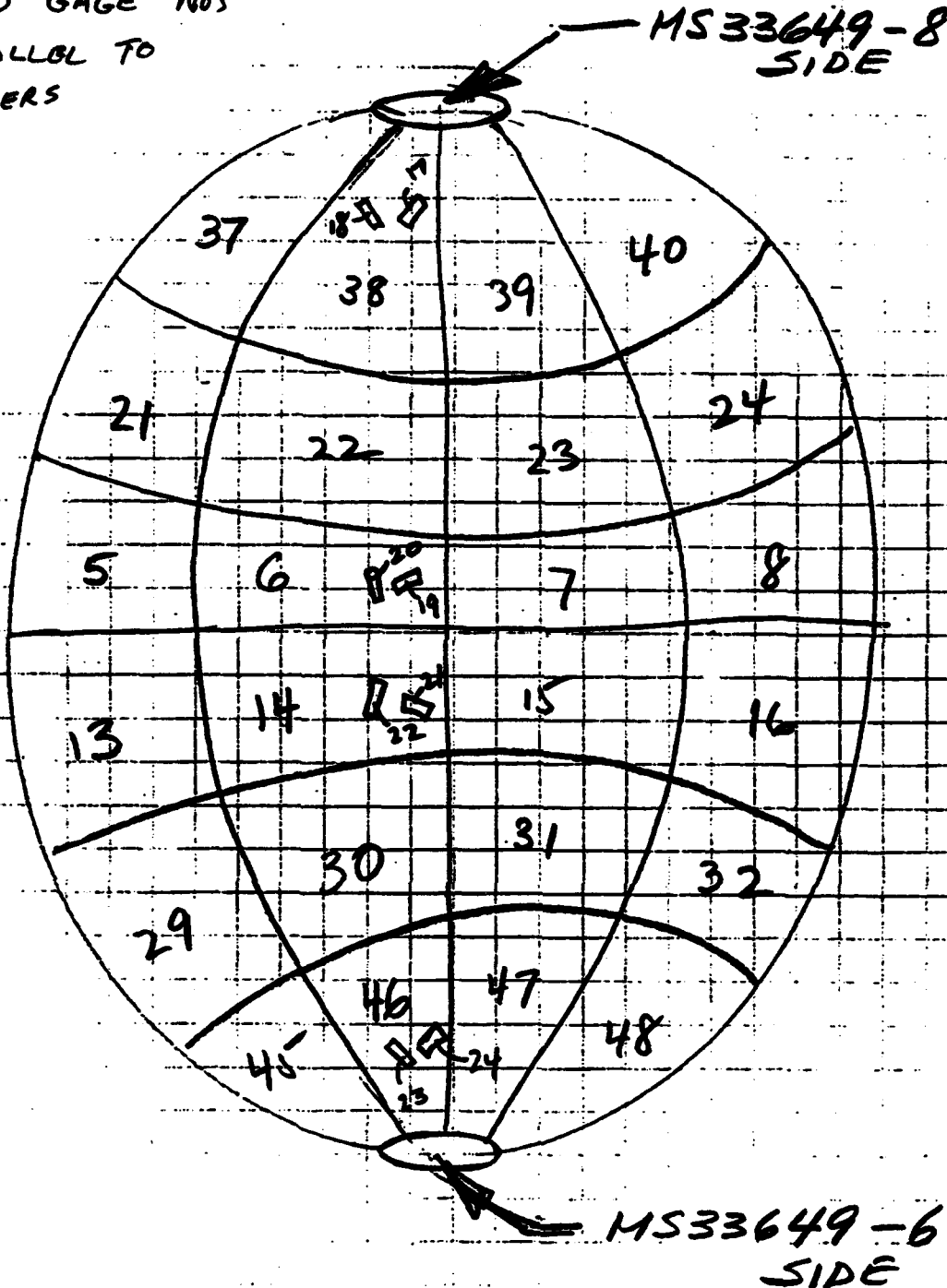
FIGURE E-71

E.6.4 Post Test Inspection

The tank was post-test inspected on the test stand. The outer fiber shell was intact. Some slight fiber damage was observed in the region between the apex and about 45°, similar in nature to RV-7 test result. The vessel was then cut open by AFAL parallel to and 3" away from the girth weld. A jagged circumferential crack around the girth near the girth weld was seen. The vessel was shipped to ARDE for further inspection. The inside liner surface was die checked, the fiber shells removed and photographs were taken at ARDE. The liner failure mode was similar to the RV-7 test result. Complete liner separation at the girth was again verified and there was no bonding between the metal/fiber interface surface. Figures E-72 and E-73 show the girth crack highlighted by die check colorization. Exterior photographic views of the cut fiber shell (Figures E-74, E-75) depict the slight fiber damage regions. The fiber/metal interface of the cut fiber and metal shells are shown on the photograph of Figure E-76. The lack of bond between fiber and metal is evident by the smooth clean and undistrubed interface surfaces.

TEST RV-9, GIRTH CRACK, DIE CHECK ENHANCED
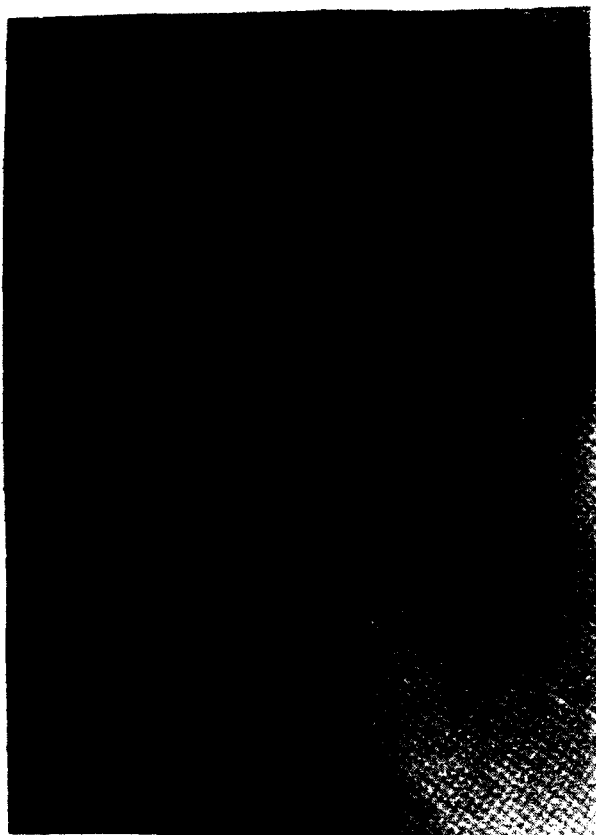
Fig. E-72

TEST RV-9, GIRTH CRACK, DIE CHECK ENHANCED
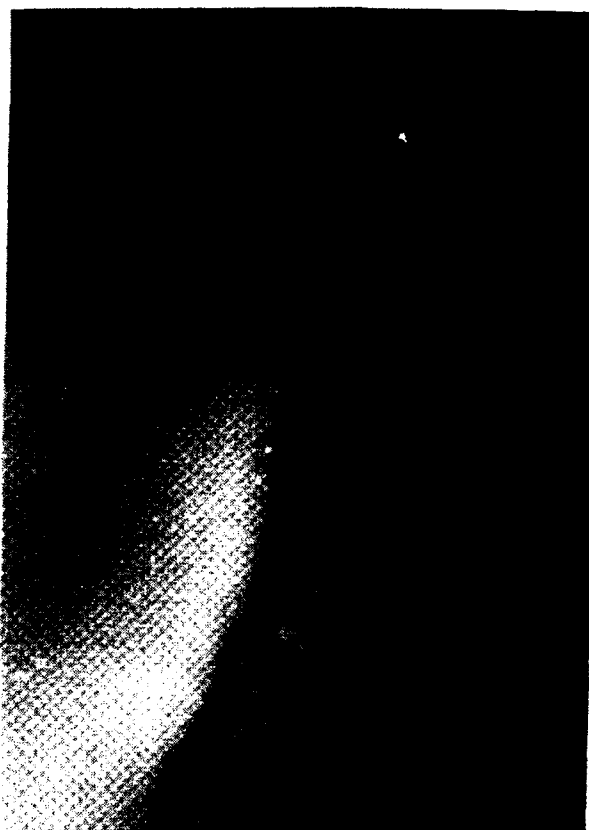
Fig. E-73

Fig. E-74

TEST RV-9, CUT FIBER SHELL, EXTERIOR VIEW

Fig. E-75

TEST RV-9, CUT FIBER SHELL, EXTERIOR VIEW

Fig. E-76
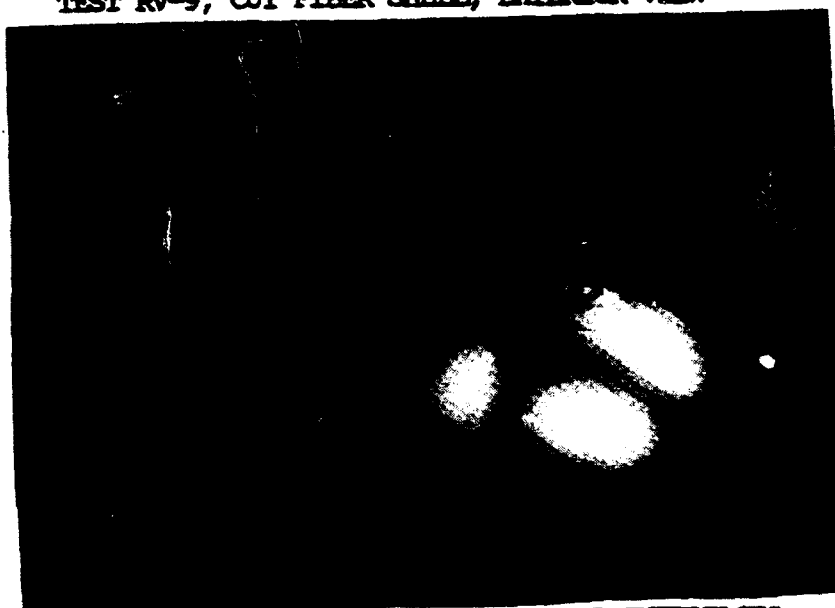
TEST RV-9, CUT SHELLS, FIBER/METAL INTERFACES

E.7   RV-10 Test (16 ø PSC

E.7.1   Test Vessel Description

●   P/N E4168, S/N 003 (Kevlar Overwrapped 301

Cryo CRES Composite Sphere.

●   Kevlar Fiber (less resin) average thickness =

.077 (50% baseline thickness)

●   Metal Thickness = .054/.051

●   Inside Radius   = 7.64

●   Hydrogen Embrittlement Mode = Local Girth Weld

●   Region Electrolyte Solution =

$$\frac{20 \text{ cc } H_2SO_4 + 980 \text{ cc Tap } H_2O}{1000 \text{ cc solution}}$$

●   Solution Additive = 500 mg Sodium Arsenite

●   Sensitize Liner Inside Surface (cold pickle)

●   Charging Current Density = .006 amps/in^2 of

surface to be embrittled

●   Charging Time = 72 hours

●   Hold Time Before Test = 2.5 hours

●   Adcoat AC818T liquid maskant on areas not to be

embrittled

Figure E-77 is a photograph of the RV-10 test tank during the hydrogen embrittlement mode prior to pressure testing. The composite vessel metal liner is used as the cathode and a lead anode is immersed in the H_2SO_4/H_2O electrolyte solution inside the tank as prior detailed in section 2.4. A controlled power source completes The circuit, providing the charging current in the electrolyte needed to generate the hydrogen embrittling gas on the liner inside surface. Figures E-78, E-79 show prior test photographs of the tank on the test stand with the Bikini gages, overpressure transducers and witness panels. A close up photographic view of strain gage and thermocouple installation of the fiber wrap outer surface is given on Figure E-80.
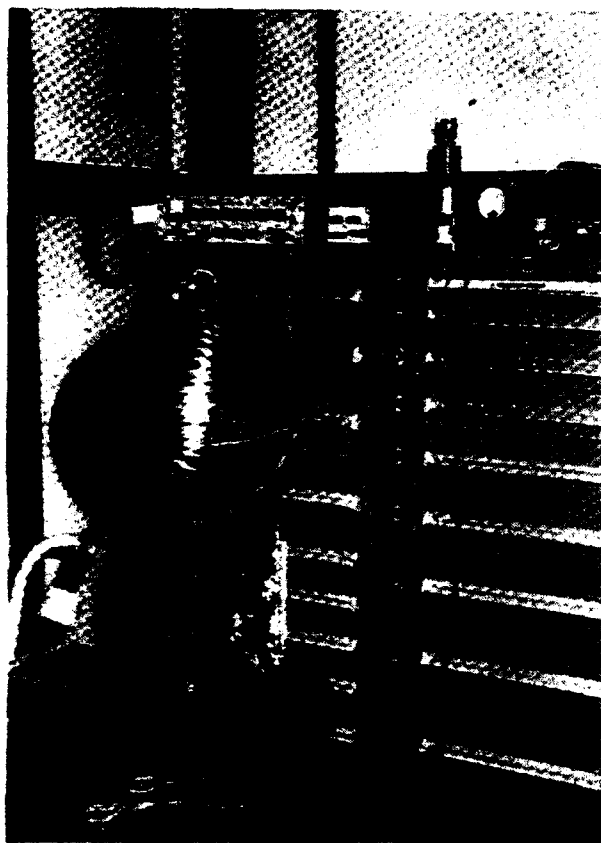
TEST RV-10, PRIOR TEST HYDROGEN
EMBRITTLEMENT MODE

Fig. E-77
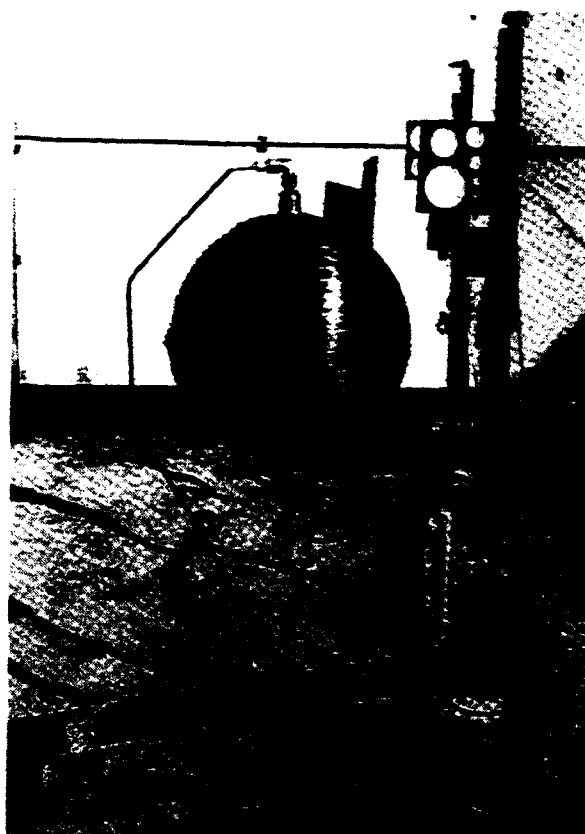
TEST RV-10, CLOSE UP, VESSEL
ON TEST STAND

Fig. E-78
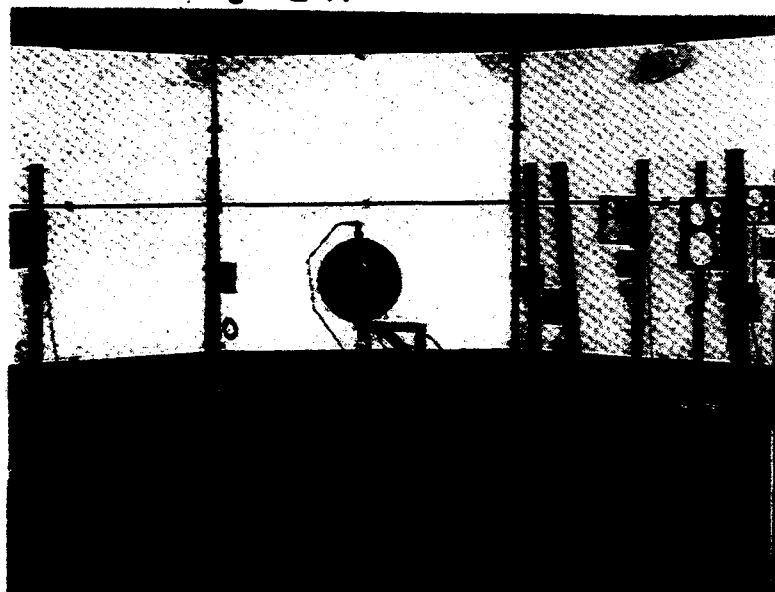
TEST RV-10, VESSEL ON TEST STAND, BIKINI
GAUGES, OVERPRESSURE TRANSDUCERS AND WITNESS
PANELS

Fig. E-79

TEST RV-10, CLOSE UP OF STRAIN GAUGE
AND THERMOCOUPLE INSTALLATION

Fig. E-80

E.7.2

INSTRUMENTATION OBSERVATIONS (by AFAL Instr. Eng.)

KEVLAR TEST 010, 18DEC87.   Project number 573000RV.

EXPERIMENTAL OBSERVATIONS.

Introduction.   Vessel S/N 003 was tested.   It was a 16 inch
diameter stainless steel sphere and had a thinned Kevlar
overwrap.   The vessel was hydrogen embrittled about the girth for
about a 1 inch width.   It was tested in a vertical configuration.
The tank pressure was increased with pressure pulses and ramps
until catastrophic rupture of the liner and overwrap rapidly
occurred.

Pressurization Ramp and Catastrophic Rupture.   The vessel was
pressurized with cool helium gas.   Initially, the pressure was
increased from ambient pressure to about 200 psig during a
cooldown period, which took about 2 minutes.   The tank was
vented.   The data system was started, and the tank pressure was
kept at ambient presssure for 16.399104 seconds before pressurre
was increased with a salvo of 30 small pulses and steps to the
beginning of a 3.3999302 second wide plateau, with a nominal
value of 2215 psig.   One additional small pulse raised the
plateau to a nominal value of 2276 psig.   A steady ramp of
pressure was started at 55.999302 seconds from a pressure of 2277
psig.   The pressurization rate was 92.606 psig/second (3269-2277
psig)/(66.7113366-55.999302 seconds).   The first significant
change in data as measured by the following sensors occurred at
the time indicated for the time between samples specified:

	delta t 0.001 sec
PTANK/1901 TANK PRESSURE	66.711336
PVSOUT/1904	66.720138
SG24	66.708402
SG1-9	66.709600

From this data, burst was definetly no later than the PTANK time
and probably before the SG1-9 (as this value is the time these
items go offscale - not the time of oscillation onset, which is
somewhere near or between 66.70920 and 66.709300 - depending on
the particular SG of interest).   The data analyst determined the
burst time to be 66.7097 seconds (S/G34/7124) or 66.7093 seconds
(S/G21 or 7121); see the Data Analyst's Comments below.

Post-run Inspection.   Witness panels, 4'X8'X1" Celotex sheets
backed with 1/16" thick aluminum, were used to collect fragments.
Some fragments penetrated the panel.   Photographs were taken, and
the locations of the major fragments were recorded elsewhere.

Other details.   ARDE collected some of the broken pieces, and the
pieces were returned to ARDE.   Acoustic emission was not used.

IMPRESSIONS FROM THE DIGITIZED FM DATA.

1

Strain Gages.

Location.

The strain gages were located IAW ARDE drawing dated 13NOV86. The locations were concentrated in the same areas as testrv9, but some of the gages were repositioned slightly. For this test, even numbers are parallel with the grain and odd numbers are perpendicular with the grain. The previous test, testrv9, had the opposite assignments.

Evaluation of the Graphs.

Of the 23 strain gages recorded, the activities before, during and after the burst for 20 gages were compared; not compared were strain gages 7, 13, and 23 because of the reasons discussed in the Data Analyst's Comments below. All 20 graphs started from better than reasonable noise floors, and most graphs progressed into a steady but short period of prominent undamped oscillation prior to rupture. However, the exact trends for duration and offset for, say, 0.01 seconds, for comparison to testrv9, cannot be determined by using the first high frequency data pass time scale; the time scale for testrv9 was 0.002 sec/div and for test10 was 0.0001 sec/div. A second high frequency data pass will be made. The oscillation's first few cycles are clearly undamped, and the damped or almost critically damped gage performances seen in testrv9 changed to undamped performances in testrv10; the differences are probably due to the thinner Kevlar wrap in testrv10. A question now arises about the onset of the oscillation. Did it start before, during or after the cracking? The metal cracking or the Kevlar failing is probably the source of excitation, for the oscillation probably didn't occur during the abrupt pressure changes and gas flows experienced during the pressure salvos (TBD). Other speculations can be experessed. One interpretation favors burst after the oscillation; this interpretation is based on observing that most SG graphs first enter into oscillation with a small compression excursion; they reverse direction and continue with a tension ramp, modulated by the oscillation, to burst.

> **Clinical confirmation of the theoretical
> prediction of SG compression behavior prior to
> burst may be obscurred by the undamped
> oscillation, however.**

The observed compression excursion at the beginning of the oscillation is probably incidental to the theoretical prediction and is most likely oscillation related. However, the compression mentioned in the prediction may be a latent data manifestation obscured in some data parameters, and digital signal processing may be needed for signal inhancement, identification and recovery.

Data Analyst's Comments. ITT, Richard M. Thomsen, states:

2

DIGITAL DATA

All channels recorded data correctly. The IRIG signal shows the burst occurring at 21:06:30.786 (66.7097 seconds from the time recording began).

The only anomaly noticed is a sudden decrease in tension strain recorded by SG24/7124 at 62.9 seconds.

FM STRAIN GAUGE DATA.

The first pass was digitized at 1000 samples per second (SPS) using an (sic) 100 HZ filter. Recording began at 24 seconds and continued through the burst. SG7 and SG13 were noisy and SG23 had bad calibration data. SG1, 3, 4, 5, 6, 7, 9, 11, 12, 14, 15, 17, 19, 20 and 21 show jumps in strain prior to burst. SG11 has a severe drop in tension strain at 58.4 seconds, then shows decreasing strain during the pressure ramp until burst.

The high frequency pass was digitized at 160,000 SPS using a 20,000 Hz filter. The IRIG time signal was used to sync the FM data to plus or minus 0.02 milliseconds and to reference it to the digital data time scale. SG7, 13 and 23 were not included for the reasons stated above. SG1, 10, 15 and 17 show large swings in strain at the burst, with a frequency of about 8000 Hz." End of ITT text.

IMPRESSIONS FROM THE QUICK-LOOK AND DIGITAL DATA ACQUISITION SYSTEM DATA.

Tank Pressure. The tank pressure functioned as described under the Pressurization Ramp paragraph.

For this test, the tank pressure sensor, PTANK/1901, was moved to the bottom of the tank where it would not be sensitive to interference from the line pressurization activity, which was observed on the previous tests. The profiles of PTANK/1901 and PVSOUT/1904 are now practically identical, and the irritating pressure spikes seen previously during the pressure salvos are gone.

Other Parameters. The performance of the other parameters was within normal limits; this was determined by a quick review of the graphs for items PHXIN/1902, PHXOUT/1900, PTRAIL/1903, THXIN/2100, TBALL/2211, TBSOUT/2210, TBSIN/2209, THXOUT/2101, TT1/2102, TT2/2103, TT3/2104, TT4/2105, TT5/2201, TT6/2202, TT7/2203, TT8/2204 and TT9/2205.

IMPRESSIONS FROM THE OVERPRESSURE SENSORS.

Bikini Gages. A Bikini gage is one piece of bond paper compressed between two metal plates containing different sized round holes. The gages are aligned so the paper is perpendicular

3

to the pressure source. Discrete pressure data can be obtained
and is a function of the location of the damaged paper
diaphrams. The approximate calibration is as follows for the
indicated hole size using bond paper:

HOLE #	PSIG	SIZE
1	7.3	5/8
2	5.2	7/8
3	3.7	1-1/4
4	2.7	1-7/8
5	1.9	2-3/4
6	1.4	3-3/4
7	1.0	5-3/8

The results of this test broke some of the diaphrams and left
others intact at the 6 and 14 foot diameters where the gages were
deployed.

	2 o'clock	6 o'clock	10 o'clock
2 ft	-	-	-
6 ft	all torn	all torn	1 left
10 ft	-	-	-
14 ft	1,2,3 left	1,2,3 left	1,2 torn
			3,4 left
			5,6,7 torn

Comparing the above Bikini data with the data from the
overpressure sensors (in parenthesis) shows an excellent
agreement. The Bikini data is discrete in nature, and only gives
information best expressed as "at least XX psig." The 6 ft
diameter experienced at least 7.3 psig (12.02 psig) overpressure
for the 2 o'clock and at least 7.3 psig (15.84 psig) overpressure
for the 6 o'clock stations and at least 5.2 psig (17.68 psig) for
the 10 o'clock stations. The 14 ft diameter experienced at least
2.7 psig (4.92 psig) overpressure for the 2 o'clock and 2.7 psig
(2.53 psig) overpressure for the 6 o'clock stations. The 10
o'clock station experienced some inconsistencies, which are
discussed below.

The inconsistencies can be seen if the pressures are drawn on a
polar diagram. The 6 foot pressure line is biased away from the
10 o'clock leg (hole # 1 is left). Conversely, if the 14 foot
pressure line is drawn, it is biased away from the 2 and 6
o'clock legs (holes 1, 2, 3 are left). Overlaying the two, the
peculiar eccentricity becomes apparent. One would think the two
pressure lines would at least be biased in the same direction.

A simple explanation would involve assuming the 1,2 hole
locations torn on the 10 o'clock leg are incorrect. Perhaps they
were torn by fragments. This speculation biases the low pressure
isobar away from the 10 o'clock leg (1,2 assumed left; 3,4 left)
and makes it consistent with the bias of the high pressure

4

isobar.

Piezolelectric Sensors.

OVERPRESSURE SENSORS. Ideally, each overpressure sensor located to measure pressure should respond to a passing pressure pulse with a characteristic graph. The graph's curve should have a prominent leading edge rising from a stable initial condition. The typical leading edge should polarize positively and rise to the curve's maximum peak pressure over a smooth and almost linear path. -At the peak pressure, the curve should inflect, and, at this reversal, enter into a characteristic depolarization decay consisting of an almost linear but slightly distorted return to below the initial condition with an undershoot, more fully described below, representing rarefaction and the start of the refractory period.

More often than not, the linear decay should gradually change into a sluggish curve containing one prominent inflection, forcing the plot into the opposite direction, but staying below the initial condition. Eventually, the pressure rarefaction should deteriorate completely, and the plot should return smoothly to the initial condition, ending the refractory period.

Modulations and variations in behavior are caused by sensor placement (parallel or perpendicular to the flow direction), reflections, pressure wave distortions, time constants, frequency response, particulate impingement, insulation resistance, short circuits, open circuits and gas cloud geometry, etc.

For this test, 9 of the 11 sensors recorded exhibited profiles as described above. The exceptions were items 1809 and 1810, which were on the 10 o'clock leg at 2 and 6 feet.

The overpressure item numbers and peak values for the overpressure sensors are shown below along with the times in seconds (in parenthesis):

	2 ft	6 ft	10 ft	14 ft
2 o'clock	1801 30.62 psig (66.710350)	1802 12.02 (66.712563)	1803 7.57 (66.714869)	1804 4.92 (66.718351)
6 o'clock	1805 46.52 (66.710526)	1806 15.84 (66.712306)	1807 5.78 (66.715076)	1808 2.53 (66.718419)
10 o'clock	1809 17.68 (66.710707)	1810 3.54 (66.712544)	1811 4.62 (66.715938)	---- ----

To easily visualize when the pressure peak passed each station

5

and in what order, draw circles around each of the above 11 data
groups and connect the circles in sequence according to time,
starting with the 2 o'clock 2 ft sensor. Note the pressure peak
always passed the stations in a 2, 6 and 10 o'clock order except
for the 6 foot stations where the order was 6, 10 and 2 o'clock.
This observation may indicate rupture activity favored the 2 and
6 o'clock positions more than the 10 o'clock position. Also, the
pressure magnitudes are larger for the 2 and 6 o'clock positions.

The pressure magnitudes on the 2 and 6 o'clock legs behaved as
expected. The pressure wave decreased in size as the wavefront
passed each station.

But, the pressure magnitudes on the 10 o'clock leg behaved in a
peculiar manner. The first station's response included a
negative pressure, and the remaining two stations recorded
increasing positive pressure! There was no 14 foot station.
Note there was also peculiar behavior reported for the Bikini
gages located on the 10 o'clock leg. The behavior of the 10
o'clock overpressure data includes pressure profiles with
oscillatory tendencies for the first and third stations and the
sluggish negative pressure at the first station. These
behaviorial characteristics are probably more atributable to
actual performance than to errors in the instrumentation system.
For example, simple signal polarity reversal can be easily
achieved with the amplifier's polarity switch, but the steepness
of the slope of the leading edge would not be changed, and we see
in item 1809 a slowness in the rarefaction not seen in any other
parameter (the adjacent station, 1810, is slightly slow compared
to the others). Also, scattered about are small positive
precursory artifacts on one-half the parameters (including 1809).
If 1809 had been reversed, its artifact would be reversed, and it
isn't. All of this notwithstanding, it still isn't too difficult
to believe 1809 is a reversed channel, particularly when the
graph is turned over and viewed through the paper from the
reverse side (the rarefaction exhibits a slow leading edge, peak,
linear decay, undershoot and a modulated recovery). The
calibration polarity was checked to settle this controversy once
and for all. The calibration polarity was the same as all the
other channels. Therefore, the channel is not reversed. Looking
at the profile again, the analyst suggested that the part of the
graph that crosses 66.7108 seconds is the actual leading edge
followed by a heavily modulated peak and linear decay. This
observation is probably the speculation of choice as the wave
arrival times for the other two 2 foot stations are within
reasonable agreement with this graph's wave arrival time; and,
more importantly, the slopes on the leading edges of the
wavefronts recorded by items 1809 and 1810 are almost identical
and are remarkedly slower than the slopes on all the other
overpressures. In other words, the heavy modulations seen on
1809 just about obscures the classic profile and makes it
difficult to see that the slope crossing 66.7108 seconds is
probably the passing of the desired wavefront.

6

The ITT data analyst, Richard M. Thomsen states:

"FM OVERPRESSURES. The overpressures were digitized at 160,000 samples per second with a 20,000 Hz filter. Each was digitized with the IRIG timing signal to sync the time scales to plus or minus 0.025 milliseconds (1 sigma). The time was then referenced to the start of the test with the burst occurring at 66.7097 seconds (SG24/7124) or 66.7093 (SG21/7121).

Two of the gauges were calibrated using the peak-to-peak AC calibration. Both had a bad R4 resistor calibration; on PV2/1802 it was the same as the R0 resistor calibration and on PV8/1808 it was maximum counts (Actually, cal resistors are not used; the calibrations are full scale voltage substitutions). The AC calibration peak-to-peak maximum and minimum counts over 20 cycles for these gauges was used with that of th PV1/1801 to determine the calibration coefficients.

Most of the overpressures show a small shift in pressure at the time of the burst, then one to nine milliseconds later the shock wave hits, with another following 0.5 to 4.5 milliseconds later. I cannot determine why there is a shift at the time of the burst, but on PV1 it is surprizingly strong. I would take this to be the shock wave except (1) it occurs too soon and (2) the shape is wrong. Usually the shock wave rises quite sharply and drops off more slowly, but this pulse does the opposite. I think the pulse at 66.7104 seconds is the one that travels out to the other gauges.

The secondary shock wave may be a reflection from the test stand (fragment panels). The wild swings in pressure may be particles hitting the gauges." End of ITT text.

7

DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE. An undated ARDE embrittlement procedure was followed; only the girth area for a width of about 1 inch was embrittled. Embrittlement was inhibited, where required, with a maskant. Embrittlement was started at _____ hours on _____. The current level was _____ amperes. Seventy-two hours of embrittlement were completed at _____ hours on _____; the tank was immediately moved from the shop embrittlement area to the test site, instrumented, hooked up and tested at _____ hours on 18DEC86. The electrolyte was sulphuric acid; sodium arsenite was added as an enhancer.

ADMINISTRATIVE INFORMATION.

Revision Record. Initial Issue: 16JAN87.   Revision A: 6MAY87:
overpressure information added.

Filename: testrv10

Distribution.   ARDE, Steve Berko, Dave Gleich
                       PI, Dr. Pius Chih Hsu Chao
                       Aerospace Corp., Dr. Yen Pan
          -            AFRPL, Jim Miller, Mike Dieckhoff, Dick Grove
                             MSgt Jim Day, John Marshall, Capt
                             Seidemann
                       ITT, Richard Thomsen, Dr. Tae-Woo Park
                       PAFB, Pete Tadie

Office of Primary Responsibility.   USAF/AFRPL/TOAE/Edwards CA
93523.

E.7.3   <u>Pressure and Strain Versus Time Plots</u>

Tank pressure and selected fiber strain versus time graphs are presented on Figures E-81 to E-86. A 20,000 Hz filter frequency and sampling and plot rate of 160,000 SPS were used to adequately define the strain spikes. Strain gages were located in the apex and girth regions on the 23° and 81° fiber wraps as sketched on Figures E-87, E-88. Even numbered gages were oriented parallel to the fibers and odd numbered gages were perpendicular to the fibers.

E.7.4   <u>Blast Overpressure Data</u>

Blast overpressure summary data has been given in prior section E.7.2. Figures E-89 to E-92 show plots of overpressure versus time for some key sensors using a 20,000 Hz filter and 160,000 samples per second (SPS). The center of the test tank is zero feet and "clock" coordinates are used to define the angular location of the sensors. Maximum measured peak overpressures were 46.52 psig at 2 foot radius, decreasing to 7.57 psig at 10 foot radius, indicating severe personnel damage potential.

E-150

Fig. E-81

KEVLAR VESSEL TEST RV-10, P/N E4168, S/N 003, 18 DEC 86

E-151
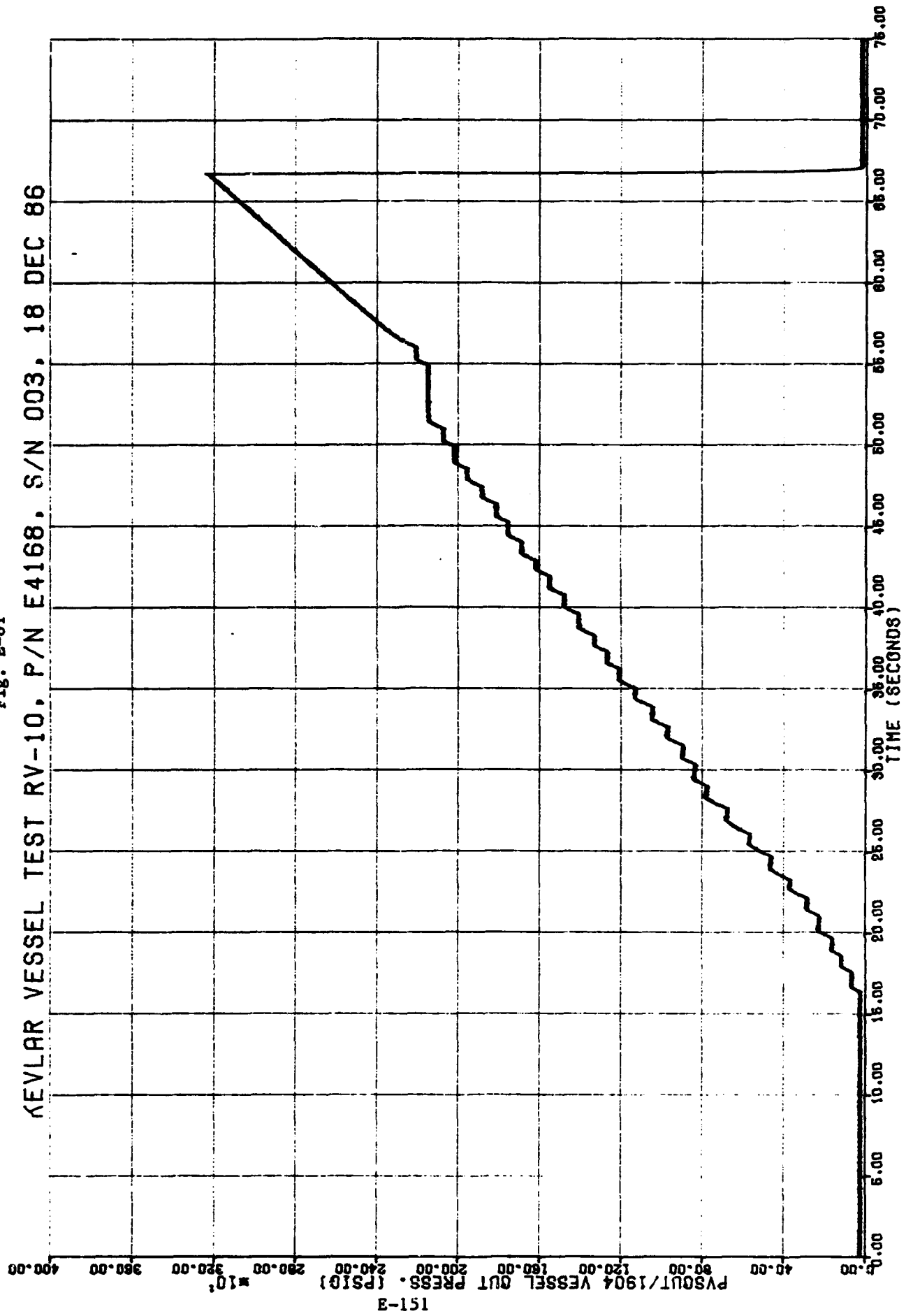
Fig. E-82

KEVLAR VESSEL TEST RV-10, P/N E4168, S/N 003, 18 DEC 86
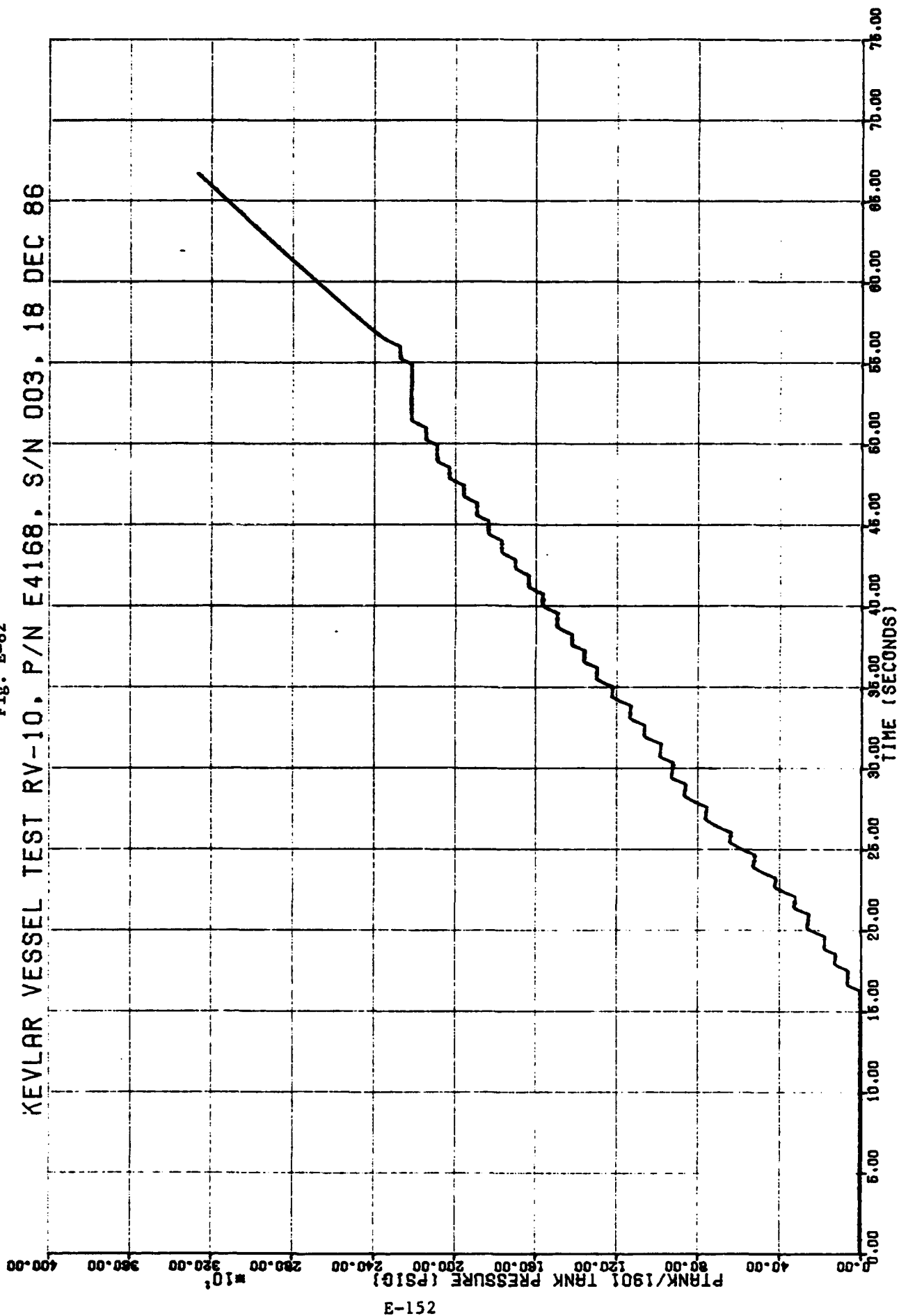
Fig. E-83

KEVLAR VESSEL TEST RV-10, P/N 4168, S/N 003, 18 DEC 86

8015/7115
SAMPLE RATE = 160.000 SPS
FILTER FREQ = 20.000 HZ
PLOT RATE = 160.000 SPS

E-153

Fig. E-84

KEVLAR VESSEL TEST RV-10, P/N 4168, S/N 003, 18 DEC 86

8016/7116
SAMPLE RATE = 160.000 SPS
FILTER FREQ = 20.000 HZ
PLOT RATE = 160.000 SPS

E-154
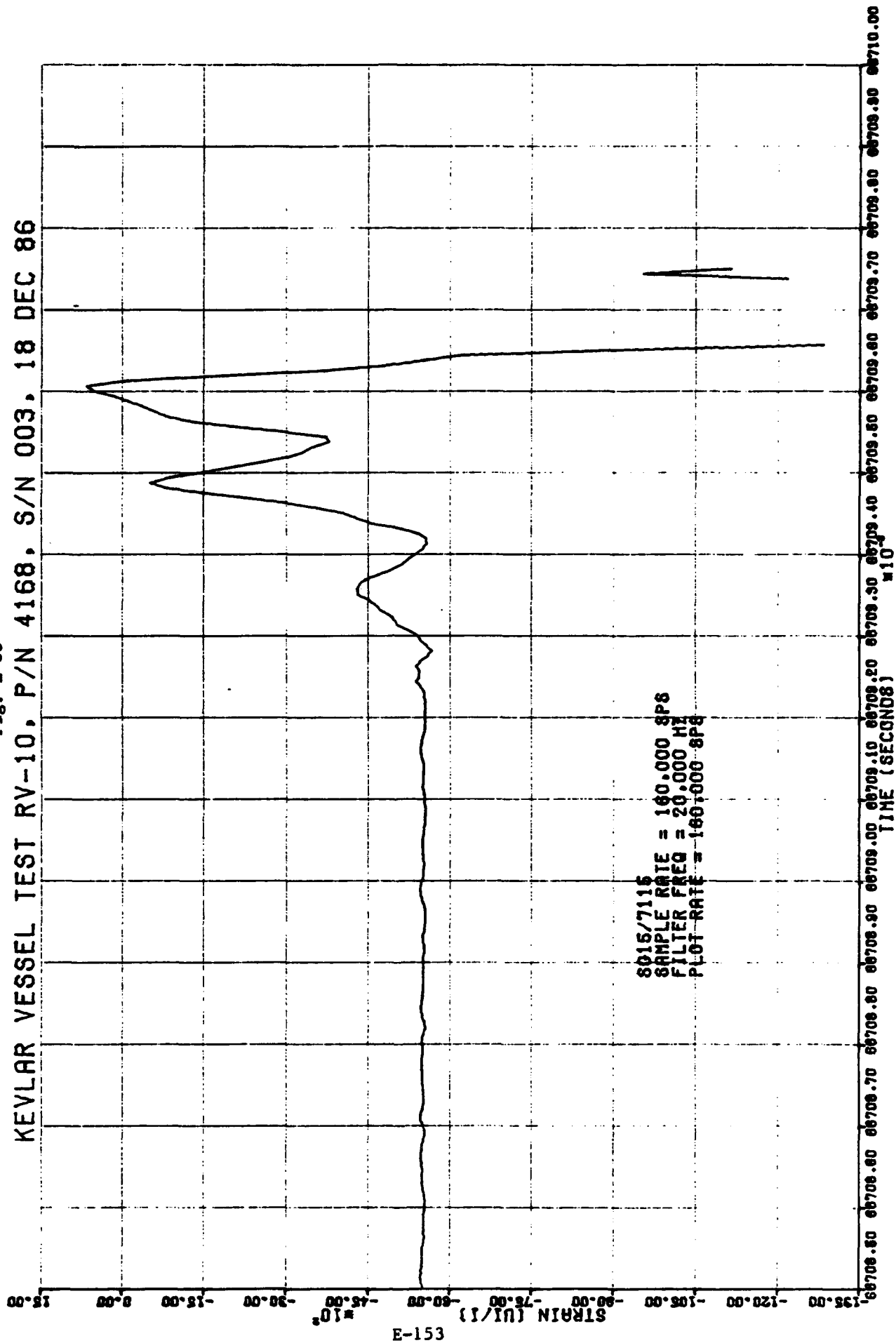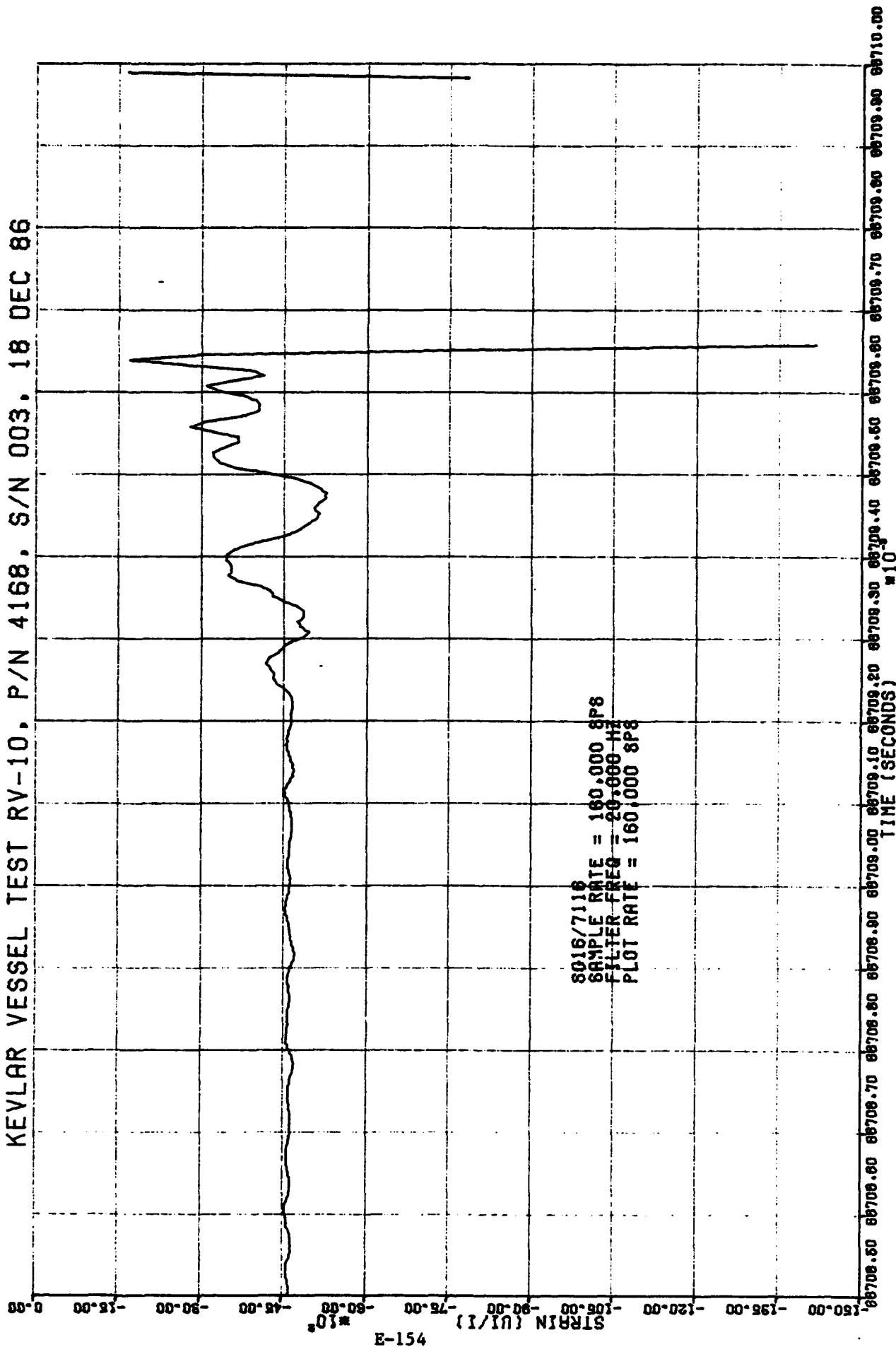
Fig. E-85

KEVLAR VESSEL TEST RV-10, P/N 4168, S/N 003, 18 DEC 86

SO17/7117
SAMPLE RATE = 160.000 SPS
FILTER FREQ = 20.000 HZ
PLOT RATE = 160.000 SPS

STRAIN (UI/1)

TIME (SECONDS)
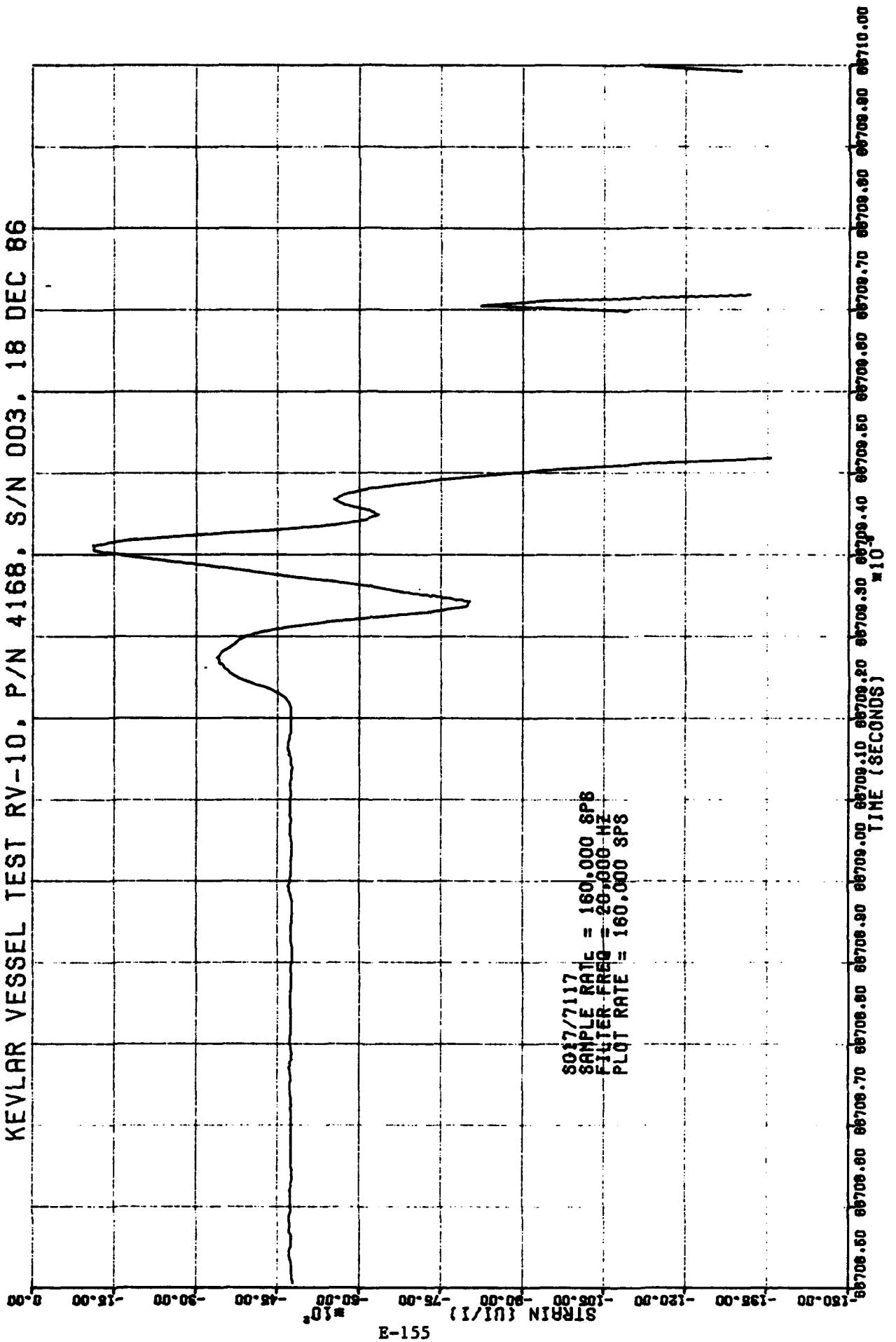
Fig. E-86

KEVLAR VESSEL TEST RV-10, P/N 4168, S/N 003, 18 DEC 86

RV-10
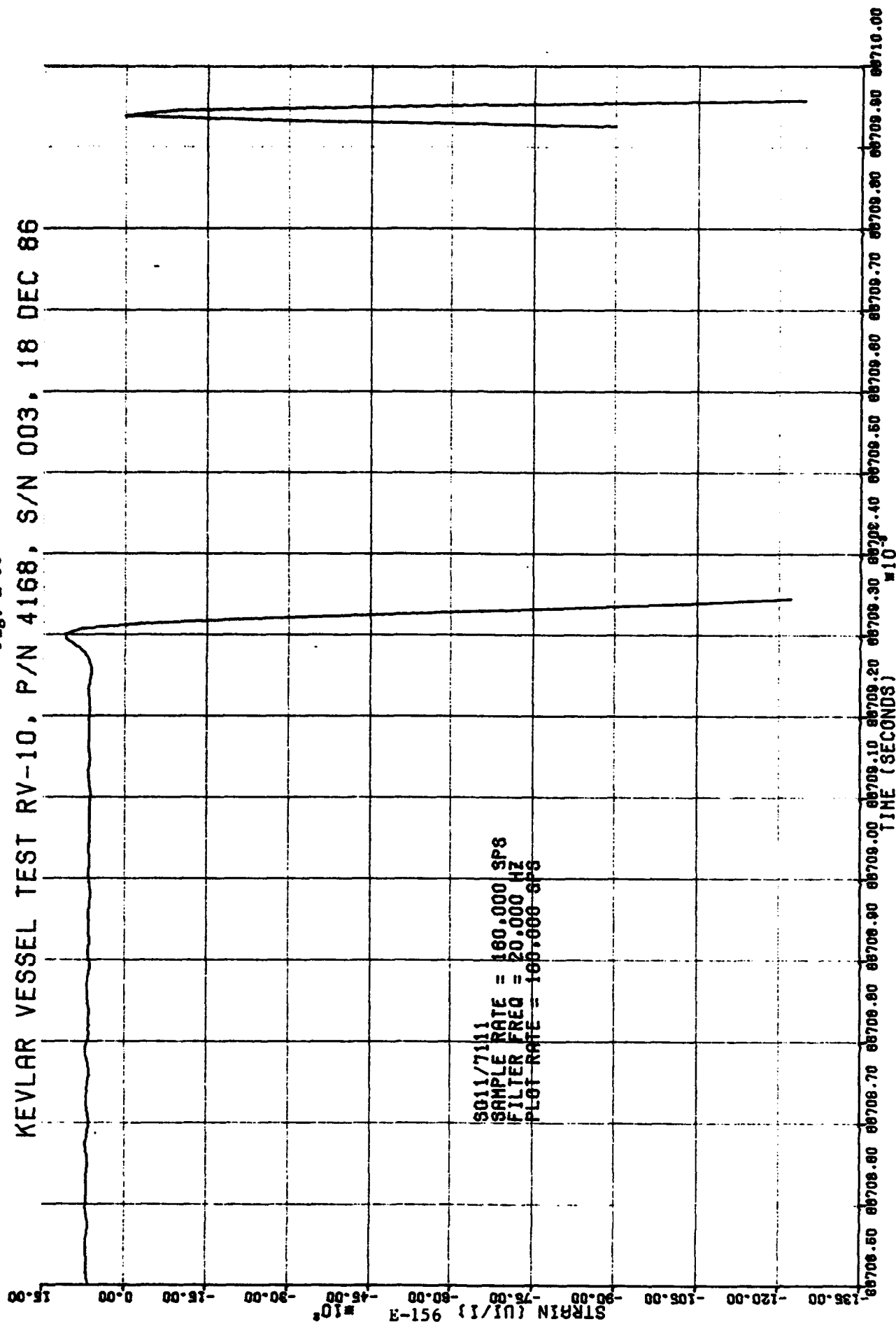
P/N E4168 S/N 003 STRAIN GAGE LOCATIONS
1/2 KEVLAR THICKNESS

EVEN GAGES = PARALLEL TO FIBERS

MS33649-8 SIDE

MS33649-6 SIDE
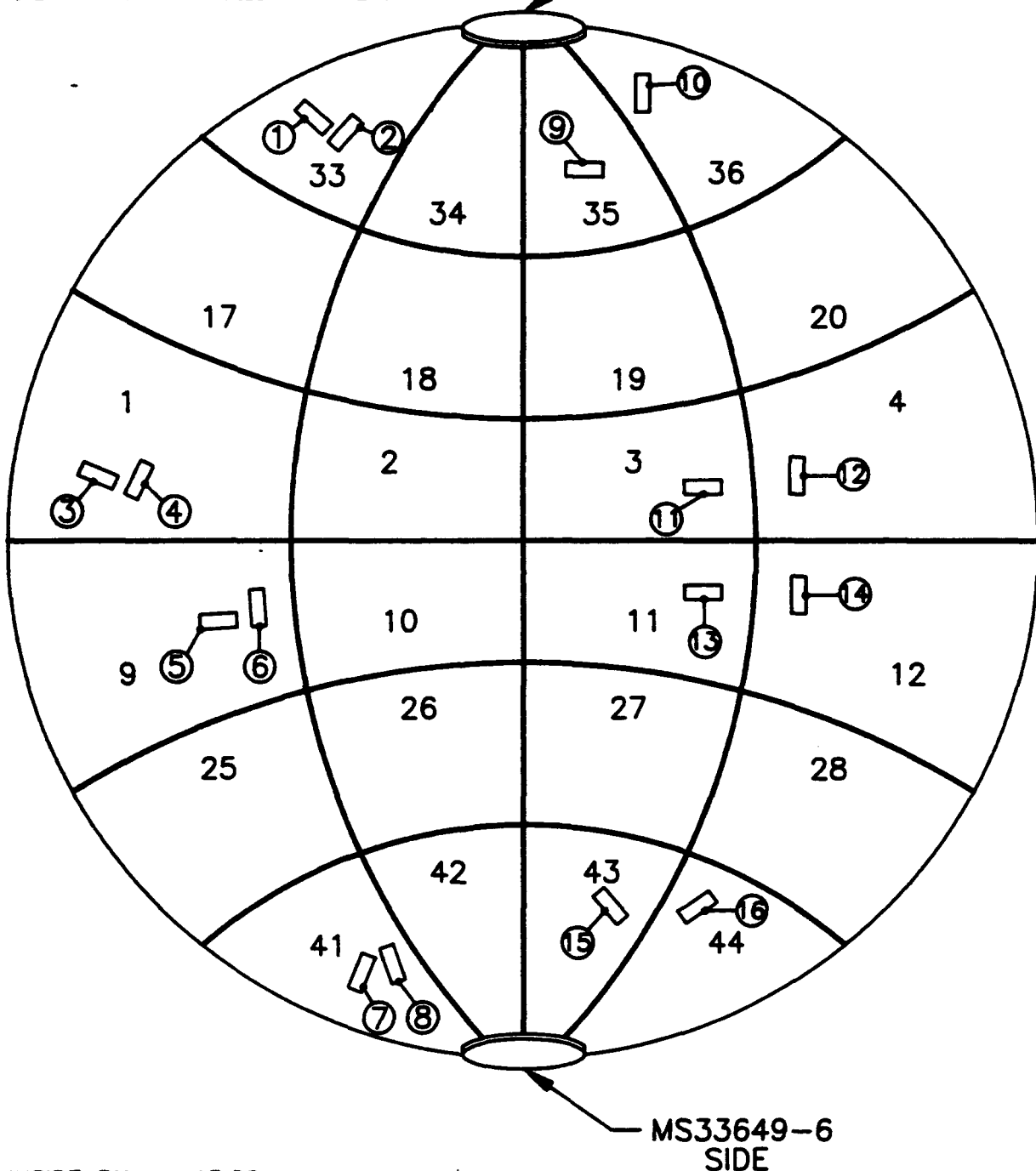
INSIDE DIA. = 15.28
METAL LINER THICKNESS = .055
FIBER THICKNESS = .078 (1/2 THE THICKNESS OF RV-7 TEST)
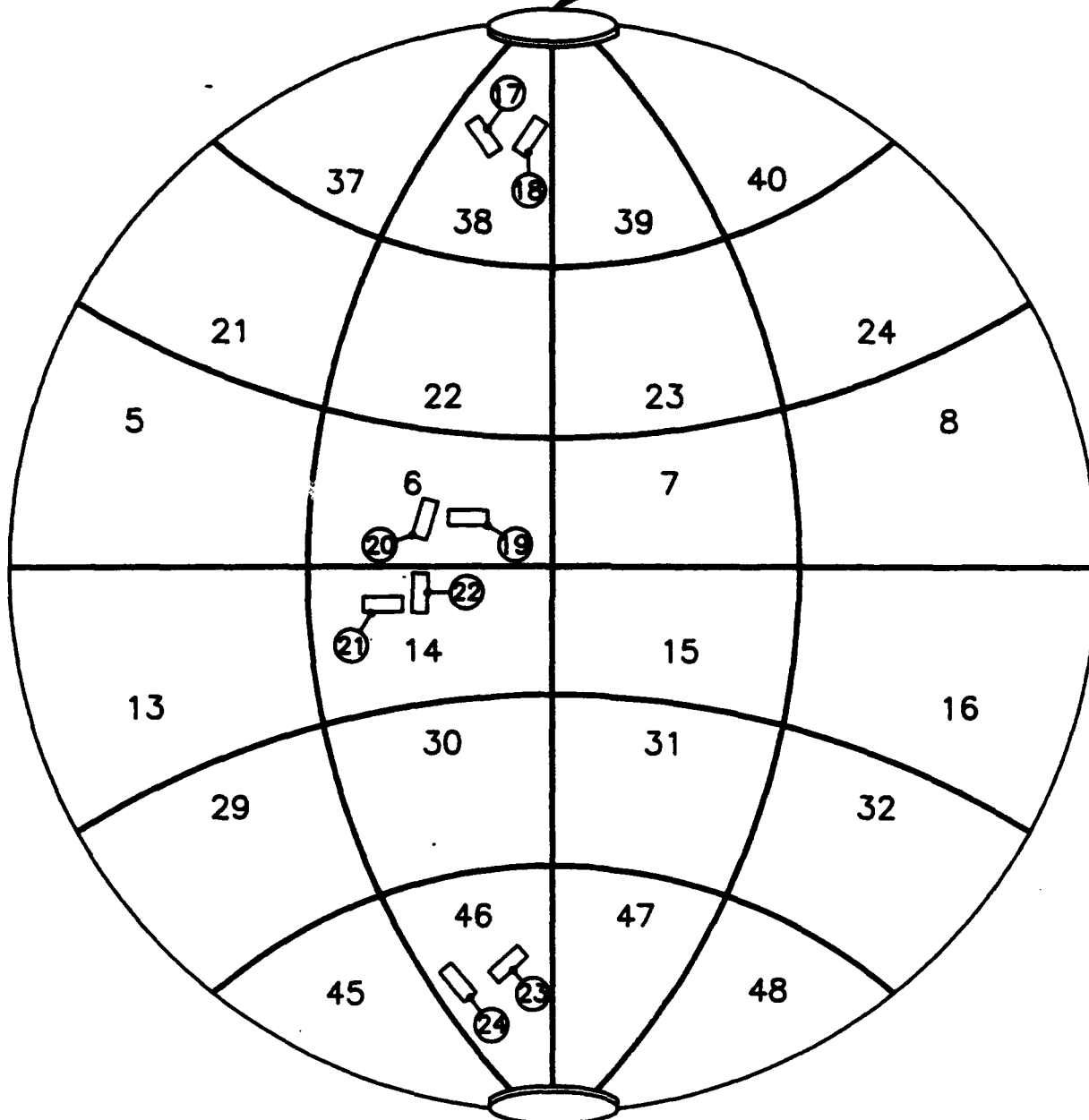
#1-48-SECTOR#'S
#①-㉔=STRAIN GAGE #'S
▭━● =STRAIN GAGE

Fig. E-87
E-157

Fig. E-88
E-158

Fig. E-89

KEVLAR VESSEL TEST RV-10, P/N 4168, S/N 003, 18 DEC 86
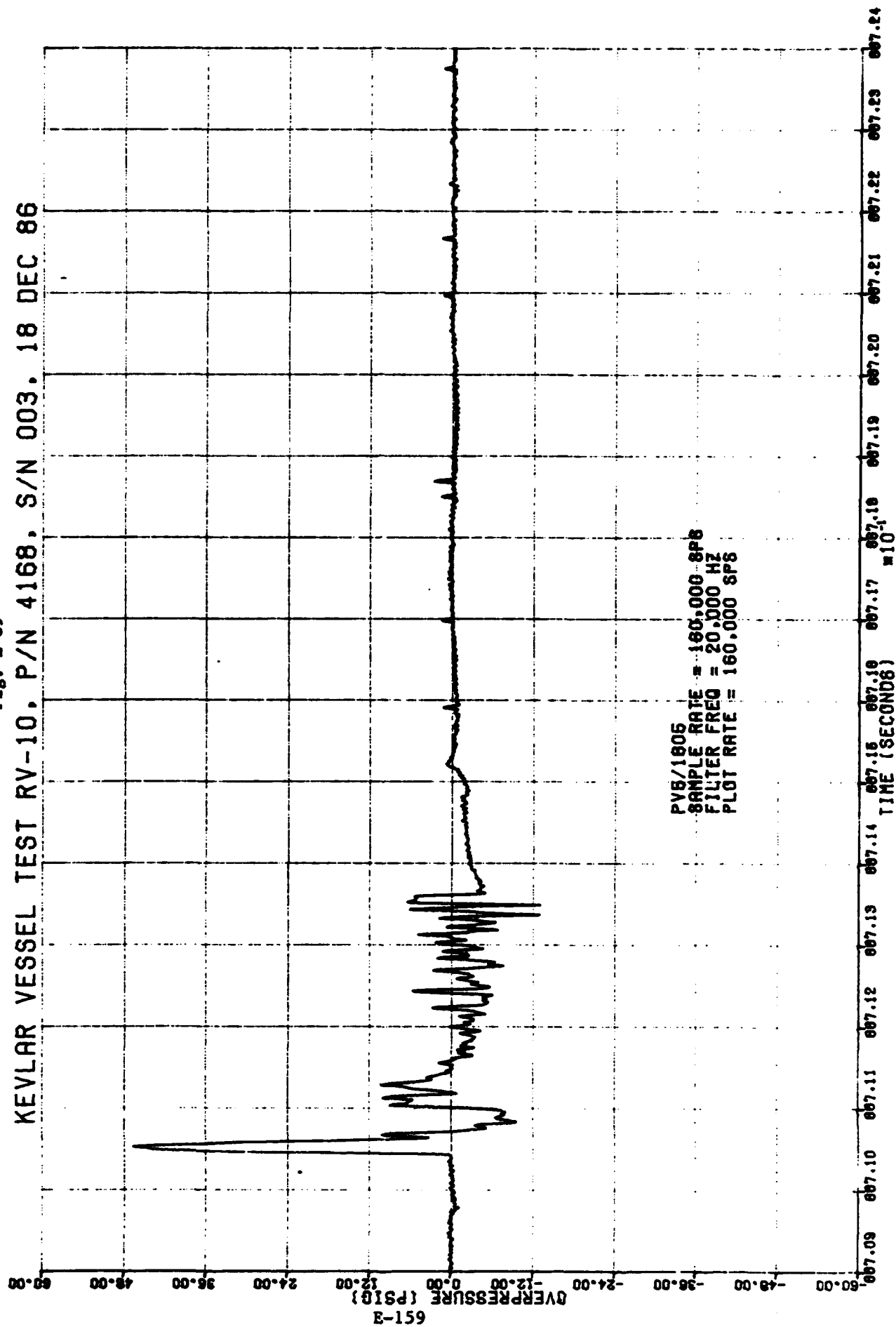
PV5/1805
SAMPLE RATE = 160,000 SPS
FILTER FREQ = 20,000 HZ
PLOT RATE = 160,000 SPS

Fig. E-90

KEVLAR VESSEL TEST RV-10, P/N 4168, S/N 003, 18 DEC 86

PVB/1805
SAMPLE RATE = 160.000 SPS
FILTER FREQ = 20.000 HZ
PLOT RATE = 160.000 SPS

OVERPRESSURE (PSIG)

TIME (SECONDS)

E-160

Fig. E-91

KEVLAR VESSEL TEST RV-10, P/N 4168, S/N 003, 18 DEC 86

PV3/1803
SAMPLE RATE = 160,000 SPS
FILTER FREQ = 20,000 HZ
PLOT RATE = 160,000 SPS

TIME (SECONDS)

OVERPRESSURE (PSIG)

E-161
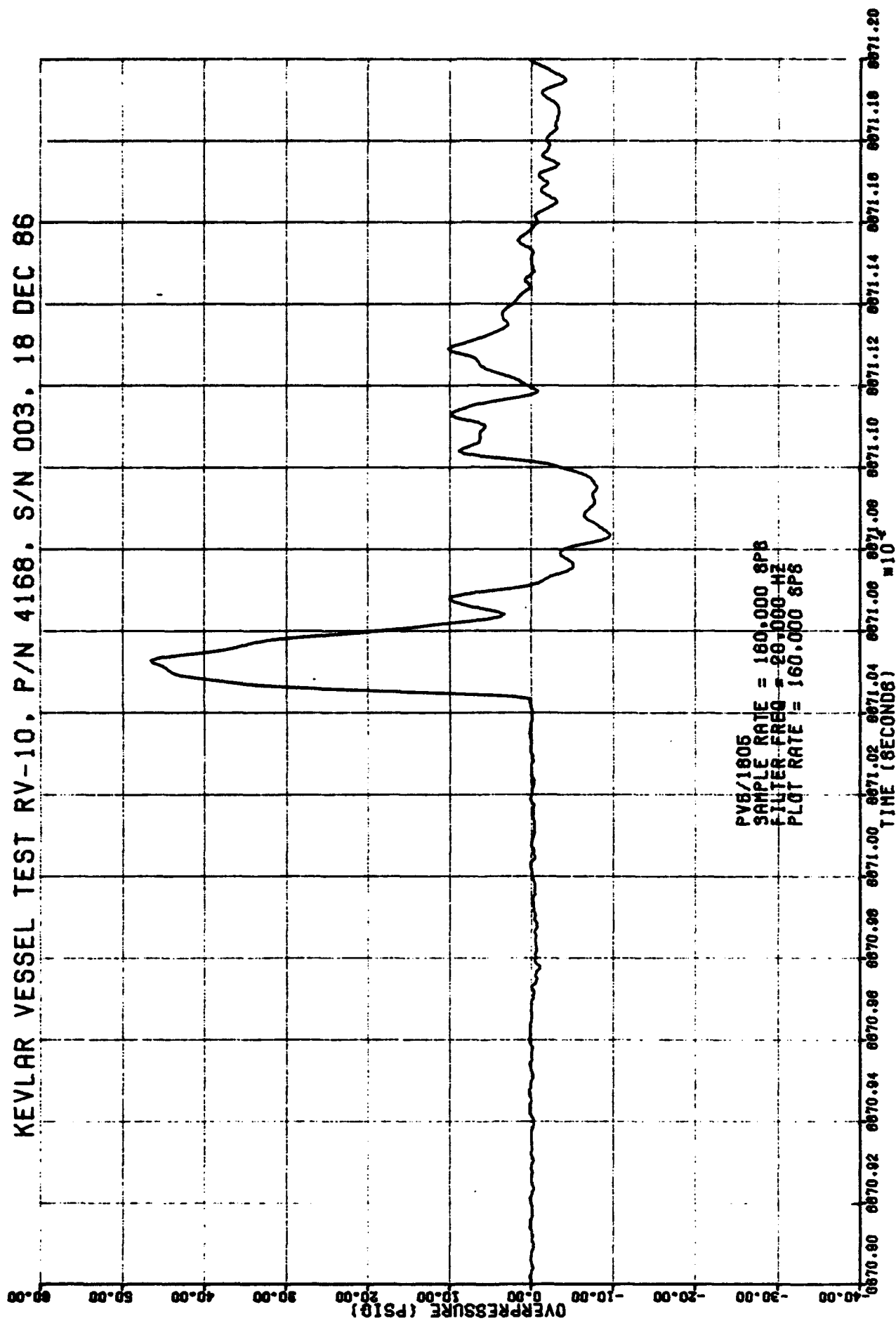
Fig. E-92

KEVLAR VESSEL TEST RV-10, P/N 4168, S/N 003, 18 DEC 86
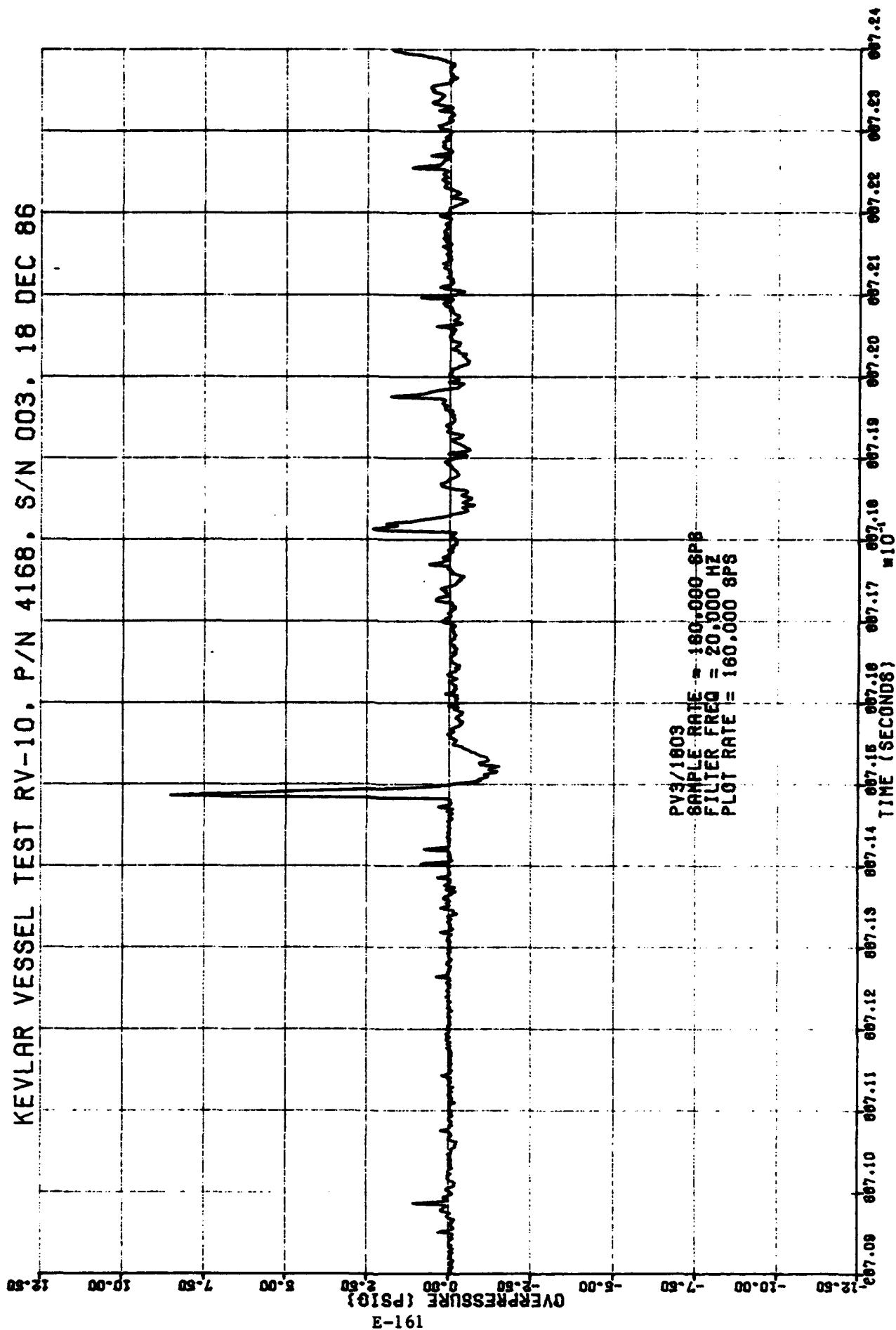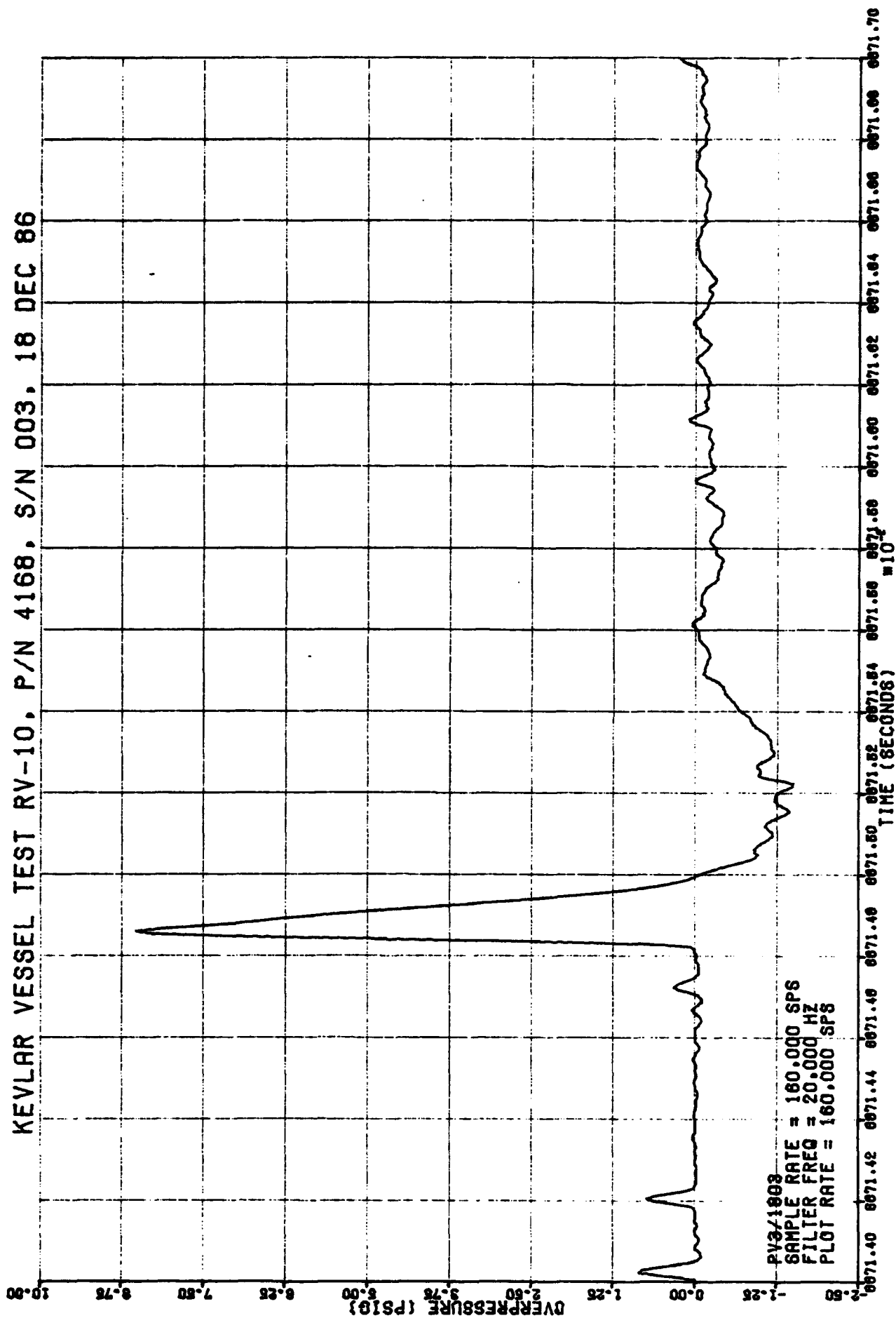
E.7.5   Post Test Inspection

The bikini gages and witness panels (used to collect fragments) were inspected. Some fragments penetrated the panels. The test stand was severely damaged. Test tank fragment locations in the test area were noted. Metal fragments were found as far as 500 feet from the test stand. This demonstrates the severe damage potential for total catastrophic failure of high pressure gas tanks. Photographs were taken.

Figures E-93, E-94 show photo views of the damaged test stand, Bikini gages, overpressure transducers, witness panels and fiber fragments. Photographs of typical metal fragments are given on Figures 2-13 and E-98. A typical fiber wrap fragment is shown on Figure E-95 and Figure E-96 shows a fragment embedded in a witness panel fifteen feet away from the test stand. Post test liner fragment debris are depicted on the photograph of Figure E-97.

Fig. E-93
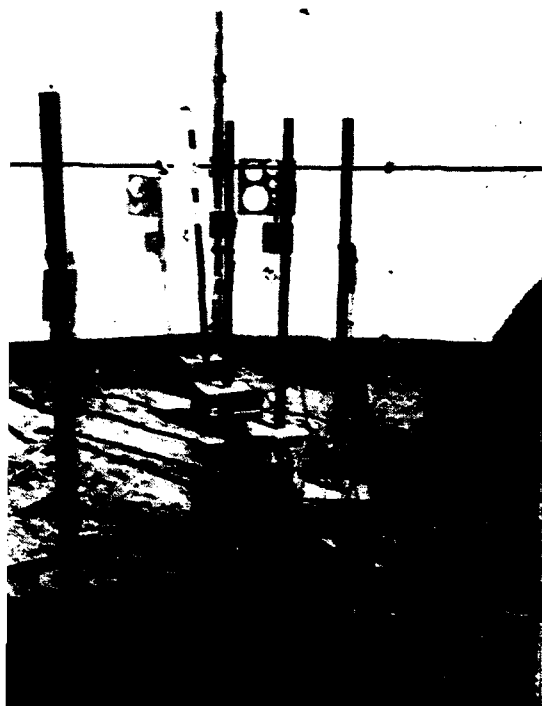
TEST RV-10, POST TEST VIEW OF DAMAGED TEST
STAND, BIKINI GAUGES, OVERPRESSURE
TRANSDUCERS AND WITNESS PANELS

Fig. E-94

TEST RV-10, POST TEST CLOSE UP VIEW OF
DAMAGED TEST STAND AND FIBER OVERWRAP

FRAGMENTS

TEST RV-10, FIBER OVERWRAP FRAGMENT

Fig.
E-95
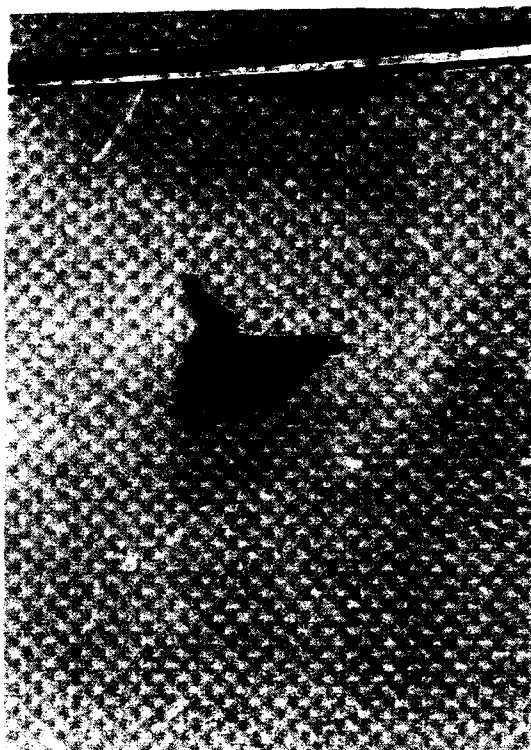
TEST RV-10, FRAGMENT EMBEDDED IN WITNESS PANEL

Fig.   E-96

E-164
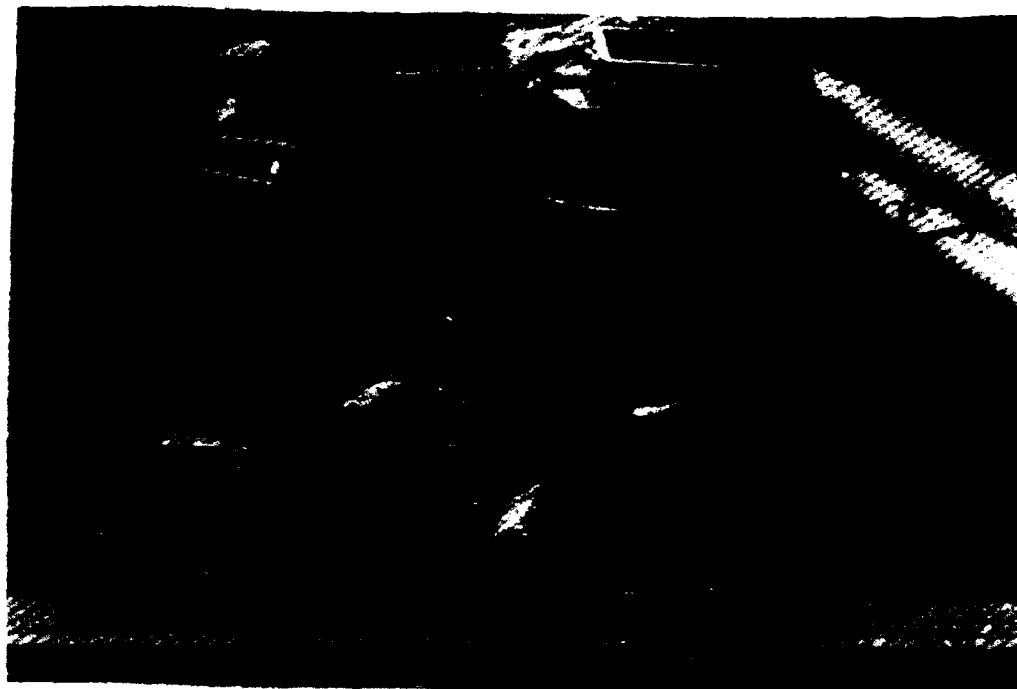
TEST RV-10, POST TEST LINER FRAGMENT DEBRIS

Fig. E-97
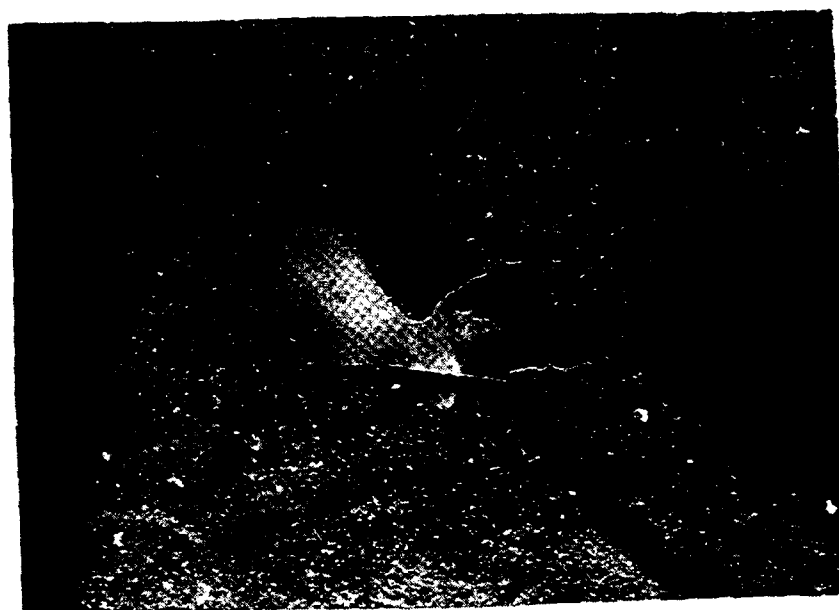
TEST RV-10, LINER FRAGMENT

Fig. E98

E.8   <u>RV-11 Test (16" φ)</u>

E.8.1   <u>Test Vessel Description</u>

- P/N E4168, S/N 004 Kevlar Overwrapped 301 Cryo CRES Composite Sphere Kevlar Fiber (less resin) Average Thickness = .130 (83% of Baseline Thickness)

- Metal Thickness = .049

- Inside Radius   = 7.64"

- Hydrogen Embrittlement Mode = Local Girth Weld Region

- Electrolyte Solution =

$$\frac{20 \text{ cc } H_2SO_4 + 980 \text{ cc Tap } H_2O}{1000 \text{ cc solution}}$$

- Solution Additive = 500 mg Sodium Arsenite

- Sensitize Liner Inside Surface (cold pickle)

- Charging Current Density = .006 amps/in^2 of surface to be embrittled

- Charging Time = 72 hours

- Hold Time Before Test = 2-1/2 hours

- Adcoat AC818T liquid maskant on areas not to be embrittled

Figure E-99 is a photograph of the instrumented composite tank mounted in the test stand. Strain gage, displacement gage, overpressure transducer and bikini gage instrumentation can be seen and readily identified in the photograph. Close up views of typical strain gage and thermocouple installations on the tank are shown in Figures E-100 and E-101.

Fig. E-99

TEST RV-11, STRAIN GAGE INSTALLATION
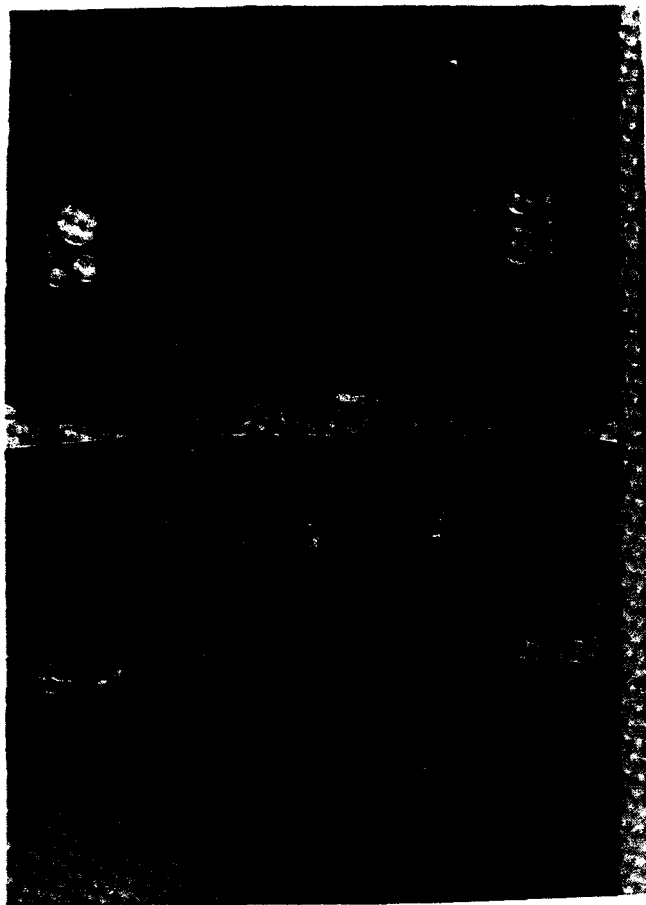
Fig. E-101

TEST RV-11, COMPOSITE TANK MOUNTED IN TEST STAND

Fig. E-100

E-168   TEST RV-11, STRAIN GAGE INSTALLATION

B.8.2

INSTRUMENTATION OBSERVATIONS (by Instr. Eng)

KEVLAR TREST 011, 1OCT87.   Project number 573000RV.

EXPERIMENTAL OBSERVATIONS.

Introduction. Vessel S/N 004, P/N E4168, was tested. It was a 16 inch diameter stainless steel sphere and had an 83% thinned Kevlar overwrap.   The vessel was hydrogen embrittled for about 1/2 inch about the girth.   It was tested in a vertical configuration.   The tank pressure was increased with pressure pulses, held for a while, then ramped up until catastrophic rupture of the liner and overwrap rapidly occurred.   Rupture of the tank generated a debris field with considerable content centered around the 6 o'clock leg; piezoelectric overpressure sensors and bikini gages registered a pressure bias toward the 2 o'clock leg.

Pressurization Ramp and Catastrophic Rupture. The vessel was pressurized with cool helium gas.   Initially, the pressure was increased from ambient pressure to about 200 psig during a cool- down period, which took about 2 minutes.   The tank was vented. The digital data system was started, and the tank pressure was kept at ambient pressure for 1.699764 seconds before pressure was increased with a series of 3 short pressure bursts, 1 long pressure burst, and another series of 7 short pressure bursts to the beginning of an 18.800094 second wide plateau, with a nominal value of 1401 psig.   At the end of the pressure plateau, a steady ramp of pressure was started at 41.599230 seconds, and the high frequency data system was started.   For the most part, the ramp of pressure was linear and progressed at a rate of 72.599637 psig/second (3274-2548 psig)/(65.099.592-55.099542 seconds).   The tank ruptured, and the main tank pressure transducer, PTANK/1901, failed at 69.399858 seconds, Failure of the other tank parameters quickly followed.   at = 3600 psi, — PTANK/1901 = 3647 psig.

Post-run Inspection. Witness panels and acoustic emission technology were not used.   Scattered about were remains of the vessel, including many metal fragments and loose Kevlar fibers. One Kevlar piece was found about 40 feet from the test site; it was a large piece - about 25% of the vessel.   This large piece did not degenerate into loose fibers, and the resin was still entact.   Some metal fragments were found about 500 feet from the site. A fragment distribution map was not made, but there seemed to be more pieces on the blacktop area near the adjacent C-D test complex and shop area, which is south-west of the test site, than in the desert area on the north side. Extensive damage to the vessel's instrumentation wiring and pressurization plumbing was observed.   The two displacement sensors used on this test were not recovered.   The sensors' 3" diameter reference disks were mounted on the vessel.   The disks were aluminum, and these disks were found 200 feet from the test site.   They were no longer flat, but had been bent around the sensors into a cup shape that even had the impression of the front of the sensor imbeded in the bottom of the cup.   The sensor support arms were found near the

1

mechanics' shop, which is 500 ft from the site. The over pressure sensors are discussed elsewhere.

IMPRESSIONS FROM THE DIGITIZED FM DATA.

<u>Strain Gages.</u>

Strain Gage Locations. The strain gages were located IAW ARDE drawing dated 9/2/87 J/N 42001-0-14, page 1 & 2. The even strain gages are perpendicular to the wrap, and the odd strain gages are parallel to the wrap. The previous test, testrv10, had the opposite assignments.

Strain Gage Temperature. Not shown on this print are the thermocouple locations. Their locations are shown by the following sequence: Field #/Thermocouple #/Nearest strain gage pair. 33/1/1,2; 9/2/5,6; 41/3/7,8; 36/4/9,10; 4/5/11,12; 44/6/15,16 (from page 1); 38/7/17,18; 6/8/19,20; 46/9/23,24 (from page 2). The 9 thermocouple loci form a family of curves with almost identical profiles. Collectively, the gages measured temperature behavior over a span between 78 and 119 degrees F, approximately. However, each gage didn't change much. The typical temperature variation didn't exceed 5 F degrees and reached its minimum temperature at the bottom of a very slowly formed single depression near the center of the locus. Of the 9 gages, 5 (55.5%) were measuring temperatures grouped between 78 and 87 degrees F, and 4 (44.4%) were measuring temperatures grouped between 94 and 119 degrees. Six (66.6%) finished above their initial conditions; two (22.2%) finished below their initial conditions; and one (11.1%) finished very near its initial condition. All had a slight depression in the middle of the graph. The vessel's temperature behavior is considered to be within normal limits.

Performance Summary. There were 23 strain gages recorded. All were functioning, and, during the initial conditions, had much better than reasonable noise floors. The noise floors are discused elsewhere under Noise Floors. All gages were destroyed as the tank ruptured.

Sign Convention. Positive strain gage polarity represents compression, and negative strain gage polarity represents tension.

Noise Floors. Except as noted elsewhere, the strain gage and other parameters' noise floors did not include major transverse or common-mode minus L(di/dt) transients, artifacts, crosstalk, atmospherics, noticeable RFI, intermodulation, spurious parasites, or sibilants. However, latent noise or data manifestations may be obscured in some parameters, and digital signal processing may be needed for signal enhancement. In general, the data appeared to be unbiased, precise and accurate. SG08/7108 had the noisiest initial condition, but it only amounted to about 4.5% of the channel's range

2

(.4X3000=1200;(1200/26666)X100%=4.5%).

Performance Exceptions.   Strain gage behavior was within normal
limits with only two exceptions.   SG17/7117 failed,   at tank
rupture, in the same manner as all the other strain gages; but it
did not show any change in strain when all the others changed at
6.93870 milliseconds,   which is the start of rupture.   Its
performance may be related to its location as it was located in
field 38 at the top of the vessel, and it was parallel to the
wrap. SG04/7104 failed almost immediately following the start of
rupture.

Strain Direction.   Disregarding the two exceptions, the remaining
21 gages exhibited similiar activity at the start of rupture.
The activity showed tension (negative polarity) strain by 19 of
the gages and compression strain (positive polarity) by 2 of the
gages before all gages are lost about 7 milliseconds after the
start of rupture.   The arithmetic mean of the net change in
strain for the 19 gages indicating tension amounted to about 3800
microinches/inch;   the   minimum   change   was   about   2300
microinches/inch for gage 10 and the maximum change was about
6000 for gage 8.   For comparison, it is interesting to note that
the strain gages for testrv9 also exhibited tension (negative)
strain activity,   and the changes were similiar to those changes
in testrv10, between 2100 and 7800 microinches/inch. The general
trend   of the tension strain is interesting and is discussed
under Pofile Categories.   The net change in strain for the 2
gages   registering   compression   was   only   +500   to   +600
microinches/inch.

Dynamic Performance.   All the loci had dynamic activity, which
presented as complex, small magnitude, damped oscillations.
Damping was completed within 5 milliseconds of the 7 millisecond
period preceeding rupture.   This behavior is considerably
different than that which was observed in testrv10.   In testrv10,
"...most (strain gage) graphs progressed into a steady but short
period of prominent undamped oscillation prior to rupture."

Profile Categories.   Based on their shape, the loci can be fit,
with considerable imagination, into either of two categories: the
slope-plateau (SP) category or the plateau-slope-plateau (PSP)
category.   Of the 19 gages sensing tension strain, 7 (36%) were
SP and 12 (63%) were PSP.   This behavior is different than that
which was observed in testrv10.   In testrv10, the strain gage
"...graphs enter into oscillation with a small compression
excursion; they reverse direction and continue with a tension
ramp,   with modulations by the oscillation, to burst." Although
there were osci..ations in testrv11, they were damped and not
nearly as great as in testrv10.

Strain Polarization.   Of the 19 gages, 11 are odd numbered
(parallel with the wrap) and 8 are even numbered (perpendicular
with the wrap).   Of the 11 parallel gages, 8 (72%) polarize
negatively at the start of rupture, and only 3 (27%) polarize
positively.   Of the 8 perpendicular gages,   only 3 (37.5%)

3

E-171

polarize negatively at the start of rupture, but 5 (62.5%)
polarize positively. At the start of rupture, this makes a total
of 11 (58%) polarizing negatively and 8 (42%) polarizing
positively. At rupture, 7 milliseconds later, only 7 (37%)
polarize negatively, and 12 (63%) polarize positively.
Speculations on the causes of this behavior are reserved. By
comparison, testrv9 had 66% of the gages registering tension,
which is slightly more than the 58% registering tension for
testrv11 at the start of rupture.

Statistical Analysis. Valid speculations about strain gage
behavior may involve biserial correlation of certain dichotomies
(positive or negative polarization) to assess their associations
(with wrap direction, etc.). For truly dichotomous
distributions, the phi coefficient can be used. Because some of
these dichotomous variables are really continuous (the magnitude
or duration of polarization, and the degree of wrap thickness,
location & direction, etc.) and normally distributed, tetrachoric
correlation may be involved. An expert statistician should be
approached with a clear statement of which variables and
associations are important if valid conclusions about some of
these data are to be obtained. An accurate evaluation of which
variables are really dichotomies and which are proportionally
continuous would also have to be prepared and passed to the
statistician.

Data Analyst's Comments. ITT, Richard M. Thomsen, states:

"Digital Data.

The data for SG24/7124 shows the burst occurring at 69.390
seconds (20:43:27.160 IRIG). The spike occurring at 69.408
seconds is only one data point and I would question its validity.
The strain gauge also shows a large shift at 54 seconds.

FM Low Frequency Data.

Four digitizing passes were done. Two Strain gauges on each of
the first three passes did not register, so the fourth picked
these up. All values should be aligned to the nearest tenth of a
millisecond. (For the first pass,) data was digitized at 1000
samples per second using a 100 Hz filter. SG03/7103 shows three
spikes several seconds before the burst. I have seen these same
type spikes on unrelated digitized FM data and would probably say
they are tape dropouts. SG04/7104 shows non-pressure related
stress changes starting at 64 seconds. SG08/7108 has several
shifts in strain. SG10/7110 has 60 Hz hum. So does SG17/7117,
DP01/8001 and DP02/8002. SG12/7112, SG14/7114, SG16/7116, and
DP02/8002 have sudden increases prior to the burst. SG15/7115
has an unusual downward, decreasing spike prior to the burst.
SG20/7120 has stress changes similiar to those of SG04/7104 prior
to burst.

FM High Frequency Strain and Displacement.

4

The sample rate restriction on the Lark drive limited the frequency response to 16 kHz. The roll-off characteristic of the Datum 1 kHz filters may be slow enough that higher frequencies come through. In fact, SG07/7101 shows a frequency of 21 kHz for a millisecond at 69.392 seconds.

The start of the burst occurred at 69.387 seconds (20:43:27.15743 IRIG) and ended with sharp changes in strain and displacment about 7.5 milliseconds later. Each item was aligned using the IRIG signal to the nearest hundredth of a millisecond."

Displacement Sensors.

General Behavior. Both displacement sensors worked very well, and they remained noise free. DP2/8002 started with an initial condition near 220 mils, went positive to near 238 mils, and then dropped to about 230 mils. DP1/8001 made a much larger excursion. It started with an initial condition near 217 mils and finally ended up near 112 mils. In other words, the gap sensed by DP2 had a net increase of about 10 mils, and the gap sensed by DP1 had a net decrease of about 105 mils. The start and end of the displacement sensors' activity correlates well with the strain gages.

The expansion of the vessel is best represented by DP12, Total (vessel horizontal diameter) Displacement, which is the sum of the two (girth) displacement sensors. The sum reflects both graphs' initial conditions, slopes, inflections and plateaus, etc., and must be used for correct interpretation of the total vessel displacement performance.

Noted in the loci sum is moderate smoothing of the dynamic constituents seen more prominently in the individual graphs. For example, the 250 Hz modulations are noticeably suppressed, and phase distortion is evident during the 3000 Hz modulations. Furthermore, the mean slope characterizing the prevailing decreasing trend increases about 31% over the mean slope seen in DP01/8001.

The dynamic variations seen by both displacement sensors between 69.3930 and 69.3940 seconds are phased in such a manner that the sum displays suppressed magnitude variations. The mean slope increases just prior to the onset of the variations and then decreases after the variation. The variation is probably valid, as it is about 3/4 the way through the 7 millisecond period of primary interest. Also, there is nothing to indicate the apparent mean slope changes are invalid. Destruction of the vessel is obvious and agrees with the PTANK/1901 graph.

Calibration Information. The zero and 0.250" calibration cuts are shown on the page just prior to the digital printout of the run data. The polarity is positive for the 0.250" calibration displacement. After the calibration, the sensors were not moved, and their initial conditions remain, as expected, near 0.250".

5

Description of Expected Performance. As the tank expands, the gaps get less, and the readings should decrease. The general trend for testrv9, and for testrv11, followed this logic, except for the variations discussed. The general trends of the data from the two sensors will not necessarily match.

Description of Actual Performance. For testrv11, DP01/8001 had a prevailing decreasing trend in the form of a negative slope with prominent modulations. The slope is slowly modulated by a 250 Hz damped oscillation, which deteriorates after several cycles. Riding on top of this carrier is another damped oscillation, seen more clearly by the other position sensor, that is oscillating near 3000 Hz and damps out after 6 cycles or 0.002 seconds.

Surprisingly, DP02/8002 increased slightly, after a very slight delay which contained no major modulations, and stayed above its initial condition in a rough plateau containing the heavily damped 3000 Hz frequency.

The frequency oscillations seen on the two graphs may be mutually related, but they are not necessarily in phase. The same frequency of oscillation is seen on both displacement sensors, and it is about 3000 Hz (3 cycles/0.001 seconds). This frequency may also be a component in the stain gage data, but it isn't immediately obvious on the graphs because of the complex nature of the frequency domain. Both displacement gages were lost when the tank ruptured and were not recovered, although the reference disks were found as discussed elsewhere. Not confirmed is the speculation DP01/8001 was located on the tank half nearest the black top. The still photos show excessive debris in this debris field, and this may be related to the fact DP01/8001 had a slope profile while DP02/8002 had a plateau profile.

IMPRESSIONS FROM THE QUICK-LOOK AND DIGITAL DATA ACQUISITION SYSTEM DATA.

Tank Pressure. PTANK/1901 was located on the top of the tank in the vent line. PVSOUT/1904 was also in the vent line, but it was located at the valve box about 15 feet from the tank. PTANK/1901 functioned as described under the Pressurization Ramp... paragraph.

The locations of the transducers was the same as test 10.

PVSOUT/1904 had readings that started about 10% higher than PTANK/1901, but changed quickly to about 20% lower for the remainder of the test. This graph's inspissated locus is due to a small amount of continuous noise, and there are numerous small magnitude bipolar spikes appearing about 1.2 seconds apart throughout the graph; the noise origins were not investigated as they do not appear to be insidious. The noise is probably not associated with the test item; it is most likely a systemic artifact recorded during data acquisition, although there is a small possibility it may be related to the data reduction process. The phase performance of PVSOUT/1904 was slightly

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behind PTANK/1901 which is consistent with the distant location of PVSOUT/1904. The general trends of both graphs agree, however.

It is interesting to note that when the tank failed, the data from the two transducers went in opposite directions. When the transducer at the tank was torn from the instrumentation line, its data abruptly went to positive full-scale overload following a very rapid rate of change. The PVSOUT/1904 transducer in the box wasn't damaged and reflects legitimate pressure loss in the line as it smoothly underwent a rate of change and progressed towards zero where it made a slight undershoot, inflected and quickly recovered without oscillation to its initial condition, which was slightly above the abscissa. This behavior is easily seen in the expanded graphs, but doesn't have much significance except to confirm the vessel's clinical performance and to verify the sensor locations.

SG24.

General Comments. The performance of SG24 is very interesting. This strain gage duplicated the tank pressure behavior, PTANK/1901, but there were some deviations particularly during the final pressurizing ramp prior to failure.

Phase Behavior and Frequency Response. Noted also is the phase behavior; the two graphs were very close together in the time domain although the sharp corners seen in the pressure graph were rounded in the strain gage graph and much less defined.

Behavior During the Final Pressure Ramp. The deviation during the final pressure ramp manifests itself in gross magnitude and slope changes. Several abrupt magnitude shifts are obvious. More obscure are the subtle changes in slope between the magnitude shifts. With a straight edge, follow the four or five slopes and note how the slopes get gradually less and less as the vessel weakens. The abrupt magnitude and slope behavior might be used in an alarm circuit to warn of impending failure of overwrapped vessels instead of more complicated non destructive methods such as acoustic emission. Unfortunately not all gages show this behavioral pattern. The pattern may be due to gage debonding, but it probably represents a weaking vessel.

Graph Expansion at Rupture. The 0 to 75 second plot was blown up between 69 and 70.5 seconds for a better look at the rupture point. A very small glitch was seen, and another graph blow up was made between 693 and 694.5E-1 seconds to look at the glitch. This graph has a locus progressing from a noise free initial condition to tension strain (negative polarity). The progression follows one smooth cycle of a 54.64 Hz oscillation distressed by the glitch seen as one negative paroxysm followed by an insipid minor variation. The glitch's magnitude is about 264 microinches/inch and represents only 0.099% of the full-scale range (26666 microinches/inch). As ITT indicated, it is only one data point wide and probably isn't significant although it occurs

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at the point of maximum interest.

Other Parameters. The performance of the other parameters was within normal limits; this was determined by a quick review of the graphs for items PHXIN/1902, PHXOUT/1900, PTRAIL/1903, THXIN/2100, TBALL/2211. TBSOUT/2210, TBSIN/2209, THXOUT/2101, TT1/2102, TT2/2103, TT3/2104, TT4/2105, TT5/2201, TT6/2202, TT7/2203, TT8/2204 and TT9/2205. The time code parameter, IRIG/3808, recorded satisfactorily.

IMPRESSIONS FROM THE OVERPRESSURE SENSORS.

Bikini Gages. A Bikini gage is one piece of bond paper compressed between two metal plates containing different sized round holes. The gages are aligned so the paper is perpendicular to the pressure source. Discrete pressure data can be obtained and is a function of the location of the damaged paper diaphrams. The approximate calibration is as follows for the indicated hole size using bond paper:

HOLE #	PSIG	SIZE
1	7.3	5/8
2	5.2	7/8
3	3.7	1-1/4
4	2.7	1-7/8
5	1.9	2-3/4
6	1.4	3-3/4
7	1.0	5-3/8

	2 o'clock	6 o'clock	10 o'clock
2'	all gone	all gone*	all gone
6'	all gone*	all gone	all gone*
10'	all gone	1 left	1,2,3 left
14'	1,2,3,4 left	1,2,3 left	1,2,3,4 left

* denotes those locations whose supports were tipped over by the overpressure blast.

From the above data, the 2 o'clock leg experienced greater than 7.3 psig at the 2, 6 & 10' locations and less than 2.7 psig at the 14' location. The 6 o'clock leg experienced greater than 7.3 psig at the 2 & 6' locations; less than 7.3 psig at the 10' location; and less than 3.7 psig at the 14' location. The 10 o'clock leg experienced greater than 7.3 psig at the 2 & 6 o'clock locations; less than 3.7 psig at the 10' location; and less than 2.7 psig at the 14' location.

The pressure bias for the 14' pressure data favors the 6 o'clock leg, and the bias for the 10' pressure data favors the 2 o'clock

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leg and, to a lesser degree, the 6 o'clock leg. These biases indicate there was an unequal pressure expansion at rupture, and the expansion favored the 6 and 2 o'clock positions. The 6 o'clock leg is the leg pointing towards the blacktop. This finding is consistent with the density and distribution of the debris field, discussed elsewhere.

Reconciliation of the bikini overpressures and bias observations using the results from the piezoelectric overpressure sensors reveals the overpressures were higher at four of the stations than the bikini gages indicated. The bias observations are similiar - both conclude there was excessive pressure near the 2 o'clock leg. The actual values measured were 4.28, 4.08, 7.83 & 15.50 psig for the preceeding 2.7, 3.7, 3.7 & 2.7 psig bikini entries in the comments following the bikini data.

It is not too suprising the bikini gages don't match the piezoelectric sensors. The calibrations listed above are not traceable. In fact, the source of calibration is unknown. The calibrations will vary depending on the type of paper (bond, vellum, carbon, rag, linen, etc.) and its thickness and water content, etc.

Piezoelectric Sensors. Ideally, each overpressure sensor located to measure pressure should respond to a passing pressure pulse with a characteristic graph. The graph's curve should have a prominent leading edge rising from a stable initial condition. The typical leading edge should polarize positively and rise to the curve's maximum peak pressure over a smooth and almost linear path. At the peak pressure, the curve should inflect, and, at this reversal, enter into a characteristic depolarization decay consisting of an almost linear component followed by a distorted exponential component that returns to below the initial condition with an undershoot, more fully described below, representing rarefaction and the start of the refractory period.

More often than not, the linear decay should gradually change into a sluggish curve containing one prominent inflection, forcing the plot into the opposite direction, but staying below the initial condition. Eventually, the pressure rarefaction should deteriorate completely, and the plot should return smoothly to the initial condition, ending the refractory period.

Modulations and variations in behavior are caused by sensor placement (parallel or perpendicular to the flow direction), reflections, pressure wave distortions, time constants, frequency response, particulate impingement, insulation resistance, short circuits, open circuits and gas cloud geometry, etc.

For this test, 12 sensors were recorded. Two sensor circuits were defective because of noise and were not evaluated, and they are discussed below (1803 & 1807). Of the 10 operating sensors, all exhibited profiles as described above with the following variations. Three had prominent peak distortion (1804, 1805 & 1812); four finished above their initial conditions (1802, 1804,

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1809 & 1811); three had a small amount of preliminary undershoot (1801,   1805 & 1806); four had moderate amounts of noise throughout the experiment (1802, 1805, 1806, 1808 & 1812); one had a moderate amount of noise, but the noise appeared only after the pressure pulse occurred (1809); one had a non-exponential decay (1801); and one had reduced rise time (1801). Except for the noise, these variations are, for the most part, within normal limits and can be justified as valid data.

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Shown in the table below are the:

Overpressure sensor item number
Peak values, psig
Time in seconds (in parenthesis)
Delta time, same leg, in seconds [in brackets]
Velocity, same leg, in ft/sec {in braces}

Note, the pressure values shown are the maximum pressures experienced, which is not necessarily the first peak measured; three items measured smaller peaks prior to the maximum peak; they were 1804 (0.99 psig @ 69.394756), 1810 (0.56 psig @ 69.394819) and 1811 (1.39 psig @ 69.394795):

	2 ft	6 ft	10 ft	14 ft
	1801	1802	1803	1804
2	123.33	15.65	----	4.28
o'clock	(69.395106)	(69.396294)	----	(69.403787)
	[0.001188]	[0.007493]	----	----
	{3367}	{1067}	----	----
	1805	1806	1807	1808
6	37.03	22.11	----	4.08
o'clock	(69.394800)	(69.396050)	----	(69.403174)
	[0.001250]	[0.007124]	----	----
	{3200}	{1123}	----	----
	1809	1810	1811	1812
10	30.99	18.07	.83	15.50
o'clock	(69.394219)	(69.396038)	(69.398900)	(69.401837)
	[0.001819]	[0.002862]	[0.002937]	----
	{2199}	{1398}	{1362}	

To easily visualize when the pressure peak passed each station and in what order, draw circles around each of the above 10 data groups and connect the circles in sequence according to time, starting with the 10 o'clock 2 foot sensor. The pattern progresses through the above data groups from bottom to top and through the 2, 6, 10 and 14 foot diameters in a left to right order. Note the maximum pressure peak always passed the stations in a 10, 6 and 2 o'clock order with no exceptions. If the order of arrival of the peak pressure is shown on a plan view of the facility (draw 4 concentric circles for the 2, 6, 10 & 14 ft diameters overlayed on a wye representing the 2, 10 and 6 o'clock legs), a reverse helix is formed; the helix winds its way outward in a counterclockwise direction through each station (skipping the 2 missing stations) in the 10, 6, 2 o'clock order already mentioned. The smaller pressure peaks seen on the three sensors discussed earlier do not enter into this reconciliation of maximum peak pressure.

Using this behavior as a premise to support the conclusion a major pressure release occurred whose location was biased away from the exact center of the vessel is one option. The

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center of the bias would be somewhere between the 10 and 6
o'clock legs. The helix propagation pattern and debris field
contents support this conclusion.

Another option would be a vessel spin mode, but this is unlikely
from a mechanical standpoint, and the motion picture films don't
back up this idea either; also, multiple pulses with decreasing
magnitudes would be seen by all the stations, and such a pattern
wasn't recorded.

Returning to the first option, a check on the velocities of
propagation of the wave front as it sequentially pasted the
sensors on each leg indicates the peak pressure's velocity
decreased as the propagation progressed. The following graph
shows the velocities, but they are plotted as if they were
measured halfway between the stations; for example, the table
shows the 10 o'clock, 2 ft velocity is 2199 ft/sec, but it is
graphed as being at 4 ft, which is halfway between 2 and 6 ft.
The graph isn't very accurate because it was fabricated using
Wordstar, and a curve in the 2-point 2 and 6 o'clock locus is
assumed because the 3-point 10 o'clock locus is curved. Draw
the graph using a French curve.

The ITT data analyst, Richard M. Thomsen states:

FM High Frequency Overpressures

The digitizing was done using a 16 kHz filter. The 20 kHz AC
calibration signal shows a rolloff of 14 db [(log 50)2-
    log(10)2*10) for PV01/1801. Timing was aligned using the IRIG
    signal to the nearest tenth of a millisecond.

    PV03/1803 was so noisy that the pulse was completely obscurered.
    The spikes at 69.4025 and 69.4035 arrive too late and are the
    wrong direction, so I would not consider them as the pressure
    pulse. PV07/1807 was too noisy to calibrate.

    A table of position vs overpressure (psig) is presented [...
    elsewhere] for comparison to the bikini gauges."

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E-180
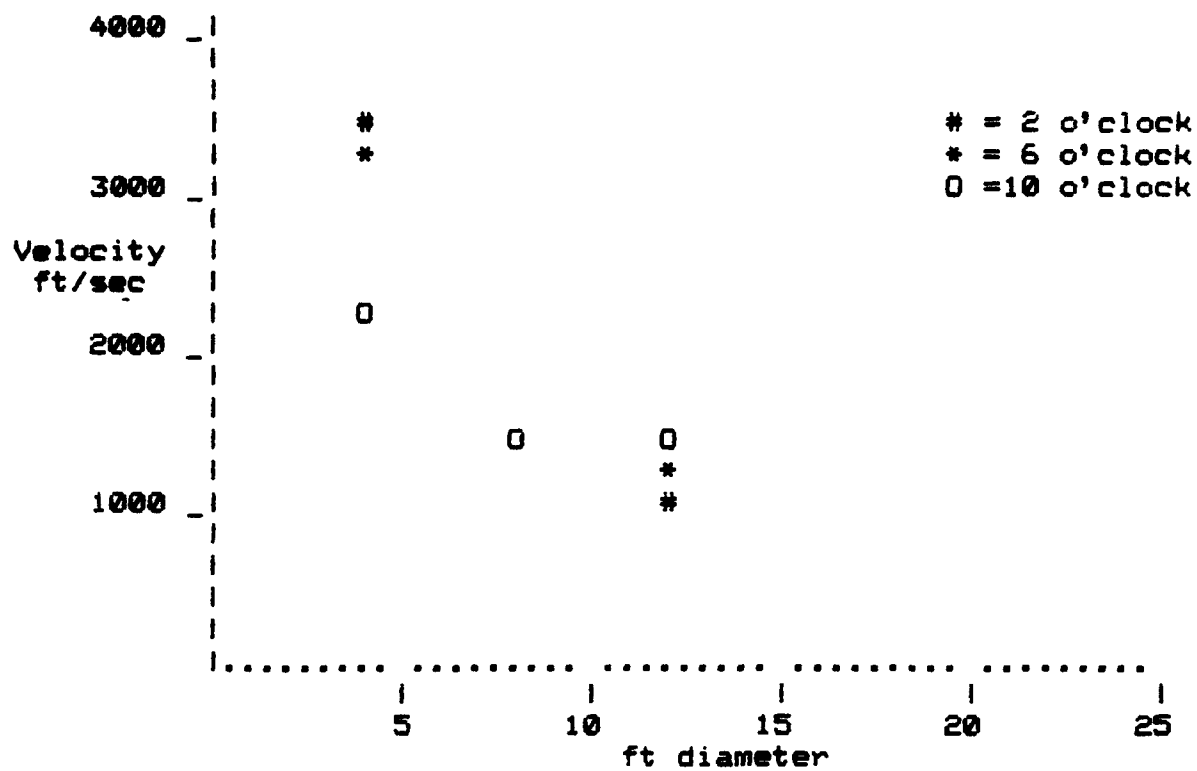
DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE.

Summary. An undated ARDE embrittlement procedure was followed; only the girth area for a width of about 1/2 inch was embrittled. Embrittlement was inhibited, where required, with a maskant. Embrittlement was started at 1130 hours on 28SEP87. The current level was 0.16 amperes. Seventy-two hours of embrittlement were completed at 1130 hours on 1OCT87; the tank was immediately moved from the shop embrittlement area to the test site, instrumented, hooked up and tested at 1315 hours on 1OCT87. The electrolyte was sulphuric acid; sodium arsenite was added as an enhancer.

Details. Tsgt Dan Hinkle reports "The vessel, ARDE P/N E4168, S/N 004, was pickled with a mixture of Nitric Acid (22% by volume), Hydrofluoric Acid (2% by volume), and potable tap water to equal one liter of total volume. Interior coverage was insured by rotating and tilting the vessel for a period of 10 minutes, including drain time. The vessel was rinsed with tap water, then alcohol, and dried with a slow purge of GN2 from 25 SEP87 to 28SEP87.

On 28SEP87 the vessel's interior was masked with Adcoat AC818T liquid maskant to just above the girth weld. The ARDE technical representative (Steve Berko) insured this level by using a boroscope. The vessel was dried with GN2 for one hour, then filled to 1/2 inch above the maskant with an electrolyte solution (20 ml of 97.3% sulphuric acid in water to equal 1000 ml total volume, with 500 mg per liter of sodium arsenite). The electrolyte was charged by 0.16 amps for a period of 72 hours. The vessel was drained, rinsed with water, then alcohol, and dried with GN2 for one hour prior to installation on the test stand. The vessel was installed and all instrumentation hook-ups were completed at 1315 hours.

The vessel's interior and boss temperatures were cooled with LN2 chilled gaseous helium with a maximum pressure of 250 psig by cycling the pressurization valve and the test article vent valves. When the interior gas and boss temperatures were reduced to 20 degrees F and 60 degrees F, respectively, a ramp up in pressure to 1400 psig was completed. During a short hold, the temperatures were checked to insure both temperature readings were within the 140 degree F called for in the test directive. The interior temperature had risen to 128 degrees F, and the boss temperature had risen to 77 degrees — both well within the parameter restrictions. A ramp up to 3700 psig was initiated whereupon the vessel burst at 3575 psig. At failure, the interior gas temperature was 30 degrees F, and the tank boss temperature was 67 degrees F."

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ADMINISTRATIVE INFORMATION.

Revision Record. Initial Issue: 28OCT87.   Revision A: 13NOV87; added text here and there.   Revision B: 4DEC87; errors fixed: 0.16 amperes was 1.6 amperes; text added to paragraphs: PVSOUT/1904; Displacement Sensors.   Revision C: 15DEC87; text added to paragraph Piezoelectric Sensors; other minor changes.

Filename: testrv11

Distribution: ARDE, Steve Berko, Dave Gleich
                     PI, Dr. Pius Chih Hsu Chao
              -      Aerospace Corp., Dr. Yen Pan
                     AFAL, Jim Miller, Dick Grove, John Marshall,
                         Dr. Tae-Woo Park
                     ITT, Richard Thomsen
                     PAFB, Pete Tadie

Office of Primary Responsibility.   USAF/AFAL/TOAE/Dick Grove/Edwards CA 93534.

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E.8.3   <u>Pressure and Strain Versus Time Plots</u>

Figures E-101 to E-107 are selected
measured pressure and fiber strain versus time

-    plots. Digital data are given on Figure
E-108, Strain gage locations are shown on Figure
E-109. Odd numbered strain gages were parallel
to the fiber wrap and even numbered strain gages
were perpendicular to the fiber wrap.

Fig. E-102

KEVLAR VESSEL TEST RV-11, P/N E4168, S/N 004, 01 OCT 87

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KEVLAR VESSEL TEST RV-11, P/N E4168, S/N 004, 01 OCT 87

Fig. E-103
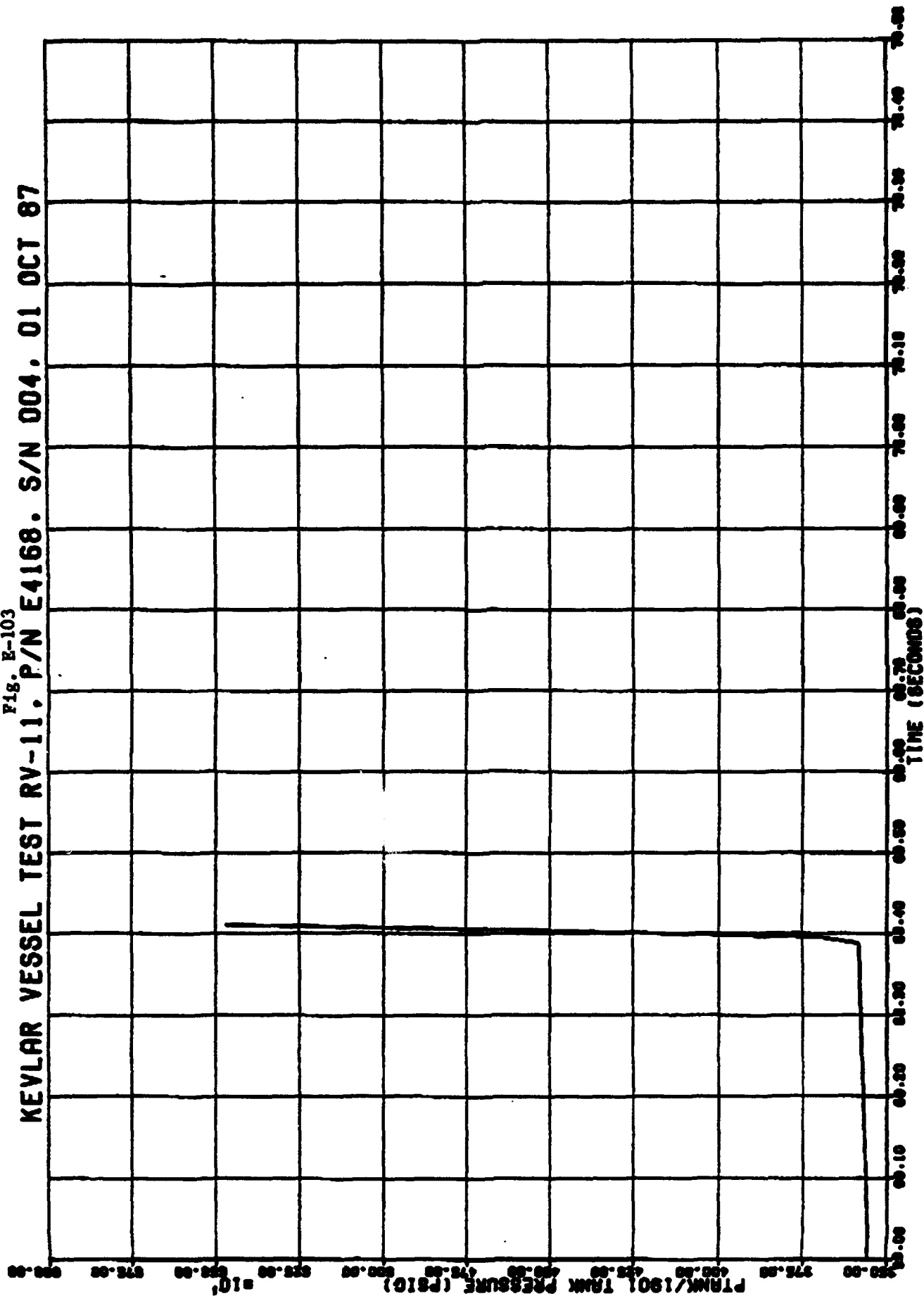
E-186

Fig. E-104

KEVLAR VESSEL TEST RV-11, P/N E4168, S/N 004, 01 OCT 87

KEVLAR VESSEL TEST RV-11, P/N E4168, S/N 004, 01 OCT 1987

Fig. E-105

Fig. E-106

TEST RV-11,   SG 4, 12, 20

N Equator Meridional

N Equator Meridional gages during pressure ramp-up.

Fig. E-107

TEST RV-11,   SG 8, 16, 24

S Pole Meridional

S Pole Meridional gages during pressure ramp-up.

TIME MILLISECONDS	SG24 U??/I	PTANK PSIG	PVSOUT PSIG	PHXIN PSIG	PHXOUT PSIG	PTRAIL PSIG
67399.848	-4277.	3441.	3399.	5189.	3801.	7317.
67599.360	-4245.	3456.	3414.	5201.	3815.	7317.
67699.312				5200.	3821.	7315.
67799.820	-4318.	3471.		5206.	3827.	7314.
67899.608	-4318.	3477.	3435.	5208.	3834.	7316.
68099.110	-4350.	3482.		5210.	3840.	
68199.852	-4436.	3500.		5221.	3853.	
68299.608						
68399.364	-4434.					
68499.074	-4365.					
68599.074	-4361.	3535.	3491.	5239.	3880.	7314.
68699.810	-4361.	3535.	3491.	5239.	3886.	7314.
68799.172	-4391.	3545.	3516.	5248.	3898.	7314.
68999.856	-4401.	3556.	3519.	5252.	3905.	7313.
69099.612		3561.		5253.	3911.	
69199.366	-4418.	3570.		5252.	3918.	
69299.124	-4425.	3577.	3537.	5259.	3924.	7313.
69399.858	-4508.	3697.	3541.	5265.	3931.	7312.
69499.614	-8916.		3283.	5265.	3001.	7311.
69699.126	-33404.		1974.	5182.	2245.	7307.
69799.880			781.	5078.	2087.	7304.
69899.636			203.	4933.	3745.	7300.
69999.372			-11.	4869.	4579.	7299.
70099.128			-109.	4961.	5266.	7306.
70199.862			-129.	5122.	5821.	7316.
70299.618			-93.	5447.	6290.	7326.
70499.130			-15.	6246.	6973.	7349.
70599.864			2.	6608.	7211.	7356.
70699.620			24.	6894.	7368.	7362.
70799.376			25.	7139.	7447.	7364.
70899.132			24.	7311.	7463.	7365.
70999.866			35.	7403.	7454.	7363.
71099.622			26.	7440.	7455.	7364.
71299.134			-17.	7441.	7455.	7364.
71399.868			20.	7429.	7456.	7364.
71499.624			23.	7423.	7456.	7363.
71599.380			20.	7420.	7455.	7365.
71699.136			27.	7414.	7457.	7364.
71799.070			21.	7413.	7455.	7364.
71899.626			20.	7410.	7455.	7365.
72099.138			29.	7414.	7455.	7365.
72199.872			30.	7415.	7455.	7364.
72299.628			15.	7417.	7454.	7364.
72399.384			17.	7412.	7455.	7364.
72499.140			13.	7413.	7455.	7364.
72599.874			33.	7418.	7454.	7365.
72699.630			20.	7411.	7455.	7364.
72899.142			27.	7417.	7454.	7364.
72999.876			-21.	7412.	7453.	7364.
73099.632			22.	7411.	7455.	7365.
73199.388			27.	7412.	7454.	7365.
73299.144			27.	7411.	7454.	7365.
73399.878			27.	7409.	7454.	7364.
73499.634			29.	7420.	7454.	7366.
73599.390			23.	7416.	7454.	7364.
73699.146			26.	7417.	7454.	7364.
73799.880			23.	7417.	7455.	7365.
73899.636			19.	7415.	7455.	7364.
73999.392			17.	7413.	7455.	7364.
74099.148			19.	7454.	7455.	7365.
74199.882			21.	7416.	7455.	7365.
74299.638			24.	7412.	7455.	7366.
74399.394			20.	7415.	7454.	7365.
74499.150			24.	7419.	7455.	7366.
74599.884			24.	7415.	7455.	7365.
74699.640			23.	7416.	7455.	7364.
74799.396			20.	7421.	7454.	7366.

FIGURE E-109 STRAIN GAGE LOCATIONS FOR TEST RV-11.
E-192

B.8.4   Blast Overpressure Data

Blast overpressure data have been given in section B.8.2 as part of "Instrumentation Observations". The maximum pressure measured by the piezoelectric sensors was 123.33 psig at the 2 foot radius for the 2 o'clock position. At 14 foot radius, the peak overpressure measured was still 4.28 psig at the 2 o'clock position and 15.50 at the 10 o'clock position. The pressure distribution was non-symmetrical due to non-symmetrical tank rupture, test rig and ground interference and reflected waves. Radii are measured from the tank center and clock coordinates define the angular position of sensors.

B.8.5   Post Test Inspection

The test stand and surrounding terrain were inspected for damage and tank fragments. Photographs were taken. The test stand was severely damaged and vessel remains (metal fragments and loose Kevlar fibers) were scattered over a considerable distance. Some metal fragments were found about 500 feet from the test

B-193

stand. Figure E-110 shows a close up photograph of the post test damaged test stand and a partial view of fragment distribution about the test site is given on the photograph of Figure E-111. The large number of fragments and their distribution over a large area extending far from the blast initiation site, coupled with the high blast overpressure discussed in E.8.4, demonstrates once again the high damage capacity of catastrophically failed high pressure gas tanks.

Fig. E-110

TEST RV-11, POST TEST VIEW OF DAMAGED TEST
STAND

Fig. E-111

TEST RV-11, FRAGMENT DISTRIBUTION

E-195

E.9   RV-12 TEST (22" ⌀)

E.9.1   Test Vessel Description

●P/N E4089-2 (Kevlar Overwrapped 301 Cryo CRES
  Composite Sphere)

●Kevlar Fiber (less resin) Average Thickness -
  .192

●Metal Thickness - .044

●Inside Radius - 10.3

●Hydrogen Embrittlement Mode - Local Boss/Head
  Weld Region

●Electrolytic Solution -

  $$\frac{20 \text{ cc } H_2SO_4 + 980 \text{ cc Tap } H_2O}{1000 \text{ cc Solution}}$$

●Solution additive - 500 mg Soldium Arsenite

●Sensitize Liner Inside Surface (cold pickle)

●Charging Current Density - .0068 amps/in^2 of
  surface to be embrittled

●Charging Time - 72 hours

●Hold Time Before Test - 3 hours

●Adcoat AC818T liquid maskant on areas not to be
  embrittled

     A pre-test photograph of the instrumented
tank mounted in the test stand is shown on Figure
E-112.
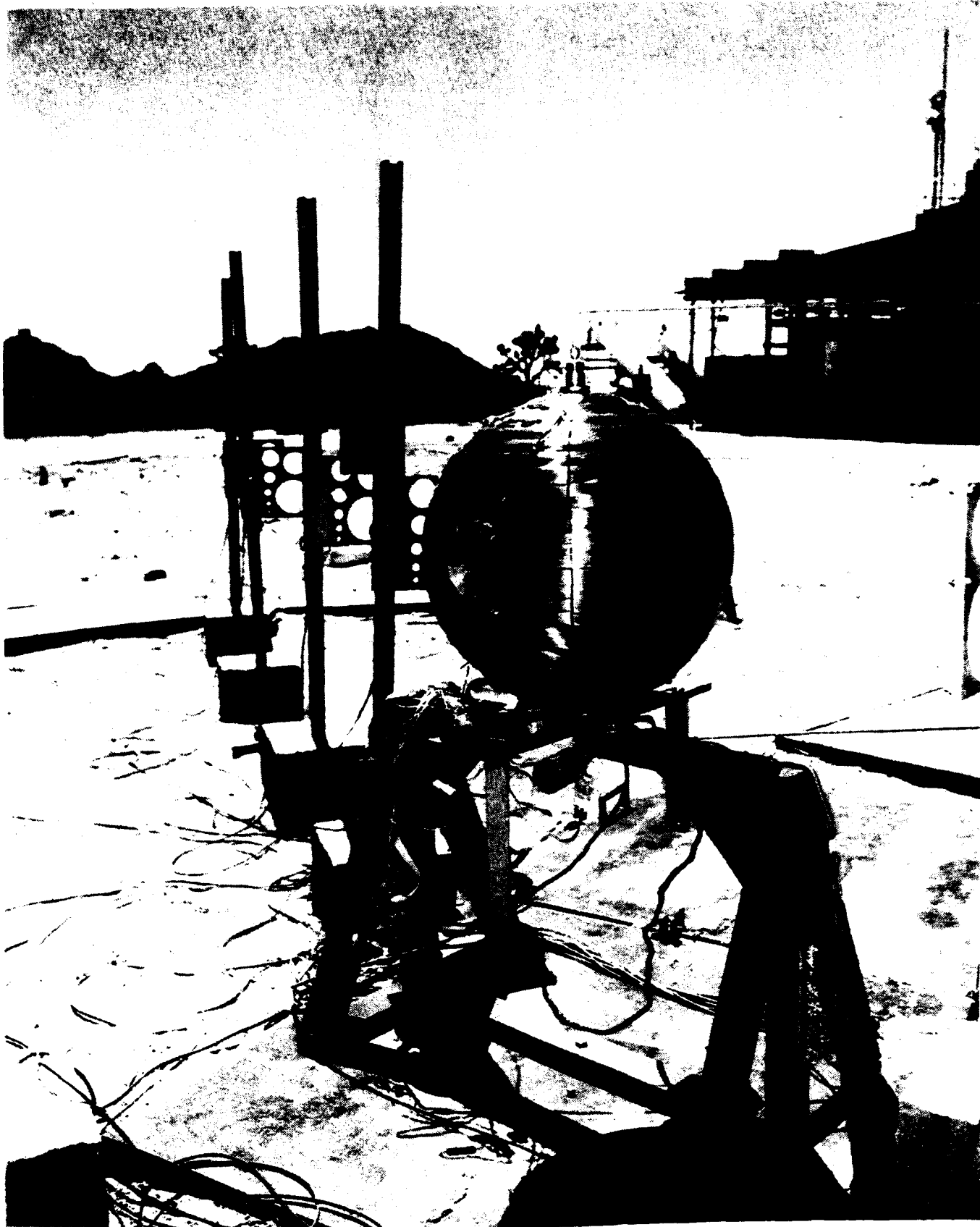
Fig. E-112   TEST RV-12, INSTRUMENTED TANK MOUNTED IN
TEST STAND

E-197

E.9.2   <u>Test Discussion</u>

Experiment RV-12 (boss/head weld hydrogen
embrittlement mode) demonstrated again a benign,
stable, leak tank failure type. Liner failure
pressure was low (2500 psig). This test was a
first time hydrogen embrittlement experiment with
the new larger tank/boss size/geometry and
resulted in too much hydrogen gas at the defect
(crack) tips leading to too low liner failure
pressure. No pressure fiber strain data was
obtained because the data acquisition system was
not operative at/near the 2500 psig liner failure
pressure as detailed in the AFAL letter and AFAL
Instrumentation observations of E.9.2.1.

The liner failure was verified by a post
test leak check at AFAL and further
proven/defined by viewing the multitude of cracks
on the die check enhanced inside liner surface of
the subsequently cut apart tank at ARDE. The
embrittled boss region was still attached to the
liner head - no boss/head separation occurred.
Figure E-113 shows a post-test close up view of
the tank on the test stand at AFAL. A small
local external fiber wrap damage in the boss/head

E-198

Fig. E-113 TEST RV-12, POST TEST CLOSE UP VIEW OF TANK

E-199

weld region can readily be seen. An overall view of the liner tangential and radial through cracks in the boss/head weld HAZ and a close-up view of the largest through crack (outlined by a black rectangular marking) are given on the photographs of Figure E-114 It is to be noted that the radial cracks are soon arrested by the ductile liner material outboard of the boss/head weld HAZ.

The local boss/head weld HAZ liner hydrogen embrittlement mode was investigated again in experiment RV-12A, discussed next. A lower liner hydrogen embrittlement current density was used to provide the desired higher liner failure pressure.
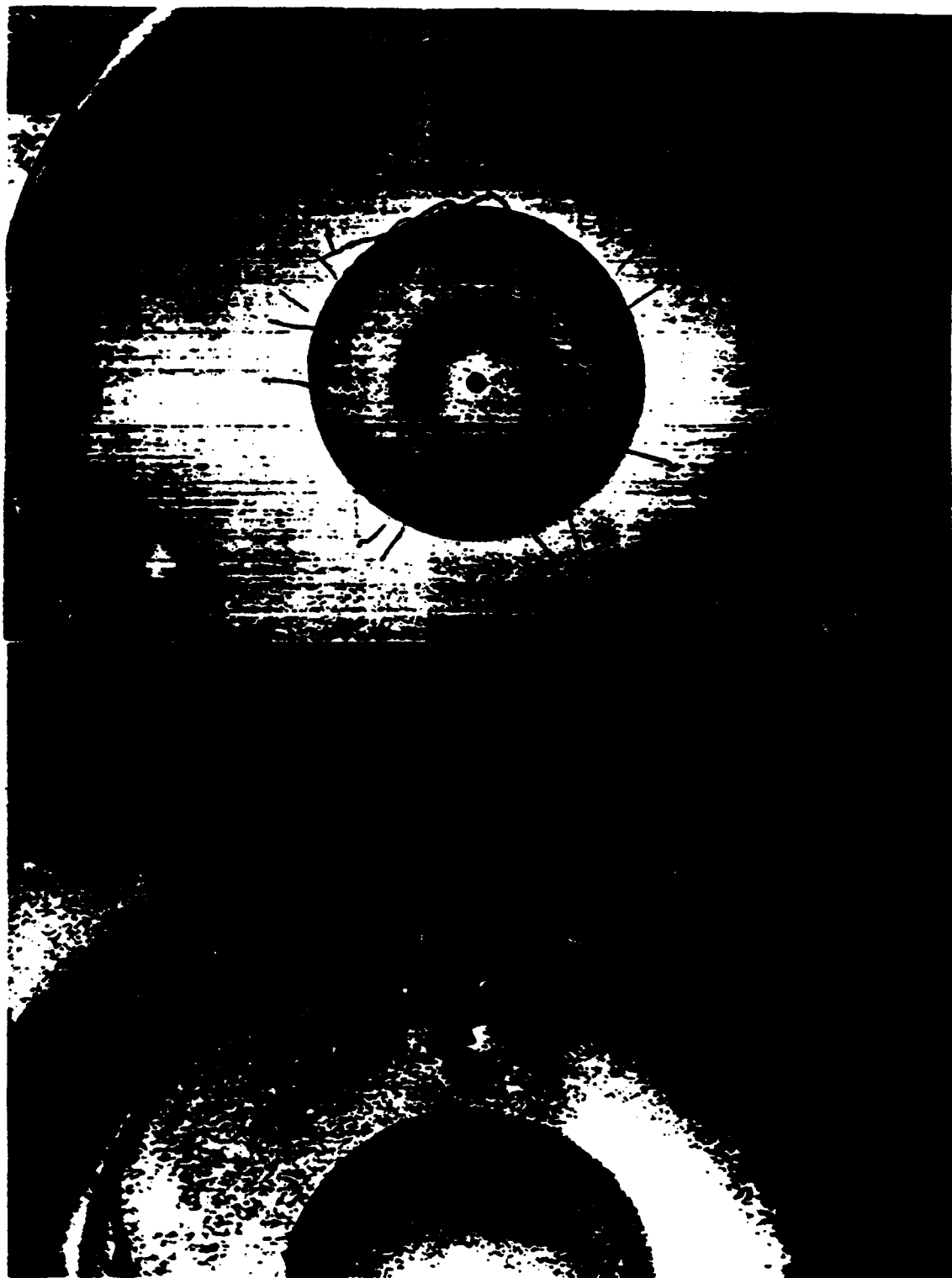
Fig. E-114   TEST RV-12, POST TEST EMBRITTLED LINER BOSS
REGION CRACKS

INSTRUMENTATION OPBSERVATIONS (by Instrumentation Eng.)

KEVLAR TEST 012, 26MAY88.   Project number 573000RV.

EXPERIMENTAL OBSERVATIONS.

Introduction. Vessel S/N 029. P/N E4089. was tested. It was a
22 inch diameter stainless steel sphere. The Kevlar overwrap was
100%.   The vessel was hydrogen embr. tled at the inlet boss.   It
was tested in a vertical configuration.

There were problems with this test.   It was necessary to conduct
an extended cool-down period because of an intermittent fast vent
valve.   Witnesses allege the tank unexpectedly leaked during the
hold period when critical data was not being acquired.   Fracture
verification could not be confirmed visually with the boroscope,
but a post-test leak check at 500 psig proved the vessel had
definitely fractured.   Damage to the Kevlar was limited; one
fiber bundle was frayed for about an inch long near the
embrittled flange; some resin debonding was evident near the
flange.

Pressurization Procedure.   The line was pressurized, vented and
a data Z-cal at zero line pressure obtained.   The data system was
started.   During cool-down, the fast vent valve was intermittent
and pressurization was very slow as the vessel gas temperature
had to be kept below 140 degrees F.   Cool-down took about one
hour until the vent valve problem cleared spontaneously; pressure
was increased to 2500 psig.   The data file had filled to
capacity, and a new data file was requested.   As soon as the new
data file started, the tank pressure had dropped to about 1200
psig, and attempts to repressurize failed. Data acquisition was
halted during a 3 minute discussion about what had happened and
what should be done.   It was decided not to repressurize again.
The data file was started again to capture the remainder of the
pressure decay.   It has not been determined how much data was
obtained with the FM tape data.

EMBRITTLEMENT PROCEDURE.   The ARDE embrittlement procedure dated
4MAY89 was followed.   The 22" diameter vessel was boss
embrittled.   Embrittlement was imhibited, where required, with a
maskant.   Embrittlement was started at 0800 hours on 16MAY88.
The current level was 0.160 amperes.   Sevent-two hours of
embrittlement was completed at 1115 hours on 19MAY88.   The tank
was immediately moved from the shop embrittlement area to the
test site, instrumented, hooked up, checked and pressure tested
at 1305 hours on 19MAY88.   The electrolyte was sulphuric acid.
Sodium arsenite was added as an enhancer.   The maskant was just
below the boss weld.

ADMINISTRATIVE INFORMATION.

Revision Record.   Initial issue: 25MAY88.   Revision A: 29AUG89:
Embrittlement Procedure added.   The word "leaked" was
"ruptured."

1

REPLY TO
ATTN OF: **TOAE**

SUBJECT: **Kevlar Test 012, 26 May 88 Project Number: 573000RV**

TO: **ARDE Inc.**
          500 Walnut St
          Norwood, New Jersey 07648

          Att: Mr Dave Gleich

          EXPERIMENTAL OBSERVATIONS.

Introduction. S/N 029. P/N E4089, was tested. It was a 22 inch diameter stainless steel sphere. The Kevlar Overwrap was 100 percent. The vessel was hydrogen embrittled at the inlet boss. It was tested in a vertical configuration.

There were problems with this test. It was necessary to conduct an extended cool-down period because of an intermittent fast vent valve. Witnesses allege the tank unexpectedly fractured during the hold period when critical data was not being acquired. Fracture verification could not be confirmed visually with the boroscope, but a post-test leak check at at 500 psig proved the vessel had definately fractured. Damage to the Kevlar was limited; one fiber bundle was frayed for about an inch long near the embrittled flange; some resin debonding was evident near the flange.

Pressurization Procedure. The line was pressurized, vented, and a data Z-cal at zero line pressure obtained. The data system was started. During cool-down, the fast vent valve was intermittent and pressurization was very slow as the vessel gas temperature had to be kept below 140 degrees F. Cool-down took about one hour until the vent valve problem cleared spontaneously; pressure was increased to 2500 psig. The data file had filled to capacity, and a new data file was requested. As soon as the new data file started, the tank pressure had dropped to about 1200 psig, and attempts to repressurize failed. Data acquisition was halted during a 3 minute discussion about what had happened and what should be done. It was decided not to repressurize again. The data file was started again to capture the remainder of the pressure decay. It has not been determined how much data was obtained with the FM tape data.

JIM MILLER, Project Manager

DICK GROVE, Instrumentation Engineer

E.10   RV-12A (22" φ)

E.10.1   Test Vessel Description

- P/N E4089-2, S/N 034 (Kevlar Overwrapped 301 Cryo
  CRES Composite Sphere)

- Kevlar Fiber (less resin) Average Thickness -
  .192

- Metal Thickness - .044

- Inside Radius - 10.3

- Hydrogen Embrittlement Mode - Local Boss/Head
  Weld Region

- Electrolytic Solution -

  $$\frac{20 \text{ cc } H_2SO_4 + 980 \text{ cc Tap } H_2O}{1000 \text{ cc Solution}}$$

- Solution Additive - 500 mg Sodium Arsenite

- Sensitize Liner Inside Surface (cold pickle)

- Charging Current Density - .0042 ma/in^2 of
  surface to be embrittled

- Charging Time - 72 hours

- Hold Time Before Test - 2-3/4 hours

- Adcoat AC818T liquid maskant on areas not to be
  embrittled

A photograph of the test tank being charged with hydrogen gas during the pre-test hydrogen embrittlement mode is shown on Figure E- 115. Figure E-116 is a pre-test photograph of the test tank mounted in the test stand, showing strain gage, bikini gage and blast overpressure sensor instrumentation. A view of Area 1-52D test pad showing the motion picture camera tower stations is given on the photograph of Figure E-117.

E-205
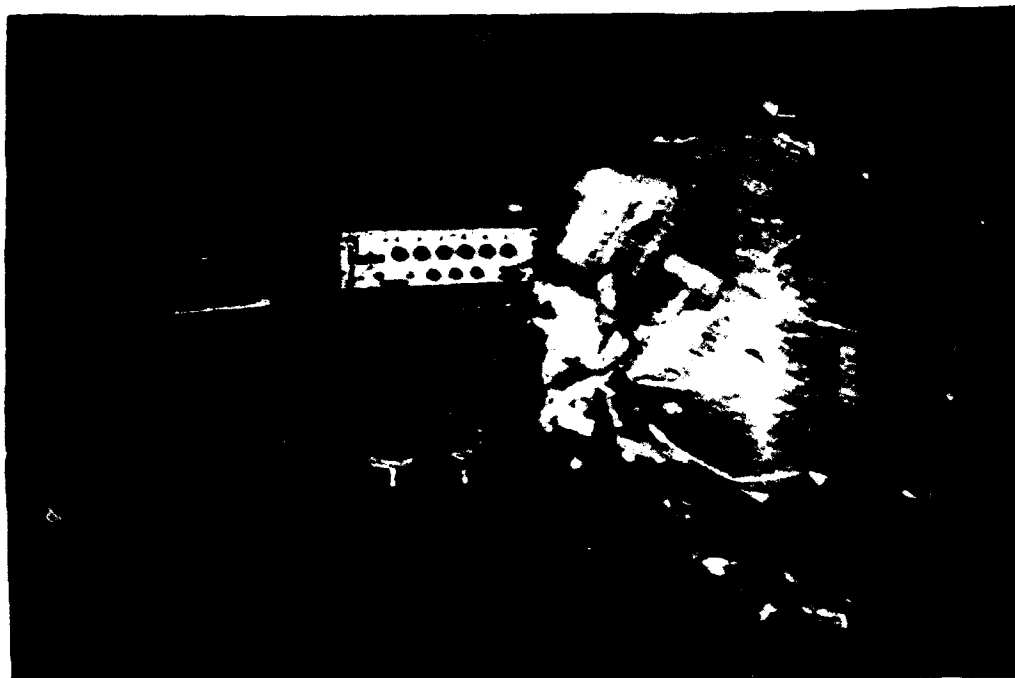
Fig. E-115

TEST RV-12A, PRE-TEST LINER HYDROGEN
EMBRITTLEMENT MODE

Fig. E-116
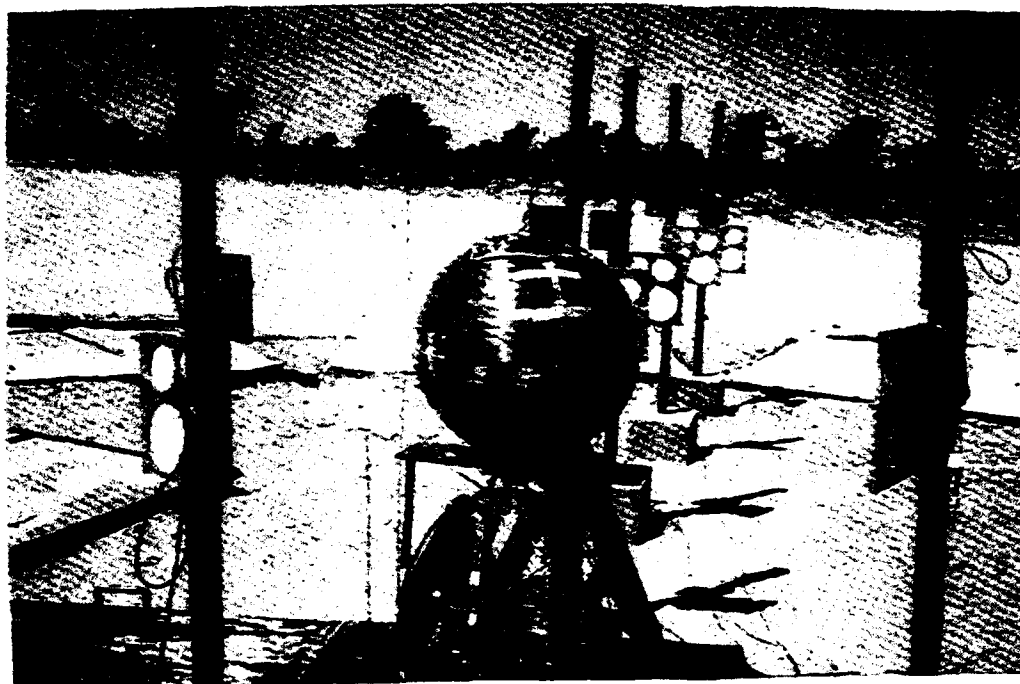
TEST RV-12A, INSTRUMENTED TANK MOUNTED IN
TEST STAND

Fig. E-117 TEST RV-12A, TEST AREA WITH CAMERA TOWER

Strain Gages.

Strain Gage Locations. The strain gages were located IAW ARDE drawing dated 3/6/89, Revision A. The even strain gages are perpendicular to the wrap, and the odd strain gages are parallel to the wrap.

Strain Gage Temperature. Not shown on this print are the thermocouple locations. See the Instrumentation Specification Sheet for the locations and item numbers. The 5 thermocouple loci form a family of curves with almost identical plateau profiles. Collectively, the gages measured temperature behavior over a span between ____ and _____ degrees F, approximately. However, each gage didn't change much during the plateau, and the typical plateau temperature variation didn't exceed about 5 F degrees. This small variation was also seen on test 11. Two thermocouples, TT3/2104 and TT4/2105 dropped rapidly at leak. Thermocouple TT5/2201 dropped slightly at leak, and the others remained steady. The vessel's temperature behavior is considered to be within normal limits, and it wasn't investigated with further detail.

Performance Summary. There were 23 strain gages recorded, and 21 functioned, although several had little activity and some had noise spikes. During the initial conditions, all gages had much better than reasonable noise floors. The noise floors are discussed elsewhere under Noise Floors. None of the strain gages were destroyed at tank leak. Two data passes were made. The first was done at 1000 SPS with a 100 Hz filter. The second was done at 128,000 SPS with a 20,000 Hz filter.

Sign Convention. Positive strain gage polarity represents compression, and negative strain gage polarity represents tension.

Noise Floors. Except as noted elsewhere, the strain gage and other parameters' noise floors did not include major transverse or common-mode minus L(di/dt) transients, artifacts, crosstalk, atmospherics, noticeable RFI, intermodulation, spurious parasites, or sibilants. However, latent noise or data manifestations may be obscured in some parameters, and digital signal processing may be needed for signal enhancement. In general, the data appeared to be unbiased, precise and accurate. SG16 was the noisiest but this is a judgement call as several others had some noise also.

Performance Exceptions. Strain gage behavior was within normal limits.

Dynamic Performance, Profile Categories, Strain Polarization. The general trend for the active strain gages was a tension strain polarization pattern proportional to vessel pressure. SG behavior was similiar to previous tests. High frequency dynamic data included oscillations at leak noted by the analyst on SG01, 08 and 13.

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Maximum SG Values and Performance Trends. The following codes are used below:

NWNL   noise within normal limits
GRZ   good return to zero
ARZ   approximate return to zero
NRZ   no return to zero
C   compression strain
T   tension strain
NTE   not to exceed
OSC   oscillation (See ITT text for frequency)
Unipolar: data predominately in one direction.

Bipolar: data in both directions but not necessarily evenly balanced between polarities. In most cases, the data carrier was unipolar in tension but contained bipolar compression excursions.

Units for strain values are in microinches/inch

SG01 Unipolar. T NTE 12,500: NWNL. OSC.
SG02 Bipolar, minor C, T not to exceed 6000, NWNL prior to leak.
SG03 -
SG04 Bipolar, major C NTE 5200, T NTE 3000, NWNL prior to leak.

SG05 Unipolar, T only NTE 3000, NWNL but some spikes, NRZ.
SG06 Unipolar, all T NTE 7500, NWNL prior to opening up, NRZ.
SG07 Unipolar, all T NTE 5000, NWNL but xome spikes, NRZ.
SG08 Bipolar, major C NTE 2500, T NTE 5000, NWNL but some spikes, NRZ, OSC.

SG09 Unipolar, all T NTE 7500, NWNL, NRZ, OSC.
SG10 Bipolar, major C NTE 3700, minor T, NWNL, GRZ.
SG11 Bipolar, minor C, T NTE 1/3 of 2500, NWNL, NRZ.
SG12 Bipolar, minor C. T NTE 1/3 of 2500, NWNL, NRZ.

SG13 Bipolar, minor C, T NTE 3/4 of 2500, NWNL, NRZ.
SG14 Bipolar, minor C, T 7500, NWNL, NRZ, OSC.
SG15 Unipolar, minor T bump of short duration NTE 1/3 of 2500, NWNL, ARZ.
SG16 No change. NWNL except for major noise spikes.

SG17 No change. NWNL.
SG18 No change, NWNL.
SG19 Bipolar, minor C, T NTE 5000, NWNL, NRZ.
SG20 Bipolar, major C&T excursions NTE 7500 pk-to-pk. NWNL, GRZ.

SG21 No change, NWNL.
SG22 -
SG23 Unipolar, T less than 2500, NWNL, ARZ.

Performance Summary: Seven of the 23 channels (30%) recorded unipolar data. Ten of the 23 channels (43%) recorded bipolar data. Three of the 23 (13%) recorded no change. The maximum unipolar strain was recorded by SG01 as tension, not to exceed 12,500 microinches/inch. The maximum bipolar strain was recorded by SG14, about 7500 microinches per inch, although it

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E-210

was mostly unipolar in nature. SG20/7120 could be considered as somewhat representative of typical strain gage performance: it tracked the vessel pressure, contained compression data as well as the predominate tension data, returned to the initial condition zero value, and did not have any oscillations, noise spikes or drop outs. Phase information correlates well for some items such as SG15 & SG11. Phase information on other parameters is shifted, such as SG19 & 20, where polarity is reversed on one excursion as well, making the observer wonder if such graphs are phase related at all. The above information was determined by inspecting the graphs and may contain subjective errors.

Statistical Analysis. Valid speculations about strain gage behavior may involve biserial correlation of certain dichotomies (positive or negative polarization) to assess their associations (with wrap direction, etc.). For truly dichotomous distributions, the phi coefficient can be used. Because some of these dichotomous variables are really continuous (the magnitude or duration of polarization, and the degree of wrap thickness, location & direction, etc.) and normally distributed, tetrachoric correlation may be involved. An expert statistician should be approached with a clear statement of which variables and associations are important if valid conclusions about some of these data are to be obtained. An accurate evaluation of which variables are really dichotomies and which are proportionally continuous would also have to be prepared and passed to the statistician.

Data Analyst's Comments.

"[ITT] 15MAY89 DATA ANALYST [Richard Thomsen] COMMENTS. The FM strain gauge data was digitized at 1000 SPS, using an 100 Hz filter. The IRIG time signal was used to align the time scale to within 0.00025 seconds.

Almost all of the plots show spikes that are probably tape drop-outs.

SG03/7103 and SG22/7122 were bad for the whole test.
SG09/7109 was bad until 184 seconds.
SG18/7118 was bad from 159.4 to 166.7 seconds.
SG08/7108, SG12/7112, SG14/7114 and SG16/7116 showed shifts in strain level prior to the burst.

Several of the gauges showed ringing after the burst."

"[ITT] 25JUL89 DATA ANALYST [Richard Thomsen] COMMENTS. The IRIG time signal was used to align the data to the nearest 10 microseconds. This was due to the distorted shape of the IRIG signal with very sharp spikes.

Strain gauges SG03/7103 and SG22/7122 were bad [no graphs].

SG01 goes bad at 286.887 seconds.
SG02 goes bad at 286.888 seconds.

4

SG06 goes bad at 286.887 seconds.
SG16 has noise spikes.
SG01 has an interesting 19kHz ring.
SG08 has an interesting 25kHz ring.
SG13 has an interesting 22kHz ring.
SG16, 17, 18, and 21 show little change.

The overpressures PV01/8901 and PV12/8912 had no change so
processing was only done on PV12, as it may show electrostatic
discharge."

End of ITT text.

IMPRESSIONS FROM THE QUICK-LOOK AND DIGITAL DATA ACQUISITION
SYSTEM DATA.

Tank Pressure. PTANK/1901 was located on the top of the tank in
the vent line. PVSOUT/1904 was also in the vent line, but it was
located at the valve box about 15 feet from the tank. PTANK/1901
functioned as described under the Pressurization Ramp...
paragraph.

The locations of the transducers was the same as test 10.

PVSOUT/1904 data were similiar to PTANK/190 except for the
reduced frequency reponse because of the long pressurization
line.

SG24. SG24 tracked the vessel pressure profile with corrections
for polarity, etc. This parameter, as in the previous tests, was
only recorded on the DACS for quick-look purposes.

General Comments. The performance of SG24 is very interesting.
This strain gage duplicated the tank pressure behavior,
PTANK/1901, but there were some deviations particularly during
the final pressurizing ramp just prior to failure.

Phase Behavior and Frequency Response. Noted is the phase
behavior; the two graphs were very close together in the time
domain.

The graphs were expanded at leak to enhance the details at leak.
SG24 at leak shows about a cycle and a half of oscillation, which
is not seen on the tank pressure graph.

Other Parameters. The performance of the other parameters was
within normal limits; this was determined by a quick review of
the graphs for items PHXIN/1902, PHXOUT/1900, PTRAIL/1903,
THXIN/2100, TBALL/2211. TBSOUT/2210, TBSIN/2209. The IRIG Time
Code, IRIG/3808 TIMING, recorded satisfactorily and can be
referenced to the motion picture data.

IMPRESSIONS FROM THE OVERPRESSURE SENSORS.

Bikini Gages. A Bikini gage is one piece of bond paper

5

E-212

comoressed between two metal plates containing different sized round holes. The gages are aligned so the paper is perpendicular to the pressure source. Discrete pressure data can be obtained and is a function of the location of the damaged paper diaphrams. The approximate calibration is as follows for the indicated hole size using bond paper:

HOLE #	°SIG*	SIZE	PSIG**
1	7.3	5/8	4.4
2	5.2	7/8	3.3
3	3.7	1-1/4	2.4
4	2.7	1-7/8	1.7
5	1.9	2-3/4	1.25
6	1.4	3-3/4	----
7	1.0	5-3/8	----

*The source for this calibration data is unknown, but these data have been used since at least 1964 by the Astronautics Laboratory. ***The source for these calibration data is from a report THEORY, CALIBRATION,. AND USE OF DIAPHRAGM BLAST METERS by W. T. Read, Division 2 National Defense Research Committee of the Office of Scientific Research and Development, NRDC Report No. A-392, OSRD Report No. 6463, Figure 18, Page 27, DEC45; this report was obtained from the Naval Surface Weapons Center, Silver Springs MD and was referenced in footnote (2) on page 3 of another report, OPERATION SANDSTONE JOINT TASK FORCE SEVEN TASK GROUP 7.1 BLAST MEASUREMENT SECTION, LAJ-8, PART II, Chapter 5.1, USE OF FOILMETERS ON OPERATION SANDSTONE, prepared by J. J. Meszaros and J. F. Moulton, Jr., 7JUN48, Fort Shafter, Oahu, T. H. This report indicates "For a considerable number of years air blast pressure measurements were made with the Aberdeen paper meter. The measurements obtained gave some indication of the peak pressure present. Early in the war Princeton University, under the auspices of NDRC, conducted an extensive experimental study. The primary results of these basic experimental sudies..." [are shown in footnote (2) discussed above]. It is not clear when the terms Bikini and Aberdeen were first used to designate diaphragm overpressure sensors. Nevertheless, the gages were used at Bikini [atoll in the N Pacific, Marshall Islands] in the 1946 atomic bomb tests (Crossroads Project) and again at Eniwetok in 1948 (Sandstone Project) and again in 1951 (Greenhouse Project). Most of the above information came from the DoD Nuclear Information and Analysis Center (DASIAC) on 12MAY88 and is the result of a lead provided by HQ/BSD/MYEB/Lt Col Don Gage to AL/TOAE/Dick Grove in FEB88. [Editor's Note: HQ/BSD was HQ/BMO prior to 21APR89 and AL was AFAL prior to 21APR89 and AFRPL prior to 22MAR87].

Reconciliation of the bikini overpressures and bias observations using the results from the piezoelectric overpressure sensors reveals overpressures sufficient to burst the paper diaphrams

6

were not reached. All of the paper diaphrams were intact.

Piezoelectric Sensors.

There was no overpressure pulse. Overpressure channel PV12 was temporarily assigned to record any electrostatic discharge (ESD) on the exterior of the Kevlar case, but the channel contained no noticeable ESD data. This crude, point contact measurement was done to rule out Kevlar as an ESD generator. In an unrelated experiment, significant ESD was seen by a similiar parameter during rapid pressurization of a Peacekeeper case, and the Kevlar was only one of several possible unidentified contributors. The observation of no ESD is probably correct in this experiment, but should be investigated further, for ESD is a major problem in the [rocket] inventory.

As indicated in earlier experiments, the overpressure sensors, if used, would have behaved as follows:

Ideally, each overpressure sensor located to measure pressure should respond to a passing pressure pulse with a characteristic graph. The graph's curve should have a prominent leading edge rising from a stable initial condition. The typical leading edge should polarize positively and rise to the curve's maximum peak pressure over a smooth and almost linear path. At the peak pressure, the curve should inflect, and, at this reversal, enter into a characteristic depolarization decay consisting of an almost linear component followed by a distorted exponential component that returns to below the initial condition with an undershoot, more fully described below, representing rarefaction and the start of the refractory period.

More often than not, the linear decay should gradually change into a sluggish curve containing one prominent inflection, forcing the plot into the opposite direction, but staying below the initial condition. Eventually, the pressure rarefaction should deteriorate completely, and the plot should return smoothly to the initial condition, ending the refractory period.

Modulations and variations in behavior are caused by sensor placement (parallel or perpendicular to the flow direction), reflections, pressure wave distortions, time constants, frequency response, particulate impingement, insulation resistance, short circuits, open circuits and gas cloud geometry, etc.

DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE. The ARDE embrittlement procedure dated 21MAR89 was followed. The 22" diameter vessel was boss embrittled. Embrittlement was inhibited, where required, with a maskant. Embrittlement was stared at 0800 hours on 3APR89. The currrent level was 0.055 amperes, a significant decrease from the 0.160 amperes used on test 12. Seventy-two hours of embrittlement were completed at 1110 hours on 6APR89. The tank was immediately moved from the shop embrittlement area to the test site, instrumentd, hooked up, checked and pressure tested at 1235 hours on 6APR89. The

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electrolyte was sulphuric acid.   Sodium arsenite was added as an enhancer.   The maskant was just below the boss weld.

ADMINISTRATIVE INFORMATION.

Revision Record.   Initial Issue: 28OCT87.   Revision A: 13NOV87: added text here and there.   Revision B: 4DEC87: errors fixed: 0.15 amperes was 1.5 amperes; text added to paragraphs: PVSOUT/19&4; Displacement Sensors.   Revision C: 15DEC87: text added to paragraph Piezoelectric Sensors; other minor changes. Revision D: 3May88: minor changes.   Revision E: 29AUG89: minor changes and some additions; embrittlement procedure added; current level added. ITT comments added.   Distribution List changed.

Filename: testrv13

Distribution: ARDE, Aris Escolona, Dave Gleicn
                       PI. Dr. Pius Cnih Hsu Chao
                       Aerospace Corp., Dr. Yen Pan
                       AFAL, Jim Miller, Dick Grove,
                          Dr. Tae-Woo Park
                       ITT. Ricnard Thomsen
                       PAFB, Pete Tadie
                       HQ/BSD/MYEB/Lt Col Don Gage

Office   of   Primary   Responsibility.   USAF/AFAL/TDAE/Dick Grove/Edwards CA 93534.

8

B-215

E.10.3   Pressure and Strain Versus Time Plots

Figures E-118 to E-129 give pressure versus time and selected strain versus time plots. Strain gage locations are sketched on Figures E-130. Odd numbered gages are parallel to the fiber wrap and even numbered gages are perpendicular to the fiber wrap. The photograph of Figure E-132 shows test control console activity in the test control building during the test.

E.10.4   Post Test Inspection

The tank was first inspected on the test stand immediately after the test. The tank fiber shell was intact. Some exterior fiber damage in the vicinity of the hydrogen embrittled boss and to a lesser extent near the other boss, were observed as shown in the photographs of Figures E-133 and E-134. Liner failure was verified by a leak check. The test tank was shipped to ARDE where it was cut apart and the liner inside surface was die checked and photographed. The E-216 liner was in one piece. The tangential

E-216

Tank pressure
Test 12 A

TEST 12A

Fig. E-118

E-217

Fig. E-119

KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 25APR89

KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 06APR89

Fig. E-120

SAMPLE RATE = 320.000 SPS
FILTER FREQ = 40.000 HZ
PLOT RATE = 320.000 SPS

6001/7101

STRAIN (UIN/IN)

TIME (SECONDS)

E-219

KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 25APR89

B-121

STRAIN (UIN/IN) *10²

TIME (SECONDS)

S002/7102
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 1000 SPS

E-220

Fig. E-122
KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 06APR89

S002/7102
SAMPLE RATE = 320,000 SPS
FILTER FREQ = 40,000 HZ
PLOT RATE = 320,000 SPS

STRAIN (UIN/IN)

TIME (SECONDS)

E-221
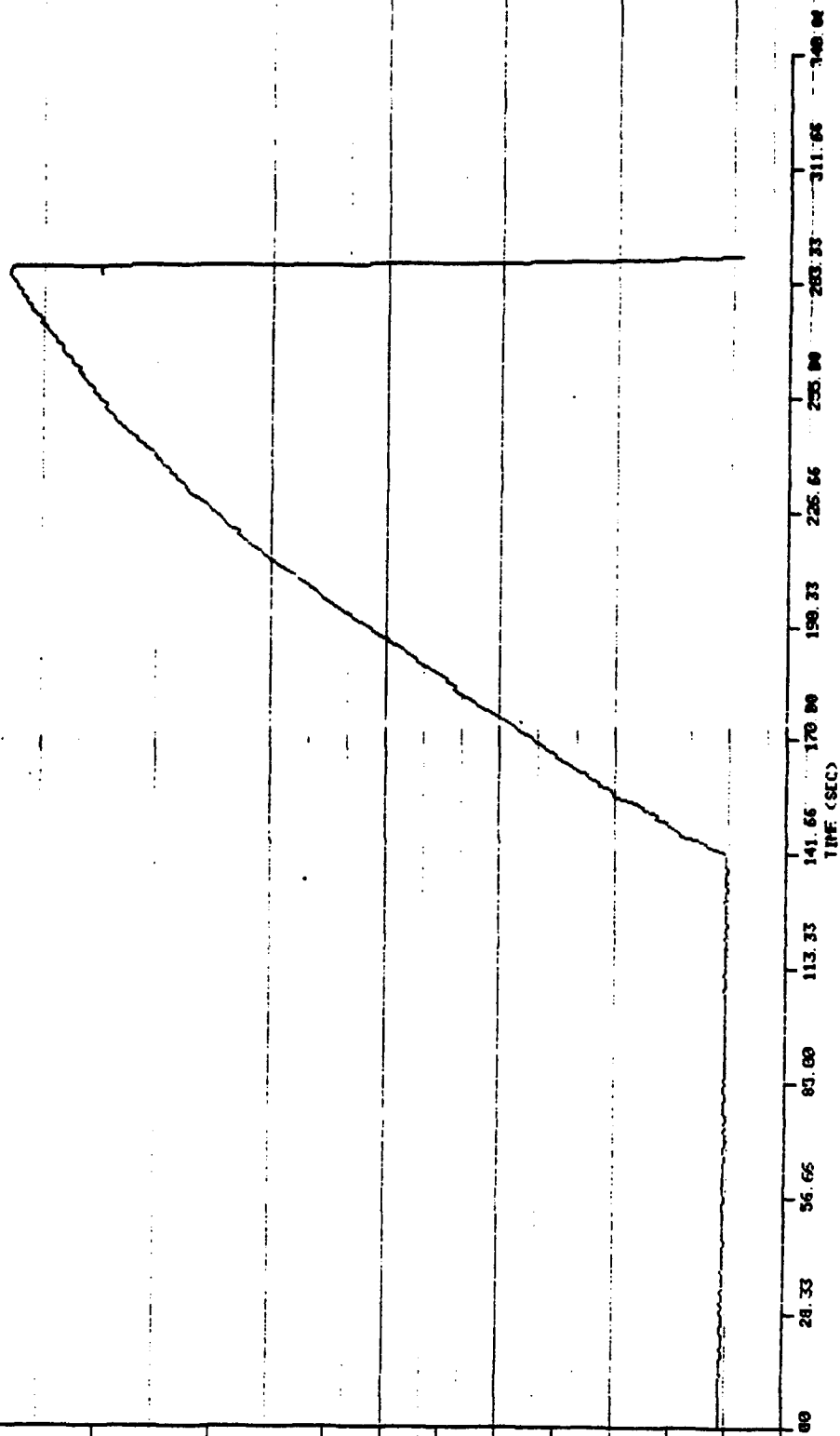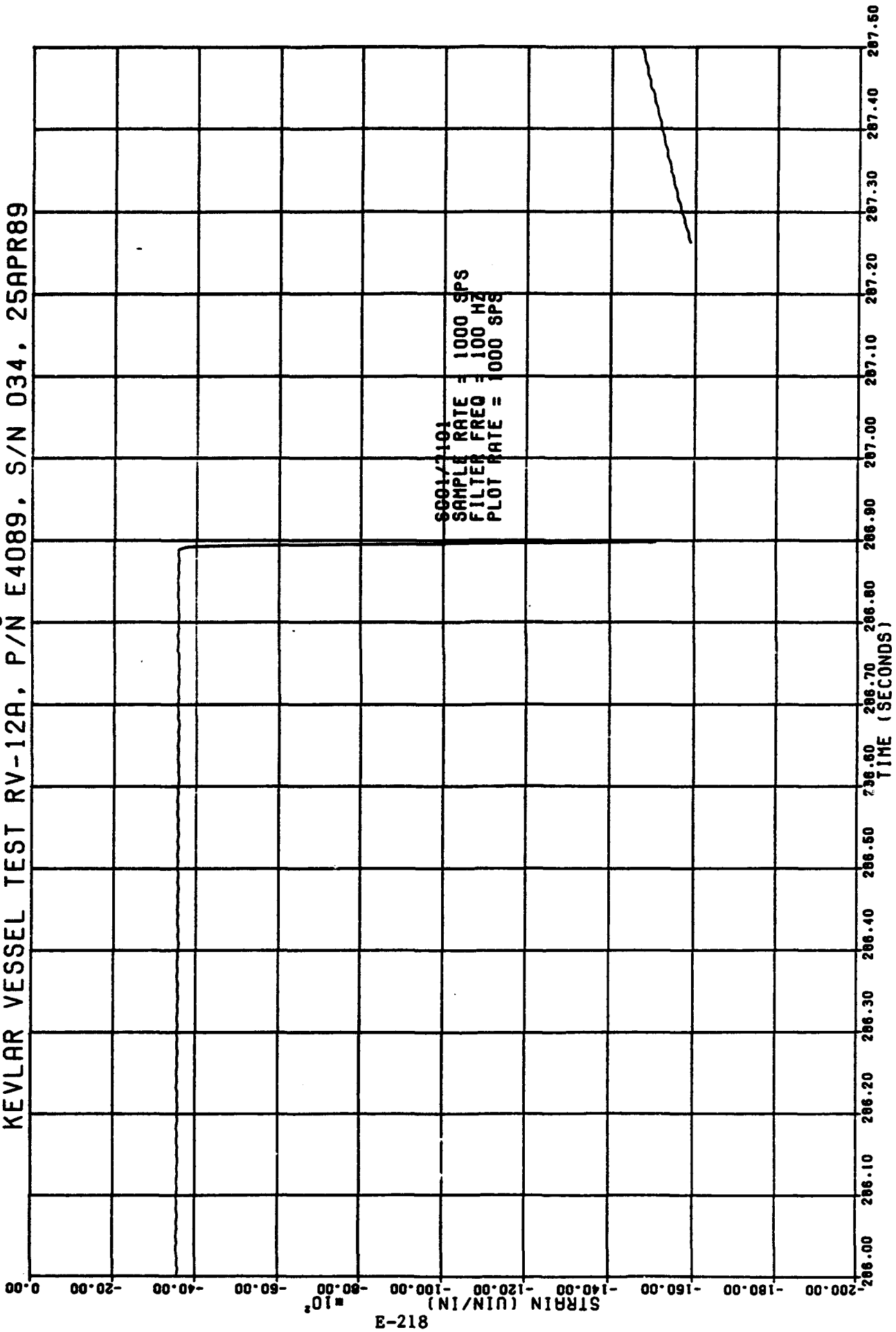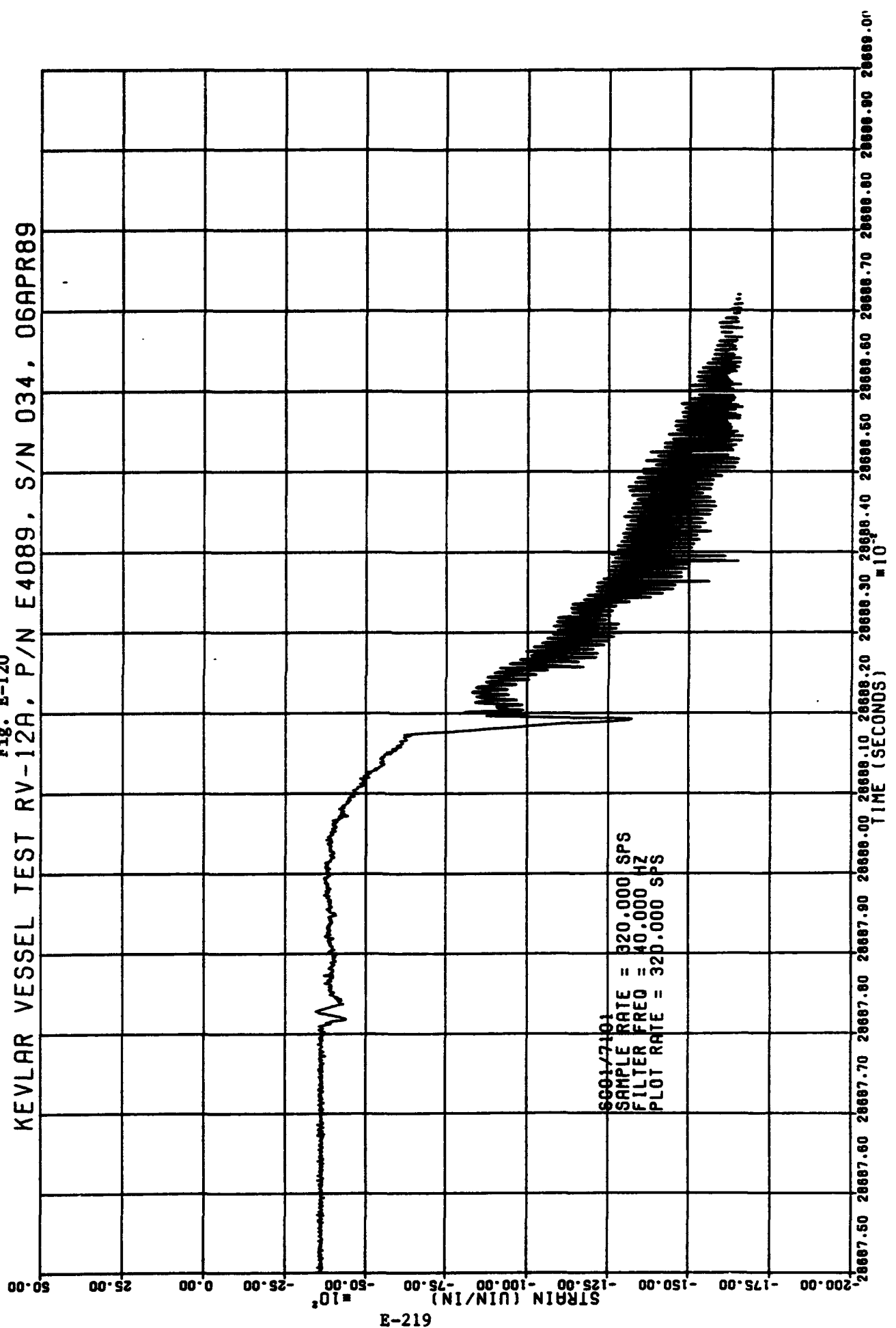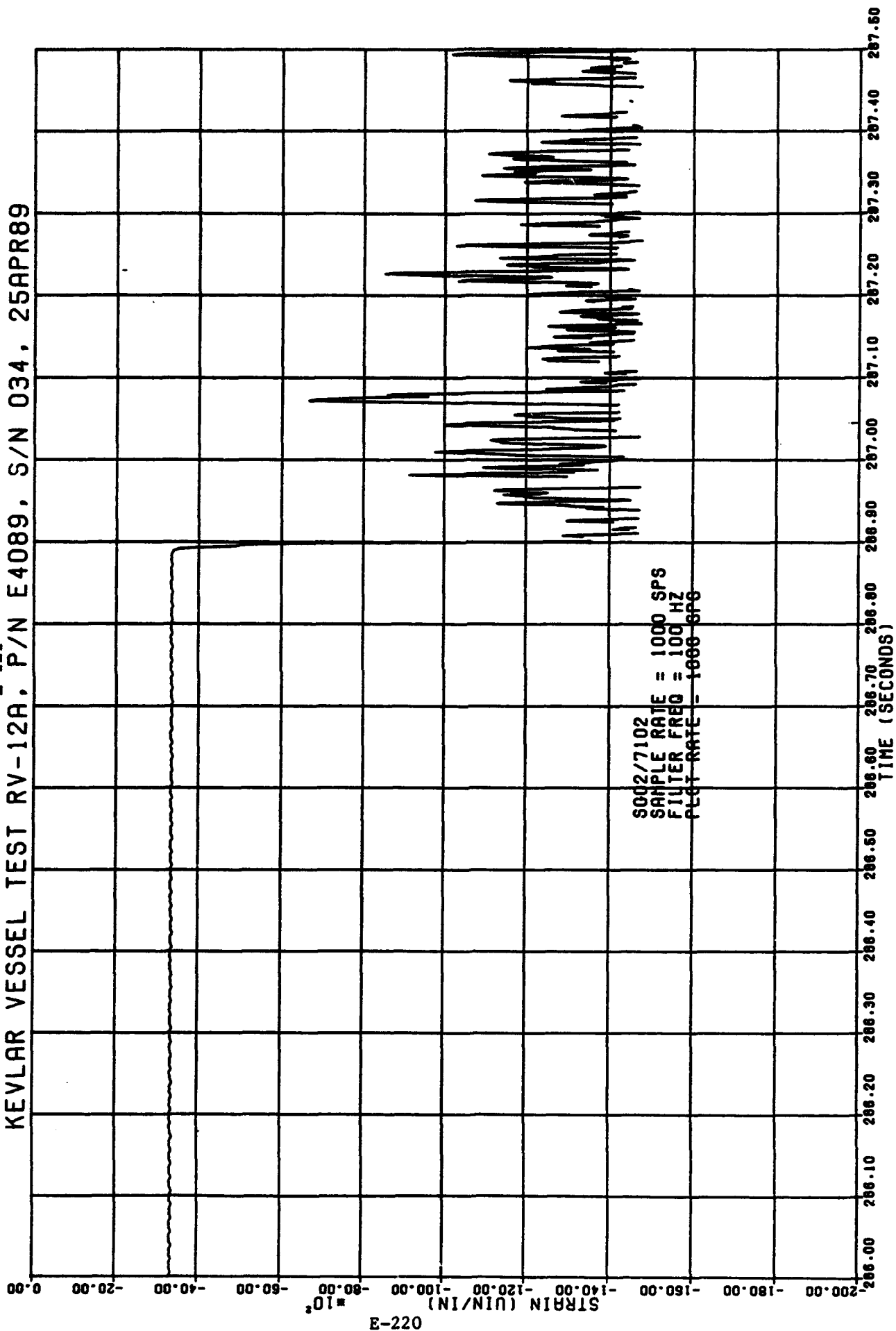
Fig. E-123

TEST RV-12A, P/N E4089, S/N 034, 06APR89

SG24 /7124
SAMPLE RATE = 1024 SPS
FILTER FREQ = 1000 HZ
PLOT RATE = 1024 SPS

E-222

KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 06APR89

Fig. E-124

SG04/7104
SAMPLE RATE = 320.000 SPS
FILTER FREQ = 40.000 HZ
PLOT RATE = 320.000 SPS

E-223
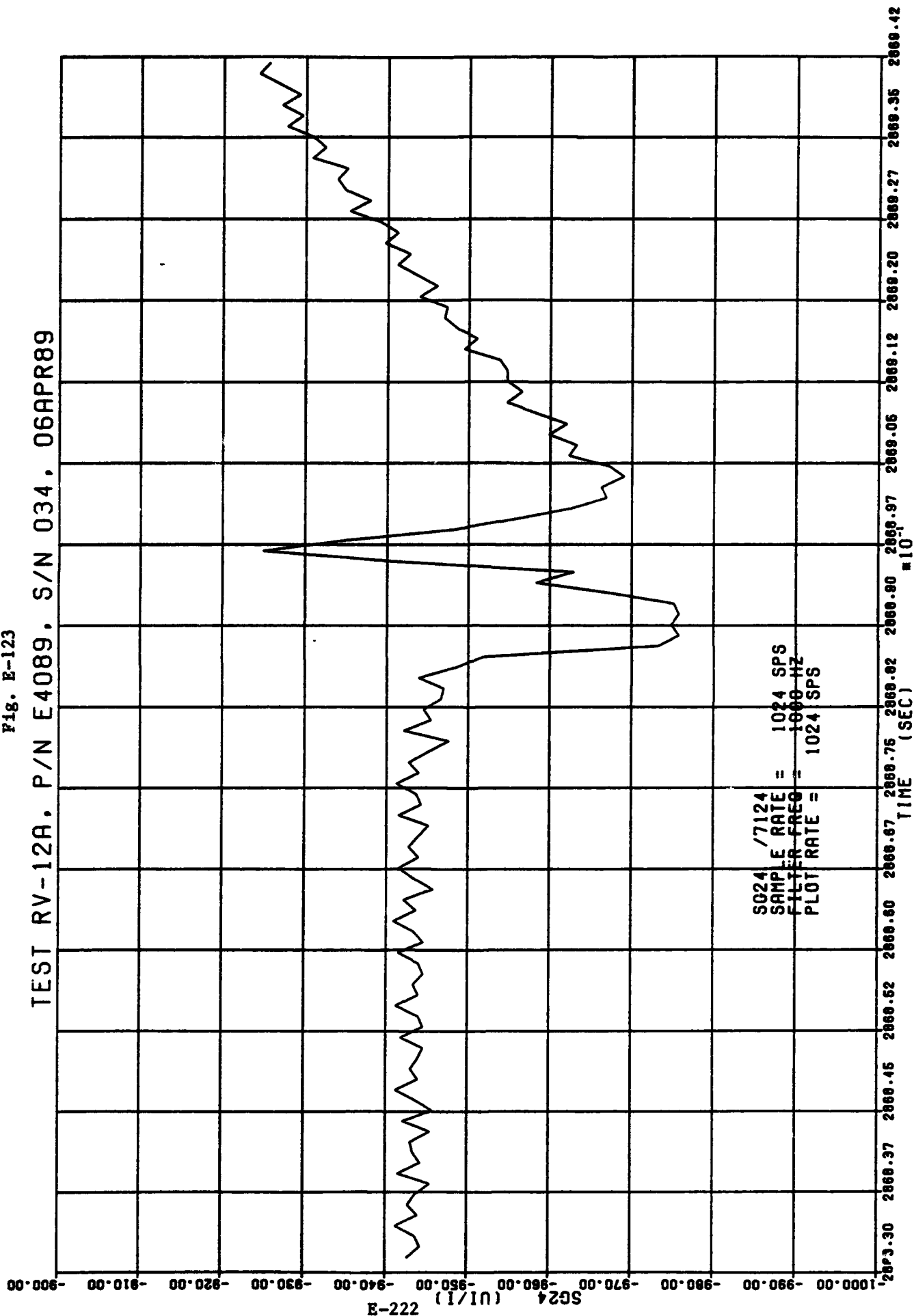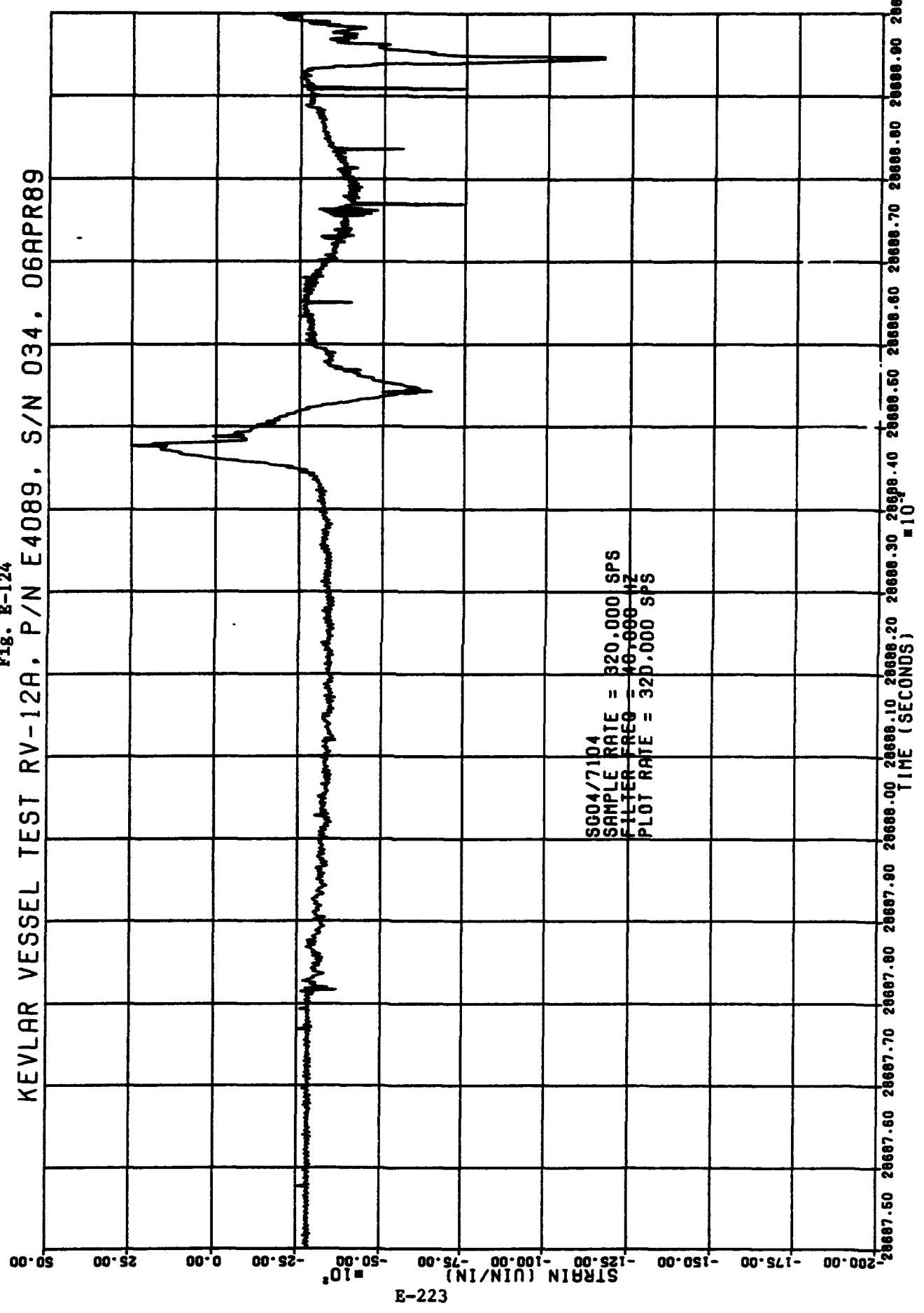
Fig. E-125

KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 25APR89

KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 06APR89

Fig. E-126

SO16/7116
SAMPLE RATE = 320.000 SPS
FILTER FREQ = 40.000 HZ
PLOT RATE = 320.000 SPS

STRAIN (UIN/IN)

TIME (SECONDS)

E-225

KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 06APR89

SG06/7106
SAMPLE RATE = 320.000 SPS
FILTER FREQ = 40.000 HZ
PLOT RATE = 320.000 SPS

Fig. E-127

E-226
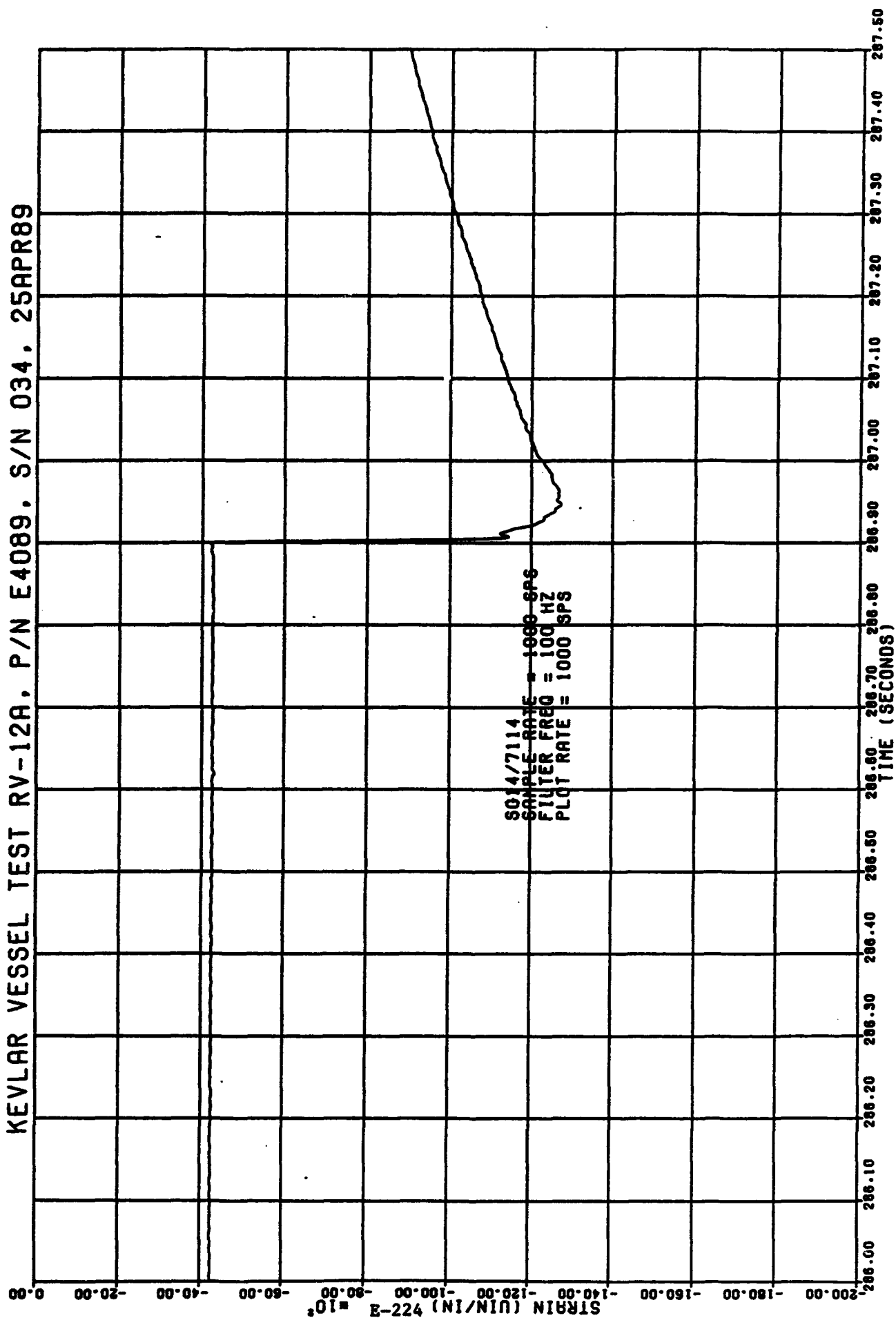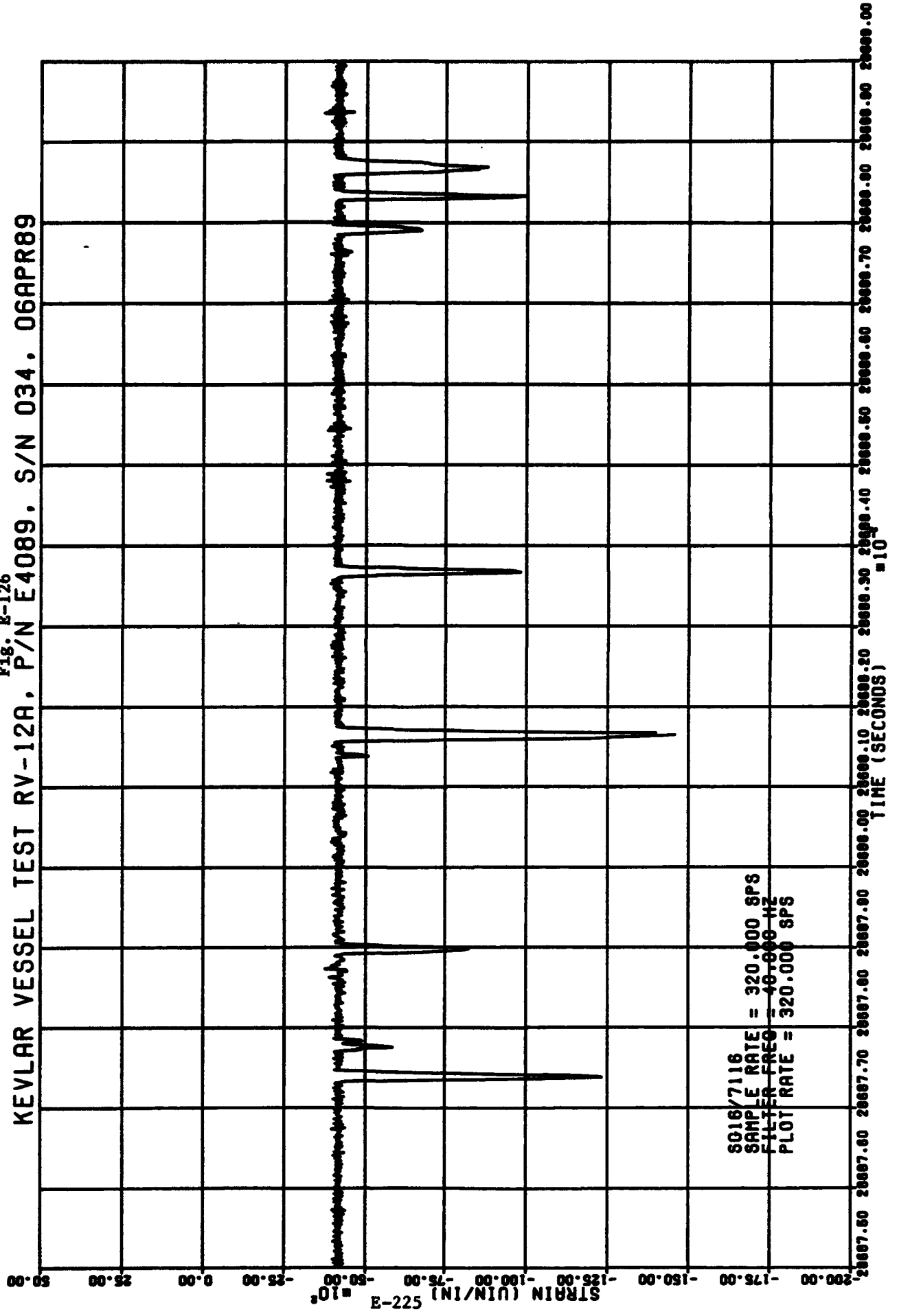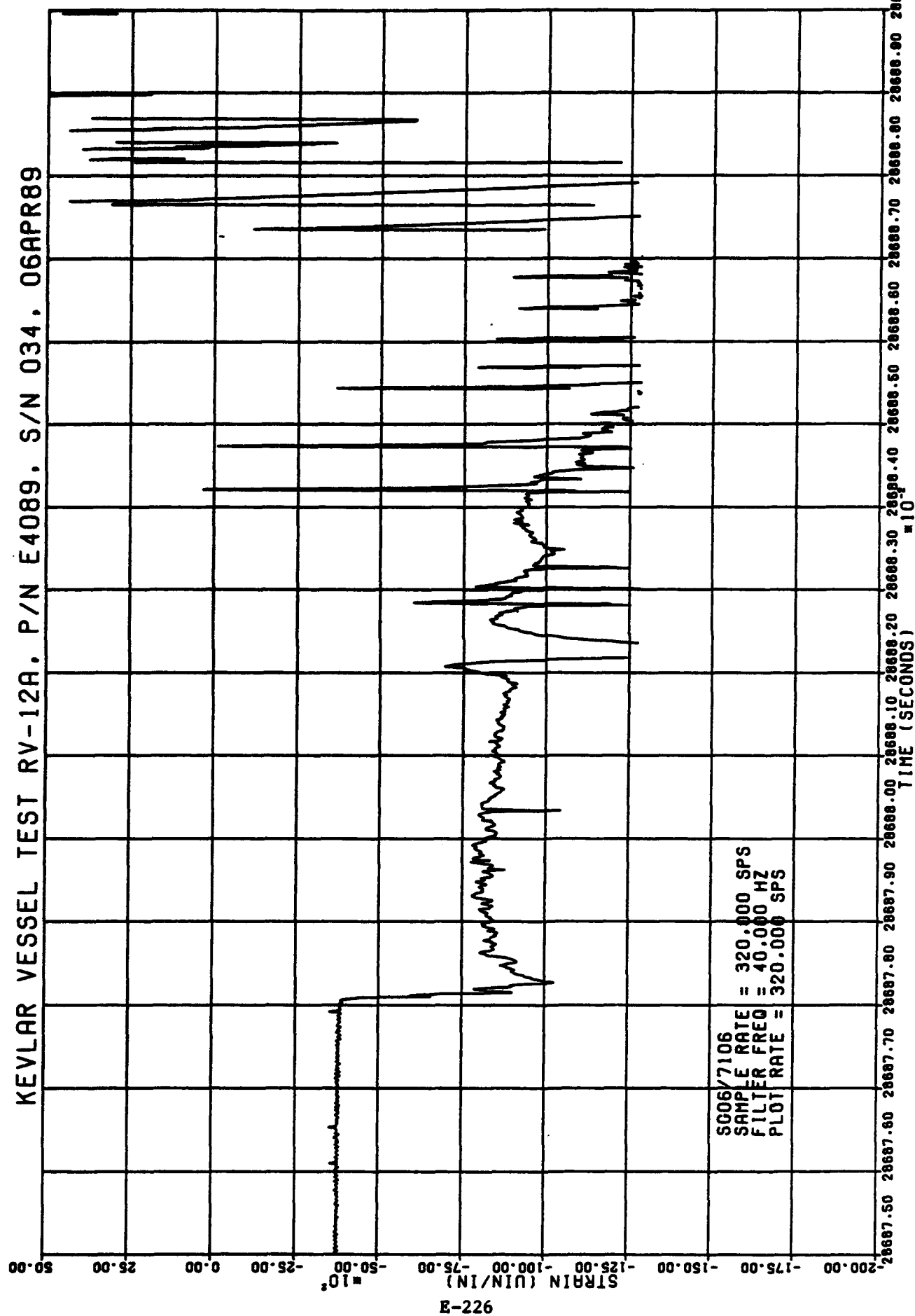
Fig. E-128

KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 06APR89

SO08/7108
SAMPLE RATE = 320.000 SPS
FILTER FREQ = 40.000 HZ
PLOT RATE = 320.000 SPS

E-227
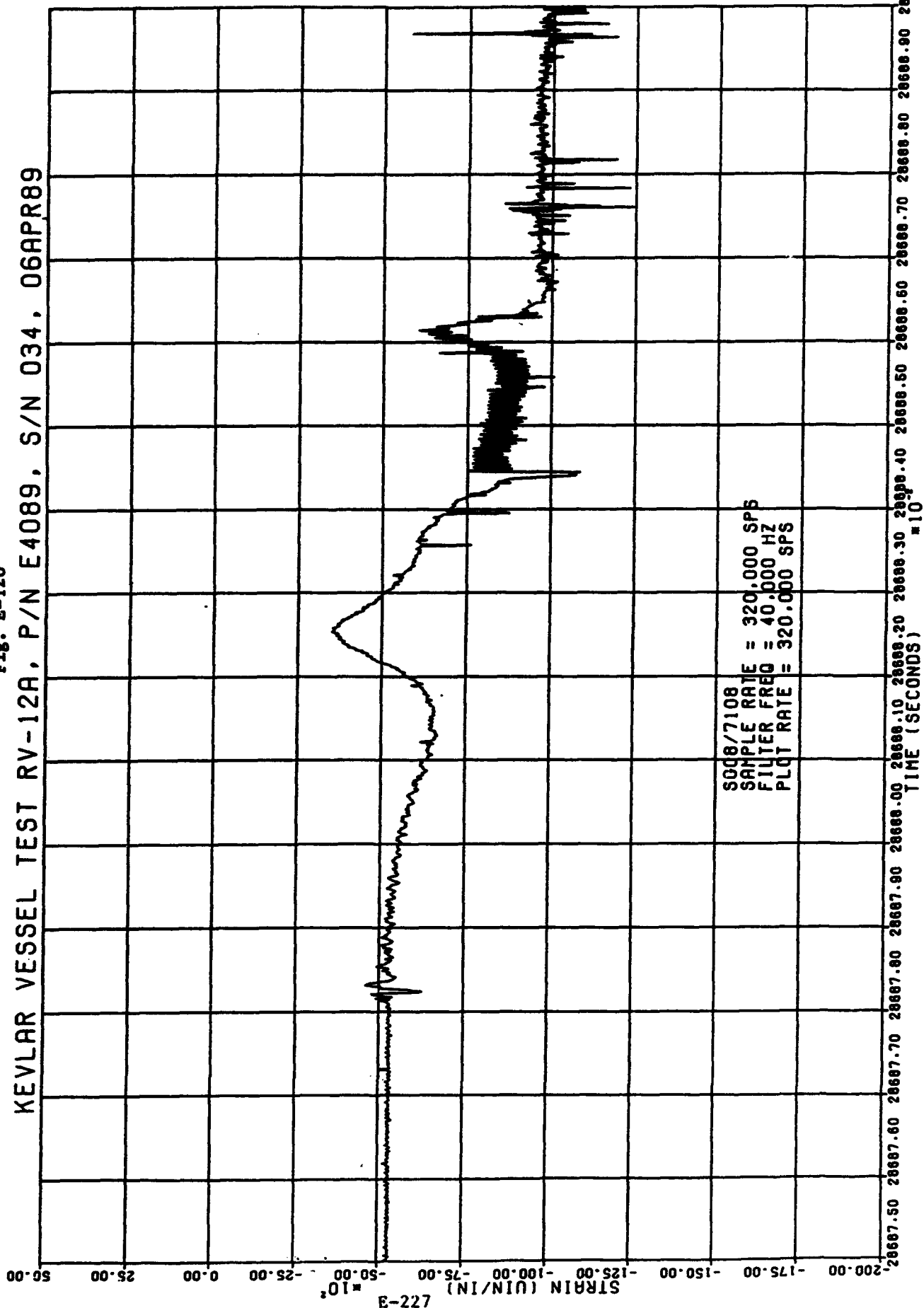
Fig. E-129

KEVLAR VESSEL TEST RV-12A, P/N E4089, S/N 034, 06APR89
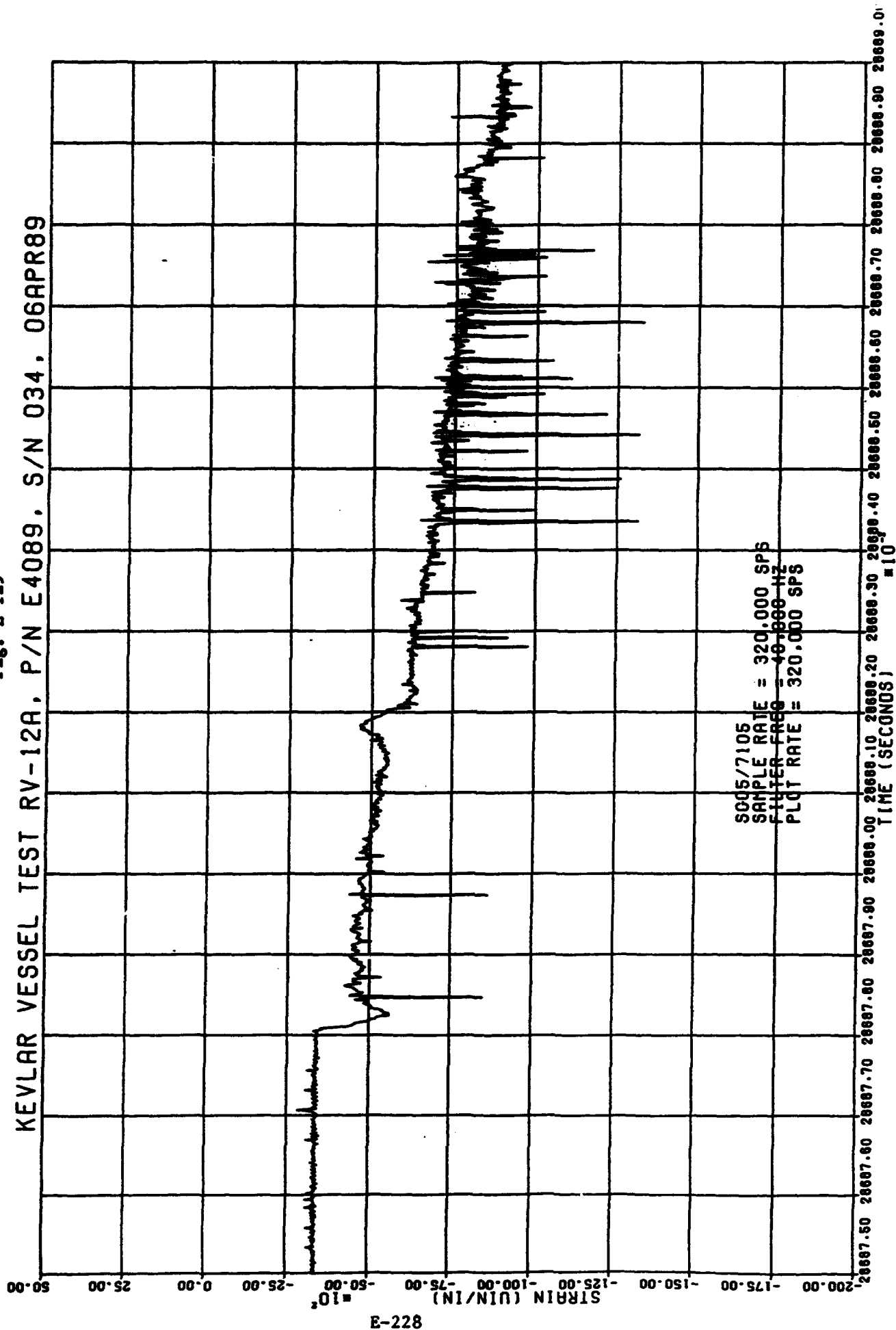
SOO5/7105
SAMPLE RATE = 320.000 SPS
FILTER FREQ = 40.000 HZ
PLOT RATE = 320.000 SPS

TIME (SECONDS)

STRAIN (UIN/IN)

E-228

3/7/89 (Rev A)
3/21/88
JN 42001-0-19 Ⓐ

P/N E4089-2 , S/N 029 Ⓐ
Experiment RV-12A Ⓐ

MS33649-4 Side

33   34   35   36

17   18   19   20

1   2   3   4

P/N, S/N

9   10   11   12

25   26   27   28

41   42   43   44

ROSAN Side
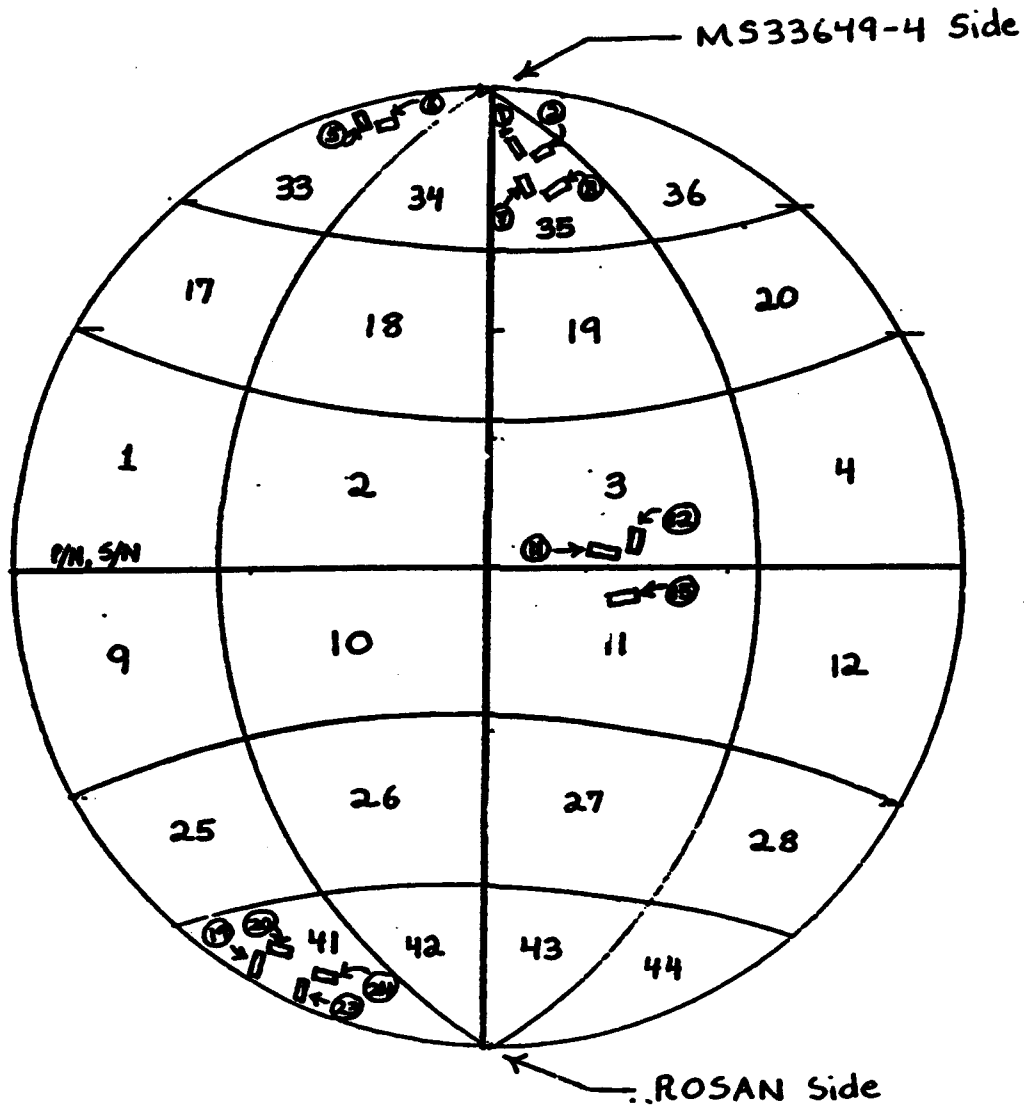
Rev A : RV-12A WAS RV-12
42001-0-19 WAS 42001-0-17

#1-#48-Sector #'s.
#①-#㉔-Strain Gage #'s
▭→Strain Gage
(Longitudinal axis of rectangle
is || longitudinal axis of
strain gage)

P/N E4089-2 , S/N 029
Experiment RV-12A Ⓐ

MS33649-4 Side

ROSAN Side
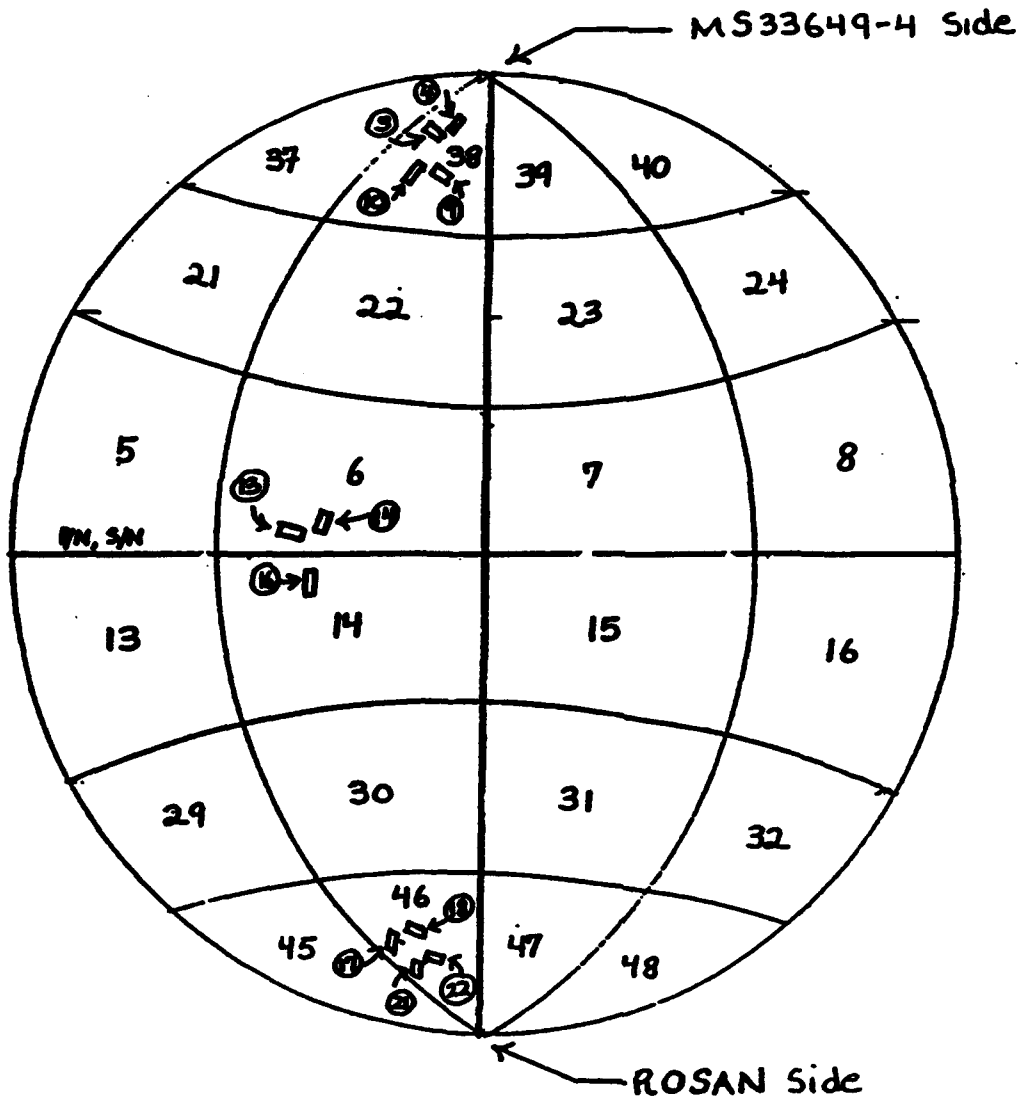
Rev A : RV-12A. WAS RV-12
J/N 42001-0-19 WAS
J/N 42001-017

(See Pg. 1)

E-230

Fig. E-132

TEST RV-12A, TEST CONSOLE ACTIVITY

Fig. E-133
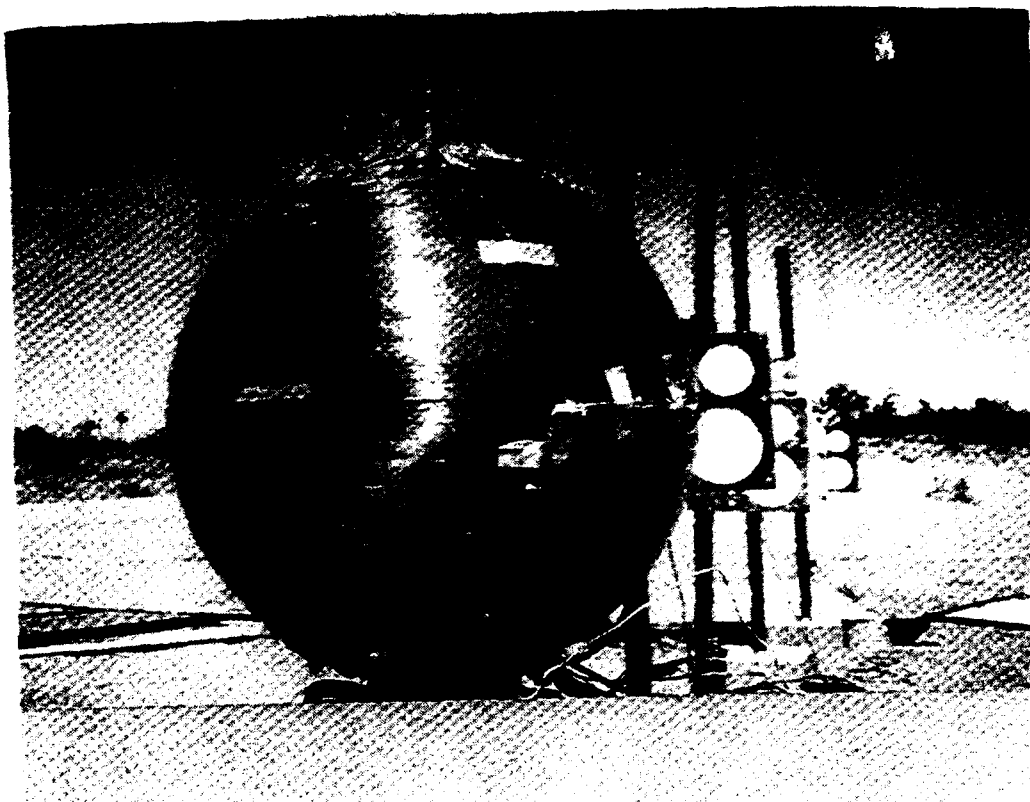
TEST RV-12A, POST TEST VIEW OF FIBER DAMAGE

through cracks in the embrittled boss/head weld
HAZ did not run completely around the entire
circumference. Discrete radial cracks running
outboard from the HAZ were also found as shown on
the photographs of Figures E-135 and E-136. It
is to be noted that the radial cracks were
arrested by the adjacent ductile liner material
outboard of the embrittled boss/head weld region.

E-232
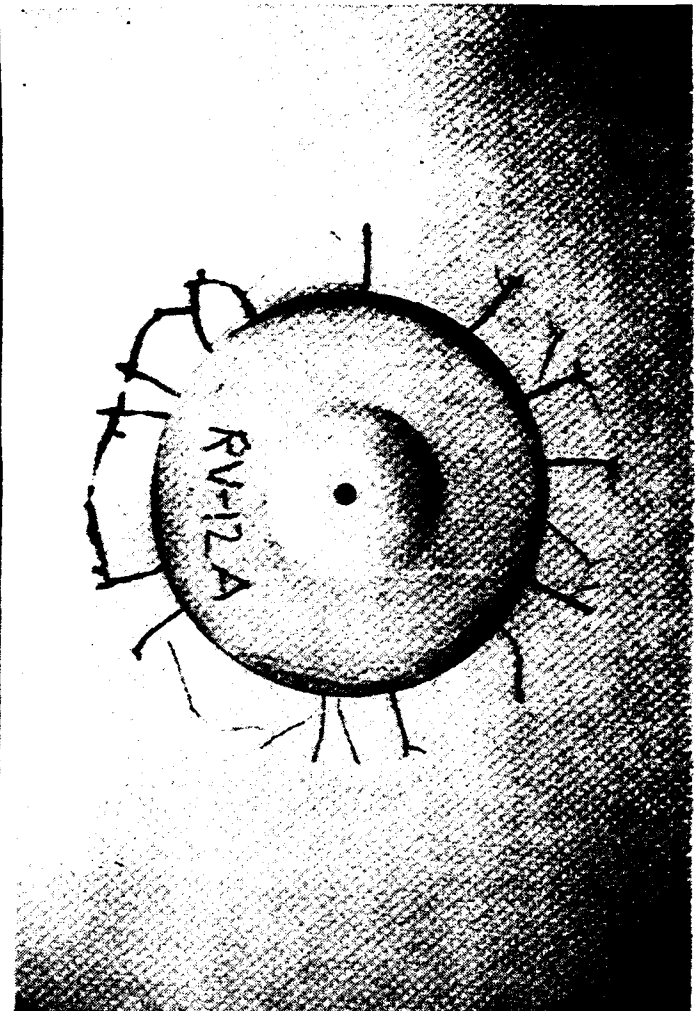
TEST RV-12A, POST TEST CLOSE UP VIEW OF FIBER DAMAGE

TEST RV-12A, CLOSE UP OF EMBRITTLED BOSS HAZ LINER CRACKS
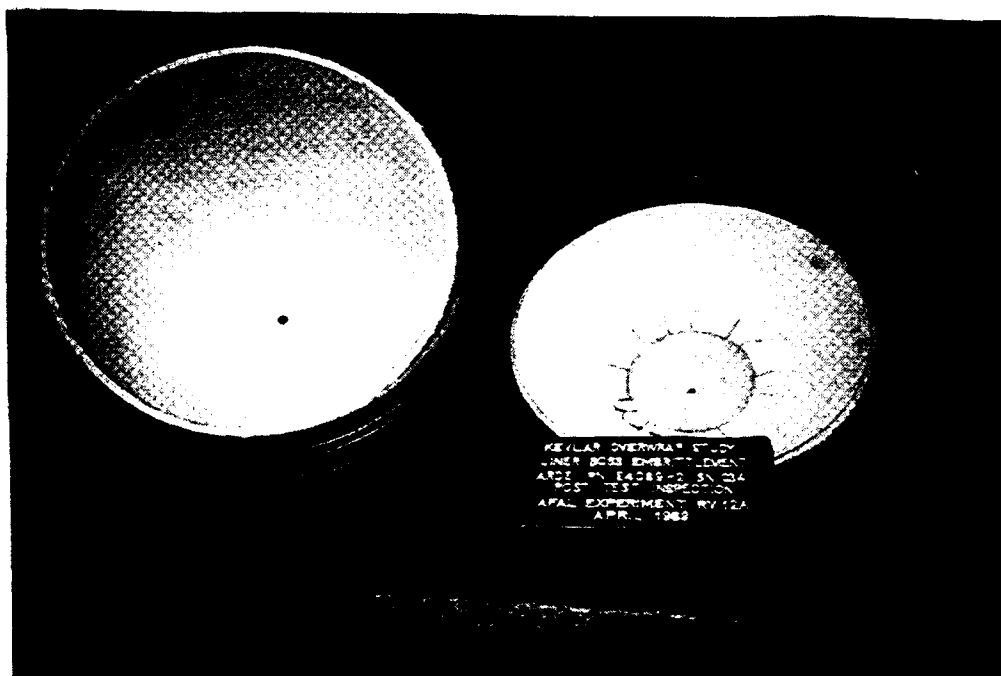
Fig. E-135

TEST RV-12A, EMBRITTLED BOSS HAZ LINER CRACKS

E.11 RV-14 Test (16" φ)

E.11.1   Test Vessel Description

- P/N E4168, S/N 006 (Kevlar Overwrapped 301 Cryo CRES Composite Sphere)

- Kevlar Fiber (less resin) Average Thickness - .143

- Metal Thickness - .052"

- Inside Radius - 7.66"

- Hydrogen Embrittlement Mode - Local Girth Weld Region

- Electrolytic Solution -

$$\frac{20 \text{ cc } H_2SO_4 + 980 \text{ cc Tap } H_2O}{1000 \text{ cc Solution}}$$

- Solution Additive - 500 mg Sodium Arsenite

- Sensitize Liner Inside Surface (cold pickle)

- Charging Current Density - .006 ma/in^2 of surface to be embrittled

- Charging Time - 72 hours

- Hold Time Before Test - 3-1/2 hours

- Adcoat AC818T liquid maskant on area not to be embrittled

E.11.2   Test Discussion and Instrumentation Observations

As detailed in the memorandum on the
following page, and the instrumentation engineers
observations herein, the liner inside surface was
pickled to sensitize it and the local girth weld
HAZ region was hydrogen embrittled. The tank was
internally pressurized with helium gas to 3800
psig operating pressure. The test pressure was
increased to 3900 psig operating pressure. The
test pressure was increased to 3900 psig when no
liner failure was noted at 3800 psig after about
six (6) minutes from pressurization start. The
3900 psig pressure was vented after eight (8)
minutes when all recording tape was expended. No
liner failure occurred as confirmed by post-test
inspection and test record review.

E-235

M E M O R A N D U M

Date: June 26, 1989

To: D. Gleich / S. Berko   pc: RW/KP/RK

From: A. Escalona

Subject: J/N 42001-0-18 - RV-14 Experiment: 90% Kevlar Wrap
           Thickness, Margin Fiber Fail Article

Test Date: Hydrogen Embrittlement - June 19th to 22nd 1989
                        Pressurization - June 22nd 1989

Test Facility: EAFAL, Edwards AFB, California

Test Procedure: Described in ARDE Letter #42001-KOS-174

    a)   Strain gages -24 . . . . .OK
    b)   Pickled . . . . OK
    c)   Rinsed with water, 2 volumes. . . . . OK
    d)   IPA rinsed & N2 dry . . . . OK
    e)   Maskant 9.31" from boss top . . . . OK
    f)   Drained & N2 dried (1 hr) . . . . OK
    g)   Electrolyte 8.75" from top. . . . . OK
    h)   Charged 160 ma for 72 hrs . . . . OK
    i)   Drained, rinsed with water, 2 vol . . . . . OK
    j)   IPA rinsed & N2 dried . . . . OK
    k)   Tested in 3.5 hrs
         Chilled at 1400 to 1500 psi
         Ramped to 3800 psi - held for 4 min. - no leak
         Raised to 3900 psi - held for 2 min. - no leak

         Note: Test was aborted just prior to FM tape ran out.
                Total test time was 9.7 MIN.

AES:sr   A. Escalona /s/

INSTRUMENTATION OBSERVATIONS (by Instrumentation Engineer)

KEVLAR TEST 014. Date: 22JUN89. Project Number 573000Rv.

EXPERIMENTAL OBSERVATIONS.

Introduction. Vessel S/N 006. P/N 24168 was tested. It was a 18 inch diameter stainless steel sphere and had a 90% Kevlar overwrap. The vessel was hydrogen embrittled about the girth. It was tested in a vertical configuration. The tank pressure was increased with pressure pulses, held for a while at 1500 psig, then ramped up to a plateau that was maintained between 3832 psig and 3788 psig over a time duration extending from 175.099164 to 421.799664 seconds. Plateau pressure was maintained with five short pressure bursts which were scattered throughout the plateau. A second pressure ramp was started at 421.799664 seconds. and this short ramp ended after only 13 seconds at 434.899974 seconds and 3914 psig. The new plateau, starting at the end of the second ramp, ended at 3881 psig and 534.119148 seconds. The new plateau contained only one pressure correction. The vessel did not leak. and tank pressure was vented at the end of the new plateau.

Venting was done with the vent valve. The vent profile was clearly demarcated. almost linear, done at a rate of approximately -170.66 psig per second, n recorded near the end. not stopped for repressurization attempts, unremarkable and within normal limits.

As in previous tests. SG24 and the other strain gages were impressive mirror images of the pressure profile. Case strain in composite cases can be detected and is proportional to case pressure. but a calibration factor must be determined. The SG performance profiles will be slightly noiser than the vessel pressure parameter and retain the risk of SG debonding.

Post-run Inspection. witness panels, displacement gages and acoustic emission technology were not used. Extensive damage to the vessel's instrumentation wiring and pressurization plumbing was not observed. The over pressure sensor data showed no change and are discussed elsewhere. No Kevlar damage was observed and fraying was not obvious near either boss. The Kevlar remained intact. No major damage to the resin was observed.

IMPRESSIONS FROM THE DIGITIZED FM DATA.

Strain Gages.

Strain Gage Locations. The strain gages were located IAW ARDE drawing dated 3/7/89, Revision A dated 21MAR89, accompaning a 21MAR89 cover letter. The even strain gages are perpendicular to the wrap. and the odd strain gages are parallel to the wrap.

Strain Gage Temperature. Not shown on this print are the thermocouple locations. See the Instrumentation Specification

1

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Sheet for the locations and item numbers. The 9 thermocouple loci form a family of curves with almost identical profiles. Collectively, the gages measured temperature behavior over a span between 115 degrees F and 153 degrees F, approximately. However, each gage didn't change much during the plateau, and the typical plateau temperature variation didn't exceed about 8 F degrees. A similar small variation was also seen on test 11. One thermocouple, TT2/2102, had a very steady rise rate. Other thermocouples, TT3/2104, TT9/2205, for example, had major temperature decreases modulating the rise rate in the last one third of the first plateau. All temperature profiles contained small bipolar modulations, some noise near the start and finish of the profile and reasonable noise floors. The vessel's SG temperature behavior is considered to be within normal limits, and it wasn't investigated with further detail.

Performance Summary. There were 23 strain gages recorded on the FM tape recorder, and 21 functioned. Most plots had substantial activity, and most plots had 6 to 12 noise spikes. During the initial conditions, all gages had much better than reasonable noise floors. The noise floors are discused elsewhere under Noise Floors. None of the strain gages were destroyed by tank depressurization.

Sign Convention. Positive strain gage polarity represents compression, and negative strain gage polarity represents tension.

Noise Floors. Except as noted elsewhere, the strain gage and other parameters' noise floors did not include major transverse or common-mode minus L(c1/ct) transients, artifacts, crosstalk, atmospherics, noticeable RFI, intermodulation, spurious parasites, or sibilants. However, latent noise or data manifestations may be obscured in some parameters, and digital signal processing may be needed for signal enhancement. In general, the data appeared to be unbiased, precise and accurate. There was no particular SG that could be identifed as the noisiest but this is a judgement call. SG10 through SG17 and SG18 through SG23 had noise during venting.

Performance Exceptions. Strain gage behavior was within normal limits, except as noted. The following comments are based on interpretations of the 100 Hz data pass.

In general, strain gage behavior was similiar to previous tests. The general trend for the active strain gages was a tension strain polarization pattern proportional to tank pressure with corrections for glitches, polarity, shifts and some possible deponding, etc. The dynamic performance did not include major oscillations. All graphs had noise floors within normal limits. Most graphs had a few glitches. Plots for SG10 through SG17 and plots for SG18 through SG23 had noise during the vent operation. Plots for SG01 through SG09 did not plot data much past 440 seconds, but the columnar data is present up to 599.99810 seconds.

2

Maximum SG Values and Performance Trends.   The following codes are used below:

    NWNL noise within normal limits
    GRZ good return to zero
    ARZ approximate return to zero
    NRZ no return to zero
    C   compression strain
    T   tension strain
    NTE not to exceed
    OSC oscillation
    Unipolar: data predominately in one direction.
    Bipolar: data in both directions but not necessarily evenly balanced   between   polarities.   In   some   cases,   the   data carrier   was   unipolar   in   tension   but   contained   bipolar compression excursions.
    Units for strain values are in microinches/inch

SG01 Unipolar, T, no data past 155 seconds.
SG02 Unipolar, T
SG03 bad
SG04 Bipolar, T & C, compare with SG12.

SG05 Unipolar, T
SG06 Unipolar, T
SG07 Unipolar, T
SG08 Unipolar, T

SG09 Unipolar, T
SG10 Unipolar, T but the plateau is suspiciously too flat.
SG11 bad
SG12 Bipolar, T & C, compare with SG04.

SG13 Unipolar, T
SG14 Unipolar, T
SG15 Unipolar, T, Exhibited the maximum net tension strain change
SG16 Unipolar, T

SG17 Unipolar, T, Represents a most typical profile
SG18 Unipolar, T
SG19 Unipolar, T
SG20 Bipolar, T & minimal C

SG21 Unipolar, T
SG22 Unipolar, T
SG23 Unipolar, T

SG24 Unipolar, T, Recorded on the DACS only. Not on FM.

Performance Summary:

All   channels   included   codes: T and NRZ.   Out   of   the   23   SG channels recorded on the FM tape recorder, two channels were bad. Twenty   channels   had   unipolar   tension   behavior.   Three   channels

3

had bipolar strain activity, probably due to debonding or legitimate abrupt changes in strain.

The maximum strain change was seen on SG:5, which started out with a strain of 1584 uin/in at 60.79981 seconds at the 1500 psig pressure plateau and decreased to a -2545 uin/in tension value at 441.79981 seconds at the 3914 psig pressure plateau, which is a net change in tension of 1584 - (-2545) = 4129 uin/in. This channel was reported to have noisy cal data although the plot during the run was within normal noise limits; therefore, the run data might be considered questionable.

More typically, most strain gages underwent a net tension strain of only 2000 uin/in. SG:7 is representative of a typical SG.

Important to note is the sensitivity of the SG channels to the pressurization maintenance pulses, which is the basis for discarding SG10 data as not valid because of the excessively flat plateau. Practically all of the SG plots reflect the pressure maintenance pulses.

Note also that some some plots don't track the slope of the pressure plateau very well. In a couple of plots the slope is minimal or flat, as in SG15 and SG16. While others the slope is more prominent as in SG 13 and SG17.

If the higher frequency data pass contains information not indicated by the 100 Hz data pass, a revision will be issued and those differences will be discussed.

The above information was determined by inspecting the graphs and may contain subjective errors.

Statistical Analysis. Valid speculations about strain gage behavior may involve biserial correlation of certain dichotomies (positive or negative polarization) to assess their associations (with wrap direction, etc.). For truly dichotomous distributions, the phi coefficient can be used. Because some of these dichotomous variables are really continuous (the magnitude or duration of polarization, and the degree of wrap thickness, location & direction, etc.) and normally distributed, tetrachoric correlation may be involved. An expert statistician should be approached with a clear statement of which variables and associations are important if valid conclusions about some of these data are to be obtained. An accurate evaluation of which variables are really dichotomies and which are proportionally continuous would also have to be prepared and passed to the statistician.

Data Analyst's Comments.

The ITT Data Analyst, Richard Thomsen, indicated on the front sheets of the three 100 Hz passes "No data on DP01, DP02, DP12" and "SG01/7101 goes bad at 155 seconds. SG03/7103 is bad. No IRIG timing signal" and "SG15/7115 noisy cal data. SG11/7111 is

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E-240

bad. No IRIG timing signal."

IMPRESSIONS FROM THE QUICK-LOOK AND DIGITAL DATA ACQUISITION SYSTEM DATA.

Tank Pressure. PTANK/1901 was located on the top of the tank in the vent line. PVSOUT/1904 was also in the vent line, but it was located at the valve box about 15 feet from the tank. PTANK/1901 functioned as described under the Pressurization Ramp... paragraph.

The locations of the transducers was the same as test 10.

PVSOUT/1904 data were similiar to PTANK/190 except for the reduced frequency reponse because of the long pressurization line.

SG24. SG24 tracked the vessel pressure profile with corrections for polarity, etc. This parameter, as in the previous tests, was only recorded on the DACS for quick-look purposes.

Phase Behavior and Frequency Response. Noted is the phase behavior; the two graphs were very close together in the time domain.

Other Parameters. The performance of the other parameters was within normal limits, except as noted below; this was determined by a quick review of the graphs for items PHXIN/1902, PHXOUT/1900, PTRAIL/1903, THXIN/2100, TBALL/2211, TBSOUT/2210, TBSIN/2209. THXOUT/2101 Heat Exchanger Output shows 6 major spikes with noticeable decay times. The spikes are apparently due to minus L(di/dt) transients from the pressurization efforts needed to maintain a pressure plateau with the pressurization valve. Suppression with a diode at the valve solenoid is required to stop the problem, or the spikes may be disregarded. The spikes appear as glitches on pressure parameters such as PHXIN/1902, PHXOUT/1900, PTRAIL/1903 and as very small deflections on temperature parameter THXIN/2100.

The IRIG Time Code. IRIG/3808 TIMING, did not record satisfactorily on the FM.

IMPRESSIONS FROM THE OVERPRESSURE SENSORS.

The vessel did not leak. There was no overpressure pulse. Overpressure data was not reduced.

The following text applies to overpressure sensors and is retained for reference.

Bikini Gages. A Bikini gage is one piece of bond paper compressed between two metal plates containing different sized round holes. The gages are aligned so the paper is perpendicular to the pressure source. Discrete pressure data can be obtained

5

and is a function of the location of the damaged paper
diaphrams. The approximate calibration is as follows for the
indicated hole size using bond paper:

HOLE #	PSIG*	SIZE	PSIG**
1	7.3	5/8	4.4
2	5.2	7/8	3.3
3	3.7	1-1/4	2.4
4	2.7	1-7/8	1.7
5	1.9	2-3/4	1.25
6	1.4	3-3/4	----
7	1.0	5-3/8	----

*The source for this calibration data is unknown, but these data
have been used since at least 1964 by the Astronautics
Laboratory. ***The source for these calibration data is from a
report THEORY, CALIBRATION,. AND USE OF DIAPHRAGM BLAST METERS by
W. T. Read, Division 2 National Defense Research Committee of the
Office of Scientific Research and Development, NRDC Report No. A-
392, OSRD Report No. 6463, Figure 18, Page 27, DEC45; this report
was obtained from the Naval Surface Weapons Center, Silver
Springs MD and was referenced in footnote (2) on page 3 of
another report, OPERATION SANDSTONE JOINT TASK FORCE SEVEN TASK
GROUP 7.1 BLAST MEASUREMENT SECTION, LAJ-8, PART II, Chapter 5.1,
USE OF FOILMETERS ON OPERATION SANDSTONE, prepared by J. J.
Meszaros and J. F. Moulton, Jr., 7JUN48, Fort Shafter, Oanu, T.
H. This report indicates "For a considerable number of years air
blast pressure measurements were made with the Aberdeen paper
meter. The measurements obtained gave some indication of the
peak pressure present. Early in the war Princeton University,
under the auspices of NDRC, conducted an extensive experimental
study. The primary results of these basic experimental
studies..." [are shown in footnote (2) discussed above]. It is
not clear when the terms Bikini and Aberdeen were first used to
designate diaphragm overpressure sensors. Nevertheless, the
gages were used at Bikini [atoll in the N Pacific, Marshall
Islands] in the 1946 atomic bomb tests (Crossroads Project) and
again at Eniwetok in 1948 (Sandstone Project) and again in 1951
(Greenhouse Project). Most of the above information came from
the DoD Nuclear Information and Analysis Center (DASIAC) on
12MAY88 and is the result of a lead provided by HQ/BSD/MYEB/Lt
Col Don Gage to AL/TOAE/Dick Grove in FEB88. [OPR's Note: HQ/BSD
was HQ/BMO prior to 21APR89 and AL was AFAL prior to 21APR89 and
AFRPL prior to 22MAR87].

Reconciliation of the bikini overpressures and bias observations
was not done as there was no overpressure pulse. All of the
paper diaphrams were intact.

Piezoelectric Sensors.

6

There was no overpressure pulse.

As indicated in earlier experiments, the overpressure sensors, if used, would have behaved as follows:

Ideally, each overpressure sensor located to measure pressure should respond to a passing pressure pulse with a characteristic graph. The graph's curve should have a prominent leading edge rising from a stable initial condition. The typical leading edge should polarize positively and rise to the curve's maximum peak pressure over a smooth and almost linear path. At the peak pressure, the curve should inflect, and, at this reversal, enter into a characteristic depolarization decay consisting of an almost linear component followed by a distorted exponential component that returns to below the initial condition with an undershoot, more fully described below, representing rarefaction and the start of the refractory period.

More often than not, the linear decay should gradually change into a sluggish curve containing one prominent inflection, forcing the plot into the opposite direction, but staying below the initial condition. Eventually, the pressure rarefaction should deteriorate completely, and the plot should return smoothly to the initial condition, ending the refractory period.

Modulations and variations in behavior are caused by sensor placement (parallel or perpendicular to the flow direction), reflections, pressure wave distortions, time constants, frequency response, particulate impingement, insulation resistance, short circuits, open circuits and gas cloud geometry, etc.

DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE. The ARDE embrittlement procedure dated 21MAR89 was followed. The 16" diameter vessel was girth embrittled. Embrittlement was inhibited, where required, with a maskant. Embrittlement was started on 19JUN89. The current level was 0.160 amperes. Seventy-two hours of embrittlement were completed at 22JUN89. The tank was immediately moved from the shop embrittlement area to the test site, instrumented, hooked up, checked and pressure tested on 22JUN89. The electrolyte was sulphuric aced. Sodium arsenite was added as an enhancer.

ADMINISTRATIVE INFORMATION.

Revision Record. Initial Issue: 8SEP89. Distribution changed.
Revision A: 19SEP89. Removed Draft Status from document. Made
major corrections per ARDE request. 16", 19JUN89, girth, 0.016
and 22JUN89 were 22", 3APR89. 0.055 and 6APR89. Added 100 Hz SG
data pass information to Maximum SG Values and Performance
Trends.

Filename: testrv14

Distribution: ARDE, Aris Escolona, Dave Gleich
            -          PI, Dr. Pius Chih Hsu Chao
                       Aerospace Corp., Dr. Yen Pan
                       AFAL, Jim Miller, Dick Grove,
                            Dr. Tae-Woo Park
                       ITT, Richard Thomsen
                       DAFB, Pete Tadie
                       HQ/BSD/MYEB/Lt Col Don Gage

Office   of   Primary   Responsibility.   USAF/AFAL/TOAE/Dick
Grove/Edwards CA 93534.

E.11.3   Pressure and Strain Versus Time Plots

Pressure and selected strain versus time plots are shown on Figures E-137 to E-139. Odd numbered strain gages are parallel to the wrap and even numbered gages are perpendicular to the fiber wrap. Strain gage locations are indicated on Figures E-140 and E-141.

E-245

KEVLAR VESSEL TEST RV-14, P/N E4168, S/N 006, 22JUN89

Fig, E-137
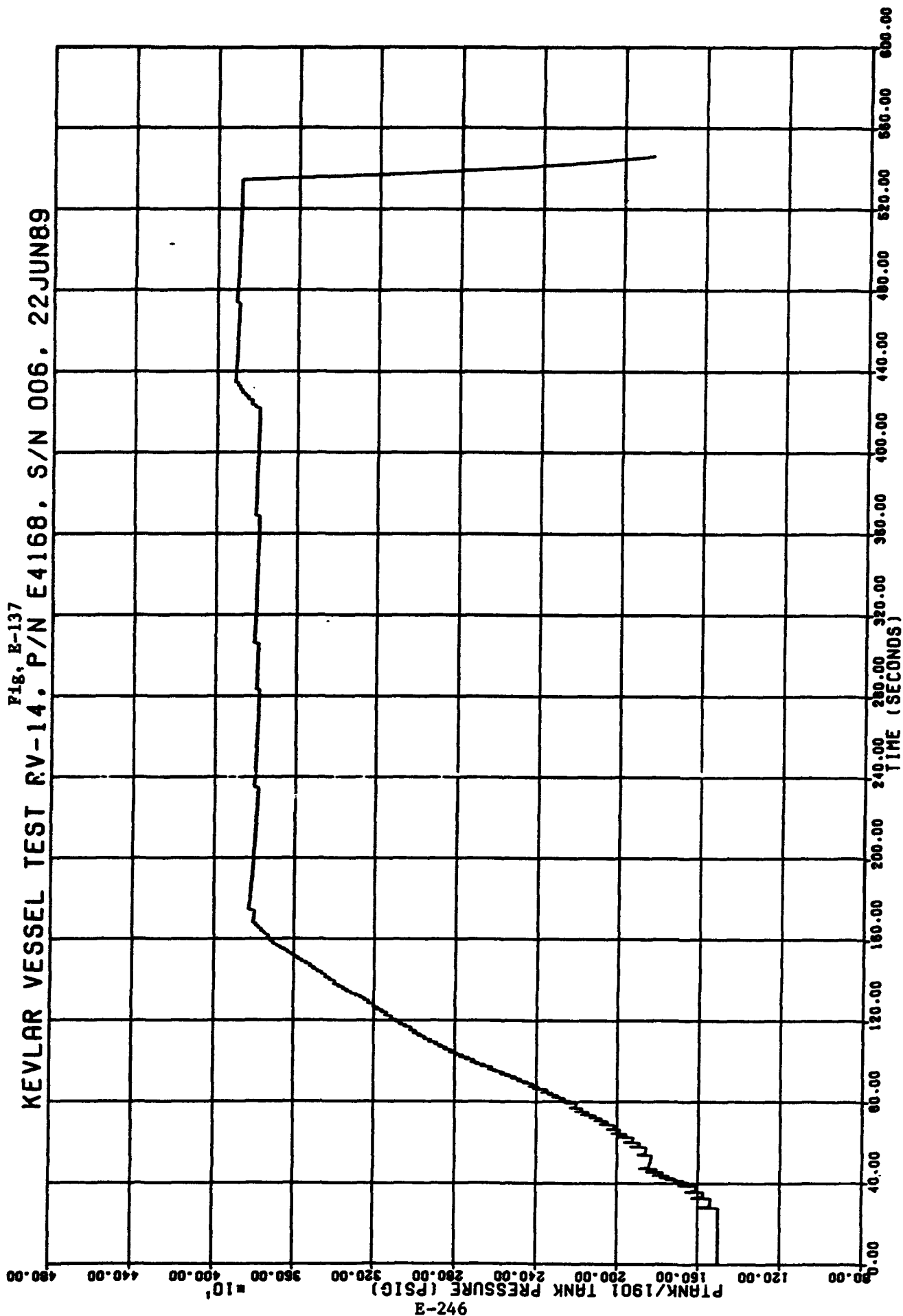
E-246

KEVLAR VESSEL TEST RV-14, P/N E4168, S/N 006, 22JUN89

Fig. E-138
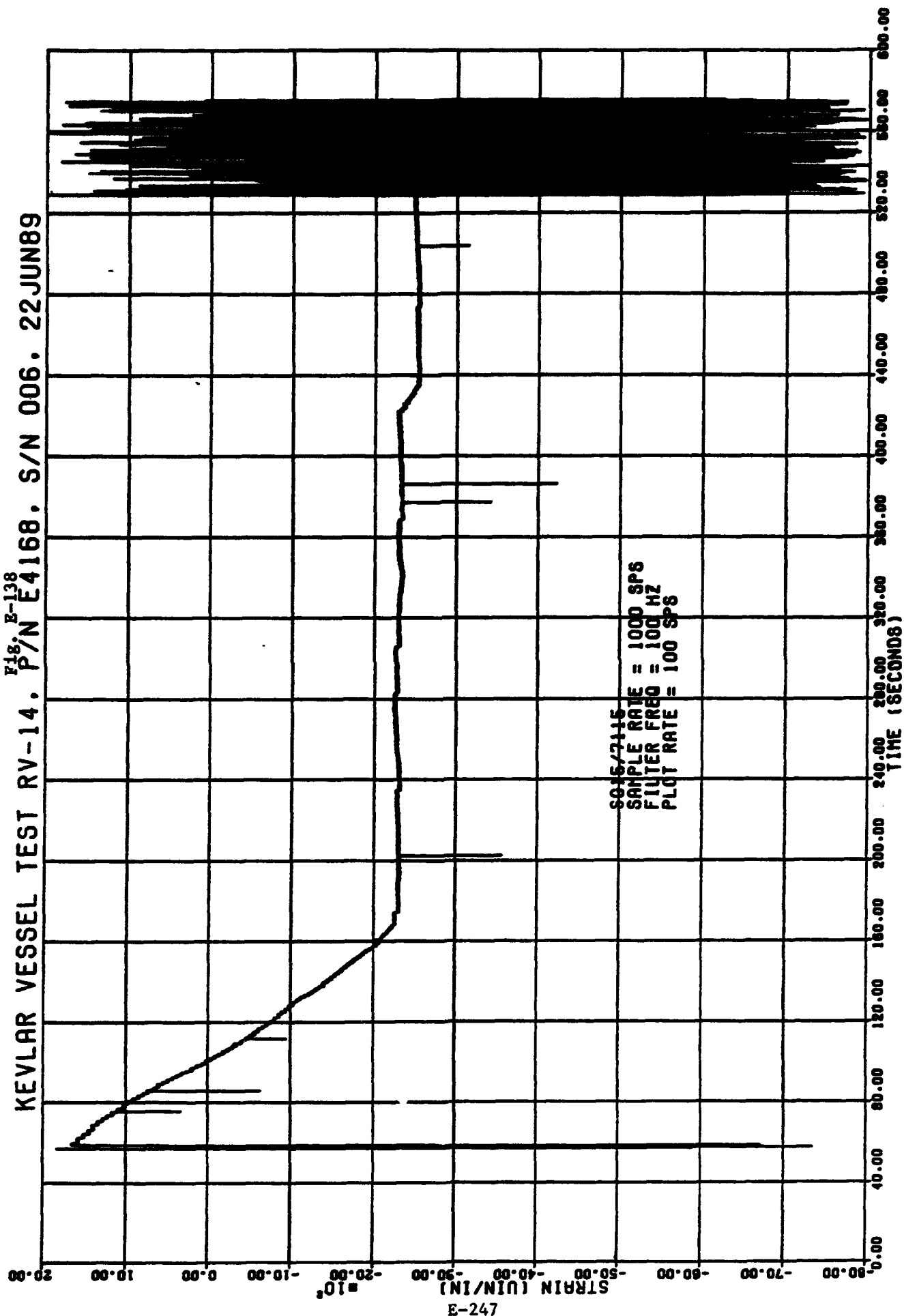
SO16/2116
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 100 SPS

TIME (SECONDS)

STRAIN (UIN/IN)

×10⁵

E-247

Fig. E-139
KEVLAR VESSEL TEST RV-14, P/N E4168, S/N 006, 22JUN89

SG17/7117
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 100 SPS

E-248

Fig. E-140

J/N 42001-0-18

RV-14

P/N E4168, S/N 006

90 % Kevlar Thickness

MS33649-8 side

MS33649-6 side
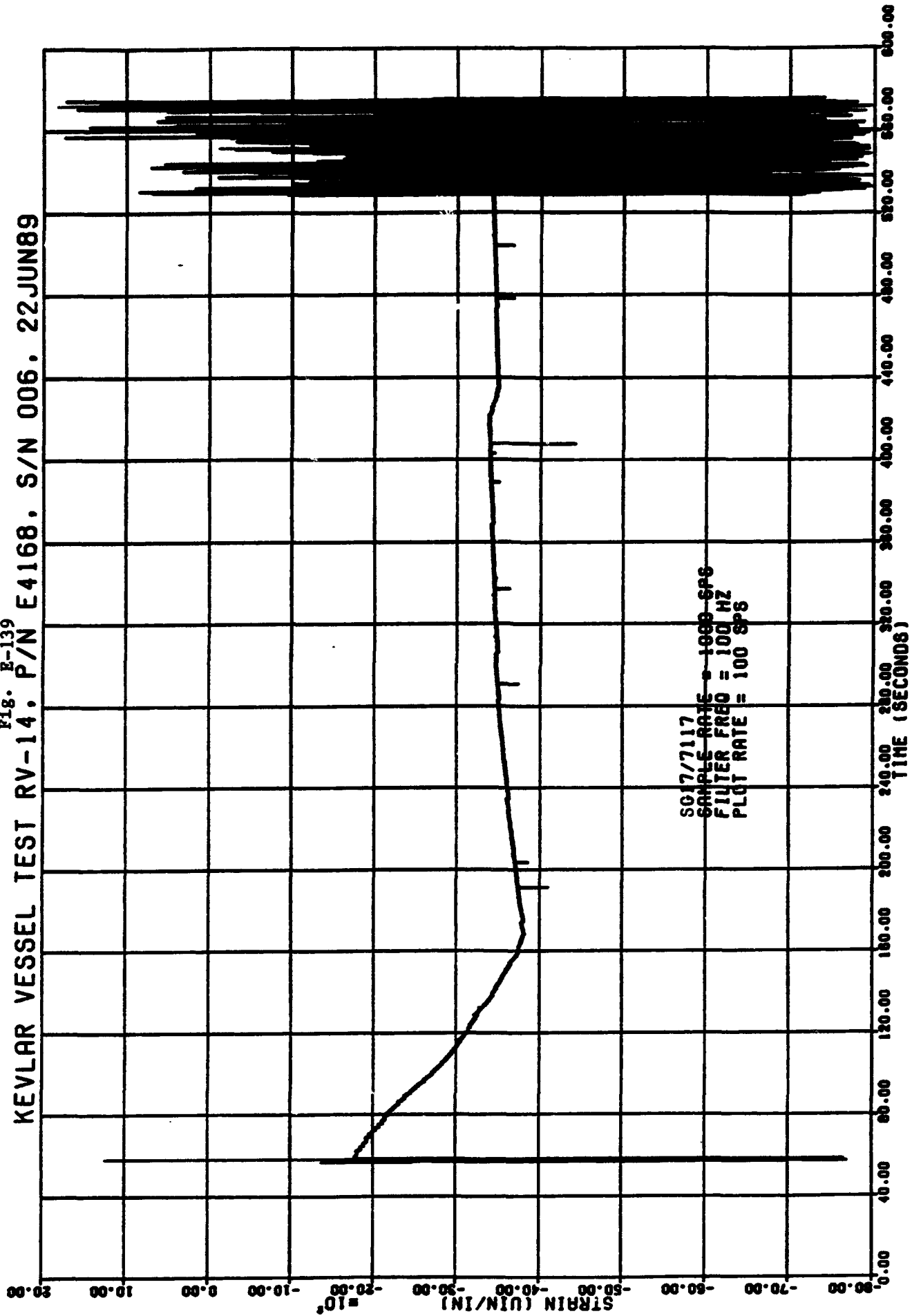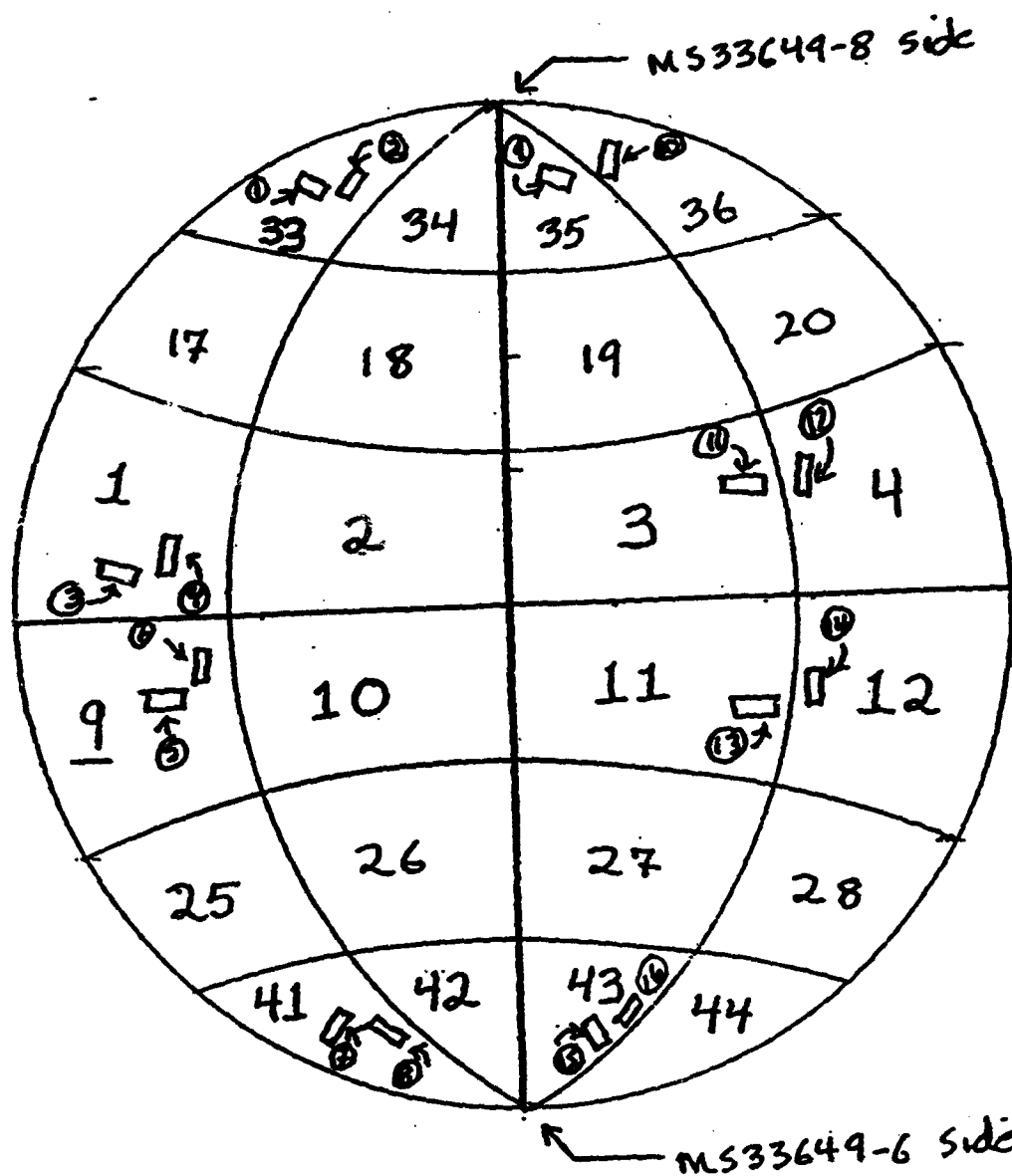
* Longitudinal axis.
rectangle II longiti
azis of strain gage

(page 1)

#1 - #48 - Section
#①- *㉔ - Strain Gag
▭ → strain Gag

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RV-14
P/N E4168 S/N 006
90% KEVLAR THICKNESS

EVEN GAGES = PARALLEL TO FIBERS

MS33649-8 SIDE

37   38   39   40

21   24

22   23

5   6   7   8

19   20

22

13   14   21   15   16

30   31

29   32

46   47

45   23   48

24

MS33649-6 SIDE
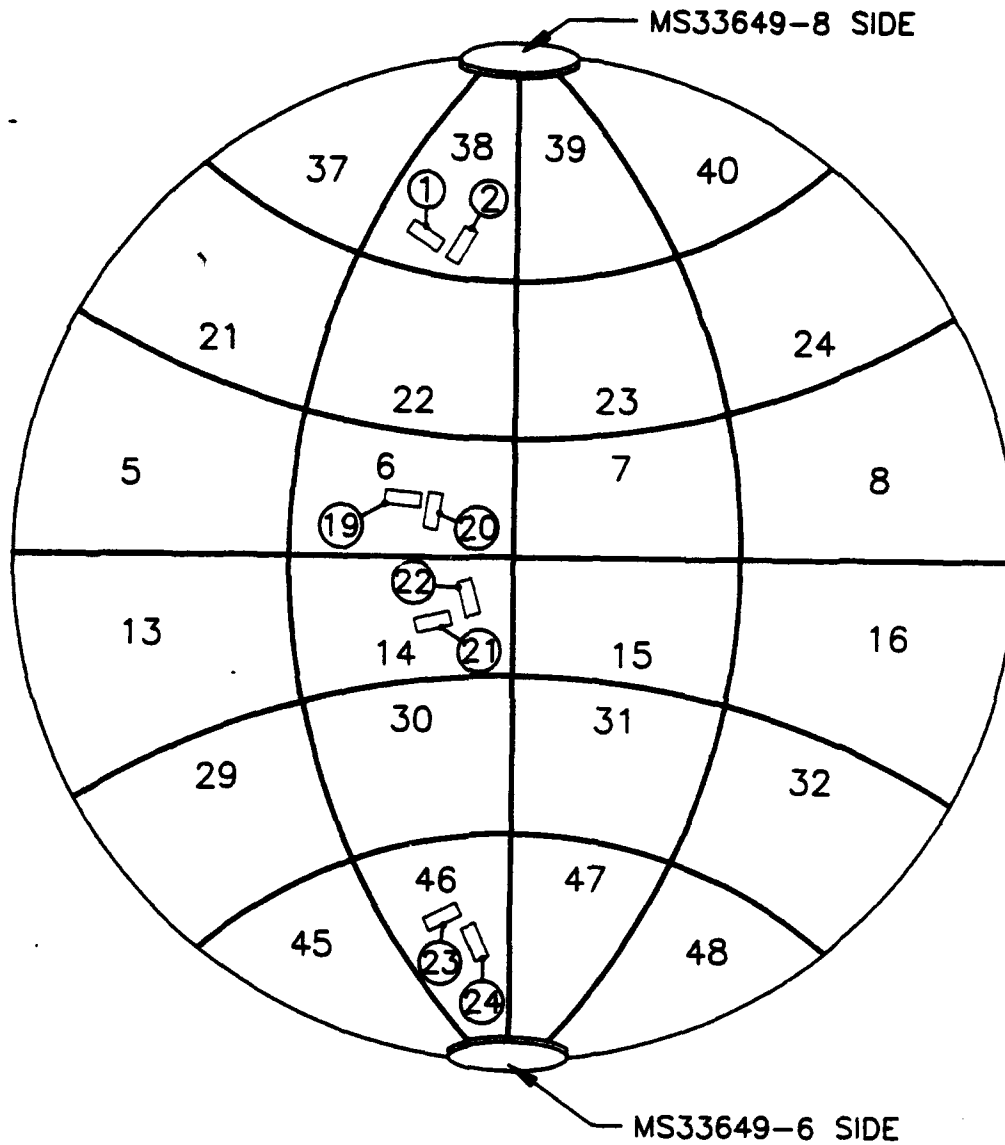
FIGURE E-141 STRAIN GAGE LOCATIONS FOR TEST RV-14.
E-250

E.11.4   Post Test Inspection

The vessel was intact and no Kevlar damage was observed. Leak checking confirmed that the metal liner was undamaged and intact.

E.12 **RV-14A Test (16" ϕ)**

E.12.1   **Test Vessel Description**

Same as RV-14 test except:

(a)   Prior test (RV-14)

(b)   Charging Current Density = .0066 ma/in^2

       (10% increase over RV-14 test)

(c)   Hold Time Before Test = 3 hours

E.12.2

INSTRUMENTATION OBSERVATIONS (By Instrumentation Engineer)

KEVLAR TEST 01S 14A. Date: 20JUL89. Project Number 573000RV.

EXPERIMENTAL OBSERVATIONS.

Introduction. Vessel S/N 006. P/N E4168 was tested. It was a 16 inch diameter stainless steel sphere and had a 90% Kevlar overwrap. This experiment was a repeat of the previous test, which did not leak. The vessel was hydrogen embrittled about the girth. It was tested in a vertical configuration. Tank pressure increases were ramps created with salvos of short pressure pulses. The tank pressure was increased from a steady state pressure of 1452 psig to about 1802 psig with five pressure pulses. The tank pressure was held for about five seconds near 1802 psig. The tank pressure was increased at 58509.280 milliseconds with eleven more pulses and held for about five seconds near 2224 psig. At 81509.884 milliseconds the tank pressure was increased with twenty more pules to exactly 3112 psig. At this pressure the tank began an immediate leak at 112.209 seconds.

At leak, the tank pressure decreased following a smooth but abrupt knee in the rising tank pressure profile caused by the twentieth pulse. The pressure decreased over a linear depressurization rate that terminated in an exponential decay. The exponential pressure decay decreased to below the 1500 psig initial condition and abruptly changed slope below 80 psig when venting was started. The pressure approached an assumed final zero asymptote. Noted in the pressure decay profile is the lack of ringing, and lack of prominent periodic modulations, major asperites, data dropouts and major glitches. Two moderate glitches mar the smoothness of the exponential decay, but the cause of these modulations remains unexplored.

The expanded plots show the SG behavior around the leak between 112.0 and 113.5 seconds. The expanded SG plots at leak show interesting variations from the typical plot. SG05 has been selected to represent typical SG behavior about the leak. Activity deviations from the typical plot includes almost no activity, SG23, to very active, SG06. These selections are judgemental, and other interpretations and speculations may also be valid.

Venting was done with the vent valve. The vent profile started after 80 psig, and it was clearly demarcated, almost linear, done at a rate of approximately -46.29 psig per second, not recorded near the end, not stopped for repressurization attempts, unremarkable and within normal limits.

As in previous tests, SG24 and the other strain gages were impressive mirror images of the pressure profile. Case strain in composite cases can be detected and is proportional to case pressure, but a calibration factor must be determined. The SG performance profiles will be slightly noiser than the vessel

1

pressure parameter and retain the risk of SG debonding.

Information For Test Personnel: Intstrumentation technicians, engineers, supervisors and panel operators must note the data loss near 50 to 58 seconds was due to encountering acquisition control file number 1, according to the Data Center printout (apparently the file was exited & reentered for some reason; or another explanation may explain the loss as there is not loss on the quick look print out for tank pressure plot immediately after the test). Also note the FM tape was started too late to capture the start of the test. There is about 8 minutes of tape time, and the start of the final ramping is important to capture, for the net strain change during ramping is required. The tape recorder should be started just prior to the start of the pressure salvos after the pause at the initial pressure condition is completed. The pause at 1452 psig was done to check for leaks and to establish thermal and pressre equilibrium near 1500 psig. Advise electricians to place a spark suppression diode in pressurization solenoid circuit to stop the minus L(di/dt) noise problem seen on PHXOUT/1900, etc. Refer to the discussion on the previous test for details.

Post-run Inspection. Witness panels, displacement gages and acoustic emission technology were not used. Extensive damage to the vessel's instrumentation wiring and pressurization plumbing was not observed. The over pressure sensor data showed no change and are discussed elsewhere. No Kevlar damage was observed and fraying was not obvious near either boss. The Kevlar remained intact. No major damage to the resin was observed.

IMPRESSIONS FROM THE DIGITIZED FM DATA.

Strain Gages.

Strain Gage Locations. The strain gages were located IAW ARDE drawing dated 3/7/89, Revision A dated 21MAR89, accompaning a 21MAR89 cover letter. The even strain gages are perpendicular to the wrap, and the odd strain gages are parallel to the wrap.

Strain Gage Temperature. Not shown on this print are the thermocouple locations. See the Instrumentation Specification Sheet for the locations and item numbers. The 7 thermocouple loci form a family of curves with almost identical profiles. Collectively, the gages measured temperature behavior over a span between 103 degrees F and 125 degrees F, approximately. For example, TT5 ranged from 117.1 to 123.4 degrees F, and TT7 ranged from 103 to 110 degrees F. TT3 read the highest temperature: 125.6 degrees F. All temperature profiles contained reasonable noise floors. The vessel's SG temperature behavior is considered to be within normal limits, and it wasn't investigated with further detail.

Performance Summary. There were 23 strain gages recorded on the FM tape recorder, and 20 functioned. Most plots had valid activity, and most plots had no noise spikes. During the initial

2

conditions, it is assumed all gages had much better than normal noise floors as most plots were very clean up to leak although data recording was delayed and was not started until after 80 seconds. The noise floors are discused elsewhere under Noise Floors. None of the strain gages were destroyed by tank depressurization although two (SG1 & SG2) didn't follow the family profile of mirroring the tank pressure profile. SG1 went very flat at leak, and SG2 rapidly changed at leak and finished with a exceptionally flat exponential curve.

Sign Convention. Positive strain gage polarity represents compression, and negative strain gage polarity represents tension.

Noise Floors. Except as noted elsewhere, the strain gage and other parameters' noise floors did not include major transverse or common-mode minus L(di/dt) transients, artifacts, crosstalk, atmospherics, noticeable RFI, intermodulation, spurious parasites, or sibilants. However, latent noise or data manifestations may be obscured in some parameters, and digital signal processing may be needed for signal enhancement. In general, the data appeared to be unbiased, precise and accurate. SG1 was clearly the noisiest in the group. Again, most plots were very clean.

Performance Exceptions. Strain gage behavior was within normal limits, except as noted. The following comments are based on interpretations of the 100 Hz and 1000 Hz data passes.

In general, strain gage behavior was similiar to previous tests. The general trend for the active strain gages was a tension strain polarization pattern proportional to tank pressure with corrections for glitches, polarity, shifts and some possible debonding, etc. The dynamic performance did not include major oscillations, except for SG01. Except as noted, all graphs had noise floors within normal limits. Only a few graphs had glitches. There was no noise on the SG plots during the vent operation.

Maximum SG Values and Performance Trends. The following codes are used below:
    NWNL noise within normal limits
    GRZ   good return to zero
    ARZ   approximate return to zero
    NRZ   no return to zero
    C   compression strain
    T   tension strain
    NTE   not to exceed
    OSC   oscillation
    EXP   exponential decay
    Unipolar: data predominately in one direction.
    Bipolar: data in both directions but not necessarily evenly balanced between polarities. In some cases, the data carrier was unipolar in tension but contained bipolar compression excursions.

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Units for strain values are in microinches/inch

SG01 Unipolar, T,
     many noise spikes. flat following burst, OSC @ 28.000 Hz
     seen on high frequency data pass for 5 msec duration.
SG02 Unipolar, T, clean, but has rapid decay
SG03 Unipolar, T, EXP,3 noise spikes,
SG04 bad on 100 and 1000 Hz passes

SG05 Unipolar, T, EXP, 2 noise spikes
SG06 Unipolar, T, EXP. 3 noise spikes
SG07 Unipolar, T, EXP
SG08 Unipolar, T, EXP

SG09 Unipolar, T, EXP
SG10 Unipolar, T, EXP
SG11 Unipolar, T, EXP, 1 noise spike
SG12 Unipolar, T. EXP. Overload due to bad cal cut on 100 & 1000
     ʹz passes

SG13 Unipolar. T. EXP. 1 noise spike
SG14 Unipolar. T. EXP
SG15 Unipolar. T, EXP, 1 noise spike
SG16 Unipolar. T, EXP, 1 noise spike

SG17 Unipolar. T, EXP, 1 noise spike, bad on 1000 Hz pass
SG18 Unipolar, T, EXP. 1 noise spike
SG19 Unipolar, T, EXP
SG20 bad on 100 Hz pass

SG21 bad on 100 Hz pass
SG22 Unipolar, T, EXP. 1 noise spike
SG23 Unipolar. T, EXP. 2 noise spikes

SG24 Unipolar. T, EXP. Recorded on the DACS only. Not on FM.
Quick-look showed no data interrupts, but Data Center data had
interrupts which are discussed elesewhere.

Performance Summary:

All channels included codes: T, NWNL. Out of the 23 SG channels
recorded on the FM tape recorder. three channels were bad. All
channels had unipolar tension behavior. Two channels had
abnormal bipolar strain activity, probably due to debonding (SG2
& SG3).

Because data recording did not start until after the 1500 psig
initial condition, net maximum strain change during the pressure
ramp was estimated as shown below.

A typical strain gage underwent a net tension strain of only 2000
unin/in. SG18 is representative of a typical SG. The strain at
the initial 1500 psig condition was determined by estimating the
strain after drawing in the missing profile by extending the
graph using the slope shown in the plot and the critial time

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points on the tank pressure plot. In this case the strain at 1500 psig was estimated 1000 uin/in. and the plot peaked at 3000 unin/in.

If the higher frequency data pass contains information not indicated by the 100 Hz data pass. a revision will be issued and those differences will be discussed. Refer to the ITT Analyst's comments for information on the higher frequency data pass.

The above information was determined by inspecting the graphs and may contain subjective errors.

Statistical Analysis. Valid speculations about strain gage behavior may involve biserial correlation of certain dichotomies (positive or negative polarization) to assess their associations (with wrap direction, etc.). For truly dichotomous distributions. the phi coefficient can be used. Because some of these dichotomous variables are really continuous (the magnitude or duration of polarization, and the degree of wrap thickness, location & direction. etc.) and normally distributed. tetrachoric correlation may be involved. An expert statistician should be approached with a clear statement of which variables and associations are important if valid conclusions about some of these data are to be obtained. An accurate evaluation of which variables are really dichotomies and which are proportionally continuous would also have to be prepared and passed to the statistician.

Data Analyst's Comments.

14A

The ITT Data Analyst. Richard Thomsen, reports: "Kevlar Test 15. Low Sample Rate FM Strain Gauges. The data were aligned to the nearest millisecond. The burst occured at 112.197 seconds (20:02:57.623 IRIG-B). Bad calibration cuts prevented processing of SG04/7104, SG17/7117, SG20/7120 and SG21/7121. There was also a cyclic noise on these channels. The noise appeared to clear up after the cal cuts on SG12/7112, so this channel was plotted. even though the cal cuts were bad, for qualitative purposes only. Some channels had noise spikes that are probably tape drop-outs. Channels SG01/1701 and SG16/7116 overranged after burst."

The ITT analyst continues with the following comments on the high frequency data pass: "Kevlar Test 15.14A High Frequency FM Strain Gages. The FM strain gauge data was digitized at 160,000 SPS using a 20,000 Hz filter. All channels were aligned to the nearest tenth of a millisecond. The vessel ruptured [leaked] at 112.197 seconds (20:02:57.620 IRIG-B). SG04/7104, SG12/7112, SG17/7117 had bad calibration values. Processing was completed for SG12 for qualitative purposes only. Almost all channels showed noise beginning at 112.197 seconds. ending at 112.201 seconds. SG01 showed an 28,000 Hz vibration beginning at 112.204 seconds and increasing until it ends at 112.209 seconds."

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IMPRESSIONS FROM THE QUICK-LOOK AND DIGITAL DATA ACQUISITION SYSTEM DATA.

Tank Pressure. PTANK/1901 was located on the top of the tank in the vent line. PVSOUT/1904 was also in the vent line, but it was located at the valve box about 15 feet from the tank. PTANK/1901 functioned as described under the Pressurization Ramp... paragraph.

The locations of the transducers was the same as test 10.

PVSOUT/1904 data were similiar to PTANK/190 except for the reduced frequency reponse because of the long pressurization line.

SG24. SG24 tracked the vessel pressure profile with corrections for polarity, etc. This parameter, as in the previous tests, was only recorded on the DACS for quick-look purposes. Note the comment elsewhere concerning skiped data near 50-58 seconds for the Data Center data, although the quick-look did not have any skipped data.

Phase Behavior and Frequency Response. Noted is the phase behavior; the two graphs were very close together in the time domain.

Other Parameters. The performance of the other parameters was within normal limits, except as noted below; this was determined by a quick review of the graphs for items PHXIN/1902, PHXOUT/1900, PTRAIL/1903, THXIN/2100, TBALL/2211. TBSOUT/2210, TBSIN/2209. THXOUT/2101 Heat Exchanger Output shows major spikes without noticeable decay times, as seen on the previous test. The spikes are apparently due to minus L(di/dt) transients from the pressurization efforts needed to increase tank pressure with the pressurization valve. Suppression with a diode at the valve solenoid is required to stop the problem, or the spikes may be disregarded. The spikes appear as glitches on pressure parameters such as PHXIN/1902, PHXOUT/1900, PTRAIL/1903 and as very small deflections on temperature parameter THXIN/2100.

The IRIG Time Code, IRIG/3808 TIMING, did record satisfactorily on the FM.

IMPRESSIONS FROM THE OVERPRESSURE SENSORS.

The vessel only leaked, and did not burst. There was no overpressure pulse. Overpressure data was not reduced.

The following text applies to overpressure sensors and is retained for reference.

Bikini Gages. A Bikini gage is one piece of bond paper compressed between two metal plates containing different sized round holes. The gages are aligned so the paper is perpendicular to the pressure source. Discrete pressure data can be obtained

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and is a function of the location of the damaged paper diaphrams. The approximate calibration is as follows for the indicated hole size using bond paper:

HOLE #	PSIG*	SIZE	PSIG**
1	7.3	5/8	4.4
2	5.2	7/8	3.3
3	3.7	1-1/4	2.4
4	2.7	1-7/8	1.7
5	1.9	2-3/4	1.25
6	1.4	3-3/4	----
7	1.0	5-3/8	----

*The source for this calibration data is unknown, but these data have been used since at least 1964 by the Astronautics Laboratory. ***The source for these calibration data is from a report THEORY, CALIBRATION, AND USE OF DIAPHRAGM BLAST METERS by W. T. Read, Division 2 National Defense Research Committee of the Office of Scientific Research and Development, NRDC Report No. A-392, OSRD Report No. 6463, Figure 18, Page 27, DEC45; this report was obtained from the Naval Surface Weapons Center, Silver Springs MD and was referenced in footnote (2) on page 3 of another report, OPERATION SANDSTONE JOINT TASK FORCE SEVEN TASK GROUP 7.1 BLAST MEASUREMENT SECTION, LAJ-8, PART II, Chapter 5.1, USE OF FOILMETERS ON OPERATION SANDSTONE, prepared by J. J. Meszaros and J. F. Moulton, Jr., 7JUN48, Fort Shafter, Oahu, T. H. This report indicates "For a considerable number of years air blast pressure measurements were made with the Aberdeen paper meter. The measurements obtained gave some indication of the peak pressure present. Early in the war Princeton University, under the auspices of NDRC, conducted an extensive experimental study. The primary results of these basic experimental sudies..." [are shown in footnote (2) discussed above]. It is not clear when the terms Bikini and Aberdeen were first used to designate diaphragm overpressure sensors. Nevertheless, the gages were used at Bikini [atoll in the N Pacific, Marshall Islands] in the 1946 atomic bomb tests (Crossroads Project) and again at Eniwetok in 1948 (Sandstone Project) and again in 1951 (Greenhouse Project). Most of the above information came from the DoD Nuclear Information and Analysis Center (DASIAC) on 12MAY88 and is the result of a lead provided by HQ/BSD/MYEB/Lt Col Don Gage to AL/TOAE/Dick Grove in FEB88. [OPR's Note: HQ/BSD was HQ/BMO prior to 21APR89 and AL was AFAL prior to 21APR89 and AFRPL prior to 22MAR87].

Reconciliation of the bikini overpressures and bias observations was not done as there was no overpressure pulse. All of the paper diaphrams were intact.

Piezoelectric Sensors.

There was no overpressure pulse.

As indicated in earlier experiments, the overpressure sensors, if used, would have behaved as follows:

Ideally, each overpressure sensor located to measure pressure should respond to a passing pressure pulse with a characteristic graph. The graph's curve should have a prominent leading edge rising from a stable initial condition. The typical leading edge should polarize positively and rise to the curve's maximum peak pressure over a smooth and almost linear path. At the peak pressure, the curve should inflect, and, at this reversal, enter into a characteristic depolarization decay consisting of an almost linear component followed by a distorted exponential component that returns to below the initial condition with an undershoot, more fully described below, representing rarefaction and the start of the refractory period.

More often than not, the linear decay should gradually change into a sluggish curve containing one prominent inflection, forcing the plot into the opposite direction, but staying below the initial condition. Eventually, the pressure rarefaction should deteriorate completely, and the plot should return smoothly to the initial condition, ending the refractory period.

Modulations and variations in behavior are caused by sensor placement (parallel or perpendicular to the flow direction), reflections, pressure wave distortions, time constants, frequency response, particulate impingement, insulation resistance, short circuits, open circuits and gas cloud geometry, etc.

DESCRIPTION OF THE EMBRITTLEMENT PROCEDURE. The ARDE embrittlement procedure dated 21MAR89 was followed. The 16" diameter vessel was girth embrittled. Embrittlement was inhibited, where required, with a maskant. Embrittlement was stared on 17JUL89. The currrent level was 0.176 amperes. Seventy-two hours of embrittlement were completed at 20JUL89. The tank was immediately moved from the shop embrittlement area to the test site, instrumented, hooked up, checked and pressure tested on 20JUL89. The electrolyte was sulphuric acéd. Sodium arsenite was added as an enhancer.

ADMINISTRATIVE INFORMATION.

Revision Record. Initial Issue: 3NOV89. Note significant delays were encountered in data reduction following the 20JUL89 experiment. The FM passes were finally provided on 3NOV89. Test RV15 is the same as RV14A. The 15 designator is used because of limits on the filename size.

Filename: testrv15 (14A)

Distribution: ARDE, Aris Escolona, Dave Gleich
                       PI, Dr. Pius Chih Hsu Chao
                       Aerospace Corp., Dr. Yen Pan
                       AFAL, Jim Miller, Dick Grove,
                            Dr. Tae-Woo Park
                       ITT, Richard Thomsen
                       PAFB, Pete Tadie

Office of Primary Responsibility.   USAF/AL/TOAE/Dick Grove/Edwards CA 93534.

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E.12.3   Pressure and Strain Versus Time Plots

Figures E-142 to E-148 give pressure versus time and selected strain versus time plots. Figures E-140 and E-141 are sketches showing strain gage locations. Even numbered strain gages are perpendicular to the Kevlar wrap and odd numbered strain gages are parallel to the wrap.

E.12.4   Post Test Inspection

The Kevlar shell was intact after the test with no fiber damage noted upon inspection with the tank still attached to the test stand. A leak-check confirmed liner leakage. The tank was cut apart, photographed and inspected visually at AFAL. Figures E-149 and E-150 show the cut apart tank. Girth cracks in the local girth embrittled zone were visually observed. The cut apart tank was shipped to ARDE for further inspection. At ARDE, the cut apart tank liner was die checked to enhance the visibility of the cracks and then photographed. Figures E-151 and E-152 show photographs of portions of the cracked liner inside surface. Continuous connected hoop cracks run around the entire girth in the local embrittled area.

Fig. E-142

14A

KEVLAR VESSEL TEST RV-15, P/N E4168, S/N 006, 20JUL89

E-263
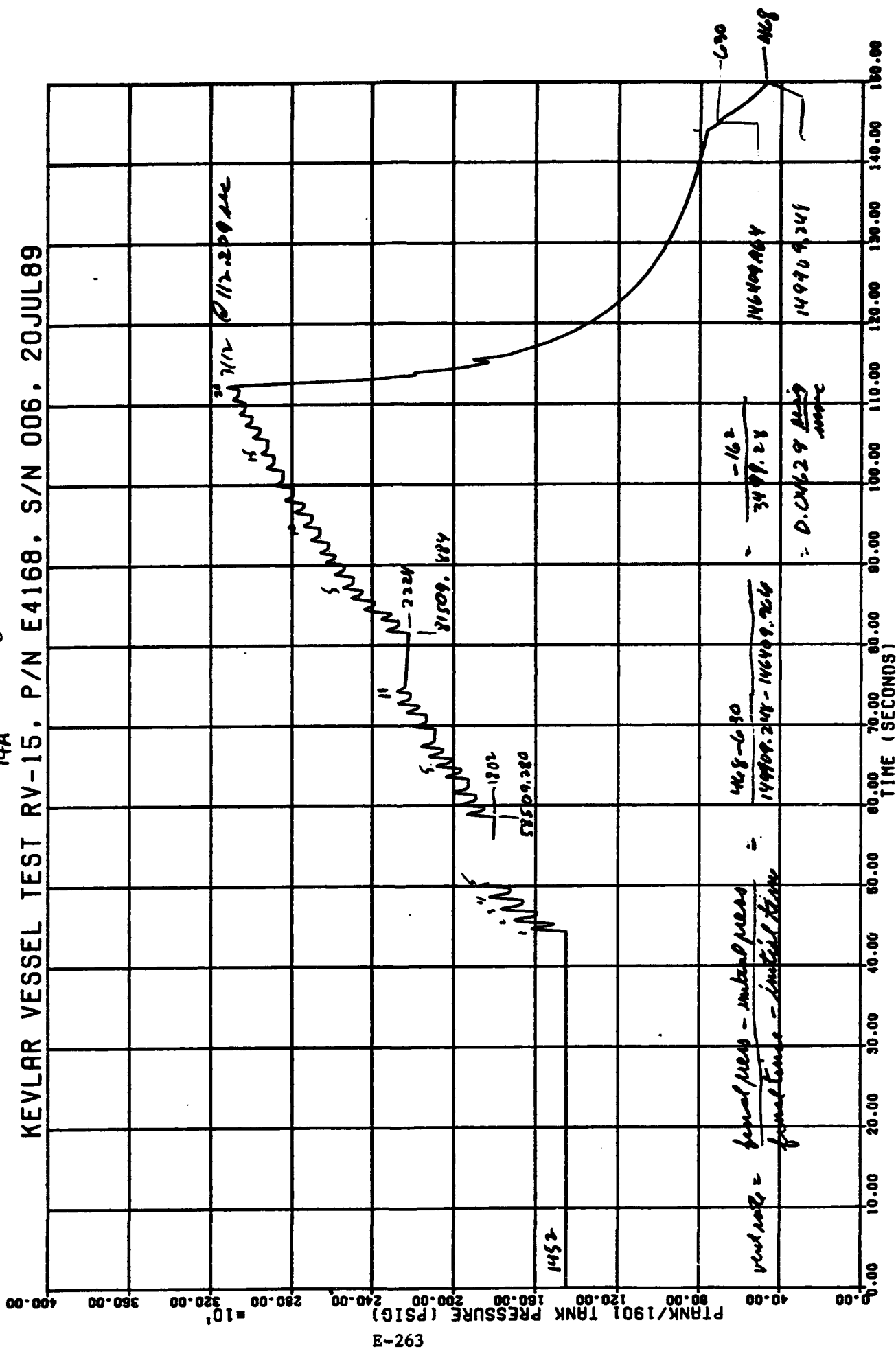
Fig. E-143

KEVLAR VESSEL TEST RV-15, P/N E4168, S/N 006, 20JUL89

14A
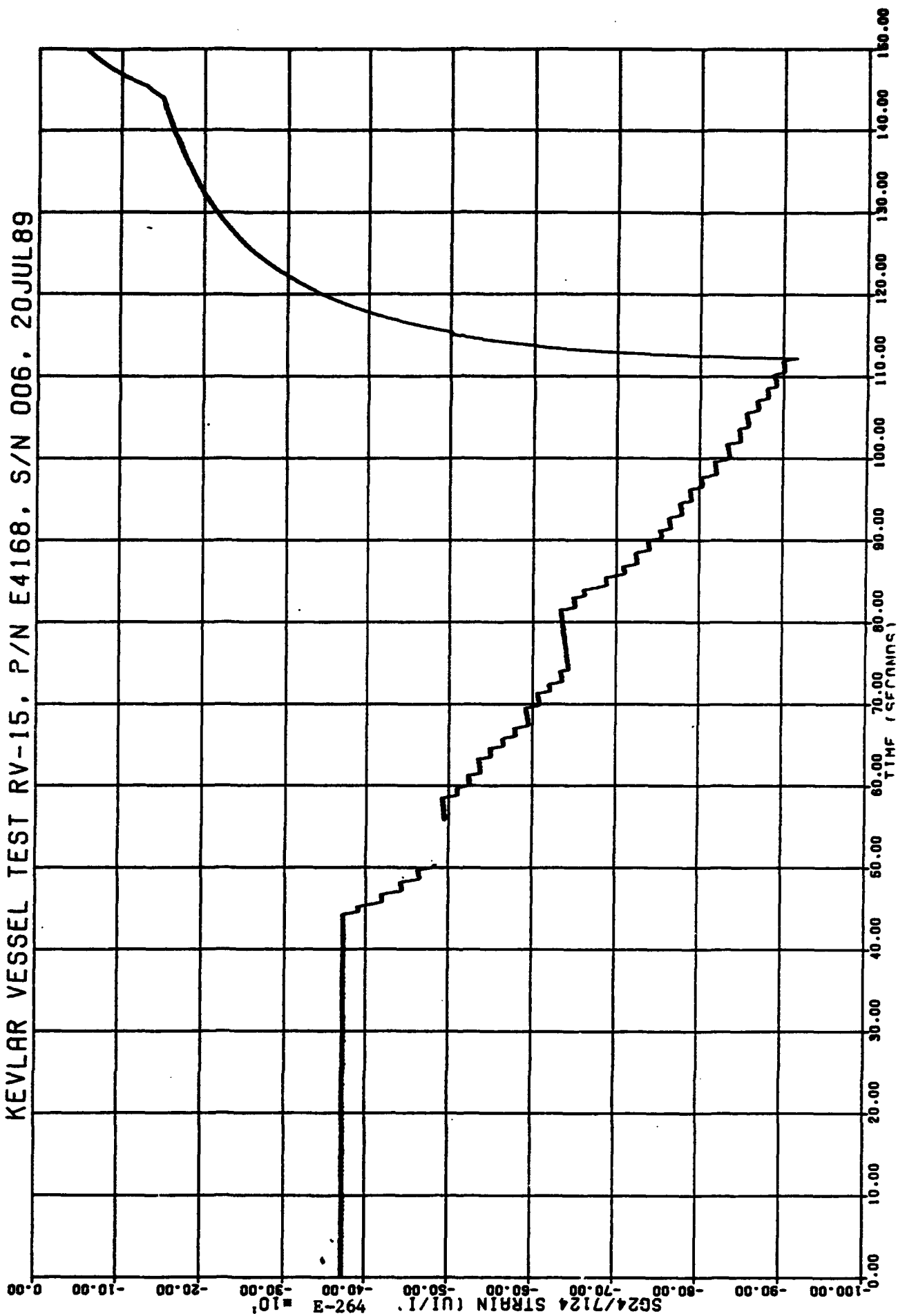
Fig. E-144

KEVLAR VESSEL TEST RV-15, P/N E4168, S/N 006, 20JUL89
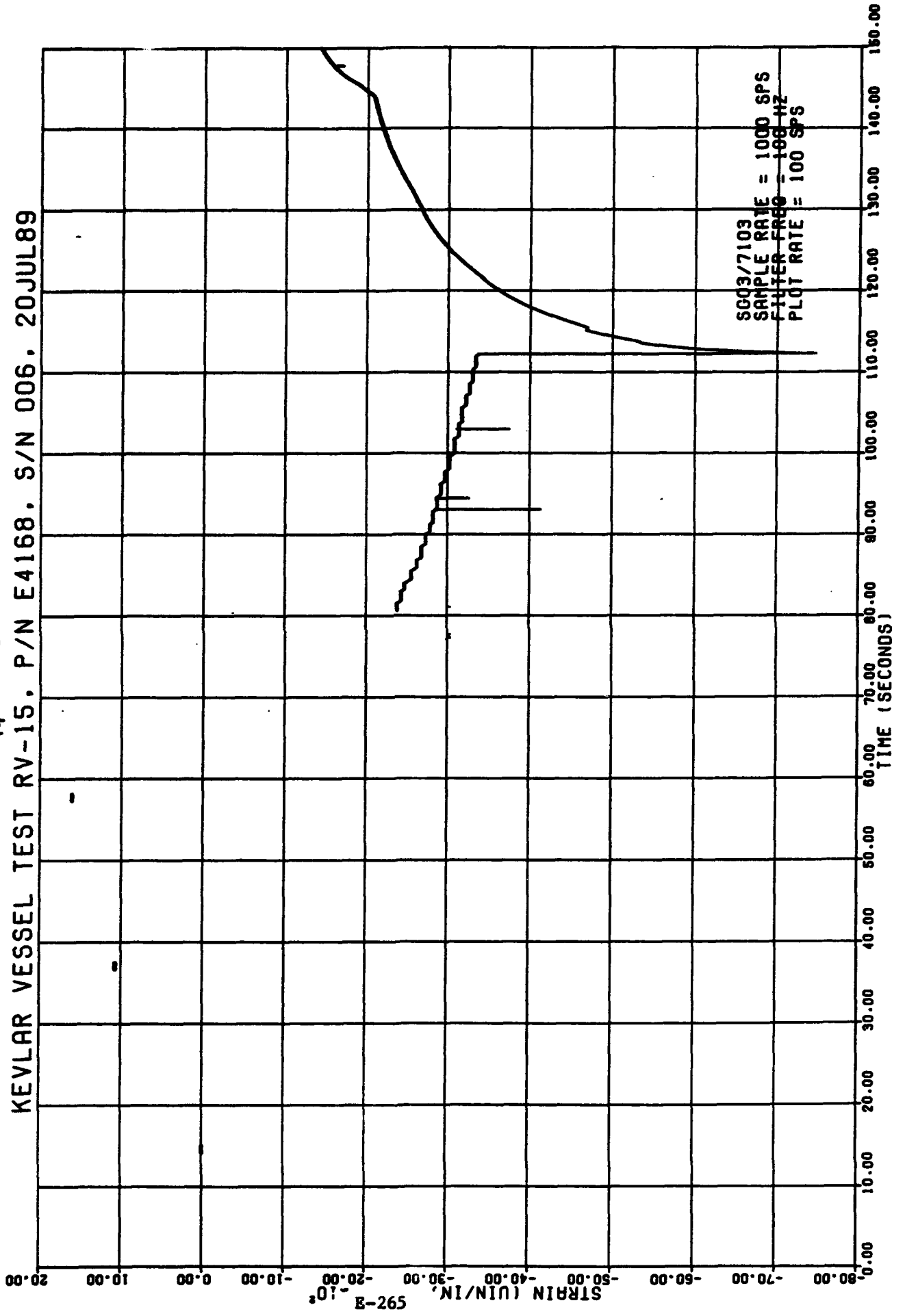
14A

SG03/7103
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 100 SPS

TIME (SECONDS)

STRAIN (UIN/IN, .10³

E-265

KEVLAR VESSEL TEST RV-15, P/N E4168, S/N 006, 20JUL89

14A Fig. E-145

STRAIN (UIN/IN) $\times 10^2$

TIME (SECONDS)

S006/7106
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 1000 SPS

992-3 E-266

40.00 20.00 0.00 -20.00 -40.00 -60.00 -80.00 -100.00 -120.00 -140.00 -160.00

112.00 112.10 112.20 112.30 112.40 112.50 112.60 112.70 112.80 112.90 113.00 113.10 113.20 113.30 113.40 113.50

14A E-146

"KEVLAR VESSEL TEST RV-15, P/N E4168, S/N 006, 20JUL89

SO12/7112
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 1000 SPS

TIME (SECONDS)

STRAIN (UIN/IN) ($*10^2$)
E-267

KEVLAR VESSEL TEST RV-15, P/N E4168, S/N 006, 20JUL89

Fig. B-147

14A

SO15/7115
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 100 SPS

TIME (SECONDS)

STRAIN (UIN/IN) *10⁸

E-268
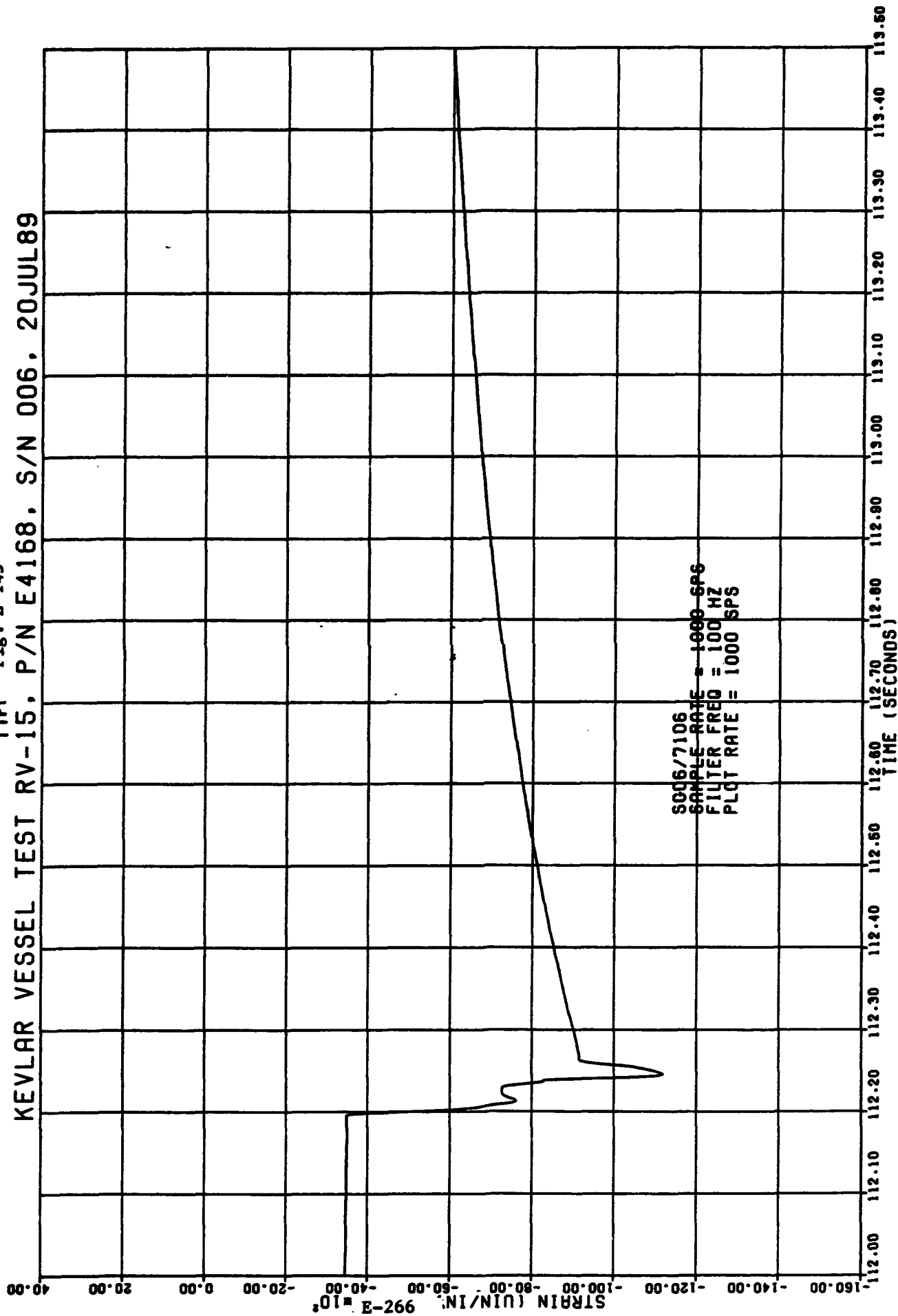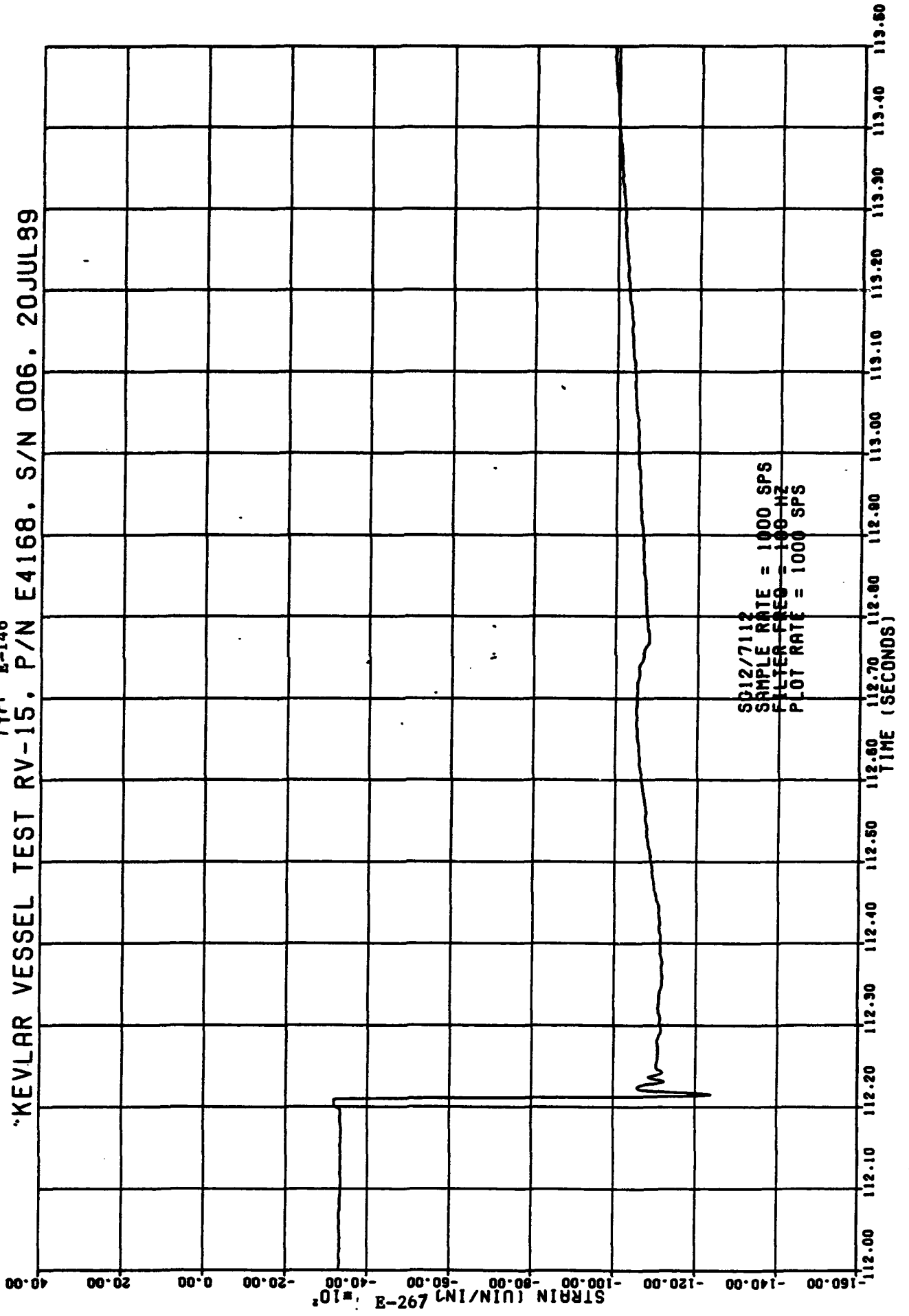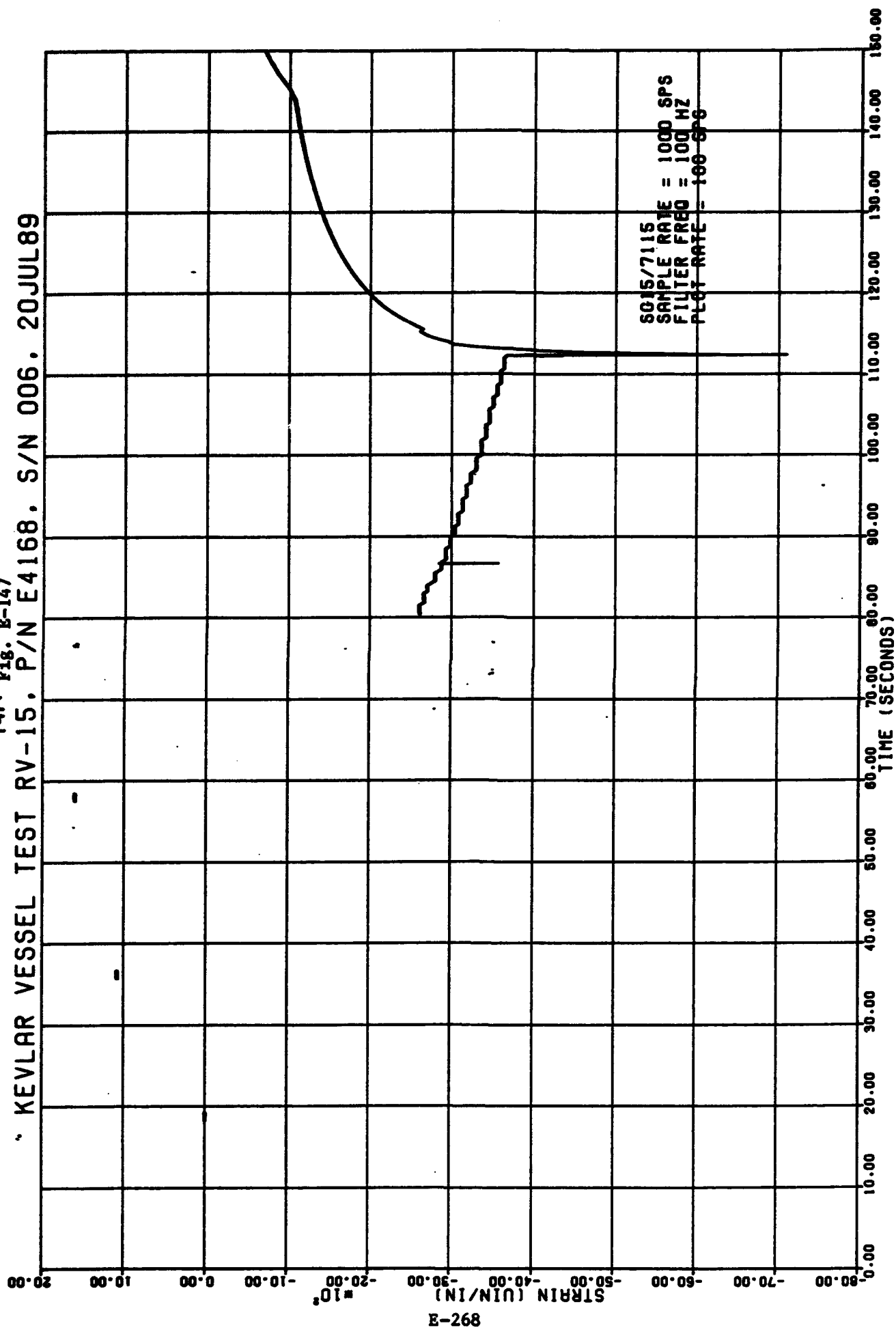
14A Fig. E-148

"KEVLAR VESSEL TEST RV-15, P/N E4168, S/N 006, 20JUL89"

5016/7116
SAMPLE RATE = 1000 SPS
FILTER FREQ = 100 HZ
PLOT RATE = 1000 SPS

STRAIN (UIN/IN) ×10²

TIME (SECONDS)

E-269
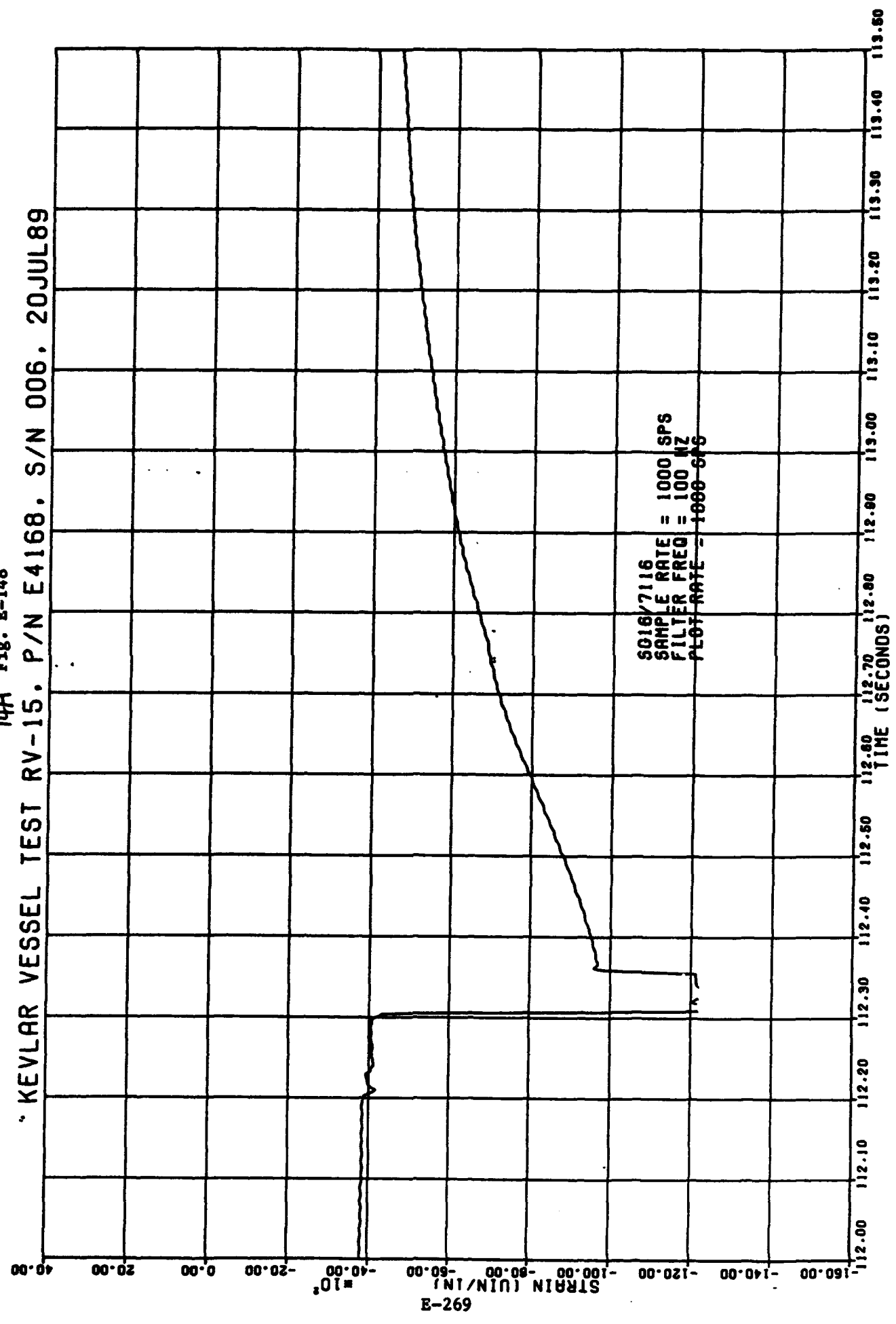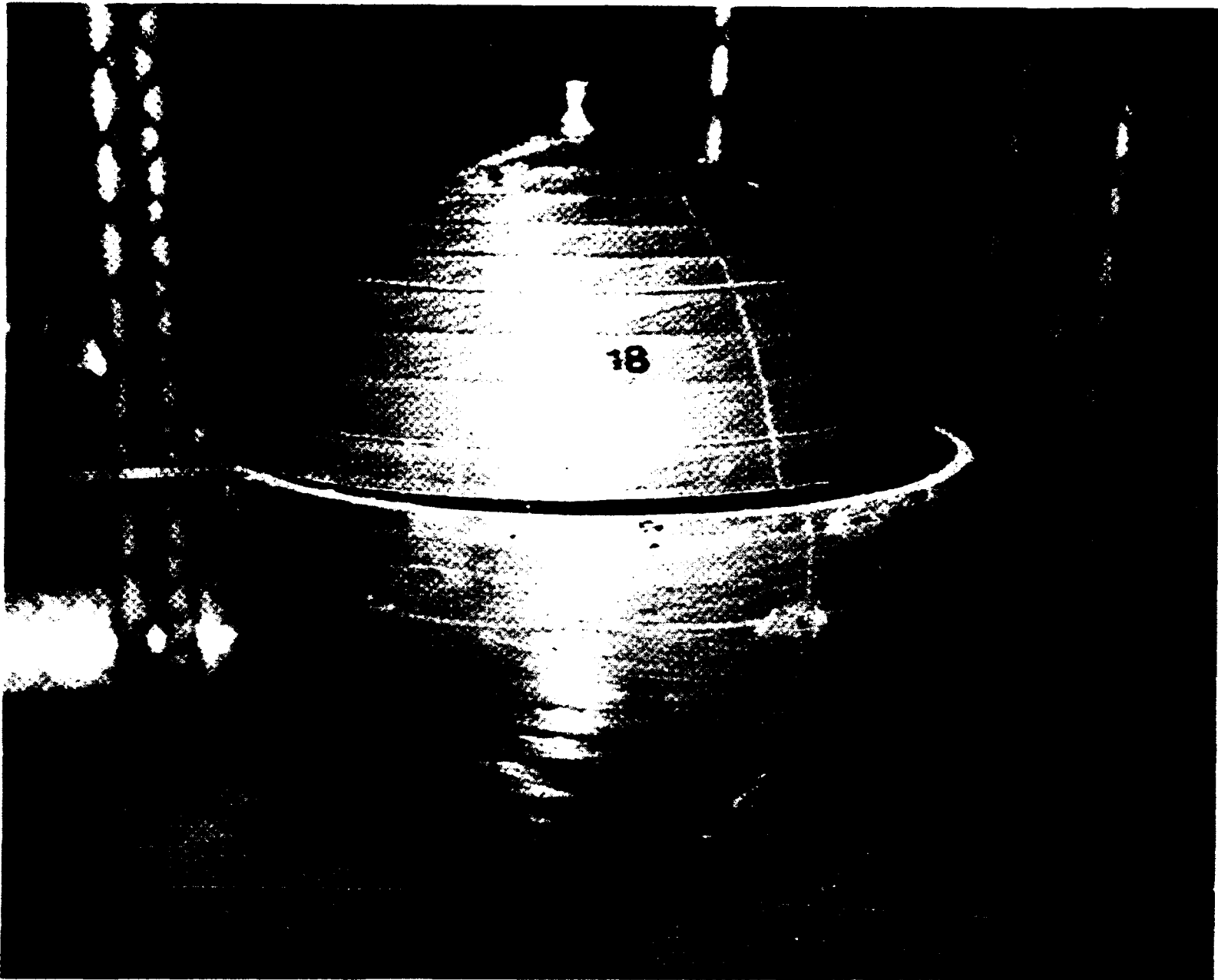
TEST RV-14A, CUT APART POST TEST TANK, EXTERIOR
VIEW

Fig. E-149

E-270
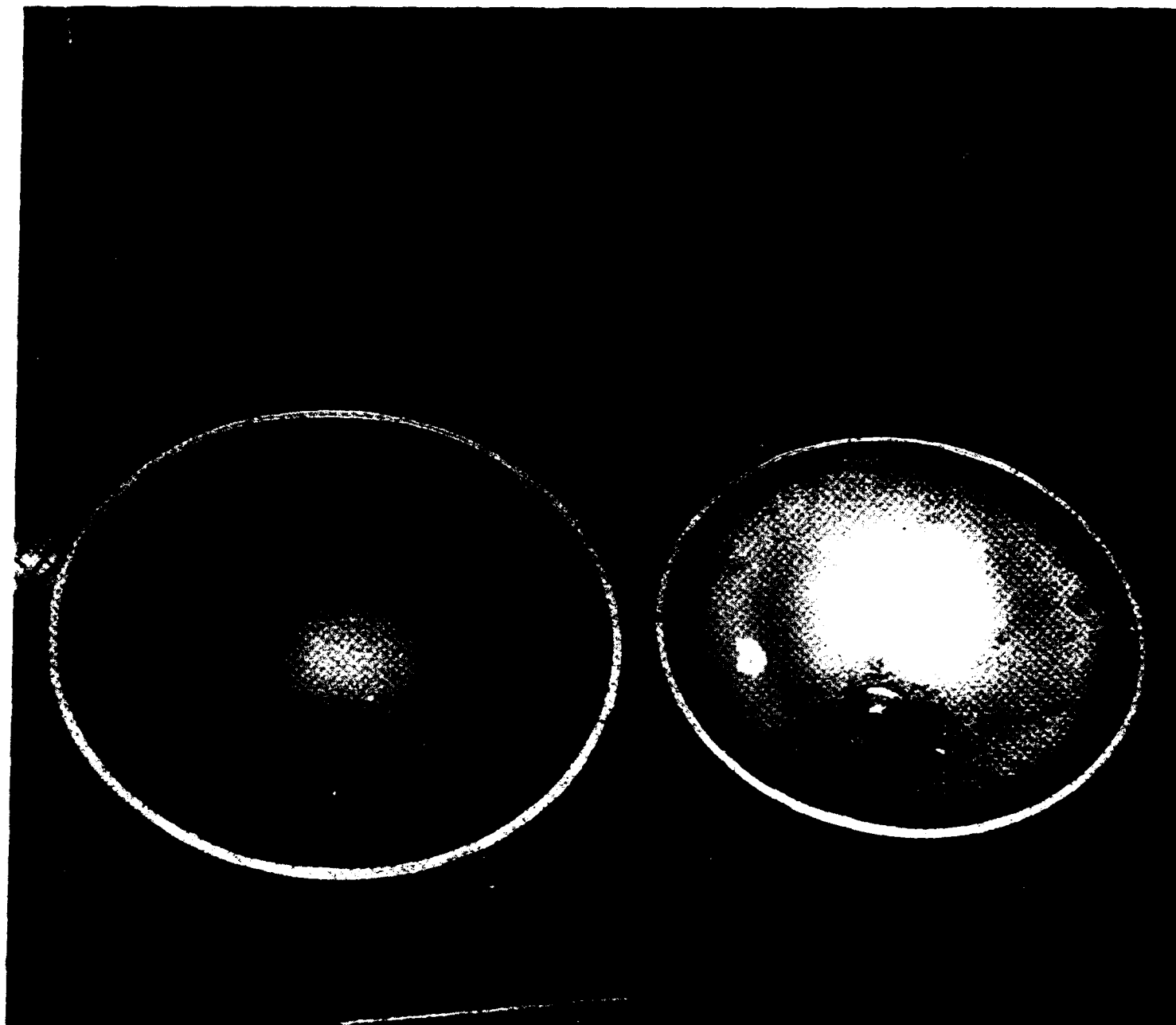
TEST RV-14A, CUT APART POST TEST TANK, INTERIOR VIEW

Fig. E-150

E-271
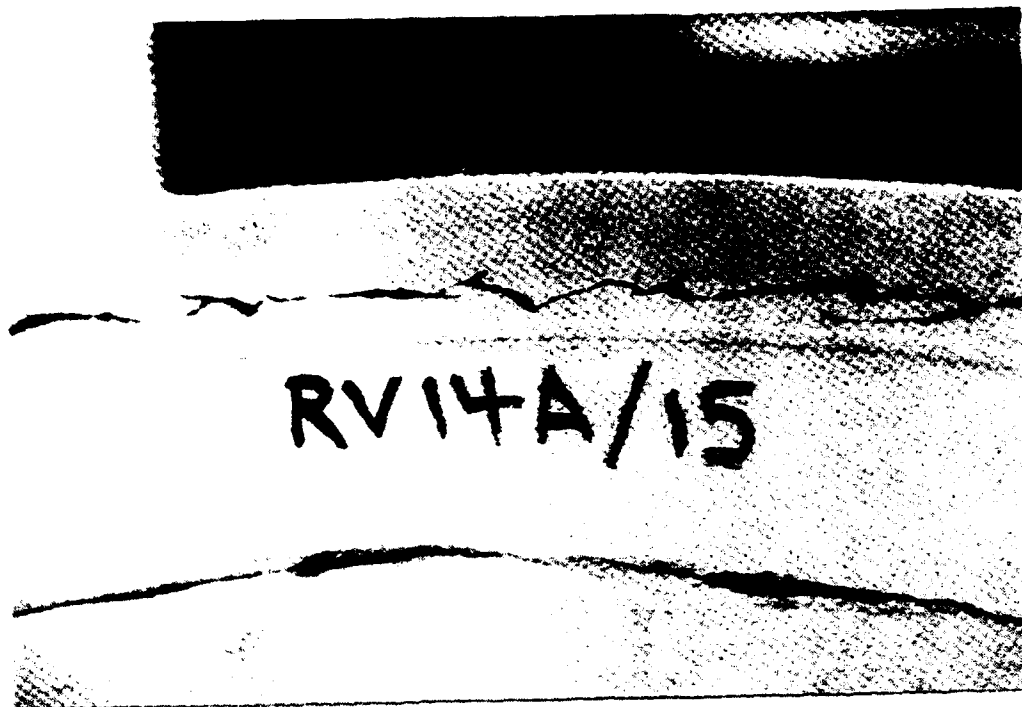
TEST RV-14A, POST TEST EMBRITTLED GIRTH

CONTINUOUS CRACK

Fig. E-151

TEST RV-14A, POST TEST EMBRITTLED GIRTH

CONTINUOUS CRACK

Fig. E-152

APPENDIX F - Full Scale Test Data Correlation

This appendix contains test data correlation examples and supporting measured pressure and fiber strain information.

Calculations given below show that the fiber strains resulting from the liner ductile, stable crack growth leak-before-burst (LBB) mode are small, and, therefore, unimportant, compared to the liner sudden unstable crack growth brittle failure mode.

F.1 Ductile Failure Mode

Figure F-1 illustrates the geometry for the case in which a ductile crack forms in the metal liner. The full tank pressure is suddenly applied to the overwrap over the area which becomes exposed. The centerline in this sketch denotes either an axis of symmetry, for a circular hole, or a plane of symmetry, for a linear crack.

For simplification of analysis, we replace the liner by the equivalent static pressure, P_w, it transmits to the fiberwrap boundary. From the results of Appendix A, we have,

$$\sigma_w = \frac{(R)P_w}{2 h_w} = \frac{(R)}{2h_w}(p^* + P_i) \text{ --- (A-33), with}$$

initial stress pressure, P_i and incremental static fiber wrap stress pressure, P^* given by,

$$P_i = \frac{2 h_w \alpha_w \epsilon_i}{R} \quad \ldots \text{ (A-34)}$$

$$P^* = \frac{p}{1 + \frac{h_M \alpha_M}{h_w \alpha_w}} \quad \ldots \text{ (A-35)}$$

For typical numerical values,

$h_M = .05$, $h_w = .23$, $\alpha_w = 6.76 \times 10^6$,

$\alpha_M = \frac{27 \times 10^6}{.7}$, $R = 7.64$,

$\epsilon_i = .0035$ and $P = 4000$, we obtain the fiber wrap static equilibrium pressure,

$$P_w = P^* + P_i = \frac{4000}{1 + \frac{.05 \times 17/.7}{.23 \times 6.76}} +$$

$$\frac{2 \times .23 \times 6.76 \times 10^6 \times .0035}{7.64}$$

$$P_w = 1785 + 1425 = 3210 \text{ psig}$$
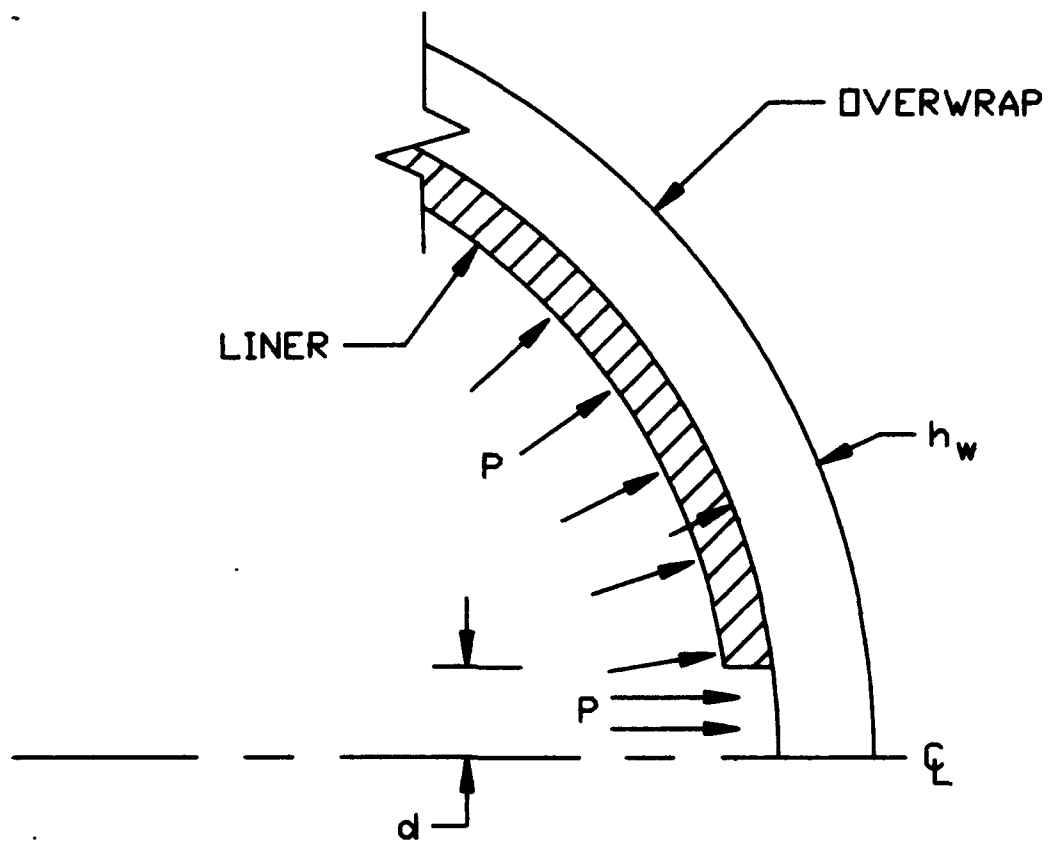
FIG. F-1   IDEALIZATION OF DUCTILE CRACK GEOMETRY

Computing now as an approximation, stresses and strains relative to equilibrium values, we define the problem as the effect of the sudden application of a pressure $P_M = P - P_w = 4000 - 3210 = 790$ psig to the exposed portion of the fiber wrap.

With this approximation, the simplified problem of a sudden stable ductile liner fracture is sketched on Figure F-2.

Assuming the liner remains attached to the fiber overwrap, we estimate the overwrap strains noting that if the crack opening is small compared to the liner thickness, the largest strains will be associated with shear. A force balance on the exposed piece of fiber overwrap gives the average shear strain ac ss the thickness of the overwrap at a distance "d" from the centerline (Figure F-2) as $\gamma = \dfrac{\tau}{G} = \dfrac{P_M d}{Gh_w}$ (linear crack) ... (A-36)

$$\gamma = \frac{P_M d}{2Gh_w} \text{ (circular crack) ... (A-37)}$$

For a crack with an opening equal to the overwrap thickness $(2d = h_w)$, for example we have for $G = 1.74 \times 10^6$ psi, $h_w = .23$ and $P_M = 790$ psi, static shear strains, γ, of .00023 in/in for a linear crack and .00011 in/in for a circular hole. These strains are very small compared to the static equilibrium strains in the fiber wrap, even if one assumes a maximum possible dynamic amplification factor of two on static shear strains.
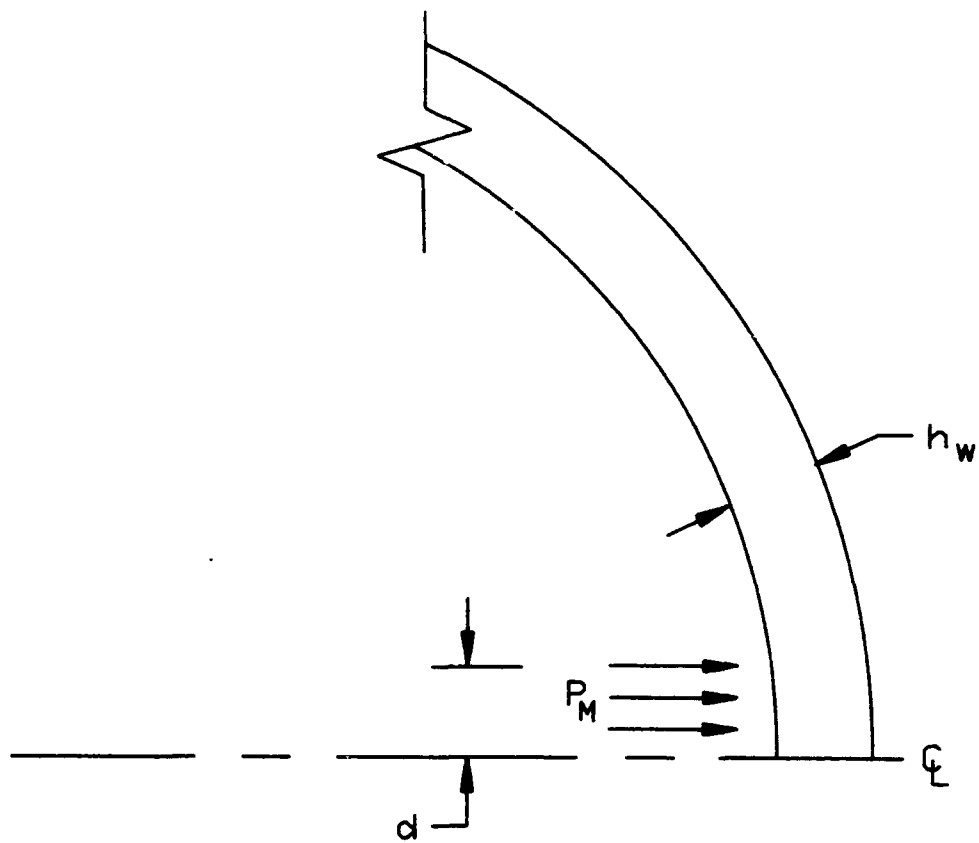
FIG. F-2 SIMPLIFIED CRACK GEOMETRY

F.2 Brittle Failure Mode

The critical liner brittle failure mode was analyzed and test data correlated using the two-dimensional PICES 2D finite difference transient computer code assuming as a worst case an instantaneous complete girth circumference brittle crack model. In addition, simplified lumped 1D spherically symmetric structural models were utilized. These 2D and 1D models have been discussed in detail in Appendix A.

F.2.1 PICES 2D Computer Program Data Correlation

PICES 2D computer runs were made for the brittle failure mode baseline tank (100% fiber thickness) and off-baseline fiber thickness tanks to assess the effects of fiber overwrap thickness, metal liner/fiber interface boundary condition ("slip" or "bond") and pressure, as well as to compare the theoretical PICES 2D results with applicable test data and the simplified 1D spherically symmetrical structural models.

F.2.2 Effect of Fiber Wrap Thickness

For a given fiber wrap thickness, the maximum fiber strains were found to be meridional at an angle of 20° from the pole where fiber thickness is minimum, as shown on Figure 2-15. In general, when comparing one fiber wrapped tank to another having the same type of wrap pattern, peak fiber strains are approximately proportional to the average lumped fiber thickness of each tank.

F.2.3   **Effect of Liner/Fiber Interface Boundary Condition**

The "slip" interface boundary condition (no friction and no cohesion) gave larger fiber strains, as shown on Figure 2-15, and correlated better with the test data compared to the "bond" interface boundary condition (infinite friction and infinite cohesion) case.

F.2.4   **PICES 2D Results Compared to Test Data**

The peak fiber strains computed by PICES 2D were reasonable, but conservative, since they were greater than the test as illustrated by the following data.

PICES 2D peak computed meridional strain for 4000 psig pressure was 17,600 micro-inch/inch, including a 3000 $\frac{\text{micro-in}}{\text{inch}}$ prestrain (Figure 2-14). The maximum delta meridional strain computed by PICES 2D was then 17600 - 3000 = 14600 $\frac{\text{micro in}}{\text{inch}}$.

Typical measured maximum meridional delta micro strains were 10,600 - 11,900 and 10,600 for pressures of 3800 and 3700 psig, respectively, for tests RV-7 and RV-9 as given in Table F-1.

Taking strain proportional to pressure for small pressure changes, we project computed delta microstrains of $\frac{38}{40}$ x 14600 = 13,870 and 37/40 x 14600 = 13,505, respectively, at 3800 and 3700

psig pressure. The PICES 2D computer model calculated strains

are thus conservative which can be seen by comparing 13505 to

13870 computed delta microstrains with 10600 to 11900 measured

delta microstrains. On the average then, PICES 2D computed fiber

strains are 22% higher than measured values.

F.2.5 Comparison of PICES 2D Results With 1D Lumped Spherically

Symmetric Model Predictions

The PICES 2D computed fiber strains were greater than those

predicted by the simple 1D transient model as shown on Figure 2-

14. In view of the good agreement between test results and the

fiber strains predicted by the simple 1D model, as subsequently

discussed in section F.2.6, and the higher computed fiber strains

of the PICES 2D, subsequent test data correlation efforts using

the PICES 2D computer code were stopped. Instead of modifying

the PICES 2D model in the search for improved results, all

subsequent test data efforts were performed using the simple 1D

structural model(s) for program cost and schedule advantages.

F.2.6 Simple 1D Spherically Symmetric Transient Model Data

Correlation

Figures F-3 to F-6 and 2-17 are test data plots of typical fiber
delta strains measured from the tank's prestrained state, i.e.,
total strain minus prestrain. Superposed on these plots are the
delta fiber strains $(\epsilon_1 - \epsilon_i)$, $(\epsilon_2 - \epsilon_i)$ and $(\epsilon_{max} - \epsilon_i)$
calculated by use of the simple 1D transient spherically
symmetric model defined in Appendix A. Table F-1, constructed by
utilizing the data of Figures F-3 to F-6 and 2-17, summarizes the
comparison between measured and calculated fiber delta strains.
It is seen that the agreement between the simple 1D analytic
model theory and test data is reasonably good.

COMPARISON OF MEASURED AND CALCULATED TYPICAL DELTA FIBER STRAINS FOR 1D SPHERICALLY
SYMMETRIC TRANSIENT MODEL

Test No.	Liner Failure Pressure (psig)	Strain Gage No.	Ref. Figure No.	Delta Fiber Strain (Micro-inch/inch)					
				$(\epsilon_{Max} - \epsilon_1)$		$(\epsilon_1 - \epsilon_1)$		$(\epsilon_2 - \epsilon_1)$	
				Measured	Calculated	Measured	Calculated	Measured	Calculated
RV-7	3800	5	F-3	11,900/ 10,600	11,200	4300	4100	7500	8000
RV-9	3700	14	2-17	10,600	11,200	3500	4300	7500/ 9000	8000
RV-9	3700	17	F-4	11,600	11,200	4400	4400	7500	8100
RV-11	3600	20	F-5	14,200	14,200	5000	4700	9000	9000
RV-11	3600	14	F-6	15,000	14,200	3000	4500	9000	9600

- SIMILAR TO ANALYTICAL MODEL.

OTHER RV-7 GAGES WITH SIMILAR RESPONSES ARE:

SG3, SG5, SG8, SG9, SG11, SG13, SG15, SG17,

SG18, SG22, SG23

RV-7, SG5, WITH 2MS, 100MS, AND 10S TIME DIVISIONS

(2 mS.)

10S
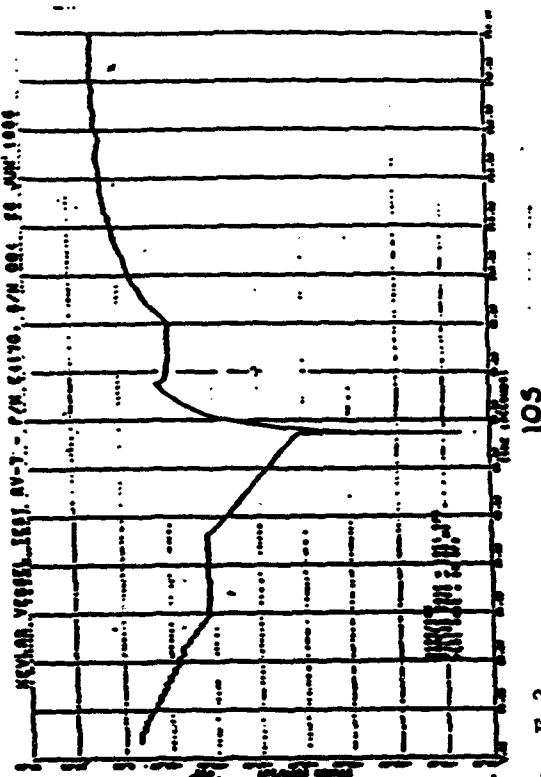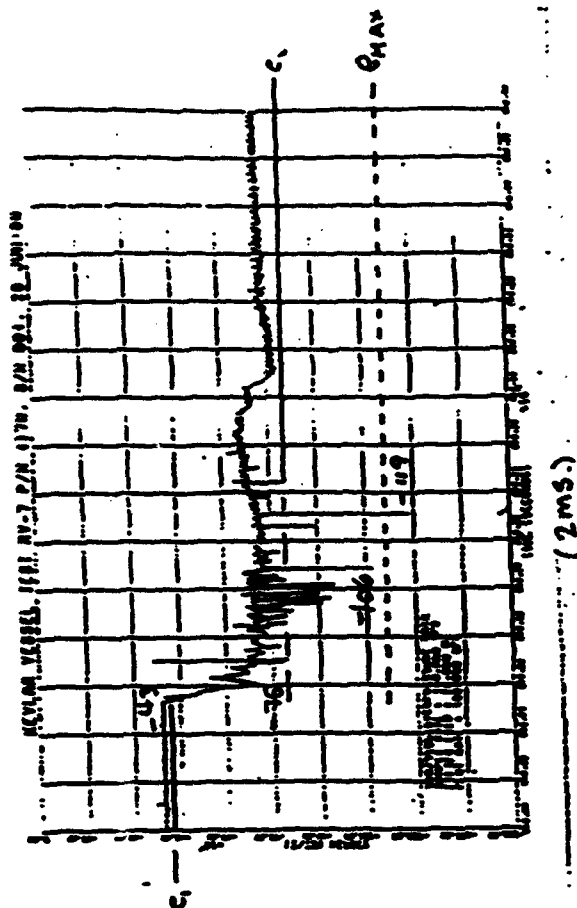
(100 mS.)

Fig. F-3
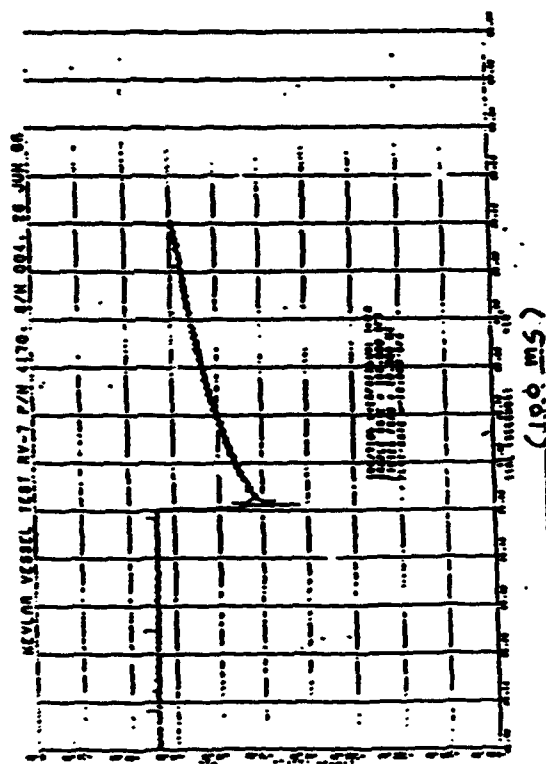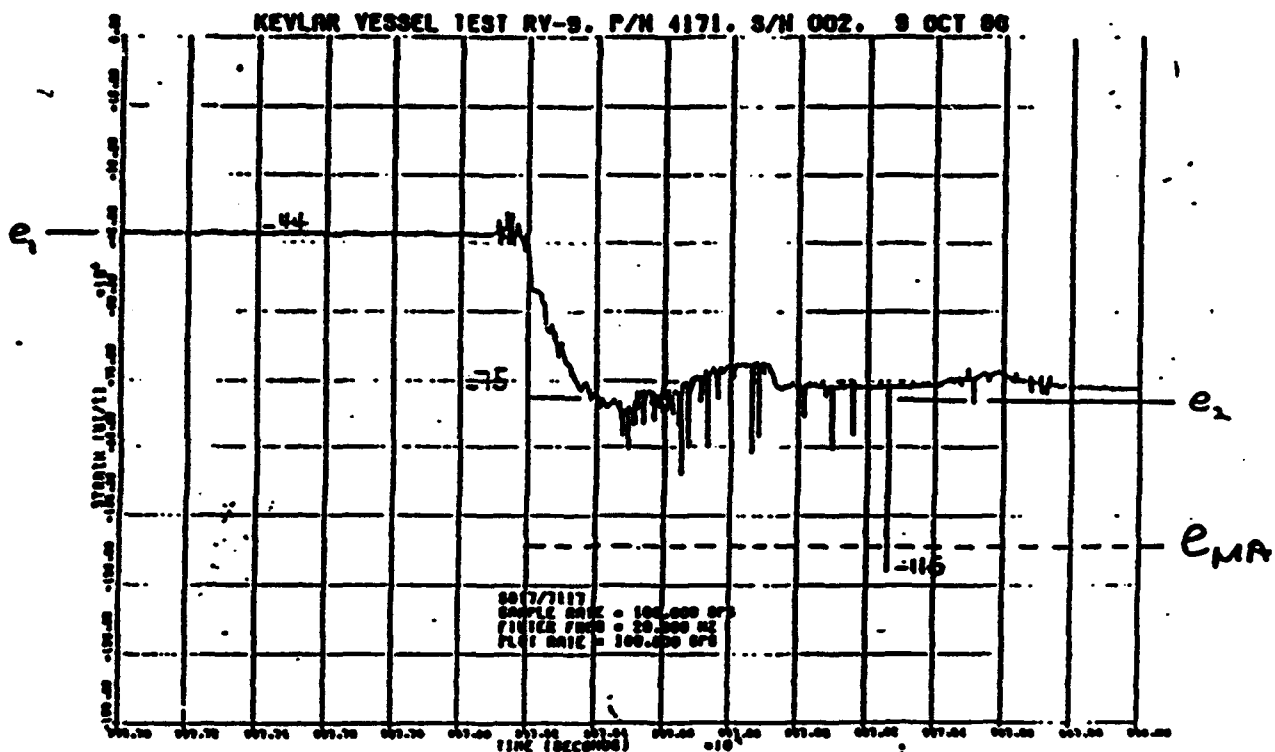
FIG. F-4
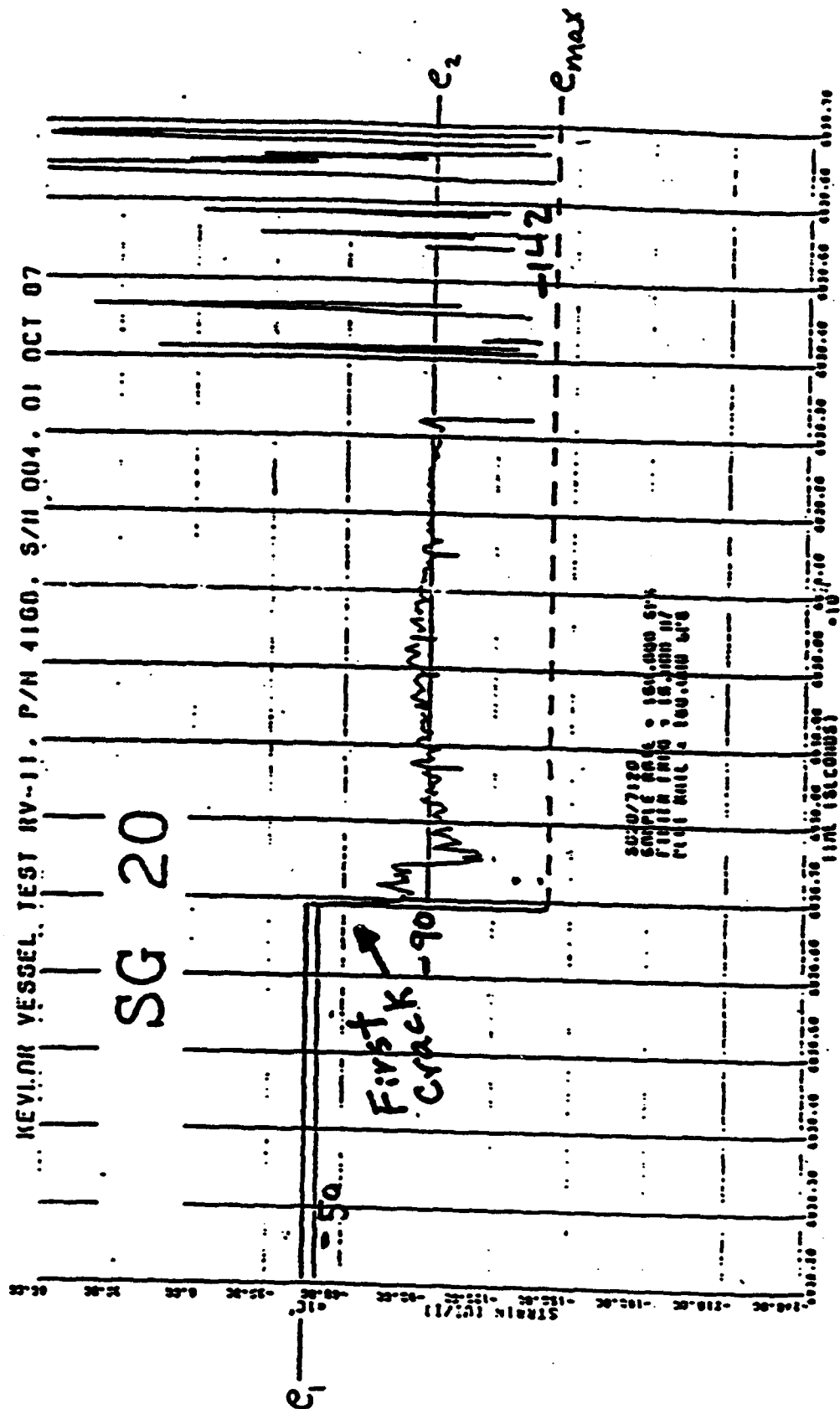
Fig. F-5
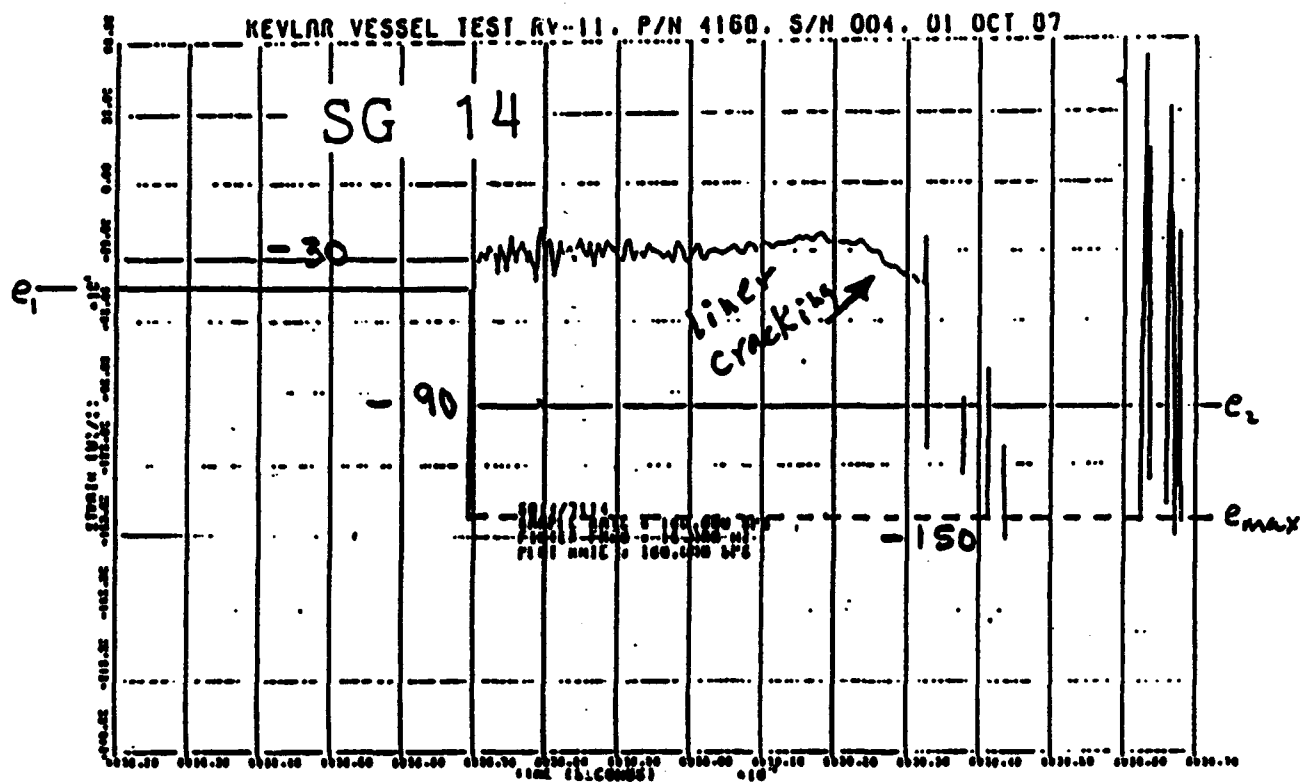
Fig. F-6

F.3 Determination of Effective Dynamic Amplification Factor For Liner Sudden Brittle Rupture Case

The one-dimensional (1D) model involving the concept that at sudden liner failure an additional pressure of dynamic amplification factor Φ times the equilibrium pressure the liner was carrying before failure is transferred to the fiber wrap, has been discussed in detail in Appendix A. Recasting those results in a form convenient for calculating dynamic amplification factor Φ from test data gives,

Fiber equilibrium strain increment,

$$\Delta\epsilon_{fo} = \frac{(R\Delta P)}{E_f t_f} \frac{(k_f/k_M)}{1+k_f k_M} \quad \dots \quad (A-38)$$

Fiber dynamic spike strain increment =

$$\Delta\epsilon_{fs} = \Phi \frac{(R\Delta P)}{E_f t_f} \left(\frac{1}{1+k_f/k_M}\right) \quad \dots \quad (A-39)$$

Fiber strain increment = $(\epsilon_f - \epsilon_{fi}) = \Delta\epsilon_f =$

$$\Delta\epsilon_{fo} + \Delta\epsilon_{fs} = \frac{(R\Delta P)}{E_f t_f} \left(\frac{1}{1+k_f/k_M}\right)\left\{\frac{k_f}{k_M} + \Phi\right\} \dots (A-40)$$

Solving (A-39) and (A-40) for dynamic amplification factor Φ yields

$$\Phi = \frac{E_f t_f \, (1 + k_f/k_M) \, (\Delta\epsilon_{fe})}{\Delta PR} \quad \ldots \quad \text{(A-41) and}$$

alternatively,

$$\Phi = \frac{E_f t_f \, (1+k_f/k_M) \, (\Delta\epsilon_f)-(k_f)}{\Delta PR \qquad k_M} \quad \ldots \quad \text{(A-42)}$$

Computations utilizing the test data for the critical liner girth embrittled mode and the local boss head weld embrittled mode in equation (A-41) and/or (A-42) gave values of dynamic amplification factor, Φ, in the range of 1.5 to 1.7. Typical calculations are given below.

F.3.1 <u>Girth Weld HAZ Embrittled Mode Data Test RV-11</u>

$R = 7.64$, $t_M = .049$, $t_f = .13$, $\epsilon_i = .00425$,

$\Delta P = 3600$, $E_f = 19 \times 10^6$, $E_M = \dfrac{27 \times 10^6}{.7}$,

$\epsilon_f = .02$ (fibers failed)

$k_f/k_M = \dfrac{19 \times .13/2}{17/.7 \times .049} = .6534$ (see section A.3.2)

$\Delta\epsilon_f = \epsilon_f - \epsilon_i = .02 - .00425 = .01575$

Using numberical values in (A-42) gives,

$\Phi = \dfrac{.01575 \; (1.6534) \times 19000 \times 130}{7.64 \times 3600} - .6534 = 1.69$

Test RV-7

$R = 7.64$, $t_M = .044$, $t_f = .154$, $\Delta P = 3800$,

$E_f = 19 \times 10^6$, $\hat{E}_M = \dfrac{27 \times 10^6}{.7}$, spike $\Delta\epsilon_{fs} = .0083$ (in/in)

$1 + k_f/k_M = 1 + \dfrac{19 \times \dfrac{.154}{2}}{\dfrac{27}{.7} \times .044} = 1.862$

Substituting in (A-41) yields,

$\Phi = \dfrac{.0083 \times 1.862 \times 19000 \times 154}{3800 \times 7.64} = 1.56$

Test RV-9

$R = 7.64$, $t_M = .053$, $t_f = .156$, $\Delta P = 3700$,

$E_f = 19 \times 10^6$, $\hat{E}_M = \dfrac{17 \times 10^6}{.7}$, $\Delta\epsilon_{fs} = .009$ (in/in)

$1 + k_f/k_M = 1 + \dfrac{19 \times \dfrac{.156}{2}}{\dfrac{27}{.7} \times .053} = 1.7249$

Using (A-41) gives,

$\Phi = \dfrac{.009 \times 19000 \times 156 \times 1.7249}{3700 \times 7.64} = 1.63$

F-17

F.3.2 Boss/Head Weld HAZ Embrittled Mode Data

Test RV-12A

Membrane theory is not strictly applicable in the boss region since there are bending effects in the liner there. Use of the extensional strain based fiber to metal stiffness ratio, $k_f/k_M = \dfrac{E_f t_{f/2}}{E_M t_M}$, defined in Appendix A, in

test data correlation is, therefore, somewhat questionable. Instead, the approach to test data correlation is to derive values of an effective k_f/k_M stiffness ratio

based on measured fiber strain data   in the vicinity of the embrittled boss/head weld heat affected zone (HAZ) region. Noting that the fractions of the pressure carried by the metal and fiber are proportional to the ratio of its stiffness to the sum of metal and fiber stiffness, one proceeds as before to calculate the dynamic amplification factor, ϕ. The calculations are given below.

From Figure E-121 (strain gage 2) in the boss/head weld embrittled area vicinity, the delta fiber strain prior to liner failure at 3750 psig is, $\Delta\epsilon_{fo}$ = 3500 micro – in/in.

Substituting numerical values (R = 10.3, E_f = 19 x 10^6, t_f = .192, ΔP = 3750) into equation A-38 and solving for the effective fiber to metal stiffness ration, k_f/k_M, one obtains k_f/k_M = .4938.

Noting from Figure E-121 that the fiber delta strain spike at liner failure, $\Delta\epsilon_{fs}$ = (14,900 – 3500) = 11,400 micro strain and using k_f/k_M = .4938 together with prior defined numerical parameters in equation A-41, gives the dynamic amplification faction, Φ, value, Φ = 1.61.

Similar calculations utilizing test data from strain gage 1 (Figure E-119) for which $\Delta\epsilon_{fo}$ = 3400 micro strain and $\Delta\epsilon_{fs}$ = 11,200 micro strain gave a dynamic amplification factor of Φ = 1.56.

APPENDIX G - DETAILED LIST OF FIGURES AND TABLES

This appendix contains a detailed list of figures and tables used to support and amplify the text of this report. For convenience of reference, the following scheme is used to aid figure/table ready identification/location.

1. In general, the first character (number or letter) of a figure or table number (e.g., 1-2, 2-3, A-1, C-2, etc.) identifies the report section or appendix in which it is located.

2. An exception is figure and table numbers with letters (A, B, C ... G) after the numerical digit (e.g., 3C) which refer to figures and/or tables in prior independently prepared documentation used to support this report text.

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