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FOREWORD

The development reported here was conducted under NASA Contract NAS1-9942, under the technical direction of C. Michael Hudson of the Langley Research Center. The work was performed at the Rye Canyon Research Laboratories, Lockheed-California Company, Burbank, California, and involved specialists from many different technical fields. Special acknowledgement is due to J. B. Harlin, who was responsible for the design of the control system, and J. B. Ryan, who contributed to many aspects of the mechanical design.

ABSTRACT

A prototype fatigue test machine has been designed and fabricated which is suitable for use by an astronaut in conducting constant amplitude materials fatigue tests aboard a Skylab or a shuttle space vehicle. The machine is comprised of a mechanical tester, which would be passed through a small (7.6-inch square) airlock to be supported in the space environment on an extendible boom, and a control console, which would provide remote control from within the space vehicle.

The maximum load capability of the machine is 625 lb. mean load ± 625 lb. varying load, suitable for testing unnotched ($K_t = 1.0$) specimens of .016-inch thick Ti-6Al-4V sheet material of 0.57-inch minimum width. This load capability was based on an experimental investigation of size effects on the mean life and test scatter in S-N fatigue test data for sheet metal specimens, on the basis of which a minimum size specimen was selected. The tester is a resonance machine which operates at approximately 60 Hz; vibratory mechanism is symmetrically arranged to minimize external reaction. A control system employing stabilized servo-loop circuits about both mean and varying load components maintains loading accuracy to better than two percent. Specimen installation and control console details are simplified for astronaut use. Power consumption from a 28 volt supply is estimated at between 50 and 80 watts.

Key Words:

Space Technology; Space Experiment; Test Equipment, Fatigue Test; Metal; Vacuum, Constant Amplitude; Size Effect

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ORBITAL FATIGUE TESTER FOR USE IN SKYLAB EXPERIMENT T032

By P. E. Sandorff
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INTRODUCTION

The objective of the program reported here was to develop a prototype axial load fatigue testing machine suitable for conducting meaningful tests of materials under constant amplitude fatigue loading while exposed to the space environment on the exterior of a Skylab spacecraft. This tester will be used for fundamental studies of fatigue mechanisms in the space environment, and for the generation of spacecraft design data. In the fundamental studies, the effects of (a) extended periods of exposure to the space environment; (b) special surface treatments; and (c) the control or elimination of trace elements on the fatigue behavior of pure metals and research alloys will be determined. In the data generation studies, the effects of (a) the high vacuum in space; (b) high radiation fluxes; and (c) micrometeorite impingement on the fatigue behavior of engineering alloys will be determined. Such studies are impractical or impossible to perform in space simulation chambers because of the long exposure times and complex environments required.

The program to develop an Orbital Fatigue Tester (OFT) was arranged in three phases. The first phase was concerned with the development of a small but meaningful specimen configuration. The results are reported in detail in Ref. 1 and summarized here. The second phase was concerned with the engineering design of an OFT which could be used by the Skylab astronauts to conduct tests of the specimen configuration determined as optimum in Phase I. In the third phase, a prototype OFT was constructed according to this design, and limited tests were performed to make the machine operational.

The program did not involve the design of the Skylab experiment itself, but the interface with Skylab established a number of the design requirements for the OFT. Typically, experiments carried in the Skylab Workshop are strongly independent and self-contained. Implementation of the OFT in accordance with this philosophy will lead to the following flight hardware requirements:

(1) The OFT, comprised of a mechanical systems assembly for applying loads to specimens and an electronics package including console which is to be used as a remote control station.

(2) A "canister" which will house the mechanical assembly of the OFT, and which will mount on the interior wall of the Skylab Scientific Air Lock (SAL). The canister will have a sealing hatch which can be opened to permit placing test specimens in the OFT. The canister will serve as an air lock chamber. When the hatch is closed, the SAL controls can be actuated to evacuate the canister and to open the SAL door. The OFT may then be passed through the SAL door out into the space environment. After the fatigue test is completed, the procedure is reversed.

(3) An extendible boom, housed inside the canister, which will support the OFT mechanical assembly during deployment.

(4) A "container" or stowage box. Canister and contents, the electronics package, cabling, and test specimens will be stowed in the container during launch and while on orbit prior to and subsequent to conducting the experiment.

Figure 1 illustrates how the OFT canister might be arranged. The electronics package of the OFT is shown integral with the canister. For the prototype OFT, a separate cabinet is used since the canister is not part of the present program. Figure 2 is a photograph which shows the external features of the OFT as developed in this program.

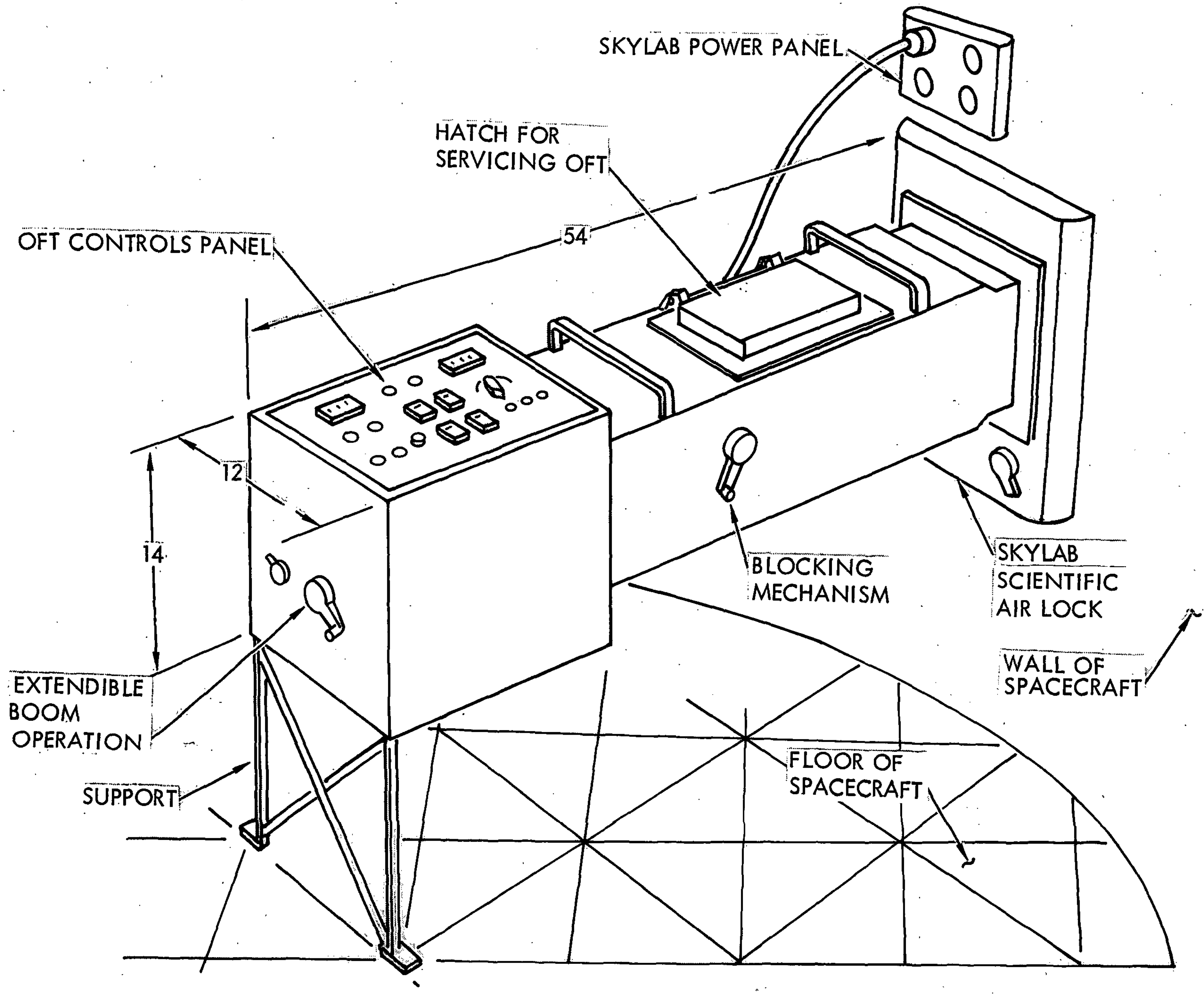

Figure 1 Canister containing Orbital Fatigue Tester mounted in Skylab (Conceptual)

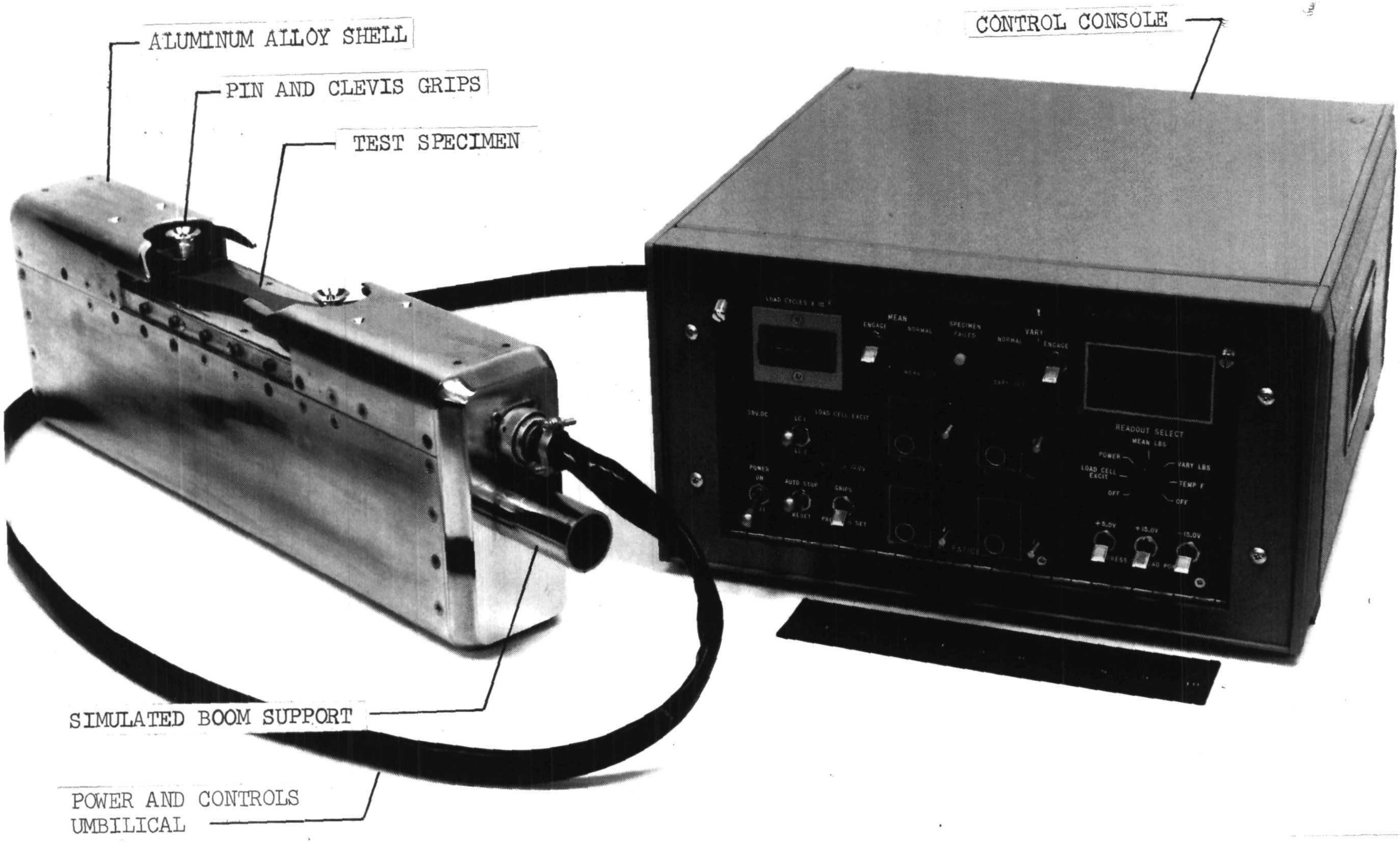

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Figure 2 Orbital Fatigue Tester Prototype Assembly

SPECIMEN CONFIGURATION

Objectives of the Phase I Experimental Program

A key problem for the OFT was the development of a small but meaningful specimen configuration, in order that power, size, and weight of the fatigue test machine could be minimized. To investigate attributes of the test specimen and so establish design requirements for the OFT, an experimental study was conducted, in which statistically significant numbers of unnotched sheet metal specimens of Ti-6Al-4V and 2024-T3 alloys were tested under constant amplitude fatigue loading. This experimental investigation, which comprised Phase I of the Orbital Fatigue Tester program and is reported in detail in Ref. 1, had the primary objective of evaluating the effect of variations in specimen size. Exploratory studies were also conducted on the effects of variations in environment, i.e., humidity, and vacuum of 10^{-6} torr.

Scope and Methods of Testing

The experimental investigation of size effects involved four sizes of 0.016-inch thick Ti-6Al-4V titanium alloy sheet specimens and three sizes of 0.032-inch thick 2024-T3 aluminum alloy sheet specimens. The "full-size" specimen in each case measured 0.750-inch in width at the minimum section and was reduced from a 2.00-inch width by radii of 7.50 inches, providing a theoretical stress concentration factor of $K_t = 1.04$. Smaller sizes were geometrically similar and ranged down to 0.250-inch minimum section. Details are shown on Figure 3, and a group of typical specimens after test is shown on Figure 4. In each test series for which specimen size and environment were held constant, tests were conducted at four or five different stress levels, providing at least 24 and in other cases up to 64 test points for determination of the S-N relationship. In the manufacture, cleaning and handling of specimens, care was taken to control such factors as might introduce variations in fatigue performance, such as machining and exposure to environmental agents. Random

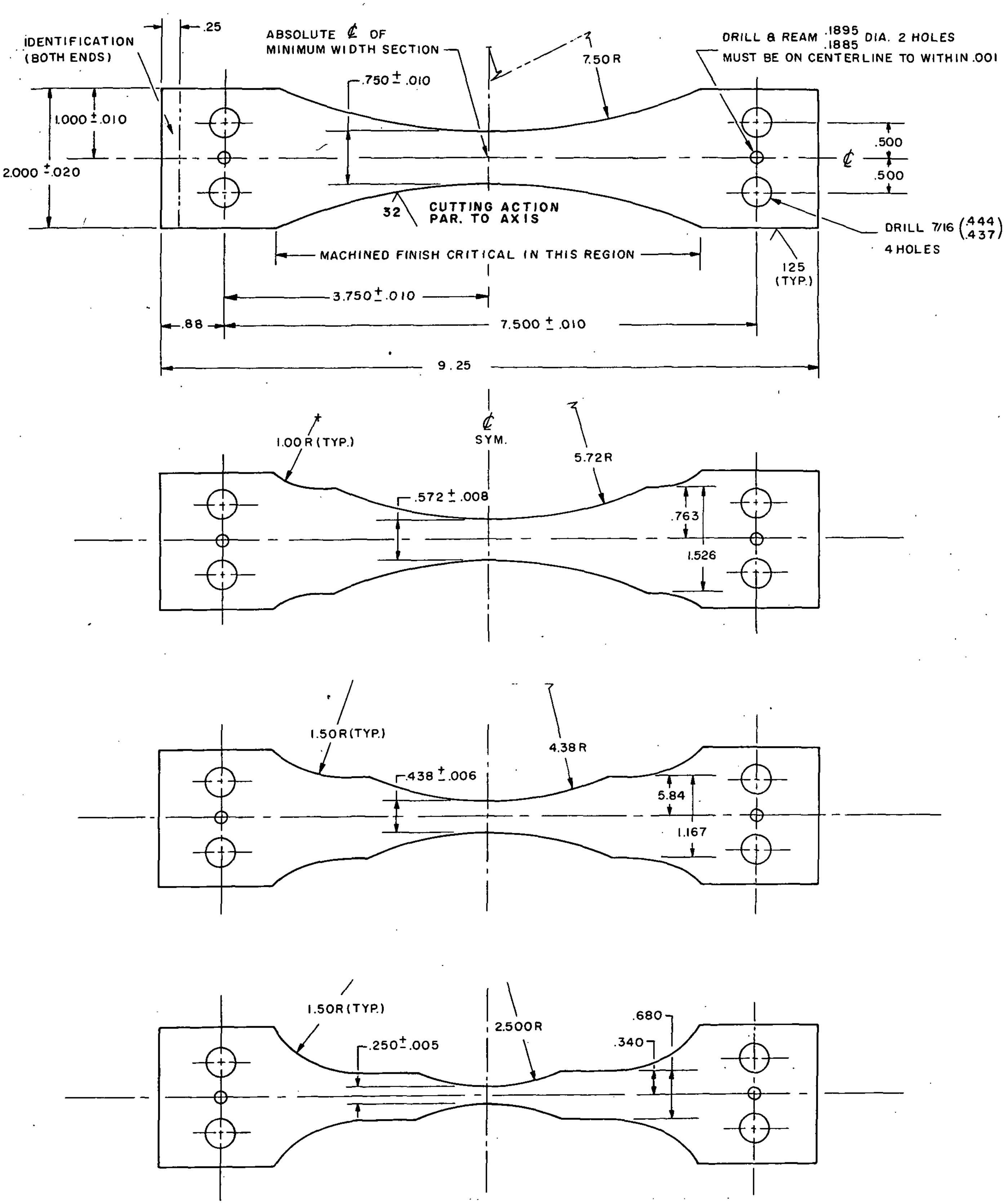
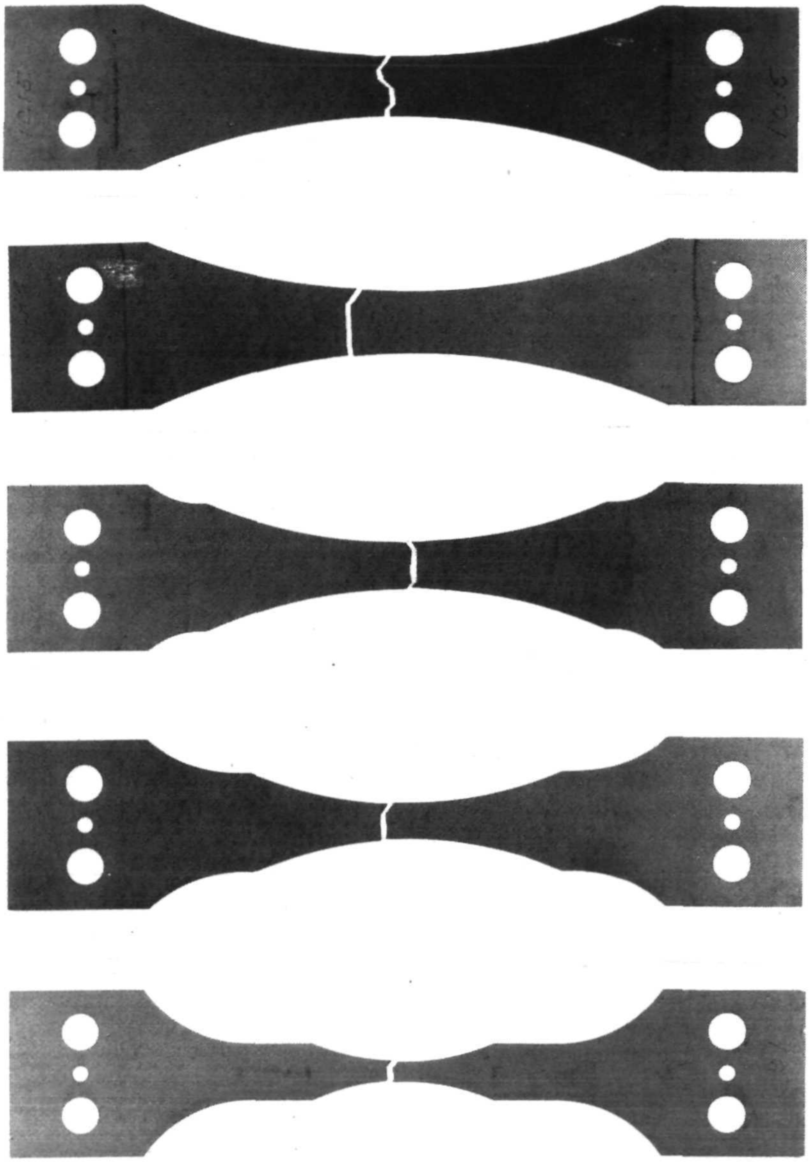


Figure 3 Fatigue Test Specimen Details



1C15
0.750-inch
130 ksi
24,900 Cycles

2H7
0.750-inch
100 ksi
5,290,000 Cycles

1D11
0.572-inch
115 ksi
70,100 Cycles

1H3
0.483-inch
110 ksi
282,700 Cycles

1G9
0.250-inch
105 ksi
2,920,000 Cycles

Figure 4 Typical Ti-6Al-4V Specimens After Fatigue Test selection means were applied to location in the original sheet stock and to testing sequence.

Fatigue test loading in all cases was constant amplitude axial load at a stress range ratio R = 0.02; that is, the applied stress varied cyclically from slightly above zero to the specified maximum tensile stress, and test life determinations at various stress levels established the S-N curve. Testing speed ranged within a few percent of 1700 cpm. Except for the exploratory study of the effects of humidity extremes on results obtained with Ti-6Al-4V specimens, and the tests of Ti-6Al-4V specimens under vacuum conditions, all tests were conducted with relative humidity of the environment controlled to between 65 and 70 percent. Temperature was monitored and remained between 70° and 80°F. The tests were conducted on a resonance-type fatigue test machine of Lockheed design and construction, using friction-type grips of a new design which minimized eccentricity of loading and eliminated fretting tendencies. The estimated probable (0.67σ) error of loading ranged from 0.7 to 1.5%.

In addition to the S-N data, variations in the nature of the failures were studied, measurements were obtained of the location and size of the fatigue cracks, and their geometrical distributions were investigated. A number of supporting studies were conducted during the course of the program, including, for example, determination of static tensile properties of the titanium alloy sheet, metallurgical and electron microscope fractographic studies, and crack growth investigations using time lapse photography.

Results of Phase I Test Program

Substantial size effects were found to occur in the unnotched S-N fatigue performance of both Ti-6Al-4V and 2024-T3 sheet specimens at test stress levels below the material proportional limit. Both an increase in the value of the mean life and an increase in the amount of test scatter were found as the specimen size was reduced. Figure 5 summarizes the observed effects, and also

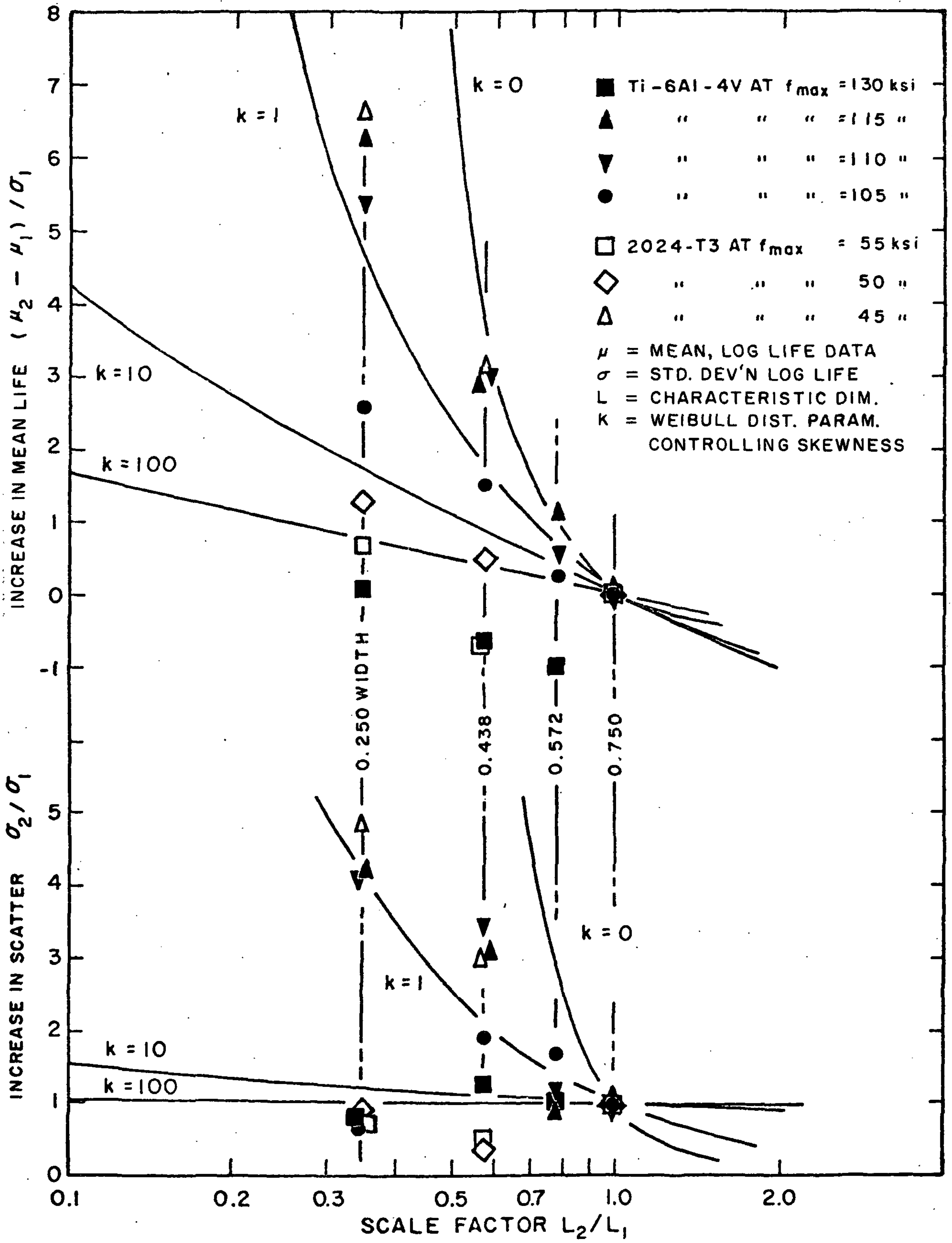


Figure 5 Size Effects in S-N Tests of Sheet Metal Specimens. Theoretical curves based on Reference 4.

furnishes a comparison with effects that might be predicted on a theoretical basis assuming that failure is determined by a random distribution of multitudinous weak spots and that test results reflect a Weibull extreme value distribution.

For use in the OFT, the increase in scatter associated with reduction in specimen size is most important, because to obtain the same precision and confidence level in the S-N data as would be obtained with a "full-size" specimen, the number of replicate tests required at any one condition increases as the square of the standard deviation. The alternative is a degradation of the perceptiveness of the test program in separating and identifying effects of the space environment from others which are unknown and uncontrollable, possibly inherent in the material. Based on these considerations, a specimen of 0.57-inch minimum width was selected as the target objective of the OFT.

Tests of Ti-6Al-4V specimens of the selected configuration under vacuum of 10^{-6} torr indicated a striking increase in fatigue life over most of the S-N curve, as shown in Figure 6. Additionally, a "ductile" mode of fatigue was discovered in these specimens, occurring at the higher stress levels, which involved considerable specimen elongation and considerable hysteresis. The ductile fatigue mode was later found to occur also under normal atmospheric pressure, but at a higher stress level, and with much shorter fatigue life, than observed in vacuum. Elongations occurring during typical tests showing ductile fatigue are compared with that occurring under normal (or true) fatigue in Figure 7. The maximum elongation remaining as permanent set in any specimen after failure was 0.11-inch. Hysteresis loops observed in a representative test are shown in Figure 8. Analysis of power measurements made in the test of a .57-inch wide specimen at 3450 cpm indicated energy dissipated in hysteresis increasing to a maximum of 4.8 watts at the time of failure. These data established certain of the performance requirements for the OFT.

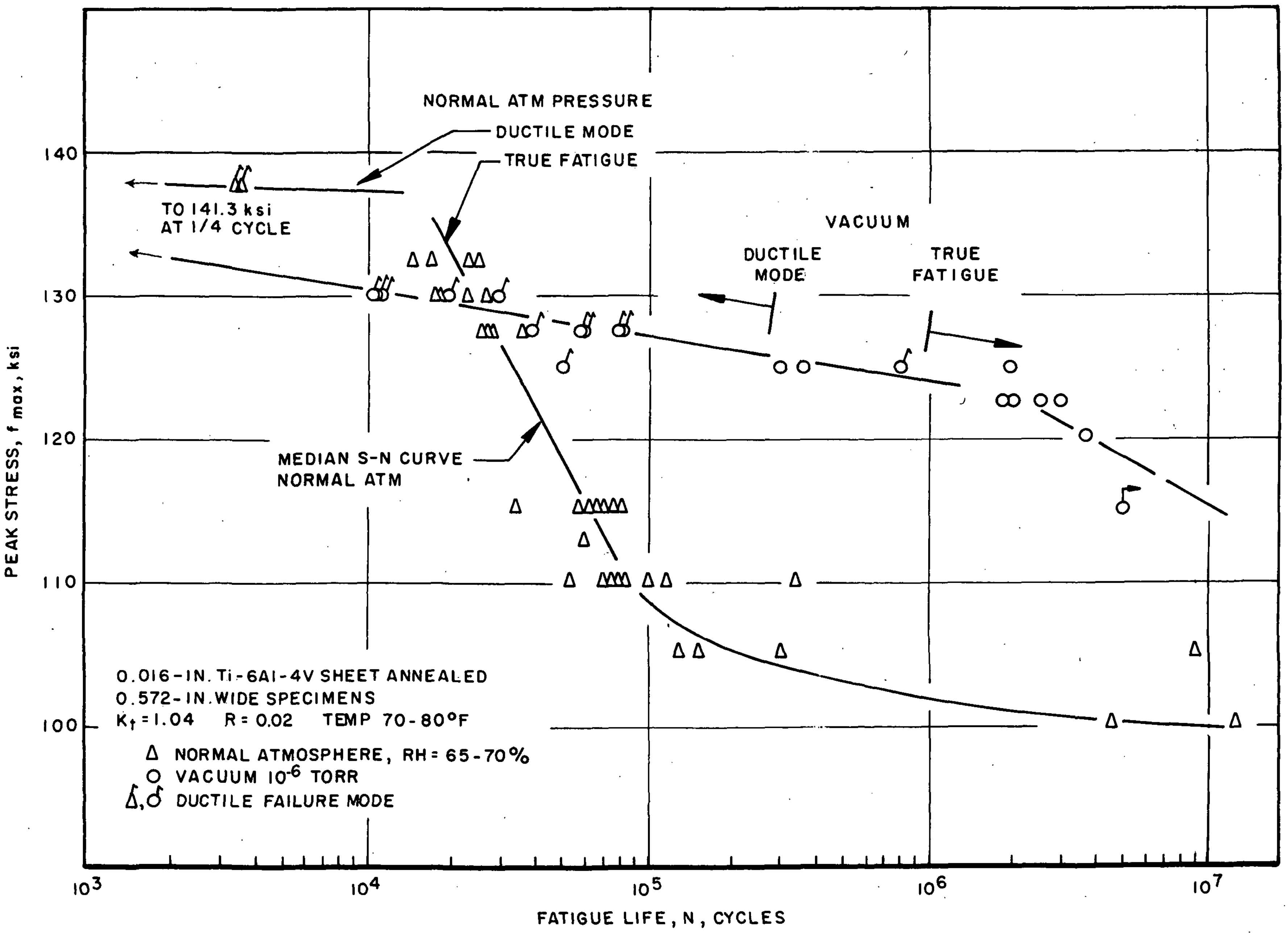


Figure 6 S-N Data Obtained on Ti-6Al-4V Specimens Tested in Vacuum Compared with Tests in Air.

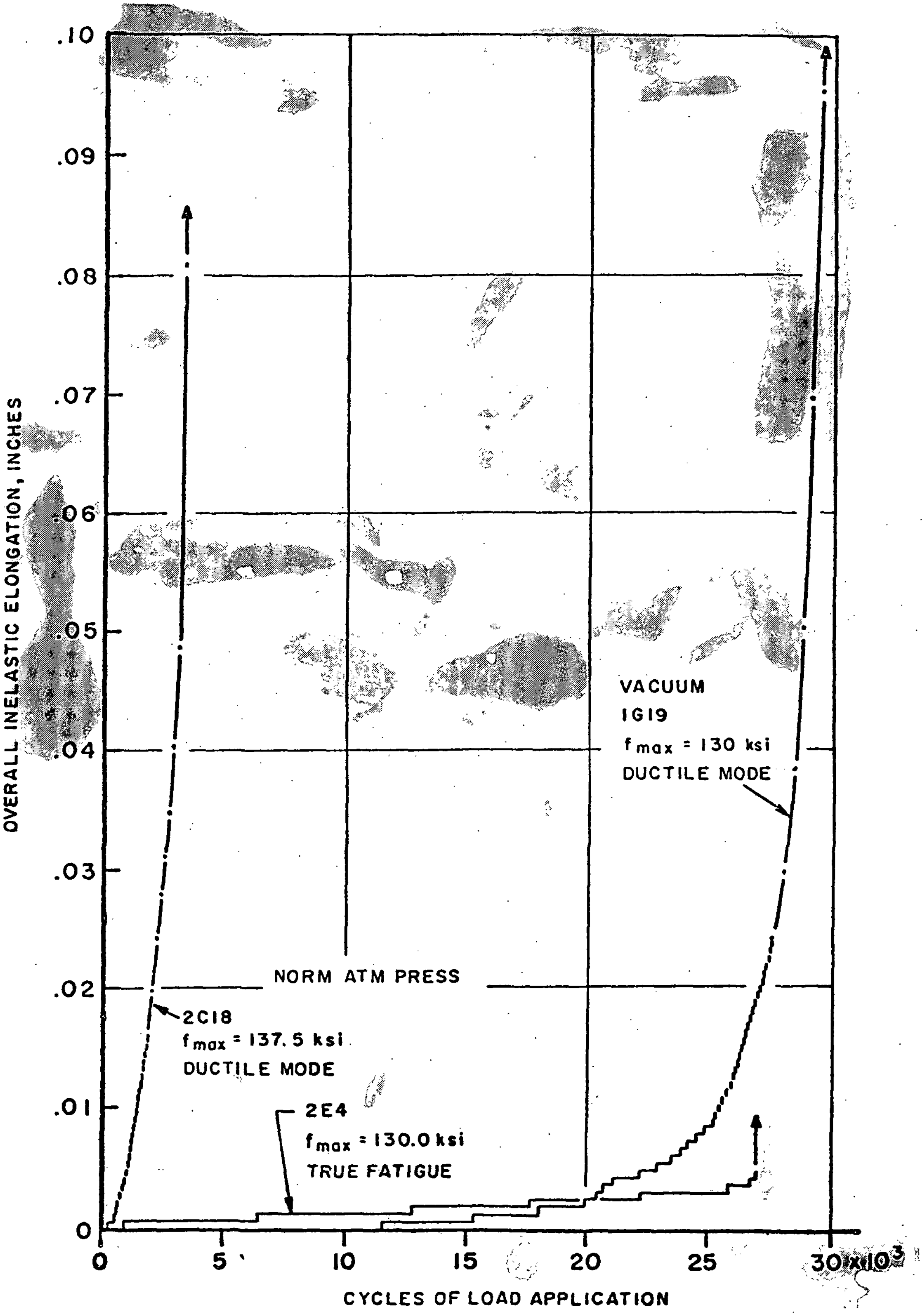


Figure 7 Inelastic Deformations Measured In Fatigue Tests of Ti-6Al-4V Specimens

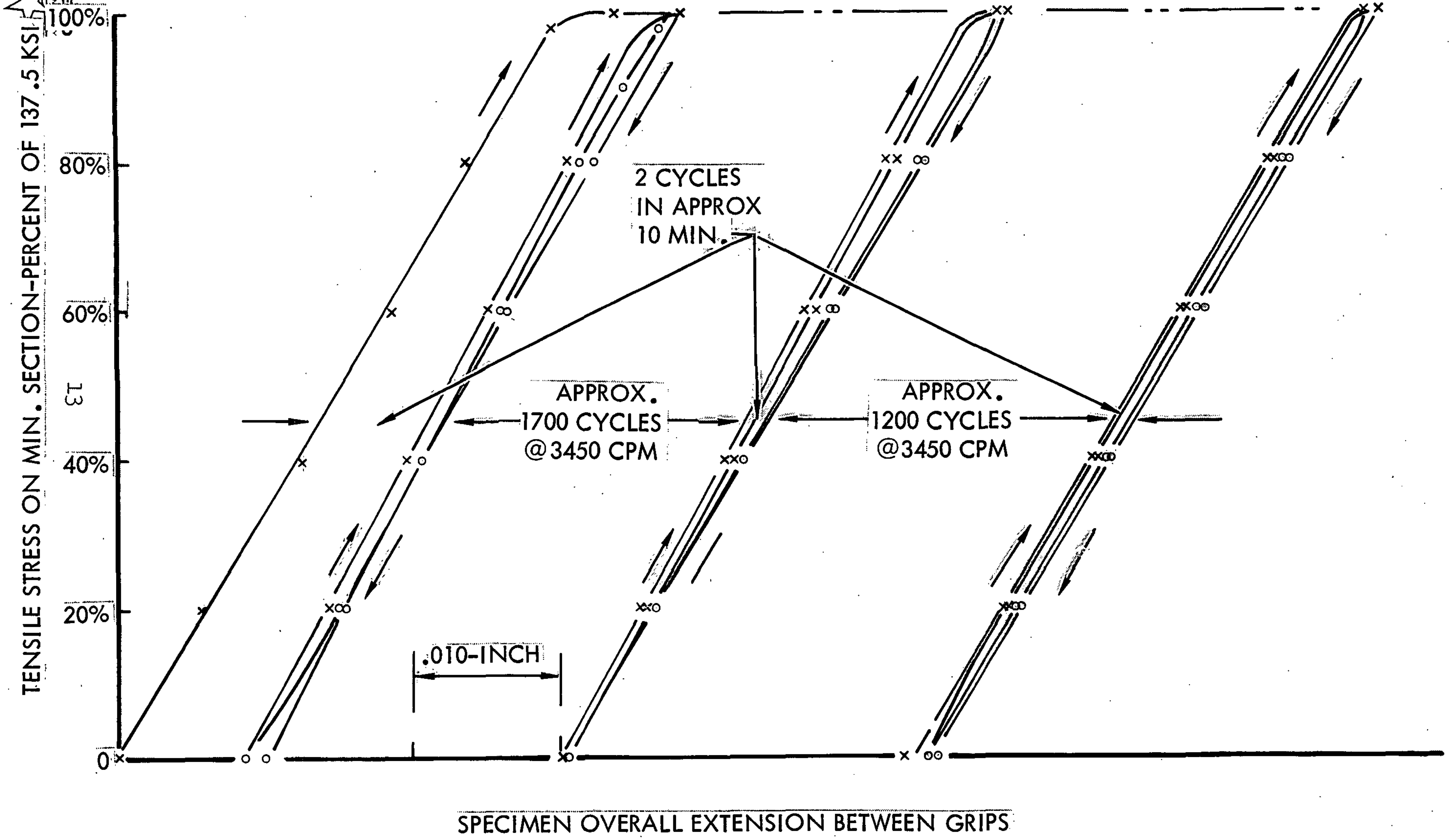


Figure 8. Load Deflection History of Ti-6Al-4V Specimen Cyclically Loaded in "Ductile" Fatigue Range

Fig 8
Pg. 13 90%

Details of the OFT Specimen Design

For simplicity and ease of test specimen installation, the Orbital Fatigue Tester utilizes clevis-type grips with loosely fitting ball-lock pins. To accept the concentrated pin load and distribute it to the test section, the two types of end-reinforcement shown in the photograph, Figure 9, have been developed. The first utilizes doubler plates which are adhesive-bonded to the sheet material of the test specimen; it would be readily adaptable to various materials and purposes. The second method uses monolithic end-plates machined from 0.125-inch thick Ti-6Al-4V, which are electron-beam welded to the 0.016-inch thick sheet material under test. The welded assembly is more costly but may be preferred in the space environment. The length and width of the selected "optimum" specimen configuration, having a 0.572-inch minimum width test section, are extended slightly to mate with the 1.75-inch width of the reinforced ends; the loading pins are 7.00 inches on center. These details are the end result of a development test program and, under the maximum operating load for the OFT (638 ± 612 lb.), provide a fatigue life in the 10^7 cycle range for the reinforced ends and infinite life for the pins and clevises.

The use of lug-ended specimens with quickly-demountable ball-lock pins is possible only for tension-tension type fatigue loading. A value of stress range ratio $R = 0.02$ is considered to be the minimum practical, to prevent relative motion and energy dissipation at the bearing surface. A diametral clearance of about 0.006-inch on the 3/8-inch pin causes bearing to be localized, with clearance assured at the 90° points where fretting usually occurs. The pin-loaded specimen has the disadvantage of requiring close machining tolerances to minimize erroneous bending stresses in the specimen due to misalignment of the holes with respect to the axis of the test section. Also, should specimens of substantially greater thickness be used, angular misalignment of the hole (i.e., with respect to the axis of the pin) will become important, because of bending which could be introduced not only into the specimen but into critically stressed components of the fatigue machine. The required tolerances can be met in any high quality machine shop.

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Figure 9 Test Specimen Configuration Developed for the Orbital Fatigue Tester. Above, adhesive-bonded end-reinforcement. Below, electron-beam welded assembly.

DESIGN OF THE ORBITAL FATIGUE TESTER

Design Requirements

The specified requirements for the OFT called for an axial load fatigue test machine capable of testing specimens of the configuration determined as optimum in the studies described in the previous section. Detailed requirements were identified as follows:

(1) The loading error for both the minimum-load peak and the maximum-load peak of the constant amplitude loading cycles shall not exceed ± 2 percent of the maximum applied load.

(2) The operating frequency shall be 3600 cpm ± 600 cpm.

(3) It will operate continuously for 200 hours at maximum load without permanently deforming or developing fatigue cracks.

(4) A method of counting cycles shall be provided.

(5) The testing machine will shut down when a specimen fractures.

(6) A fatigue experiment can be started, including load setting and monitoring, by remote control at any time after the experiment is placed into orbit.

(7) An astronaut can replace a broken specimen using simple hand tools and conduct another test while the testing machine is in orbit.

(8) The fatigue tester must be of such size that it can be brought into the Skylab workshop through the Scientific Air Lock for specimen replacement.

(9) The weight and volume of the testing machine are at a minimum.

(10) It will operate in the space environment while mounted on the exterior of a Skylab spacecraft.

(11) It will be powered by the on-board power supply. (The on-board power supply is at 28 volts d-c. The guideline power allotment for the testing machine is 200 watts for 24 hours, or 40 to 60 watts for 720 hours.)

(12) It will produce fatigue failures in Ti-6Al-4V (annealed) specimens tested at R=0 in the life range 10^4 to 5×10^6 cycles. These specimens shall have approximately the configuration determined as optimum in Phase I and shall require a maximum test loading of 500 lb. mean load and ± 500 lb varying load.

(13) It shall be compatible with the space vehicle and other Skylab experiments.

(14) The environment of the test specimen shall not be appreciably changed or contaminated by the testing machine.

A number of constraints were imposed on the OFT design by the interface with the Skylab Workshop. These are summarized below:

(1) The OFT must be passed through a 7.600 x 7.600-inch aperture established by the attachment flange of a typical "canister" structure which contains the OFT and mounts on the Skylab Scientific Air Lock (SAL).

(2) The OFT will be supported on an extendible boom and powered through an umbilical which initially are enclosed in the canister.

(3) The third (length) dimension of the OFT is not constrained but should be held to aminimum, as it will adversely affect boom and canister size and weight.

(4) Access to the OFT for specimen change will be through a door located on one side of the canister.

(5) During a launch, prior to start of, and following completion of the experiment, the canister/OFT assembly, control console/electrical systems unit, cabling, and experiment supplies will be stowed in a "container". The container will be bolted to the floor of the Workshop, probably adjacent to the SAL. The container may be shock mounted and may be hermetically sealed if necessary.

(6) An outlet panel for approved cable connectors is located on the wall of the Workshop immediately adjacent to the SAL. Power available consists of two 28-volt dc outlets, regulated to + 2, -2½ volts, one of 5 amp capacity, the other of 10 amp, having a common ground. Also available on this panel are two outlets for

connection to the Skylab's data and telemetry systems, which may be wired according to specific experiments requirements.

(7) There is no means of observing the experiment in space unless it were extended several feet beyond the outside of the vehicle when it might be marginally visible through a nearby observation port.

(8) The atmosphere in the Workshop during habitation in orbit is a 70-30 mixture of O_2 and N_2, nominally at a total cabin pressure of 5.2 psi. Other conditions, ranging from $-20^\circ F$ to $+130^\circ F$ and from space vacuum to +34 psi absolute, exist at times during launch pad checkout, launch, and coast on orbit.

A detailed statement of general requirements for flight hardware to be placed aboard the Skylab vehicle is identified in Ref. 2. Included are stipulations such as:

(1) Flammability requirements for wiring insulation, materials and accessories.

(2) Toxicity requirements for wiring, insulation and materials.

(3) Quality assurance and reliability requirements appropriate to space use for purchased components.

(4) Test requirements for qualifying fabricated components and assemblies.

These requirements were applied to the prototype OFT insofar as was practical, and where deviation might affect performance evaluation. A list of deviations is included as Appendix A.

Additional design considerations stemmed from the fact that performance evaluation of the OFT would require operational testing in a vacuum chamber. To avoid difficulties in achieving high vacuum, apparatus which will be placed in the chamber utilizes materials which have low outgassing characteristics and which can be baked out without suffering deterioration. Cadmium plated parts are avoided because of the possibility of sublimation and redeposition under long exposure to vacuum. In addition, detail design minimizes air entrapment or slow air leakage by providing venting to cavities such as occur below screws in tapped holes, and avoiding broad metal surfaces in contact. All components receive special cleaning and baking treatments prior to assembly. A list of non-metallic materials used in the mechanical systems assembly is included in Appendix B.

General Description

The OFT is basically a resonant-beam type of fatigue machine, arranged so that a varying load can be superimposed on an initial bias or mean load. The mechanical systems is completely symmetrical, as illustrated in the schematic drawing, Figure 10, with the test specimen as a central member. Mean load is applied by a motor-driven ball-screw jack which acts through a cantilever spring and lever system. A load cell placed in series with the specimen furnishes a signal proportional to the specimen load. A servo-loop control around the mean load actuator provides continuous correction of any variation from the command value set at the control console.

The system for applying the varying load is comprised of two flexible beams carrying inertial masses which are arranged as the arms of a tuning fork. The test specimen constitutes a link between the beam ends. Vibratory motion of the beams is excited by means of electromagnetic shakers which are driven by an amplified electrical signal derived from the output of the load cell. The system is thus an electromechanical oscillator which operates at resonance. Resonant amplitude is servo-controlled by a driver system which supplies power to the shakers, using the ac component of the load cell signal averaged over a number of cycles as a measurement of the varying load. The high mechanical efficiency of the vibratory system insures that individual cycles of varying load are essentially sinusoidal and do not deviate perceptibly from the average.

A simplified functional schematic of the control system is presented in Figure 11.

The mechanism comprising the tester is placed within an enclosing shell structure that makes possible thermal radiation control and temperature isolation from the space environment. It also serves structural purposes and provides mounting at one end on a boom for deployment through an airlock on the space vehicle.

Selection of this configuration for the OFT was based on the following considerations:

(1) Because of power limitations, a resonant loading system of high efficiency (i.e., high "Q") must be used. Power losses can be minimized with a resonant mechanical system which utilizes flexure pivots and high-bearing-stress friction joints throughout.

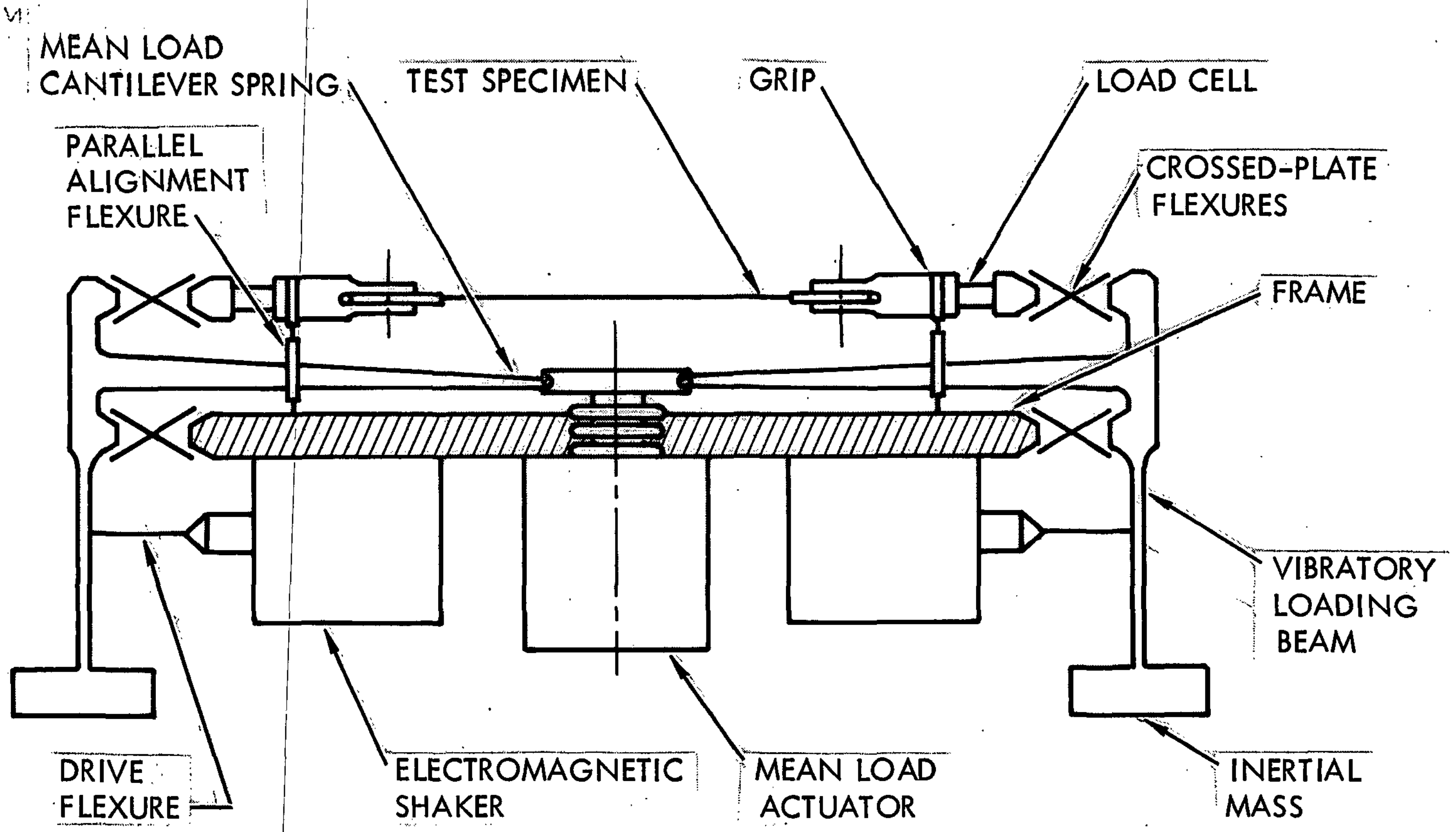
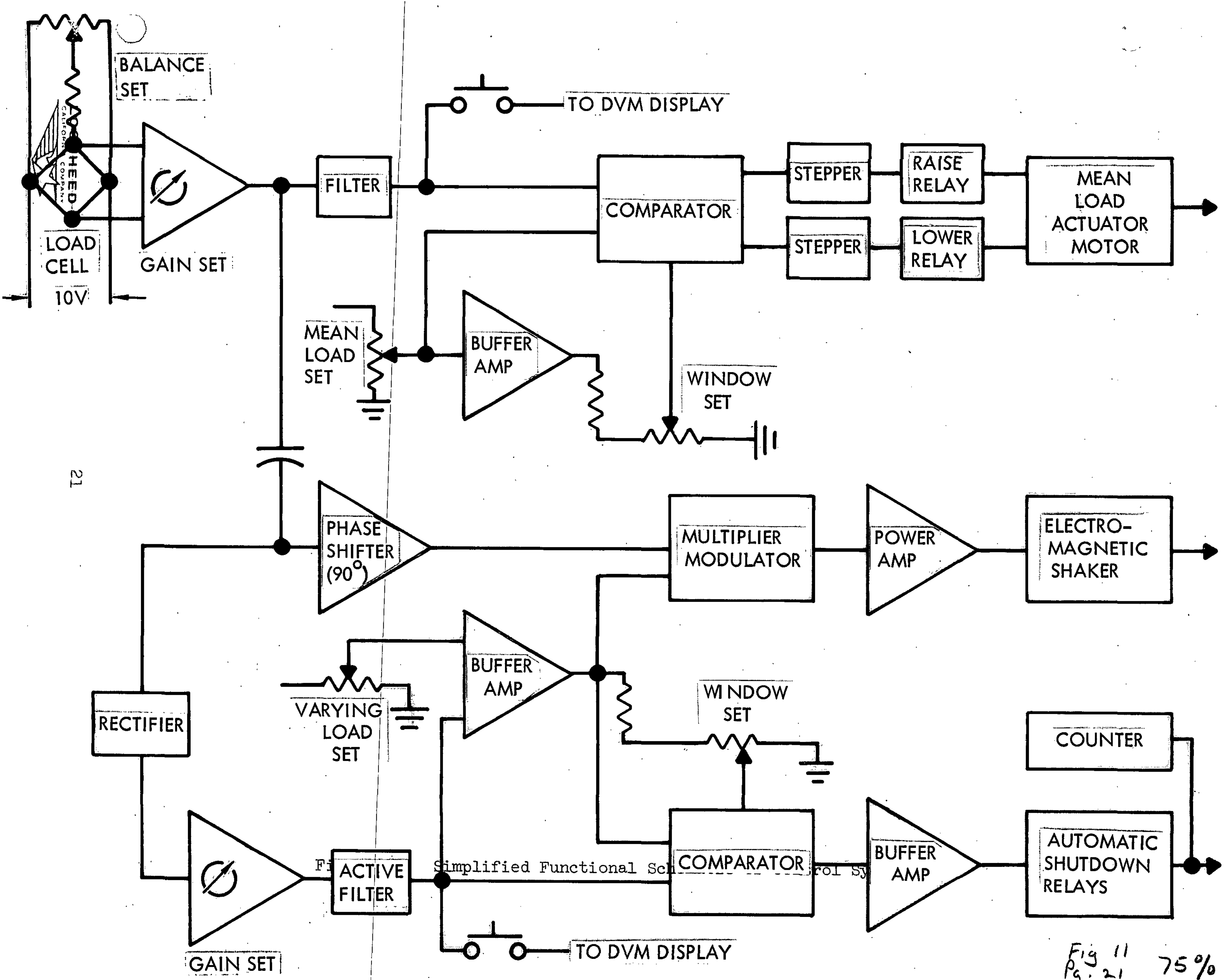


Figure 10 Orbital Fatigue Tester Mechanical Systems - Schematic



Fi Simplified Functional Sch rol Sy

Fig 11
Pg. 21 75%

(2) In a resonant loading system, the requirement that cyclic load be biased above zero requires a mean load apparatus. Separation of the loading mechanism into mean and varying load systems establishes functional organization of the control system.

(3) Speed of operation, magnitude of loading, and size limitations lead to an inertial mass mounted on a flexible cantilever as the only suitable design solution for applying the vibratory loading.

(4) A symmetrical arrangement of loading systems, with loads internally reacted, is necessary to minimize residual vibratory forces which could be transmitted to the spacecraft.

(5) Continuous measurement and servo-regulation of loading are necessary to meet the required accuracy of performance.

Mechanical System

Details of the mechanical configuration are governed by the requirements of function and strength within the overriding constraints imposed by the limitation in size. The aluminum alloy shell structure surrounding the tester has a clearance, top and bottom, of 0.12-inch as it passes through the 7.60 by 7.60-inch square aperture in the Skylab Scientific Air Lock; a similar clearance of 0.12-inch is provided for mechanical elements within the shell. Primarily, this establishes overall dimensions of the vibratory loading beams. By using tungsten alloy masses, high strength materials and tapered sections, these beams are made maximally efficient in obtaining large inertial forces. Leverage proportions, however, are determined by inherent limitations of the flexure pivots. The deflection requirements for the beam pivots are established by the lever arm and the translation which may occur in the case of a ductile specimen (for which an elongation of 0.12-inch is allowed) on which is superposed the "overswing" motion that accompanies specimen failure.

The overswing condition is a special problem caused by the sudden release of potential and kinetic energy extant in the mean load beams and the vibratory beams when the specimen fails. In the OFT, this energy is absorbed non-impulsively by the mean load beams in bending and dissipated by incidental damping. The overswing condition establishes load and deflection requirements for most of the flexural members in the assembly, as well as the stroke requirements for the shaker armatures and the tension loading requirements for the mean load actuator.

The mean load beams are also space-limited and are tapered in thickness to obtain maximum deflection for the available length. The spring rate of the mean load beams is a compromise between the requirements of precise control (a soft spring provides a small step-correction in mean load under the minimum incremental actuator motion) and the problems of overswing loading (a stiff spring leads to small overswing displacements).

All flexural elements in the mechanical assembly are constructed of 18Ni (300) maraging steel. This material was selected because the high ratio of allowable stress to modulus is advantageous in detail design, and the low temperature required in heat treatment reduces warpage problems and permits finish machining in the annealed state. Generous, smoothly blended fillets are used throughout, leading to elastic stress concentration factors of the order of 1.10. To ensure high performance under cyclicly repeated stress, all fatigue critical surfaces are hand polished to remove any evidence of transverse marks visible under 30 x magnification. The surfaces are protected from corrosion and superficial damage by a thin coat of epoxy primer.

Motive power for the vibratory loading system is provided by two electromagnetic shakers of the permanent magnet type widely used for small vibrational test work. The magnet and base assemblies are obtained from commercially available units (Ling Model 203) with minor modifications. The armature windings are of self-supporting construction, with copper wire laid in epoxy resin; dimensions are optimized for maximum thrust per ampere. The armature structure is aluminum alloy, with a beryllium copper flexural suspension, to provide for heat dissipation in the space vacuum by conduction and so minimize coil temperature and related I^2R losses. The armature suspension is a set of simple fixed-ended flexures which provide an exceptionally large stroke.

The linear actuator for the mean load system is a purchased unit designed and constructed to OFT requirements (EEMCO D3200). It is powered by a permanent magnet dc motor, driving a 1/8-inch lead ball screw jack through a 3500:1 spur gear train. Limit switches at either end of 0.58-inch stroke prevent accidentally exceeding displacement limits of either the actuator itself, or the OFT structure. The actuator is completely enclosed and hermetically sealed in a stainless steel case, the actuator motion being accommodated by a bellows.

Detail design requirements which govern the mechanical design are of three types:

Kinematic:	Compatibility of displacements, deflections, and fabricational tolerances.
Strength:	Infinite life under vibratory loading 10,000-cycle life under mean load and overswing condition.
Dynamic:	Proper fundamental vibratory frequency. No disturbing dynamic modes.

To insure ample margin in meeting the specified loading requirements (item 12 page 17), a target design loading condition of 625 ± 625 lb was selected. Analysis in support of the mechanical design is presented in Reference 3.

Control System

The electrical and control system contains the provisions for powering the OFT, for introducing commands, for sensing the performance, and for automatically correcting the error. The various subsystems, described below, function essentially independently of each other.

Power Supply: A dc to ac converter is used to supply ac to three transformer-rectifier-regulator modules which in turn supply the required dc power for the electronic control system.

The output of one of these modules is further reduced and regulated to 10.00 volts to provide the excitation for the strain gage bridges of the load cells, the grip position sensor, and the temperature sensor network. A metering switch and a vernier control are provided on the control panel to allow the operator to monitor and to adjust the bridge excitation voltage to approximately 0.1% accuracy.

Load Measurement: Two load cells are provided in series with and symmetrically located to either side of the specimen. One of these is the primary load sensing device and controls machine operation. The second serves as a spare, and may be interchanged with the first at any time by means of a switch located on the control panel, or it may be used for external monitoring.

In the detail arrangement, the load sensing elements are integral with the "loading heads". These are tee-shaped members which transfer the load from the large-width flexural pivots to the specimen grips. A tubular section of reduced area is provided in each, and electrical resistance strain gage bridges are mounted internally. The two units are padded to obtain identical, compensated calibrations and are hermetically sealed.

The output of the load cell bridge is a voltage signal which varies in proportion to the instantaneous load in the specimen. This signal is separated into its mean and varying components by low-pass and high-pass active filters. The mean signal is fed to a stable amplifier, the gain of which is set to provide 5.00 volts at 625 lb load. This adjustment is made internally when the machine is "calibrated" against an instrumented dummy specimen. For display purposes, the mean load signal is scaled by a precision voltage divider in the ratio of 5.00 volts to 625 millivolts, and the millivolt output can be monitored on the Digital Volt Meter (DVM) on the control panel as a reading which represents pounds load.

A load cell balance control is provided by which the indicated load can be set to 000 when there is no load on the specimen. The balance may be checked, and reset if necessary, each time a test is started. This is most easily accomplished before the specimen is inserted and with the grip in "zero" position. It can also be accomplished remotely with a specimen installed, should this be desired, using the grip position control (described below) to obtain a no-load condition on the specimen.

The varying load component of the load cell output is full-wave rectified, using an integrating (averaging) instead of a peak-type rectifier circuit. This system provides excellent immunity from switching transients and other electromagnetic interference and is permissible because of the pure sinusoidal wave form provided by the high-Q mechanical system. An active filter following the rectifier removes the rectifier ripple. The signal is amplified, the gain being set to obtain 5.00 volts for a peak value of varying load equal to 625 lbs. This calibration point is established while the machine is operating by means of equipment which will read or display peak signal values. This adjustment of the amplifier gain for the varying load signal is made internally.

Mean Load System: A control on the operator's panel labeled "Mean Set" supplies a command reference voltage representing the desired mean load. This command voltage is compared with the mean load signal to obtain a difference signal which actuates a relay controlling power to the mean load actuator, driving it in the direction which will make the mean load equal to the commanded value. The "Mean Set" control has a digital dial which is scaled such that it will approximate the value of the desired load. A final adjustment will usually be necessary, using the DVM readout as the accurate indication.

The mean load power circuit is designed so that when a mean load error signal is established, the response will be in the form of a small step-correction, unless the error is quite large when the steps run together and become continuous. The size of the step is adjusted to correspond to about half of the remaining ripple voltage in the mean load signal. The "window" or dead zone of the comparator circuit must be at least as large as the ripple voltage to avoid excessive wear and relay chatter, but the stepping action permits using the peaks of the ripple voltage to achieve a more accurate intermediate load setting. The same improvement in accuracy could be obtained by reducing the ripple voltage with better filtering, but this would result in a larger time constant.

Varying Load System: The resonant loading system functions as an amplitude-controlled oscillator. A "Vary Set" control is provided on the operator's panel similar to the "Mean Set" control in form and function. As in the case of mean load, the digital dial of the "Vary Set" control provides only a first approximation to the varying load in pounds, and the operator must make a final adjustment by reference to the DVM readout.

This control setting provides a command value for the varying load, which is compared with the actual value as given by the rectified and filtered signal from the load cell. The difference of these is fed to the "Y" input of a four-quadrant multiplier. The "X" input of the multiplier is fed by a signal which is taken from the load cell before rectification and shifted in phase by 90°. The product is fed to a phase inverter and to a push-pull complementary-symmetry solid state amplifier which drives the shaker motors. Positive feedback, in the form of a force in phase with the velocity of vibratory motion, is present when the rectified varying load signal is less than the command value. The system then becomes a self-excited oscillator whose frequency is controlled by the mechanical system. The loop gain is such that damping is approximately critical to prevent load overshoot on start-up.

Automatic Shutdown System: In the event of a specimen failure, there is a sudden loss of both mean and varying load signals. Unless the power to the mean load actuator is turned off, the mean load control system will continue to function until stopped by the limit switch in the actuator. To provide an immediate power shutdown, the analog signal for the varying load is connected to a window comparator which operates two relays when the varying load signal falls below some preset fraction of the command value. One set of contacts on each relay latch the relay on and another set opens the coil circuits of the respective mean and varying load power relays, rendering both systems inoperative. An indicator light on the panel signals a specimen failure. The automatic shutdown system is placed in operation by a switch on the control panel; during specimen installation and test start-up, this switch is in the manual override position.

Grip Position Control: A special grip position sensing and control system is provided by means of which the grips can be returned to a preselected zero reference position. This operation would be employed after removal of a failed specimen, preparatory to installing the next specimen. It can also be used if it is desired to interrupt a test, to return the load to zero.

Grip position control is accomplished by a switch on the control panel, which by means of two latching relays interchanges the input from the load cell with that from a position sensing transducer of the bending beam type and simultaneously energizes the mean load power relay. (This circuitry is not shown on Figure 11.) Under servo control, the mean load actuator then drives the grips back to their proper position for reloading. The "grip position" dial provides vernier control of the zero position to take care of minor variations in the length of specimens if needed.

Load Cycle Counting System: This system consists of a monostable multivibrator driven from the varying load power amplifier, which generates a 10 millisecond pulse for each load cycle. These pulses feed into a two-stage electronic decade counter which, at a count of 100, drives a six digit electromechanical totalizer via a switching transistor. This provides a total count capability of 10^8 load cycles readable to 100 cycles. The totalizer must be manually reset at the start of each test.

Temperature Control System: The OFT enclosure utilizes both passive and active thermal control measures to maintain the interior structure at approximately $300^{\circ}K$ ($80^{\circ}F$) while in the space environment. During the earth shadow phase of the orbit, some thermal input will be required to maintain this temperature. To minimize this requirement, the mechanism is placed in a nearly isothermal enclosure. Because space limitations preclude the use of multilayer insulation, the enclosing structure is provided with surface treatment designed to maximize radiative coupling within the enclosure, and to minimize radiative interchange with the space environment. The external surface treatment is designed such that, when the OFT is in the shadow of a cold spacecraft and also shielded from earth radiation, a maximum rate of heat loss of about 20 watts will occur. To make up for this radiated heat loss, a bank of etched-foil heaters, having a capability of about 30 watts, is mounted on the internal surface of the enclosure. Thus the most severe anticipated conditions can be handled by about a 70% duty cycle.

In the prototype OFT, the mix of low emittance-low absorptance surface coatings is not used. Instead, the external metal surface is polished to a near-specular finish, to obtain minimum radiative emittance. This treatment is less sensitive to damage by handling and will control the heat losses during tests in a cold-wall vacuum chamber to about the same maximum rate as would occur in the space application.

Four temperature sensors are located on the inside surface and connected to an appropriate linearizing and attenuating network to provide an output voltage proportional to the average temperature. The sensors and associated circuitry comprise a bridge which is balanced to zero at 0°F. Output voltage from the bridge is amplified with a stable high gain amplifier. The gain is adjusted to give 10.00 volts out at +200°F. This voltage is scaled with a precision voltage divider to 200 millivolts so that it can be read on the DVM and interpreted as degrees F.

In the temperature control system, temperature analog voltage is compared with a command reference (set point) voltage; when the analog falls below the set point, the comparator actuates a relay to energize the heating elements in the OFT. When the temperature analog exceeds the set point, the heaters are turned off. Small positive feedback in this control circuit provides over-center snap action to prevent relay chatter.

Design Characteristics

Estimated Accuracy of Performance: A summary of the estimated probable errors contributed by various components and operations which affect the accuracy of loading is presented in Table I. A total probable error for the system of 1.6 percent of full range is indicated. The largest sources of inaccuracy are the load cell calibration, power supply voltage stabilization, and non-uniformity of specimen loading. With modest effort these could be improved, so that a total probable error of 1% or better appears possible.

To the probable error of the test machine the experimenter must also add that introduced in the determination of specimen cross-sectional area. Even with considerable care this may amount to 0.5% or more. However, further improvement may be of marginal value, since a similar size random inaccuracy in section area appears to be introduced by scatter in the location of failure from the section of minimum width, as found in the tests of Ref. 1.

Power Requirements Estimate: Actual power requirements data for the prototype OFT under vacuum or simulated space environment conditions are not available. Based on an analysis of the requirements of individual components, modified by a limited number of power measurements made on the prototype OFT, an estimated summary of Power Requirements is presented in Table II.

Weight Breakdown: A weight summary, based on data taken on the prototype OFT, is presented in Table III. Total weight for the mechanical assembly, as it would be used in Skylab, is 36.2 lb. This does not include weight of the boom, umbilical, or the canister and stowage provisions. The prototype control console weighs 27.9 lb. total. For actual space use a considerable weight reduction would be achieved by the use of printed circuit boards and further miniaturization. Further overall weight savings would be available by combining the housing for the control system with the structure of the canister.

Engineering Drawings: A complete list of engineering drawings for the OFT is presented in Table IV.

TABLE I - ESTIMATED ACCURACY OF PERFORMANCE

	Basis			Probable Error (0.67σ) % of 1250 lb
	Test or Experience	Vendor's Data	Estimate or Calculation	
Random Errors				
Load Cell Accuracy				
Drift	x	x		0.2
Linearity		x		0.07
Calibration	x			0.7
Operator's Settings				
Mean Load Amplifier Gain (Internal)	x			0.1
Varying Load Amplifier Gain(Internal)	x			0.2
Bridge Voltage	x			0.3
Command Settings	x			0.1
DVM Accuracy		x		0.2
Circuitry				
Power Supply and Bridge Voltage Stab.	x	x		0.5
Amplifier Linearity	x			0.1
Drift of Characteristics	x			0.1
Servo Loop				
Mean Load (±2 lb. step)	x	x		0.2
Varying Load (±1 lb. control)	x			0.1
Specimen Concentricity (±.001-in)			x	1.05
RMS Sum				1.47
Fixed Errors				
Parallel Flexure Load (+0.7 lb)			x	
Grip Mass Inertial Load (-2.0 lb)			x	
Net Error (-1.3 lb)				.10
Total Probable Error				1.6

TABLE II -- ESTIMATED POWER REQUIREMENTS

(Includes allowances for efficiency of conversion from 28^V source)

Electronics	All sensing, measurement, control, and display circuits, including DVM panel meter; continuous		23 watts
Mean Load Actuator Drive	Relays, pilot lights, and motor operation on the basis of 5% duty cycle.		10 watts
Varying Load Shaker Drive	Power amplifier, at an estimated 2x power required by shakers	Elastic specimen in vacuum " " in air Ductile specimen in vacuum	20 watts 32 watts 44 watts
Thermal Control	Total internal heating required, including waste heat of mechanical systems	In space, sunlight In space, shadow In laboratory vacuum chamber	0 watts 20 watts 20 watts

Condition	Power to Operate OFT	Heat Dissipated in Mech. Assy.	Addit. Heat Required in Shadow or Vacuum Chamber	Total Power Required		
				In Sun	In Shadow	Earth Lab.
Idle	23	0	20	23	43	23
Test of Elastic Specimen						
In Vacuum	53	6	14	53	67	67
In Air	65	10	-	-	-	65
Test of Ductile Specimen						
In Vacuum	77	17	3	77	80	80

TABLE III -- WEIGHT BREAKDOWN

Mechanical Systems Assy (153001)			36.2
Internal Mechanism		29.3	
Base	2.39		
Main Flexures	.45		
Vibratory Beams (inc.mass)	10.03		
Mean Load Beams	1.56		
Actuator Linkage	.42		
Loading Heads	1.00		
Parallel Flexures	.14		
Grips (inc pins)	.78		
Drive Flexures	.02		
Position Sensor	.02		
Mean Load Actuator	3.95		
Shakers	7.84		
Attachments	.69		
Enclosing Structure		5.5	
Lower Shell	2.88		
Upper Shells	0.98		
Deck	0.20		
End Bells	1.48		
Thermal Control		0.4	
Heater Installation	.16		
Ext Surface Covering	.20		
Miscellaneous		1.0	
Wiring	.30		
Attachments & Misc.	.74		
Elect. and Cont. Systems Assembly (153002)			27.9
Control Panel		4.0	
Control Card Assemblies (less mounting)		3.4	
Power Supply Panel		5.0	
Enclosure, Card Cage, and Harnesses		15.5	
Cable Assembly (153003)		1.3	
Laboratory Stand (inc. simulated boom) (153009)			10.0

TABLE IV LIST OF ENGINEERING DRAWINGS

Drawing No.	Title	Size
153000	Orbital Fatigue Tester, Assy of	E
153001	Mechanical Systems, Assy of	F
153010	Internal Mechanism Assy	F
153011	Base	F
153012	Flexure Plate, Main	C
153013	Beam Assy, Vibratory	F
153014	Inertial Mass	C
153015	Beam, Mean Load	C
153016	Linkage Assy, Actuator	D
153017	Loading Head Assy	D
153018	Parallel Flexure	C
153019	Grip, Clevis	C
153020	Pin Assy	C
153021	Drive Flexure	C
153022	Position Sensor Assy	C
153023	Actuator, Mean Load	C
153024	Shaker, Electromagnetic	E
153025	Shell, Lower	F
153026	Shell, Lower, Blank for	C
153027	Shell, Upper	F
153028	Shell, Upper, Blank for	C
153029	Deck Assy	C
153030	End Bell, Inbd., Assy	D
~~153031~~	~~End Bell, Inbd., Cstg of~~	~~D~~
153032	End Bell, Outbd., Assy	C
153033	End Bell, Outbd., Cstg of	C
153034	Heating System Instl	F
153035	Wiring Instl, Mechanical Systems	E
153036	Thermal Control Surf Instl	F
153037	Hardware, Miscellaneous	C
153038	Screws and Bolts	C
153002	Electrical & Control System Assy	E
152990	Enclosure, Control System	E
152991	Control Panel	F
152992	Relay Card	C
152993	Temperature Control Card	C
152994	Mean Load Control Card	C
152995	Vary Load Control Card	C
152996	LC Amp. & Vary Rect. Card	C
152997	Comparator Card	C
152989	Bypass Capacitor Card	C
152998	Power Amp. & Counter Card	C
152999	Functional Schem/Circuit Diagram	J
153003	Cable Assy	C
153004	Specimen, Adhesive Bonded Assy	D
153005	Specimen, Electron Beam Welded Assy	D
153009	Stand, Laboratory	F

PROTOTYPE ORBITAL FATIGUE TESTER

Construction

A prototype OFT was fabricated and assembled according to the engineering drawings of Table IV, page 34. Photographs of components and assemblies in various stages of completion are presented in Figures 12 through 36, inclusive.

Operation

The prototype machine was made operational and fatigue tests of a number of specimens have been conducted under normal atmospheric conditions. These included a 6-hour demonstration test at design load (approximately 2 million cycles at 665 ± 638 lb) using a dummy specimen, and some 22 million cycles at loadings varying from 470 ± 450 lb up to 600 ± 575 lb, in S-N tests of 24 specimens of the type illustrated in Figure 9, **reported in Ref 5.**

A set of operating instructions for the OFT is presented in Appendix C.

Modification to Vibratory Beams

At some point during the operational loadings described above, a fatigue failure initiated in the minimum width section of one of the 153013 vibratory beams. An overstress condition is attributed to rotatory inertia effects of the inertial mass, which redistributes some of the bending moment outboard, combined with transverse plate-restraint effects in the tapered plan-form beam, which results in larger angular beam deflections and aggravates the rotatory inertial loading. The original vibratory beams have been replaced with a modified detail which operates at a stress level 75 percent as high as that in the original, thus assuring a greatly extended service life. The modification is documented in Dwg 153013B.

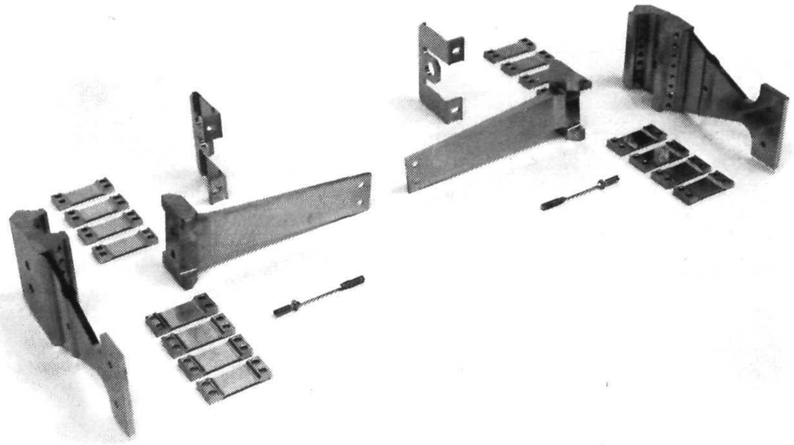


Figure 12 Beams and flexures machined of 18Ni (300) maraging steel.

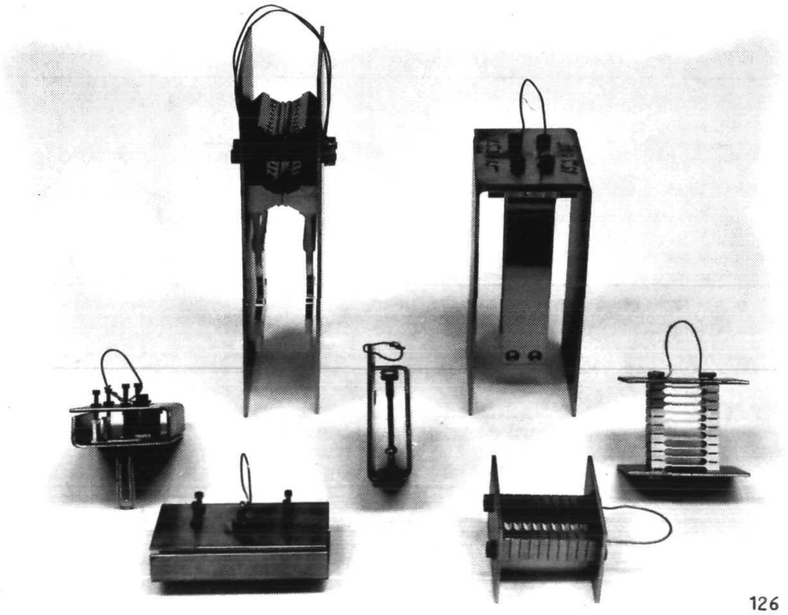


Figure 13 Methods of packaging 18Ni (300) maraging steel parts for heat treatment, to protect polished surfaces.

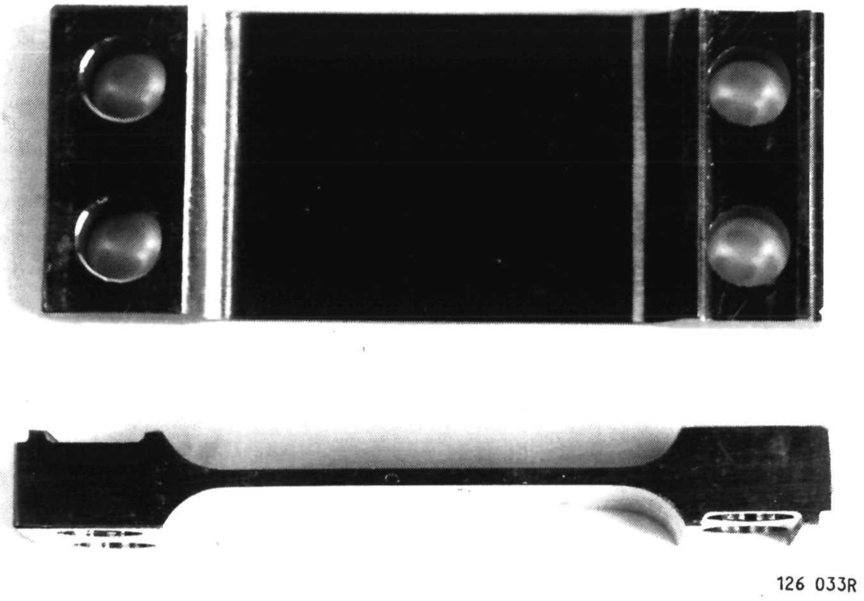

126 033R

Figure 14 Close up view of main lower flexure plate.

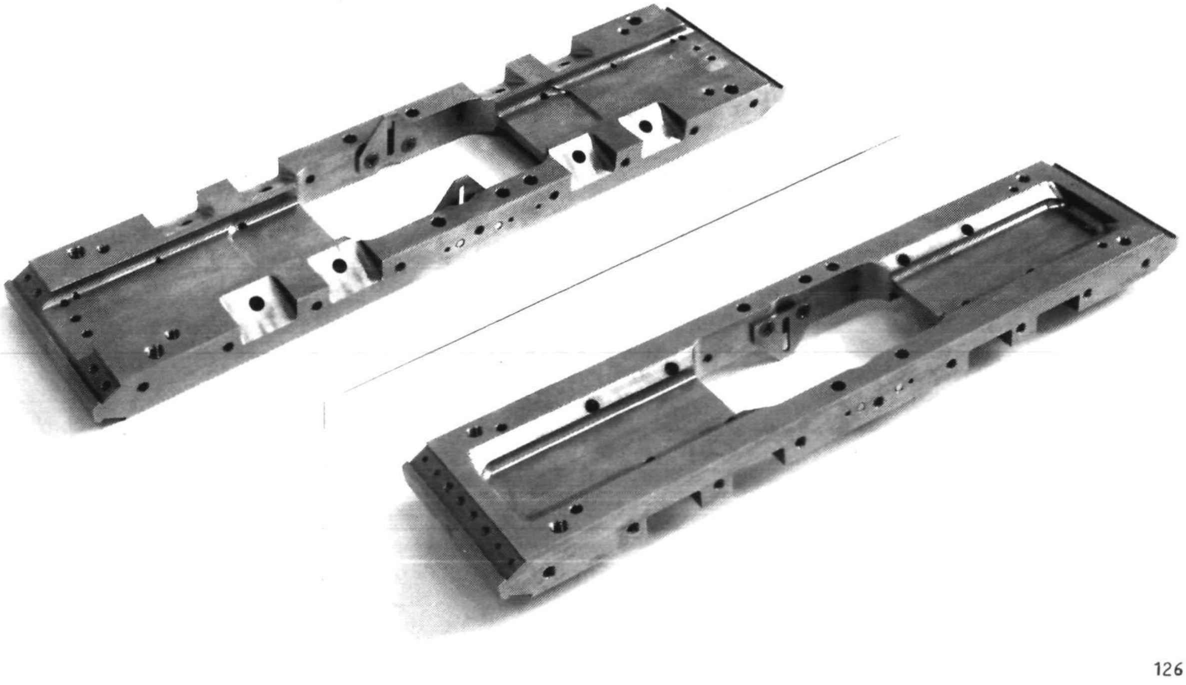

126 032R

Figure 15 Views of the Ti-6Al-4V structural base of the machine, from above and from below.

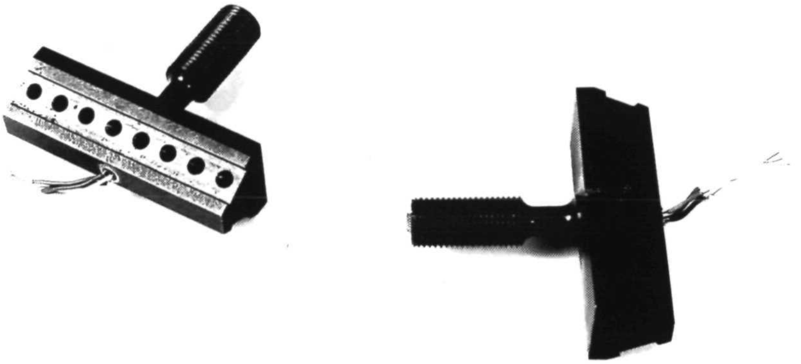

126 054R

Figure 16 Loading heads. Strain gages installed internally in section of reduced diameter to provide hermetically sealed load cells.

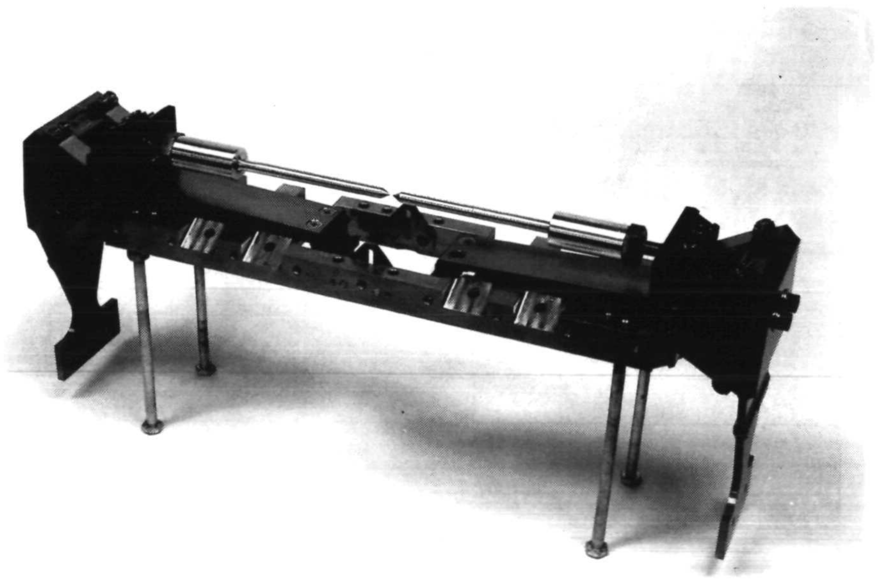

126 203R

Figure 17 Partial assembly of mechanism, illustrating use of alignment tooling for loading column.

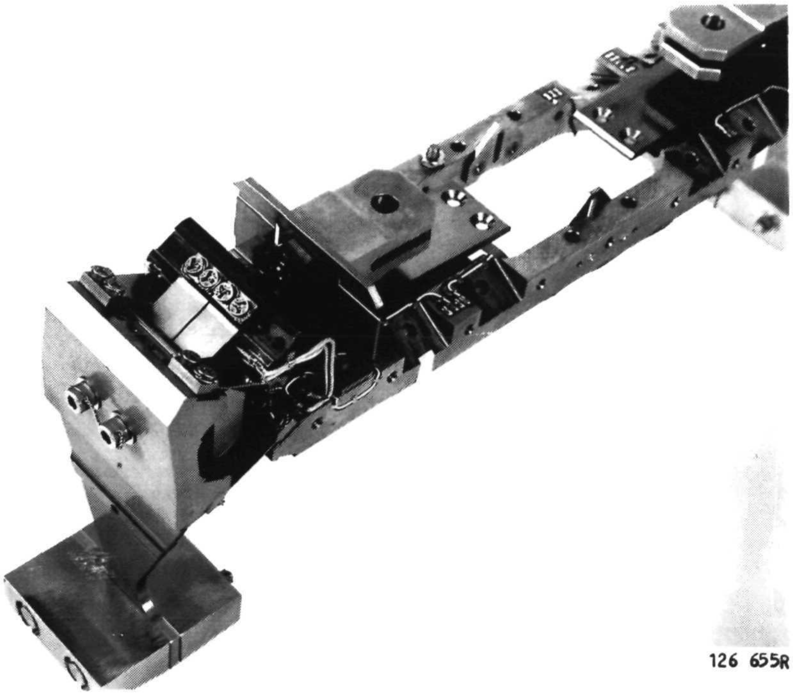


Figure 18 Internal mechanism partial assembly, after wiring installation.

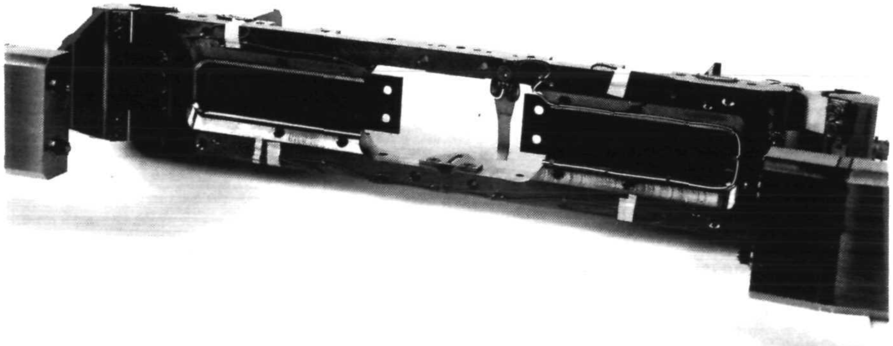


Figure 19 Same as Figure 18, view from below.

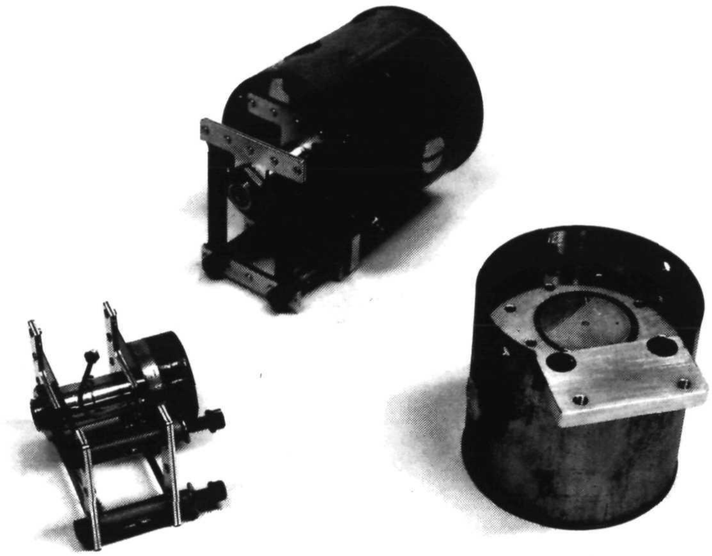

126 053

Figure 20 Shaker Assemblies.

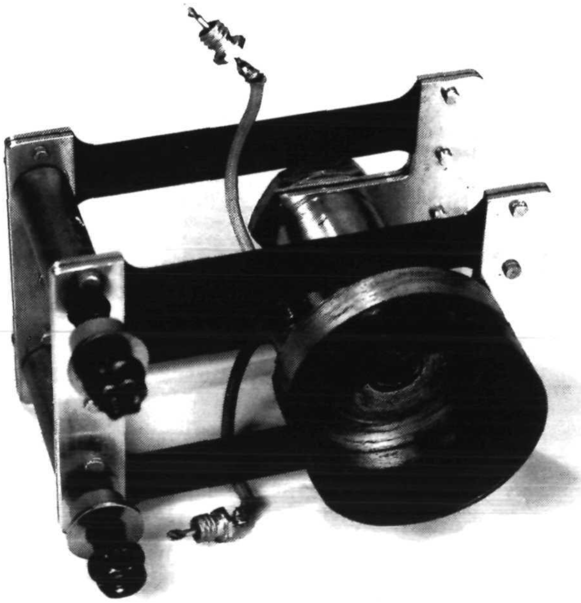
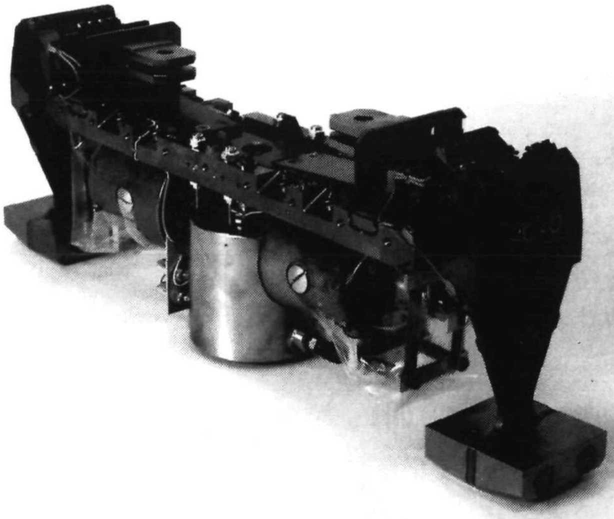
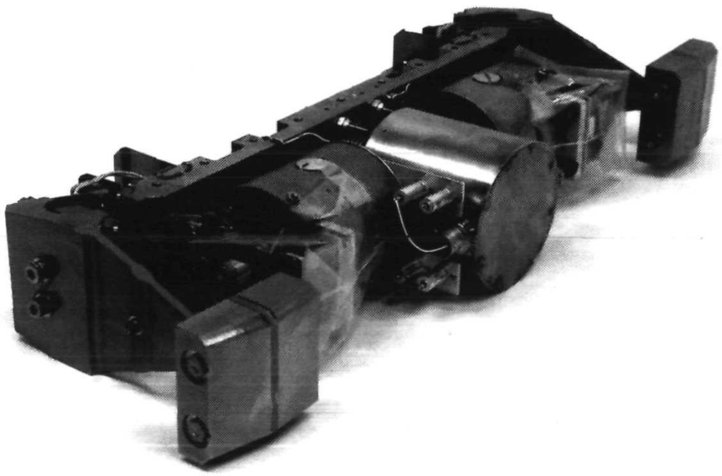

126 052R

Figure 21 Shaker armature and suspension assembly.



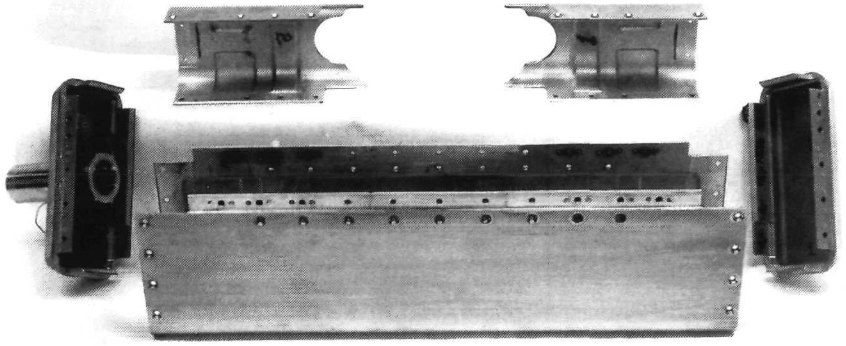
127 049R

Figure 22 Internal mechanism assembly complete. Protective polyvinyl coverings were removed from shakers prior to installation in shell. (Three-quarter view from rear inboard.)



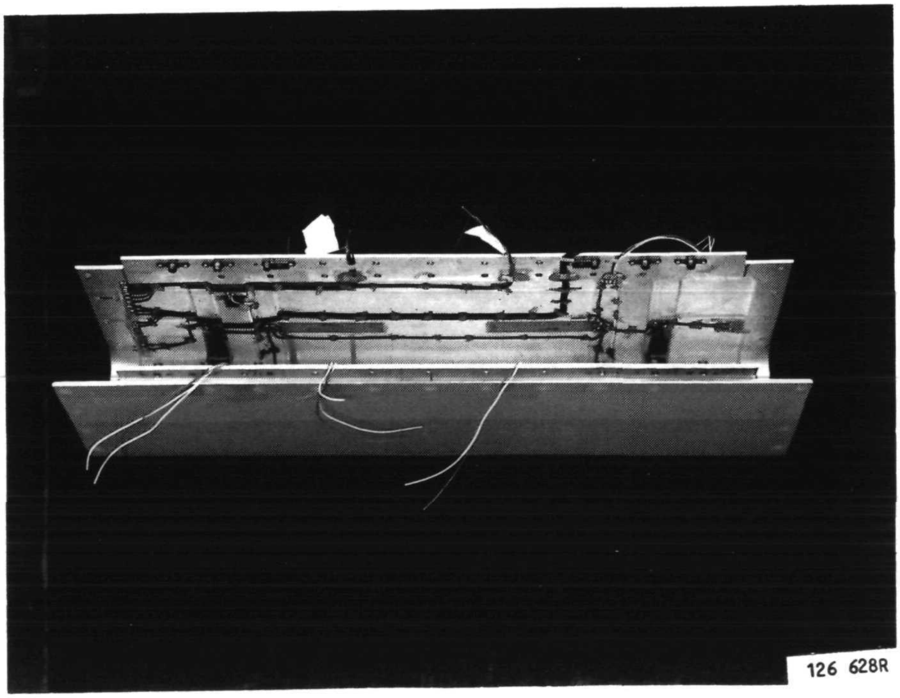
127 050R

Figure 23 Same as Figure 22, view from below and inboard.



126 034R

Figure 24 External shells and end bells.



126 628R

Figure 25 Lower shell showing installation of heaters, temperature sensors, and wiring.

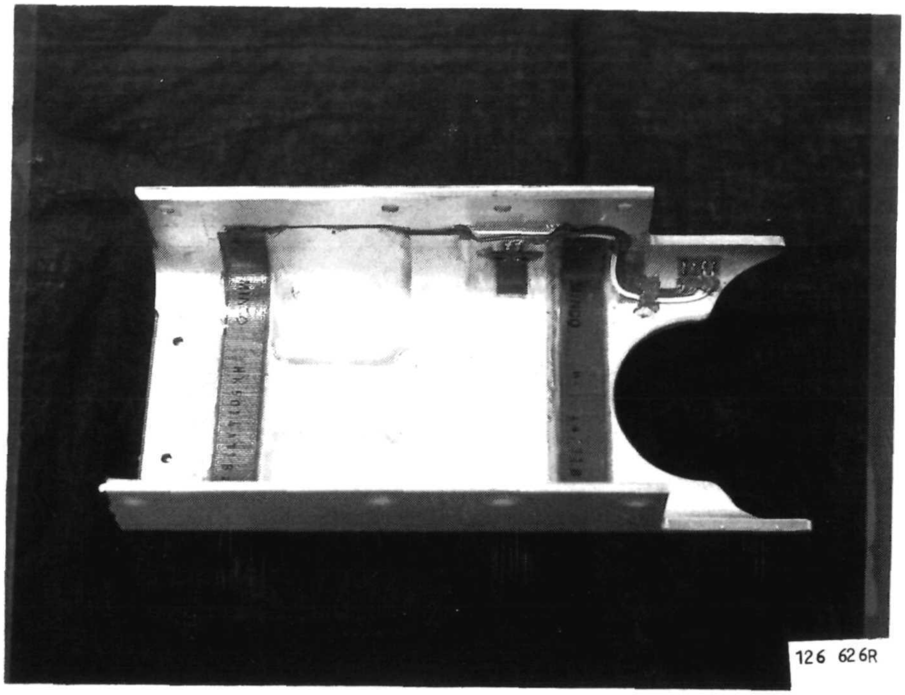

126 626R

Figure 26 Upper shell showing installation of heaters, temperature sensors, and wiring.

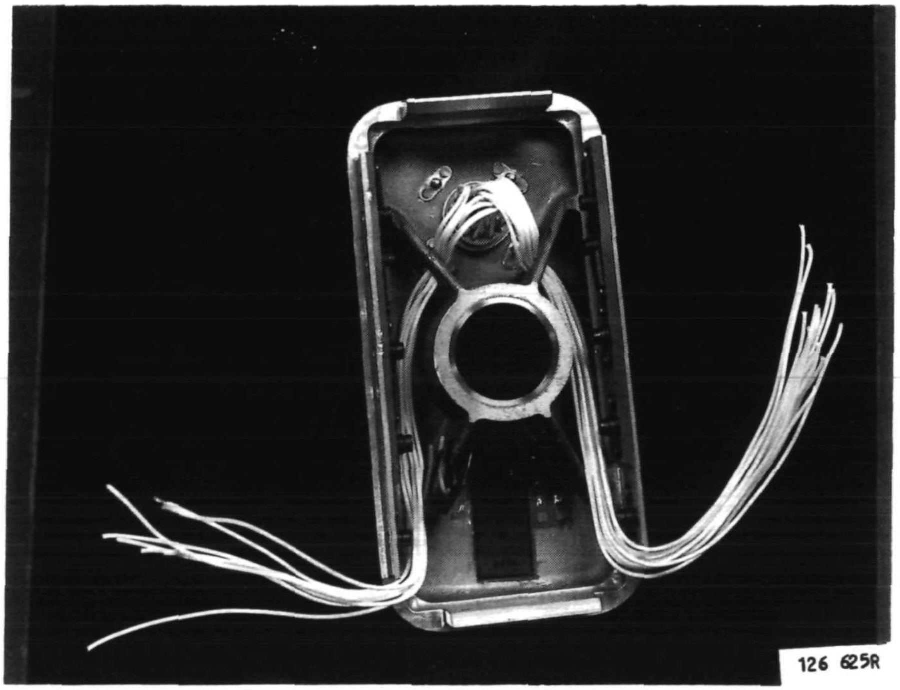

126 625R

Figure 27 Inboard end bell showing installation of heater, temperature control unit, and wiring.

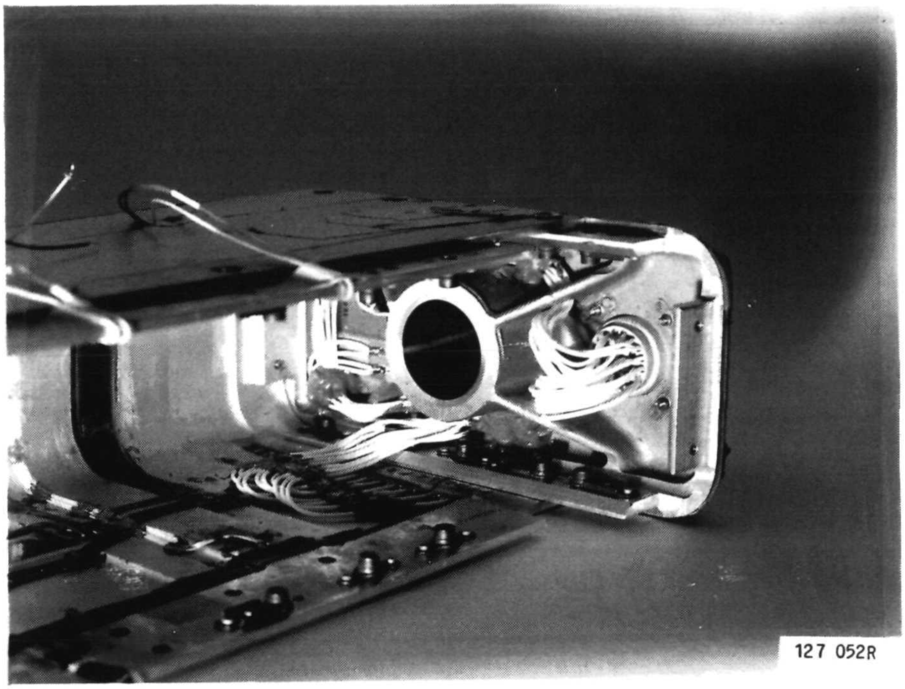


Figure 28 Assembly of inboard end bell to lower shell, three-quarter view of rear panel.

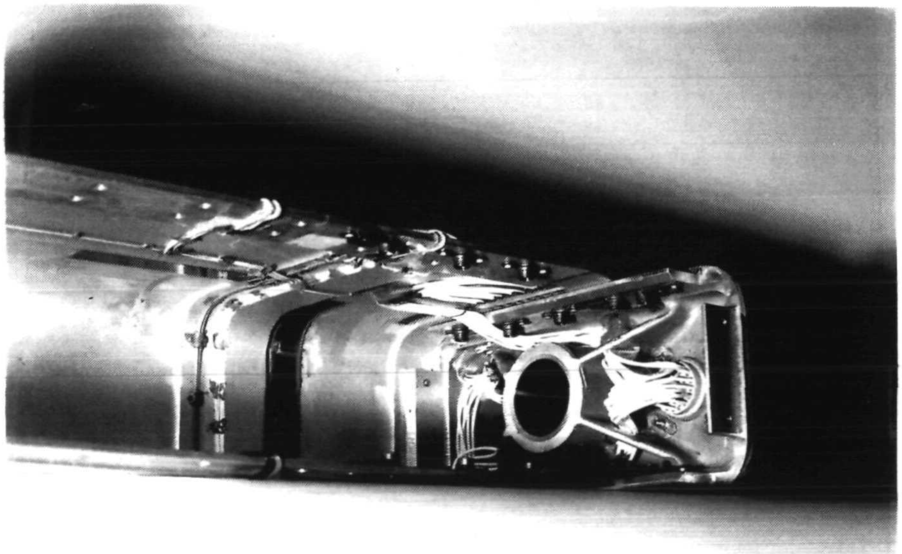


Figure 29 Same as Figure 28, three-quarter view of front panel.

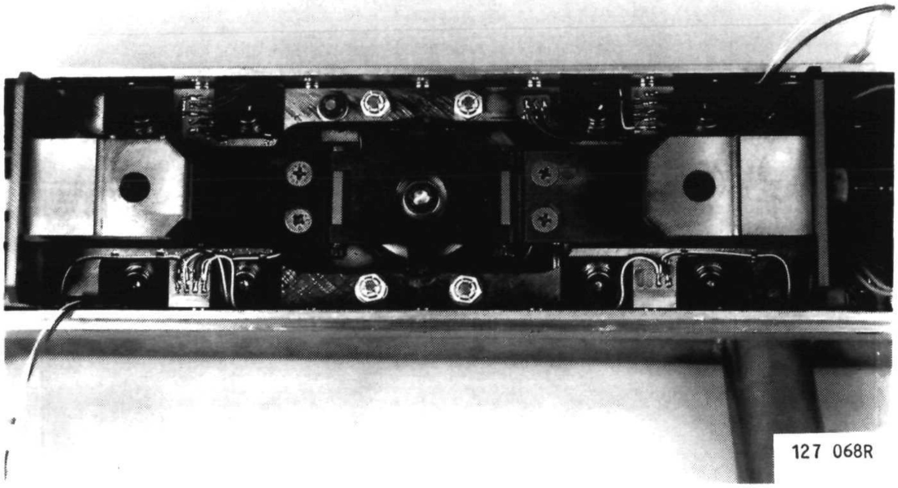


Figure 30 Mechanism installed in shell; view of wiring installation from above.

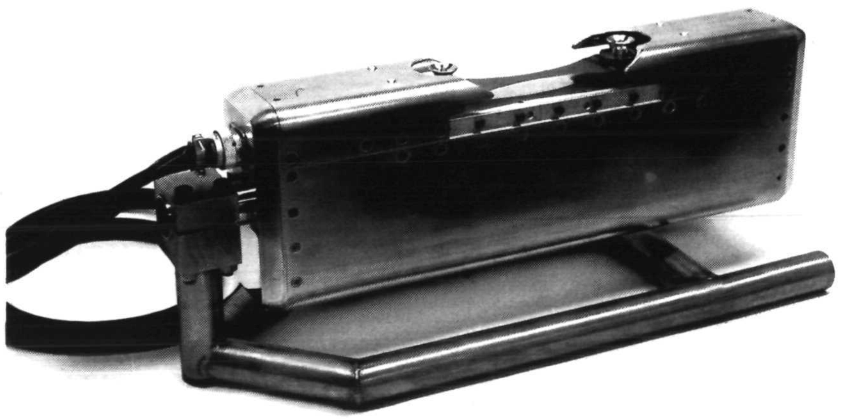


Figure 31 Mechanism assembly on simulated boom support in laboratory stand.

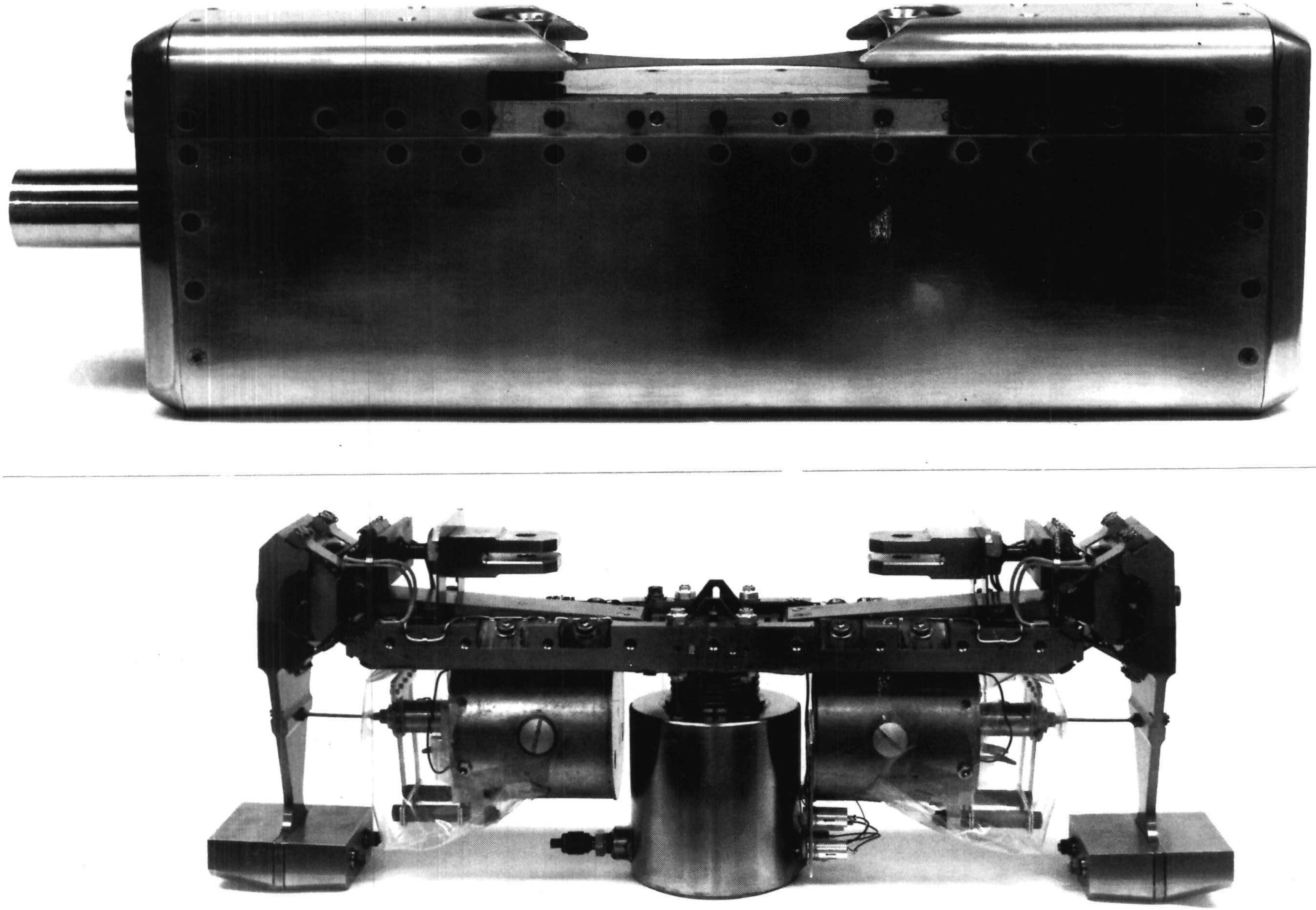
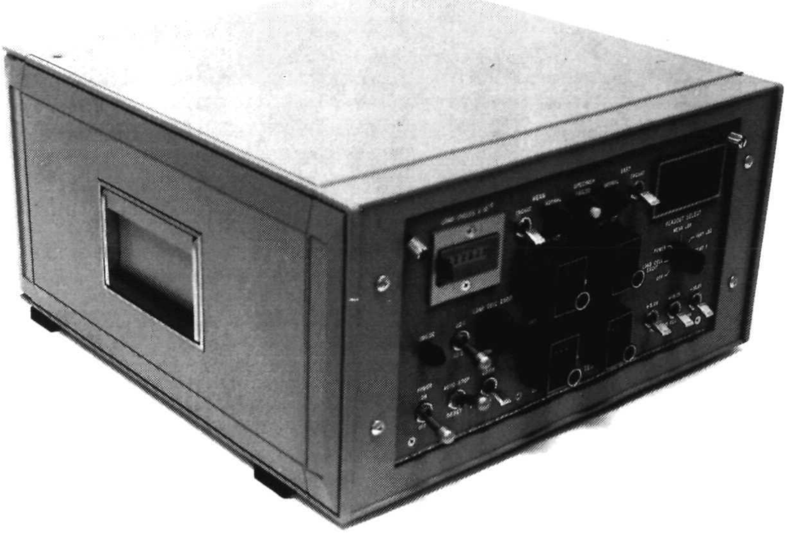
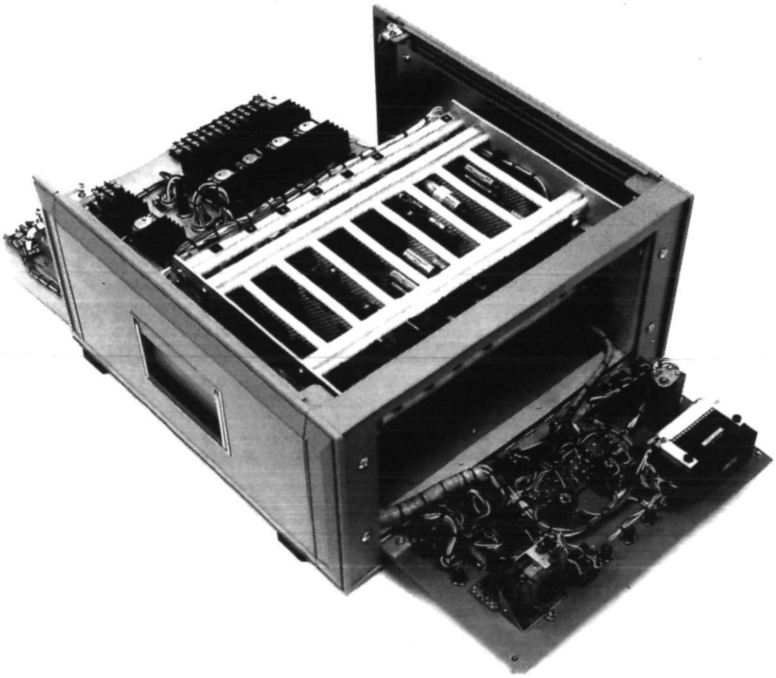


Figure 32 Mechanism assembly. External view above; internal mechanism, below.



127 054R

Figure 33 Electrical and control system in console.



127 056R

Figure 34 Internal view of control console, three-quarter front view.

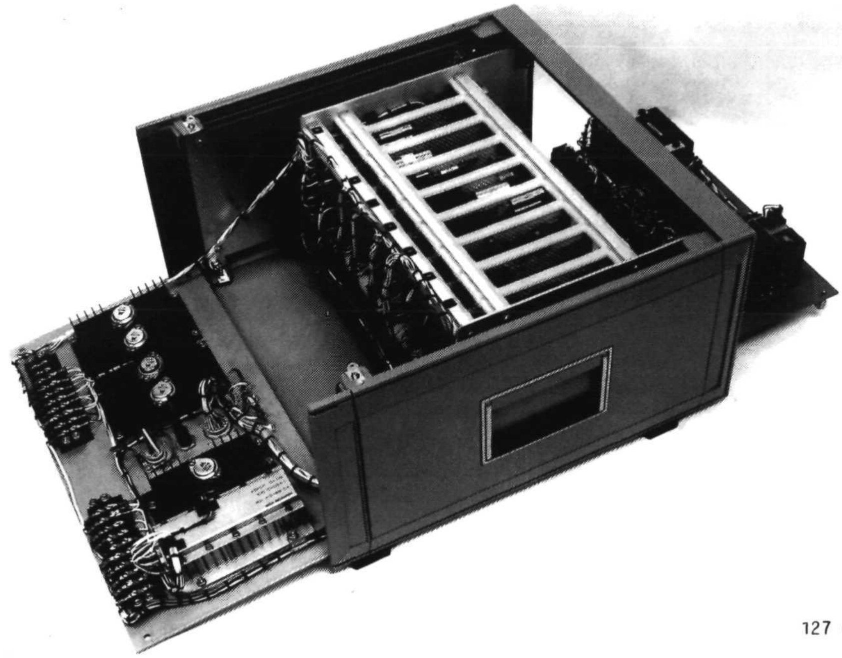


Figure 35 Same as Figure 34, three-quarter rear view.

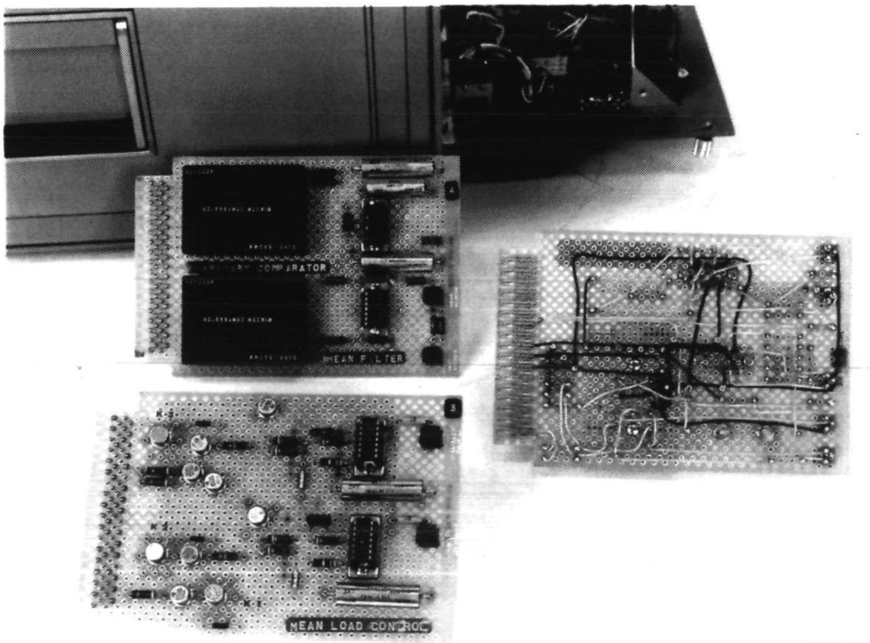


Figure 36 Representative control card assemblies.

APPENDIX A

DEVIATIONS FROM SPECIFICATIONS FOR SPACE-QUALIFIED HARDWARE IN OFT PROTOTYPE

Control System Electronics Components

All components in the control system have been selected from the preferred parts lists Ref. 6 and/or Ref. 7 where these listings were applicable to the requirements of the Orbital Fatigue Tester design concept. Applicable MIL specs are shown in the bill of materials appearing on the pertinent engineering drawing. Certain electronic sub-assemblies were not available from these lists; namely, the high-gain amplifiers, comparators, multipliers, integrated circuit chips and the digital voltmeter.

All of the power and signal switching relays were purchased to the specifications of Ref. 7 and were reliability-tested by the vendor. For economic and schedule reasons it was not practicable to obtain reliability-tested components for the entire system. All manual switching elements are hermetically sealed and are of a type recommended as suitable for space application but were not purchased to reliability specifications. The power supply module was not furnished either as a space-qualified or reliability-tested item; however, it is similar in design and construction to components used in the Apollo TV systems.

Electronic components used in the prototype OFT may consequently be classified in four categories as follows:

(1) Space-qualified components (including complete reliability-testing):
All power and signal switching relays
Drawing 152999 Find No. 13 Relay
Drawing 152999 Find No. 14 Relay

(2) Not reliability-tested but selected from Ref. 6 and 7:

Drawing 152999 Find No. 12 Relays
Drawing 152999 Find No. 15, 16, 17, 18, 19 Resistors
Drawing 152999 Find No. 39, 40, 41 Transistors
Drawing 152999 Find No. 38 Diodes
Drawing 152999 Find No. 25, 26 Capacitors-Tantalum

(Note: The bill of materials on Drawing 152999 calls for RNR types; deviation to RN 65C and RN 20 types was made in construction of the prototype because of inordinate cost and delay in delivery.)

(3) Selected to MIL spec but not listed in Ref. 6 or 7.

Drawing 152999 Find No. 8, 9, 10 IC Chips
Drawing 152999 Find No. 21, 22 Variable Resistors
Drawing 152999 Find No. 23, 24 Plastic Film Capacitors
Drawing 152999 Find No. 29 Capacitor
Drawing 152999 Find No. 32 Hermetic Switch
Drawing 152999 Find No. 33 Power Supply
Drawing 152999 Find No. 45, 46, 47, 48 Connectors
Drawing 152991 Find No. 8, 9, 10, 11, 17 Switch Actuator

(4) Commercial Grade Components:

All other items not listed above. Included are components which may require special design and/or construction for use in space, but which will not affect laboratory evaluation of the prototype, such as pin-connectors.

Control System Assemblies

Design and construction of the control system is in accordance with current aircraft practice, and the engineering drawings identify a Lockheed corporate specification for wiring and assembly which meets the minimum requirements of MIL-W-5088 except for wire identification coding. The applicable specifications for space flight hardware impose special requirements which vary somewhat depending on the program application. Such deviations are not expected to affect laboratory evaluation of the prototype performance.

Specific deviations from the requirements of Ref. 2 include:

- Teflon insulation is used in the wiring of control cards, 152989 and 152992 through 152998, not permitted in Apollo hardware for toxicity reasons.

- Design did not include specific consideration of shock and vibration test requirements. No qualification tests of this type have been conducted.

Mechanical System

Detail design and strength analyses of mechanical components and assemblies include consideration of all the requirements of Ref. 2, including shock and vibration test requirements. The latter are assumed to apply only in the stowed configuration, which requires support at the blocking points and a dummy specimen to be installed. However, no qualification tests, except the operational tests noted on page 35, have been conducted.

The traceability of materials utilized in the manufacture of space hardware must in general be thoroughly documented. For the prototype OFT, all structural materials and processing were purchased under appropriate federal specifications and with vendor's certification; no more detailed control was exercised. The requirement of corrosion protection for all metals not corrosion resistant is followed in all cases except at critical bearing surfaces which would be adversely affected by such a coating (e.g.,contact areas for the 153014 inertial masses on the 153013 vibratory beams; polished holes in the 153016 linkage components). In no instance has cadmium plating or cadmium plated parts been used.

Wiring details employed in the mechanical assembly (ref. Drawing 153035) are suitable for laboratory and vacuum chamber evaluation but will require redesign for space flight application. The development of a wiring harness, support and connector details was omitted from the final phase of the program in accordance with a reduction in funding. Positive protection of soldered joints from moisture is not provided. Additionally, the wiring utilized in the prototype installation utilizes teflon insulation, which introduces a toxicity hazard when the OFT is inside the space vehicle. Insulating materials of equivalent electrical and mechanical characteristics, such as "Space Kynar" sleeving (Raychem Corp.), will be used in flight hardware.

APPENDIX B

NON-METALLIC MATERIALS USED IN OFT MECHANICAL ASSEMBLY

Because of possible outgassing problems under vacuum test conditions, the use of non-metallic materials in the OFT mechanical systems assembly was restricted. Non-metallics cannot be completely avoided, because of the requirements of electrical insulation, adhesive bonding, and corrosion protection. Materials which are employed are recognized as having favorable outgassing characteristics and being stable under elevated temperature (i.e., in the range of 275°F). A list of all non-metallics in the 153001-101 mechanical systems assembly is presented below.

Electromagnetic Shakers (153024)

Armature Winding: Phelps-Dodge "armored polythermaleze 2000" magnet wire, which is insulated with a first coat of high temperature polyester resin, covered with an overcoat of amide imide linear polymer, rated for 20,000 hr life at over 400°F. Wire laid in 3M Co. Scotchweld 2214 high temperature epoxy adhesive, a one-part modified epoxy with aluminum filler, cured at 350°F.

Armature Leads: Insulated and reinforced with teflon sleeving.

Loading Heads (153017)

Load Cell Installation: Hermetically sealed at one end with fused glass-insulated 4-wire header and steel plug at the other; both sealed to steel body with 3M Co. 2214 high-temperature epoxy adhesive, cured at 300°F min.

Protective Coating: American Cyanamide BR-127 epoxy primer, 0.1-mil coat, over external steel surfaces. Cured at 275°F.

Wiring Insulation: Teflon sleeving, header-to terminal tabs. Silicone impregnated woven fiberglas sleeving, loading head to 153011 base.

Terminal Tabs: Micro-Measurements bondable printed circuit terminal strips of fiberglas-reinforced epoxy construction. Bonded to loading head with Mithra 200 high temperature adhesive, a two-part filled epoxy, cured at 300°F.

Mean Load Actuator (153023)

Electrical Terminals: Hermetically sealed in fused glass-insulated connector, Cannon KPT1H10-6PN.

Position Sensor (153022)

Strain Gage: BLH Corp. type FAET, etched foil on polyimide backing, mounted with Mithra 200 epoxy adhesive, cured at 400°F.

Terminal Tabs: Micro-Measurements fiberglas-reinforced epoxy construction, bonded to metal surface with Mithra 200 epoxy adhesive, cured at 400°F.

Heating System Installation (153034)

Surface Heaters: Minco Products, Inc., etched foil elements laminated in "Kapton" (a resin film system comprised of polyimide with teflon surface). Bonded to aluminum alloy surfaces with Mithra 200 high temperature epoxy adhesive, cured at 275°F.

Temperature Sensors: A Micro-Measurements product, fabricated as a pure nickel grid encapsulated in glass fiber reinforced epoxy-phenolic film, temperature range up to 500°F. Bonded to aluminum alloy surfaces with Mithra 200 epoxy adhesive, cured at 275°F.

Matching Network: Micro-Measurements product, encapsulated in a molded epoxy case. Bonded to 153030 End Bell with 3M Co. 2214 high temperature epoxy adhesive, cured at 250°F.

Voltage Divider: BLH Corp. type FAET strain gages constructed of foil on polyimide backing, mounted with Mithra 200 epoxy adhesive, cured at 275°F.

Wiring Installation (153035)

Terminal Tabs: Micro-Measurements, fiberglas-reinforced epoxy construction, bonded to metal surfaces with Mithra 200 epoxy adhesive, cured at 250°F.

Wiring: Teflon insulated. Supported at intervals with 3M Co. 2214 epoxy resin, laid sufficiently thick to surround the wire bundle, and cured at 250°F.

Main Connector: Cannon KJ2R18-30P, which uses a core of silicone rubber.

Connections to Actuator: Solder connections to pins of KPTIH10-6PN connector, insulated with teflon sleeving. Radio frequency interference suppression system of Erie type 1215-022 EMI filters (hermetically sealed in silverplated steel cases) and Unitrode 5081 Zener diodes (sealed in fused glass covers).

General

Corrosion Protection: All 18(Ni) 300 maraging steel parts (153012, 153013, 153015, 153018, and 153021), loading heads (153017), linkage components (153016), and the ends of the structural base (153011) coated with American Cyanamide BR-127 epoxy primer 0.1-mil thick, cured at 275°F.

Lubricant: All self-locking nuts and plate nuts are standard MS parts of A286 stainless steel, which are treated with a dry film lubricant. A mixture of Celvacene vacuum grease, a high temperature castor oil-based compound recommended for vacuum use at 10^{-9} torr (Consolidated Vacuum Corp., Rochester, New York), and graphite is used for lubrication of the 153016-109 linkage pins.

APPENDIX C

OPERATING PROCEDURE

Initial Start-Up

(1) POWER switch on.

(2) Allow warm-up period of 20 to 30 minutes.

(3) Using the READOUT SELECT switch to obtain desired readout on the Digital Volt Meter (DVM), confirm power supply voltages 5, +15, and -15 volts. Deviation more than 2 percent indicates either supply voltage beyond usable range or OFT power conversion module not controlling properly.

(4) Confirm load cell excitation voltage of 10.00 volts. Adjust if necessary, and lock the LOAD CELL EXCITATION voltage control.

(5) Place the AUTO STOP/RESET switch in manual override (up) position, then momentarily press the GRIPS/PUSH TO SET switch upward, to initiate automatic return of grips to zero position if not already there. When operating in this mode, the DVM will give an indication of grip position when the selector switch is set to MEAN. (The grip position control uses the mean load servo-circuit; the readout is proportional to position over approximately the last tenth inch of grip travel.)

(6) Install new specimen. Use teflon tape or teflon sheet to space specimen ends centrally in the clevis grips. Deviations up to ± .010-inch in hole centerline to hole centerline length of the specimen from 7.00 inches can be accommodated by adjusting the GRIP POSITION control on the console. (Greater deviations in specimen initial length may cause strength and deflection limitations of the OFT to be exceeded.) After making adjustment, lock the GRIP POSITION control.

(7) If the automatic grip return of (5) above has been used, return the AUTO STOP/RESET switch to normal (central) position, and momentarily press the MEAN ENGAGE switch. This returns the load cell to the load measuring circuit.

(8) Adjust the LOAD CELL BALANCE control to obtain 000 lb mean load indication on the DVM.

(9) Reset the cycle counter (LOAD CYCLES x 10^{-2}) to zero.

(10) Place the AUTO STOP/RESET switch in manual override (up) position.

(11) Set the desired mean load on the MEAN SET load control. Momentarily depress the MEAN ENGAGE switch. The machine will apply approximately the desired value automatically; when the load is on, the green light under MEAN NORMAL will come on. Do not exceed 625 lb.

(12) Read out the actual mean load applied on the DVM. Make fine adjustment of MEAN SET load control to obtain the desired value to within a few pounds.

(13) Set the desired varying load on the VARY SET load control. The varying load should always be somewhat less than the mean load; more than 96% of mean load (i.e., an R value less than 0.02) is not recommended. Set the DVM selector switch to read VARY load. Momentarily depress the VARY ENGAGE switch. Varying load will be automatically applied, and the cycle counter will start counting; the green indicator light under VARY NORMAL will come on when the loading is slightly below the set value. Do not exceed 625 lb.

(14) Monitor the actual varying load on the DVM. Make fine adjustment of the VARY SET load control. For accuracy of loading this adjustment should be made as soon as possible.

(15) The cycle counter may be reset at this point to obtain a more accurate count of cycles applied at full load. The counter reset button may then be safetied to prevent accidental loss of count.

(16) Recheck the mean load on the DVM. (The indicated value will cycle a pound or two above and below the true value as a result of DVM sampling limitations.) If necessary make further correction to obtain the desired value within a few pounds. Lock the MEAN SET load control.

(17) Place the AUTO STOP/RESET switch in automatic shut-down (central) position. Upon specimen failure, the yellow indicator light will then come on, and machine circuits will be shut off. (If automatic shut-down is not set, the mean load servo control will sense specimen failure as a drop in the load below the command value and will attempt to make correction, causing the grips to run to their extreme position.)

(18) Continue to monitor the mean and varying load components as appears necessary. Ordinarily an additional correction of the varying load, amounting to about 1/2%, may be required during the first 10,000 cycles of loading, as a result of seating of the bearing surfaces of the specimen at the loading pins.

Succeeding Tests in a Series

Following the testing of a specimen ending in failure and automatic shut down, many of the operations recommended for initial start-up may be omitted and an abbreviated procedure followed:

(1) Place the AUTO STOP-RESET switch in manual override (up) position.

(2) Remove failed specimen. Note cycle counter reading. Reset counter to zero.

(3) Actuate the automatic GRIPS/PUSH TO RESET grip position return.

(4) Install new specimen.

(5) Reset mean load, if different from previous test. Engage servo. When MEAN NORMAL light comes on, confirm on DVM and make fine adjustment.

(6) Reset and apply varying load in same manner.

(7) Set AUTO STOP-RESET switch in automatic shut-down (central) position.

General

(1) Stray magnetic fields from 60 Hz equipment (such as caused by a power transformer) can affect the control circuitry. Maintain sources of EMI distant from the control console.

(2) Testing may be interrupted at any time by turning off the power or by reducing the VARY SET load control to zero. Mean load may be removed either with the MEAN SET load control, or by placing the AUTO STOP/RESET switch in override (up) position and actuating the GRIPS/PRESS TO SET switch. (The varying load must be reduced completely to zero if this is done, or an undesirable oscillatory feedback may occur.) To resume testing after such an interruption, actuate the MEAN ENGAGE switch and the VARY ENGAGE switch in sequence. Then restore the AUTO STOP-RESET switch to automatic (central) position.

(3) Some specimens, especially those of small size, when tested at very low R-values, tend to vibrate transversely in a "violin-string" mode. This mode may be excited by end moments at the loading pins, resulting when the specimen is not positioned centrally in the clevis grip, or when the hole surface in the specimen is not normal to the plane of the specimen. Such a condition also imposes moments on the grips, and must be prevented to avoid overstressing the parallel restraint flexures. If specimen vibration persists in spite of near-perfect alignment, it may be eliminated by providing

some light transverse damping restraints at the third points, as described in Ref 1. Four mounting points are provided in the 153029 Deck of the OFT to which such auxiliary equipment may be fixed.

Internal Adjustments

The following adjustments to the operating characteristics of the OFT are available behind the control panel of the console. They are in the nature of machine calibration and should be made only by qualified personnel, at infrequent intervals.

Mean Load Calibration: On Control Card No. 5 (Load Cell Amplifier and Vary Rectifier Card, 152996) is mounted a Gain Adjust pot with which a fine adjustment can be made to the load cell amplifier gain, to correct the mean load analog signal and simultaneously bring the DVM readout into agreement with actual pounds applied between the grips. The latter reference should be established by an instrumented calibrated dummy specimen or a proving ring under static loading conditions. Static load alone up to 800 lb. maximum may be applied by the mean load actuator system without exceeeding structural capabilities. Ordinarily a traverse would be made which would indicate linearity over the range of the calibration loading. A linear extrapolation of system characteristics to the maximum dynamic load of 1250 lb. is necessary; the gain adjustment would be such as to minimize overall error.

Varying Load Calibration: Also mounted on Control Card No. 5 is a Vary Calib Adjust pot, to correct the varying load analog signal and simultaneously correct DVM readout of varying load. This operation should be performed after static (mean load) calibration. The amplified load cell signal, available at the Red Test Point on Control Card No. 5, may be displayed on an oscilloscope. With a rigid specimen between the test grips, a static load (e.g., 625 lb.) is applied with the mean load system. Varying load is then applied until the lower peak of the load cell signal indicates a value 4 percent above the original zero reference point on the oscilloscope. The Vary Calib Adjust may then be set to obtain a varying load readout on the DVM of 600 lb. The procedure should be repeated at various load levels over the operating range, and an optimum setting obtained, if any non-linearity is apparent.

Window Width: Pots controlling the comparator window width in the mean load circuit are available on Control Card No. 6 (Mean Filter, Mean and Vary Comparator Card, 152997). These should be set during dynamic operation of the fatigue machine, to obtain as small a window as practicable yet avoid hunting. Also available on this card is a pot labeled Vary Window adjust; this controls the point (in proportion to the commanded value of varying load) at which the Automatic Shut-Down circuit is triggered, currently set at about 75 percent.

Mean Load Correction Pulse Width: Adjustments controlling the "up" and "down" corrective pulse widths of the mean load actuator are available on Control Card 3 (Mean Load Control Card, 152994). These settings determine the amount the correction extends into the comparator window (see above); optimally, a third to a half of the window width.

Varying Load Drive Phase Adjustment: A Phase Adjustment pot is provided on Control Card No. 4 (Vary Amplitude and Phase Inverter Card, 152995) by which the varying load drive voltage supplied to the electromagnetic shakers is placed in 90° phase relationship to the displacement or load cell signal. Phase relationship may be observed while making this adjustment by displaying the amplified load cell signal (Red Test Point on Card No. 5) and the varying load driver signal (Red Test Point on Card No. 4) on an oscilloscope using the x vs. y mode.

Varying Load Drive Loop Gain: Also on Control Card No. 4 is a pot labeled Loop Gain Adjust. This adjustment was used in early check-out tests of the machine, to limit response under unexpected vibrational modes. It is currently set for optimum servo-loop gain, to provide minimum error over the entire range of power requirements.

Temperature Control System Adjustments: On Control Card No. 2 (152993) a pot labeled Temp Set is provided for adjustment of the temperature regulation of the OFT. When the average temperature of the mechanical system falls below the set point, the heaters are turned on; when the temperature rises above the set point, heaters are off. Adjustment is made by placing the mechanical assembly in a stabilized environment at the desired regulation temperature with no other systems operative.

The regulation temperature is currently set at 80°F, in accordance with estimated requirements in space and calculated performance of the thermal control surface treatment. For best load cell accuracy, operation between 60°F and 100°F is desirable, although a much wider range would be permissible.

Also provided on Control Card 2 are various adjustments which permit calibration of the temperature measuring circuit.

Offset Balance Adjustments: Various adjustments are provided on Control Cards 2, 5, and 7, identified as Offset Adjust. These permit rebalancing the circuit in the event replacement of a major component is at some time necessary.

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