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HIGH CYCLE RANDOM FATIGUE TESTING

LOCKHEED-GEORGIA COMPANY
MARIETTA, GEORGIA

JULY 1975

TECHNICAL REPORT AFFDL-TR-76-50
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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

NOTICE

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

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19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*
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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Report discusses conceptual designs of automatic digitally controlled vibration fatigue test facilities for inducing high cycle random flexural fatigue of coupon specimens; recommends a facility for use at AFFDL; presents block diagrams and charts of major system components and subsystems. Report also describes random flexural fatigue tests conducted on aluminum and titanium riveted cantilever beam specimens with zero mean stress; presents data for 2024-T81 bare aluminum alloy at 75°F and 250°F, and for 6Al-4V annealed titanium alloy at 75°F and 600°F, for the range of 10^6 through 10^9 cycles to failure.

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PREFACE

This report was prepared by the Lockheed-Georgia Company, Marietta, Georgia, for the Air Force Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, under Contract F33615-75-C-3062. The work described herein is a continuing part of the Air Force Systems Command's exploratory development program to establish tolerance levels and design criteria for acoustic fatigue prevention in flight vehicles.

The work was directed under Project 1471, "Aero-Acoustic Problems in Air Force Flight Vehicles," and Task 147101, "Sonic Fatigue." Mr. Forrest A. Sandow (AFFDL/FBF) was the Project Engineer. The Lockheed Program Manager and principal investigator was Mr. Harold W. Bartel, assisted by Mr. Cecil W. Schneider who accomplished Phase II.

This report describes all work performed under this contract and is identified by Lockheed as LG74ER0121. Submittal of the technical report by the author in May 1976 completed the technical effort, which was begun in March 1975.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

I. INTRODUCTION AND SUMMARY

1. INTRODUCTION

Acoustically induced fatigue in aircraft structure is prevented from being a major problem only by the continued extension of state-of-the-art design data, principles, and practices. This sonic fatigue design information must be applied to structural arrangements and vehicle missions that differ with each new airplane. The incorporation of higher performance, longer life, and increased reliability into new airplanes requires that sonic fatigue design data and principles be continuously extended to the limits of usefulness. One area in which sonic fatigue design data is frequently extended beyond its valid range is in the application of S-N (stress versus cycles to failure) data to long-life design. This is of necessity since random loading, reversed bending, S-N data for values of N above 10^7 cycles is rare for any material, and virtually nonexistent for N above 10^9. Sonic fatigue designers frequently encounter the need for such data. For example, the skin-stiffener structures in some aircraft nacelle cowlings and partitions, fan ducts, tail pipes, and pylon trailing edges are exposed to random noise at high frequencies, at levels sufficient to cause damage during normal cruise. If such structure is resonant at 200 Hertz, and has a design service life of 30,000 hours at cruise, with a design scatter factor of 4 (reasonable for military hardware), it should be designed to 8.6×10^{10} cycles. Data to support the designer in this case simply do not exist. Similar predicaments occur in designs of thin-walled ducts which carry high velocity flow, and in thin lightweight structures exposed to pressure fluctuations in boundary layers. Future STOL and supersonic airplanes present the designer with the same problem of long-life design, with increasing regularity, involving larger areas of structure, and with the added complication of simultaneously superimposing widely varying temperatures and static stresses on the structure.

Continuing to design and build airplanes without the benefit of high cycle random fatigue data involves unjustifiable risk--structural failure, excessive maintenance, and increased down-time on the one hand, or excessive weight and reduced payload on the other. In either case, the result is unwarranted cost. Thus, the need for high cycle S-N data at, and beyond, the region of 10^9 cycles to failure is clear. Unfortunately, the difficulty of obtaining such data is equally clear. The method most commonly used to obtain random loading, reversed bending fatigue data is resonant excitation of coupon specimens on an electromagnetic shaker. These tests are generally conducted at frequencies below 200 Hz. Defining a point on an S-N curve at 10^9 cycles, using this method of test, requires about 8 months, testing 8 hours per day, 5 days per week. And this is for only a single material, temperature, mean stress, and joint configuration. The duration of a program covering a reasonable range of these variables would approach an engineer's career lifetime. Obtaining a data point for an S-N curve at 10^{10} cycles is beyond hope using such test methods--over 6 years for a single data point.

Obviously, more productive test capabilities are required for generating the high cycle random fatigue data so much in need. The program reported herein was aimed at both needs--development of a high cycle fatigue test system, and generation of high cycle random fatigue data. Substantive results were produced in both areas.

2. SUMMARY

A three-phase program of analytical, design, and experimental work was conducted to achieve the objectives of (1) defining and specifying a test system to be used for conducting high cycle random loading, reversed bending fatigue tests, and (2) obtaining high cycle (10^9 cycles) random loading S-N data for 2024-T81 aluminum alloy and 6Al-4V annealed titanium alloy at ambient and at elevated temperatures.

In the analytical studies of Phase I, methods for generating or exciting random stresses in test specimens were examined, along with methods of specimen mounting, load application, joint simulation, materials, and specimen design. The governing requirements for the fatigue test method were established, and a technique was derived for systematically ranking the various candidate methods of specimen excitation and the means of applying the excitation, specimen fixity, and specimen deformation. These studies resulted in the conclusion that conventional electromagnetic vibrators (shakers), base exciting multiple specimens at resonance was the preferred method for conducting high cycle, random reversed bending fatigue tests.

Phase II then proceeded with the formulation of design criteria, definition of functional requirements and interfaces, selection of suitable components, and preparation of system specifications. Two alternate test methods were carried through this conceptual design phase--one comprised of a single shaker with multiple specimens, the other comprised of multiple shakers with single or multiple specimens. The design ultimately recommended was an automatic digitally controlled vibration fatigue test facility, embodying five independent excitation subsystems, with a capability for continuous unattended operation.

Phases I and II served the first objective cited above. The second objective was served by Phase III, which ran concurrently.

Two sets of coupon type cantilever beam fatigue test specimens were designed, fabricated, and tested in Phase III. One set was 2024-T81 bare aluminum sheet riveted to a doubler of the same material. The other was 6Al-4V annealed titanium riveted to a doubler of the same material. The aluminum specimens were tested at 75°F and 250°F; the titanium at 75°F and 600°F. In both cases, high frequency (up to 950 Hz) resonance test techniques were employed, with multiple specimens (3 to 6 on a shaker), at flexural strain levels consistent with fatigue failure over the range of 10^6 to 10^9 cycles. This series of tests resulted in four S-N curves: aluminum at 75°F, aluminum at 250°F, titanium at 75°F, and titanium at 600°F; all for random loading, reversed bending, and zero mean stress.

II. PHASE I - ANALYTICAL STUDIES

A comparatively brief study was made to determine the preferred method for conducting reversed bending random fatigue tests. The fundamental criteria which governed the scope of the study, and in some cases limited the various test methods considered, were as follows:

- Accommodate coupon type specimens incorporating structural joints.
- Accommodate isotropic and anisotropic sheet, sandwich, or laminates.
- Accommodate any aerospace material, including aluminum, copper, hastelloy, inconel, magnesium, steel, titanium, plastics, glass/boron/graphite reinforced plastics, and hybrids of composites of plastics and metals.
- Apply flexural loading to specimens.
- Generate random amplitude strain in specimens, with normal amplitude distribution.
- Maintain constant specimen temperatures at up to 600°F.
- Simultaneously test up to 10 specimens.
- Obtain 10^9 or more strain reversals in a reasonable time; obtain failure in as few as 10^6 strain reversals, and as many as 10^9 strain reversals.

The first five of the aforementioned criteria eliminated the conventional fixed-frequency rotating beam or axial loading fatigue testing techniques from consideration, and limited the study to test methods involving forced resonant vibration. It should be noted that "test method" refers to the overall means for obtaining S-N data and consists of several elements, the principal elements being:

- Excitation - the technique or principle used to generate the random force.
- Force application - the manner in which the random force is imparted to the test specimens.
- Specimen fixity - the manner in which the specimen is held or supported.
- Specimen deformation - the mode or shape in which the specimen is forced to deform in order to induce strain.
- Specimen configuration - the manner in which the specimen simulates "real" structure and structural joints.

Each of these elements could have been a field for study. There are many candidates worth considering, and many combinations of candidates. Thus, a procedure was needed to systematically weigh the merits of each candidate so as to obtain an objective ranking of the candidates in order of preference. Upon selection of the most promising elements and combinations of elements (which became candidate test methods), the same procedure could be used to obtain a ranking of test methods in order of preference. Such a procedure was formulated, and consisted of the following steps:

1. Identify candidates for each test method element.

2. Identify selection factors which are important to the ranking process and relate to the fundamental criteria.

3. Assign a weighting value to each factor according to relative importance.

4. For each candidate (Step 1), assign a figure of merit (point value from 1 to 5) describing the quality of the candidates in relation to each of the selection factors; obtain the total points for each candidate.

5. Select the preferred test method elements and combinations of elements, from among the best candidate determined in Step 4.

6. Consider other factors or constraints not quantifiable, such as equipment/ facilities commonality, funding limitations, etc.

7. Repeat Step 4 for the candidate test methods determined in Step 5.

8. Select the recommended test method.

Of the many candidates identified in Step 1, the majority were eliminated by deduction or simple analysis in light of the fundamental criteria. Only the more promising were carried through the test method selection process. These were:

Excitation

- Direct electromagnetic excitation
    - Solenoid type (soft iron core surrounded by high-current windings) driving single specimens
    - Field proximity type (soft iron mass in proximity to high-current parallel conductors) driving single specimens
    - Voice coil type (permanent magnets with high-current conductors in air gap) driving single specimens

    - Rotor type (DC motor shaft oscillating through small angles at specimen resonance) driving single and multiple specimens
- Indirect electromagnetic excitation
    - Small shaker driving one specimen
    - Large shaker driving gangs of specimens
    - Resonant auxiliary beam driving single and multiple specimens
- Hydraulic shakers driving multiple specimens
- Acoustical Excitation
    - Grazing incidence in wave tube, using siren or electropneumatic transducer
    - Normal incidence in horn, using loudspeaker/driver, siren, or electropneumatic transducer

Force Application

- Node excitation at resonance
- Node excitation above resonance
- Antinode excitation at resonance
- Antinode excitation below resonance
- Antinode excitation above resonance

Specimen Fixity

- Clamped-clamped
- Clamped-hinged
- Clamped-free
- Hinged-hinged
- Hinged-free
- Free-free

Specimen Deformation

- Fundamental resonance mode shape--distributed load
- Fundamental resonance mode shape--concentrated load
- Second order resonance mode shape--distributed load
- Second order resonance mode shape--concentrated load

Specimen Configuration

- Specimen and complete segment of adjoining substructure
- Specimen and portion of adjoining substructure in contact with panel
- Specimen and portion of adjoining substructure imparting stress concentrations
- Specimen in permanent fixture simulating substructure.

In order to evaluate and compare the candidate elements, the factors that the candidate were to be graded against were defined, and assigned a weighting value that expressed their relative importance. These factors and their weighting values are shown in Figure 1.

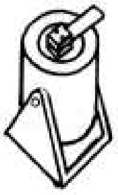
Each of the aforelisted candidate elements were then considered in light of these factors, and significant advantages and disadvantages were noted. Based upon these critiques, figures of merit were developed for each candidate. These figures of merit were numerical quantities between 1 and 5 (1 being poorest and 5 being best) which described the relative quality of each candidate in relation to the various selection factors. The products of figure of merit and weighting value, for each selection factor, were summed to obtain a total point count for each candidate. This total point count then indicated the preferred test method elements. This process is exemplified to some extent by the sample assessment of candidate excitation methods, shown in Figure 2. The preferred test method elements obtained in this fashion were next put together in various combinations to form complete test methods, and the entire process was repeated for these candidates.

Despite efforts to make these assessments objective, they remained somewhat subjective and open to argument, since some of the selection factors are not directly quantifiable. However, the objectives of Phase I and the intended use of the results did not warrant more in-depth quantifications or tradeoffs.

Following several iterations, three test methods were determined to be approximately equal and desirable, and are outlined below, along with some of the more noteworthy advantages and limitations.

WEIGHTING VALUE	FACTORS
3	Initial Cost - Initial cost to establish test method, including development cost, if any.
3	Test Cost - Average man-hours, electrical power, specimen costs, setup cost, etc. to run tests.
3	Test Time - Calendar time required to develop a complete S-N curve.
2	Reliability - Ability to complete tests and obtain all required data without malfunction, fatigue, wearout, etc.
2	Specimen Response - Ability to control or vary strain amplitude and peak distributions, strain level, spectrum width and frequency, and to duplicate actual strain distributions.
2	Versatility - Ability to accommodate variations in specimen design, including joints, materials, damping, stiffeners, size, etc.
1	Mean Stress - Conformance with need to apply mean bending or mean axial stress in specimen.
1	Maintenance - Man-hours, materials, spare parts, and replacements required to maintain tests.
1	Specimen Heating - Complexity imposed on system to apply heat and control temperature; conformance with preference to heat specimens to higher temperatures.

Figure 1. Test Method Selection Factors

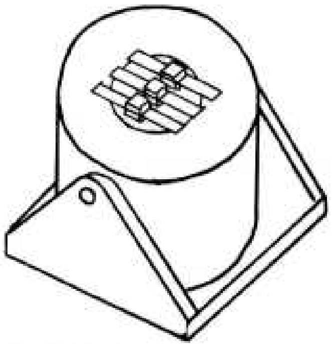


Indirect electromagnetic excitation; small shakers; single specimens at resonance.

Factors	M	W	P
Initial Cost	4	3	12
Test Cost	5	3	15
Test Time	4	3	12
Reliability	5	2	10
Specimen Resp	5	2	10
Versatility	5	2	10
Mean Stress	4	1	4
Maintenance	4	1	4
Specimen Htng	4	1	4
Total Points			81

Advantages: Provides individual control of specimen response; stable strain conditions throughout test. Avoids lost time; shakers can be kept "loaded." Relatively low power consumption; low initial cost. Versatile. Permits incremental buildup of test facility (building block approach). Low hazard level with unattended operation.

Disadvantages: Requires multiple controls; monitoring; safety; and peripheral equipment. Small shakers operating at max. capacity require frequent maintenance. Requires multiple heater systems. Strain gage, thermocouples and lead wires exposed to vibration. Shakers must be protected from heat.

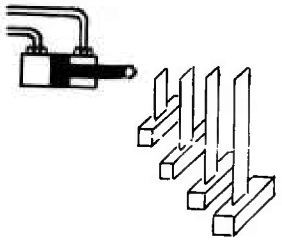


Indirect electromagnetic excitation; large shaker; gang testing at resonance.

Factors	M	W	P
Initial Cost	3	3	9
Test Cost	4	3	12
Test Time	4	3	12
Reliability	4	2	8
Specimen Resp	3	2	6
Versatility	5	2	10
Mean Stress	4	1	4
Maintenance	5	1	5
Specimen Htng	5	1	5
Total Points			71

Advantages: Provides larger quantity of data for each setup necessary. Ample exciter power available for occasional stiff or tough material.

Disadvantages: Difficult/cumbersome to run two strain levels simultaneously. No individual control of strain levels. Requires wider test spectrum band width (more shaker power) to encompass all resonances. Strain gages, thermocouples, and lead wires exposed to vibration. Shaker protection from heat required.



Direct hydraulic excitation; single or gang testing; below, at, or above resonance.

Factors	M	W	P
Initial Cost	1	3	3
Test Cost	2	3	6
Test Time	1	3	3
Reliability	3	2	6
Specimen Resp	3	2	6
Versatility	5	2	10
Mean Stress	5	1	5
Maintenance	3	1	3
Specimen Htng	4	1	4
Total Points			46

Advantages: Very powerful. Can accommodate virtually any specimen design and material combination. System can be designed to gang test large numbers of specimens simultaneously. Strain gages, thermocouples, lead wires, heaters, etc. are not exposed to vibration. Shaker system remote from specimen heaters.

Disadvantages: Exciter connections to specimens require frequent inspection and/or maintenance. Requires large hydraulic pump, and control valve capacities to achieve reasonable displacement at moderate frequencies. Cumbersome. Inefficient. Noisy. Limited to relatively low frequencies necessitating long test time. Requires system, and fixture development.

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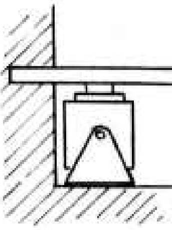
1. M = Merit figure; scale of 1 to 5; 5 being best.
2. W = Weighting; relative importance of factors
3. P = M x W; point allocation

Figure 2. Assessment of Specimen Excitation Candidates

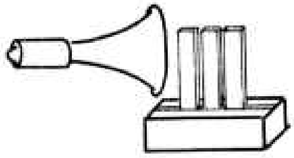


Indirect electromagnetic excitation at antinode, using resonant auxiliary beam; single or gang testing; at or above specimen resonance.

Factors	M[1]	W[2]	P[3]
Initial Cost	**1**	**3**	**3**
Test Cost	**3**	**3**	**9**
Test Time	**5**	**3**	**15**
Reliability	**3**	**2**	**6**
Specimen Resp	**5**	**2**	**10**
Versatility	**2**	**2**	**4**
Mean Stress	**5**	**1**	**5**
Maintenance	**3**	**1**	**3**
Specimen Htng	**5**	**1**	**5**
Total Points			**60**

Advantages: Only known practical way to drive specimens (above resonance) at very high frequencies. Reduces test time to shortest possible duration. Strain gages, thermocouples, and lead wires not exposed to vibration. Shaker system remote from specimen heaters.

Disadvantages: Very noisy. High "G" forces at area of auxiliary beam in contact with specimen, with potential for wear or excessive maintenance. Unproven; requires system development, and massive, rigid fixture. Cumbersome to adjust auxiliary beam resonance and specimen attachment to suit specimen variations.

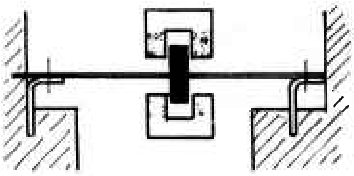


Acoustic excitation; normal or grazing incidence; single or gang testing at resonance.

Factors	M	W	P
Initial Cost	**4**	**3**	**12**
Test Cost	**1**	**3**	**3**
Test Time	**2**	**3**	**6**
Reliability	**2**	**2**	**4**
Specimen Resp	**2**	**2**	**4**
Versatility	**4**	**2**	**8**
Mean Stress	**5**	**1**	**5**
Maintenance	**2**	**1**	**2**
Specimen Htng	**5**	**1**	**5**
Total Points			**49**

Advantages: Good simulation of actual loading conditions. Strain gages, thermocouples, and lead wires not vibrated.

Disadvantages: Heater elements exposed to high level noise. System requires large quantity of air and special enclosure. Very inefficient. Extensive maintenance necessary; costly to operate on continuous basis. Limited to low frequencies due to specimen area necessary to obtain required strain levels. High strain levels difficult to obtain. Poor control of individual specimen strain.



Direct electromagnetic excitation; solenoid, voice coil, or plate type; single specimen testing at resonance.

Factors	M	W	P
Initial Cost	**2**	**3**	**6**
Test Cost	**5**	**3**	**15**
Test Time	**4**	**3**	**12**
Reliability	**5**	**2**	**10**
Specimen Resp	**5**	**2**	**10**
Versatility	**5**	**2**	**10**
Mean Stress	**5**	**1**	**5**
Maintenance	**5**	**1**	**5**
Specimen Htng	**4**	**1**	**4**
Total Points			**77**

Advantages: Provides individual control of specimen response, stable strain conditions throughout test; low power consumption. Versatile. Permits incremental buildup of test capability. Relatively low exciter system cost, once developed. Minimum hazards with unattended operation. Strain gages, thermocouples, and lead wires not vibrated.

Disadvantages: Requires multiple controls; monitoring; safety; and peripheral equipment. Requires multiple heater system. Exciters exposed to heat; with potential need for cooling, or frequent replacement. Exciter mass reduces frequency. Unproven for random excitation of fixed-fixed beam specimens; requires initial system development.

1. M = Merit figure; scale of 1 to 5; 5 being best.
2. W = Weighting; relative importance of factors
3. P = M x W; point allocation

Figure 2. (Cont.) Assessment of Specimen Excitation Candidates

A. Direct electromagnetic excitation, with one exciter per specimen applying force at the antinode of a resonant beam specimen having a concentrated load at the antinode, utilizing clamped-clamped specimens when mean bending or axial stress is applied, and clamped-free specimens when no mean stress is required.

Restrictions - Requires considerable development time and cost, which must precede system acquisition. High operation work load during test startup.

Advantages - Once the electromagnetic exciter is developed, acquisition and installation of the test system can be funded incrementally. Only those exciters in use need be operated, reducing operating costs for tests involving only a few specimens. Low procurement and operating cost.

B. Indirect electromagnetic excitation, with one small shaker per specimen applying force at the node of a resonant beam specimen having distributed load; utilizing clamped-clamped specimens when mean bending or axial stress is applied and clamped-free specimens when no mean stress is required.

Restrictions - High operation work load during test startup. High initial cost.

Advantages - Acquisition and installation of the test system can be funded incrementally, with only one or two amplifier/shaker subsystems procured each year. Only those shakers in use need be operated, reducing operating costs for tests involving only a few specimens. Good test flexibility and versatility; mean stress and temperature can be accurately controlled for each individual specimen.

C. Indirect electromagnetic excitation, with one large shaker exciting a group of specimens at resonance and applying force at the node of beam specimens having distributed load; utilizing clamped-clamped specimens.

Restrictions - Requires large one-time funding of system. Entire system must be operating even if only one specimen is tested. Requires large, massive test fixture. Very little flexibility in test specimen stress or temperature variation between the multiple specimens during a given test.

Advantages - Operator work load small once test is set up. Requires minimum floor space of all systems considered. Lowest procurement cost for 10 specimen capability.

To aid in final selection of a single test method from the three preceding alternatives, several assumptions were made to supplement the fundamental criteria cited at the outset:

o Hardware development can be conducted, but development costs (if incurred) must be included in the initial cost. Equipment installation expense must also be included in the initial cost.

- No schedule restrictions imposed. Time to put test method into operation is not a factor in the test method selection process.
- No funding increment restrictions imposed.
- Specimen excitation equipment must be sized to accommodate application of a mean axial or bending load, concurrent with flexural loading.
- Specimen excitation equipment must be sized to the most severe test case (stiffest specimen, strongest material, highest strain, heaviest fixture).
- Overall test system considerations will be handled independently and will not be taken into account in test method selection. This includes control system cost, floor space requirements, etc.

After due consideration of all criteria, factors, assumptions, and technical and financial risks, it was concluded that the second of the three alternative methods was preferable. It is recognized that some of the advantages of the multiple shaker test method may be offset when the associated control system and peripheral equipment are considered. Hence, the next subordinate selection, the single shaker "gang" test method, was also carried through the Phase II test system design studies.

III. PHASE II - TEST SYSTEM DEFINITION

The conceptual design of an automated random fatigue test facility to be installed at the Air Force Flight Dynamics Laboratory was the primary objective of this phase. The test facility will be used to conduct random loading flexural fatigue tests in the low-amplitude, high-cycle range (up to 10^9 cycles), as well as in the high-amplitude, low-cycle range, at temperatures up to 600°F.

Phase I, discussed previously, defined the test methods and shaker/amplifier size requirements. This data was used during Phase II to define the system functional requirements and specifications. Detailed component and interface design was not attempted since it was beyond the scope of this effort.

This section presents the results of the Phase II effort in which design criteria and functional requirements for the system were formulated. Both single and multiple shaker systems were included in the design study, and functional requirements are presented for alternative test facilities comprised of one, five and ten shaker systems. A single facility design consisting of five shaker/amplifier systems controlled by a single spectrum shaping system is ultimately recommended.

1. DESIGN GOALS

The test facility will be used to conduct random loading fatigue tests of coupon specimens at up to 10^9 cycles of stress reversal. The facility shall also be capable of conducting high-amplitude/low-life fatigue tests. Provisions will be provided to apply mean stress and/or heat to each specimen. Design goals include:

- Automatic operation - The facility shall operate automatically, without an attendant, 24 hours per day.
- Multiple specimens - The facility shall be capable of testing up to 10 coupon specimens simultaneously.
- Mean stress - The test fixture shall provide an optional capability of applying a mean stress to the specimen.
- Heating - The facility shall provide the capability of heating the test specimens to 600°F for elevated temperature fatigue tests.

2. GENERAL SYSTEM CRITERIA

The test facility design will be governed by the following general criteria:

Availability

- The test facility design shall be based on use of existing off-the-shelf equipment to fulfill the system design objectives. No hardware design or redesign shall be considered.

- Alternative methods or instruments shall be employed when existing equipment is not available to accomplish a specific function.

- Whenever possible, existing software shall be used for component functions involving a digital computer. Software development and programming shall be minimized, particularly software development by the computer manufacturer.

Automation

- The test facility shall be designed for automatic operation, unattended, on a 24 hour/day basis when conducting either ambient or elevated temperature fatigue tests. A safety monitor may be required to be present during elevated temperature fatigue testing because of potential fire hazards; however, the safety monitor shall not have an active role in the test conduction unless an emergency arises.

- The control system shall be designed to provide semi-automatic startup of the test system for initiation and setup of a specific test. All subsequent restarts of the system for the same test shall be completely automatic.

- The control system shall be designed to provide automatic shutdown of the shaker system at the end of a predetermined test time, in the event of specimen failure, in the event of component malfunction or line power failure, and upon operator initiated emergency shutdown command.

- The control system shall record all test data at predetermined intervals. These data will be later recalled and additional computations performed.

- Adequate safeguards shall be incorporated into the control and monitor subsystems to prevent damage to the specimen or to the test equipment.

- The control system shall provide automatic output of all significant data to retrievable storage in the event of line power failure.

Safety

- The test facility shall incorporate safety features to minimize the probability of damage to test specimens or test equipment.

- Adequate safeguards shall be incorporated into the high power and high temperature components and around moving surfaces to prevent electrical shock, burns or other harm to test personnel. All high voltage areas shall be interlocked with the system control or locked to prevent entry.

- The system control shall continually monitor operating parameters and switch closures (events) of critical components in the facility. Out-of-bound operating parameters and event indications shall interrupt the system operation and initiate controlled shutdown of the facility. Appropriate failure diagnostic messages shall be printed out for the test operator.

- A master shutoff switch shall be provided on the control console to enable the test operator or safety monitor to initiate emergency shutdown of the test system. This action shall not affect the operation of the control computer, but will be limited to the excitation and heating subsystems.

- The shakers and power amplifiers shall be enclosed in a separate, soundproof room to prevent test personnel exposure to excessive noise.

- The system shall conform to the applicable safety standards of Air Force Regulation 127-101.

Cost

- System procurement costs shall be minimized by selection of existing proven equipment components. No hardware design or redesign will be considered.

- Software development shall be minimized to reduce costs of special purpose computer programs.

- System operating costs shall be considered in the design and, where appropriate, a tradeoff of operating vs. initial costs shall be made to optimize the overall facility costs.

- Individual hardware components shall incorporate on/off switches so that unused equipment can be turned off to conserve power and extend life.

System Integrity

- All major hardware components of the control and analysis subsystems shall be obtained from the same source to minimize interface problems.

- Digital computer programs shall be protected against inadvertent or unauthorized program modification while the system is in operation.

Heating

- The test facility shall include provisions for heating the test specimens to elevated temperatures during fatigue testing. An insulated thermal enclosure shall be provided around the specimens and fixtures to maintain uniform air temperatures around the specimen.
- The temperature controller shall be capable of maintaining uniform specimen temperatures, constant in time.
- The test fixture shall include cooling provisions to keep heat transfer in the shaker head within the temperature capability of the shaker.
- The heating fixtures and thermal enclosure shall be readily removable to provide open access to the test specimen.
- The cooling baseplate shall be removable to reduce the mass in motion during ambient temperature, high strain amplitude tests.

Specimen Flexibility

- The test system shall be capable of testing as many as 10 individual specimens simultaneously.
- Clamped-free (cantilever) beam specimens shall be the principal type of test specimen to be fatigue tested. The test fixture shall simulate the desired boundary condition while retaining the capability of simulating other boundary conditions, such as a dual cantilever beam, or an end-supported beam.
- The test fixture shall include provisions to simulate clamped-clamped boundary conditions, with or without an applied mean stress. The mean stress fixture shall be removable to reduce the mass in motion during high strain amplitude tests not requiring mean stress applications.

Maintenance

- The test facility shall utilize hardware from a single contractor to the maximum extent possible to simplify spares provisioning and maintenance.
- When multiple equipment items are required to perform the same function, all items shall be the same model.
- Solid-state hardware shall be used in all systems to increase life and reliability, to reduce cooling requirements, and to reduce power consumption.

- Useful life of the control and analysis subsystems shall be five years. Useful life of the excitation equipment shall be 10 years.

Expandability

- The test facility shall be designed so that future changes or additions can be made to the system without major rework to the existing components.

3. FUNCTIONAL REQUIREMENTS

There are obviously many different approaches toward attaining automatic operation of the test facility. It is possible to generate and shape the random amplitude input to the shaker using analog instrumentation; this has been the only method available until recent years. However, it is now possible to accomplish most, if not all, of the functions necessary for random vibration test control using digital equipment. This concept offers increased accuracy, reliability and versatility at reduced costs over the comparable analog systems. Based on an initial investigation of analog versus digital techniques, it was decided to use digital equipment to the maximum possible extent to take full advantage of the latest technology and increase the useful life of the test facility.

A conceptual diagram of a test facility based on digital electronics is shown in Figure 3. Control and data analysis functions are accomplished by dual digital minicomputers, coupled together for control and data transfer. This diagram depicts the major functional areas as well as the signal flow-paths.

Control Subsystem

The control subsystem will provide overall test control and sequencing, monitoring of critical system safety parameters, and control of data processing during all test operations. During attended operation, the test operator will have over-ride ability over the control subsystem via a keyboard or emergency shutoff switch. During unattended operation, the keyboard will be locked out of the system to prevent unauthorized or accidental alteration of the test.

The control system will provide semi-automatic startup of the test facility, through the operator/controller interface, to initiate a test. This may be accomplished by interactive controller/operator questions and answers. This startup mode will be used at the beginning of a particular test to define the required test parameters. A second, automatic startup mode will also be available for restart of a test after interim shutdowns. In this mode, the controller will automatically recall from memory all initially determined test parameters and restart the test upon operator command. Likewise, the controller will provide an automatic shutdown capability upon completion of the test or in response to any abort situation, whether controller or operator initiated.

The controller will monitor all data and safety parameters, and record data at preselected intervals. The recorded data will be output to appropriate peripheral devices

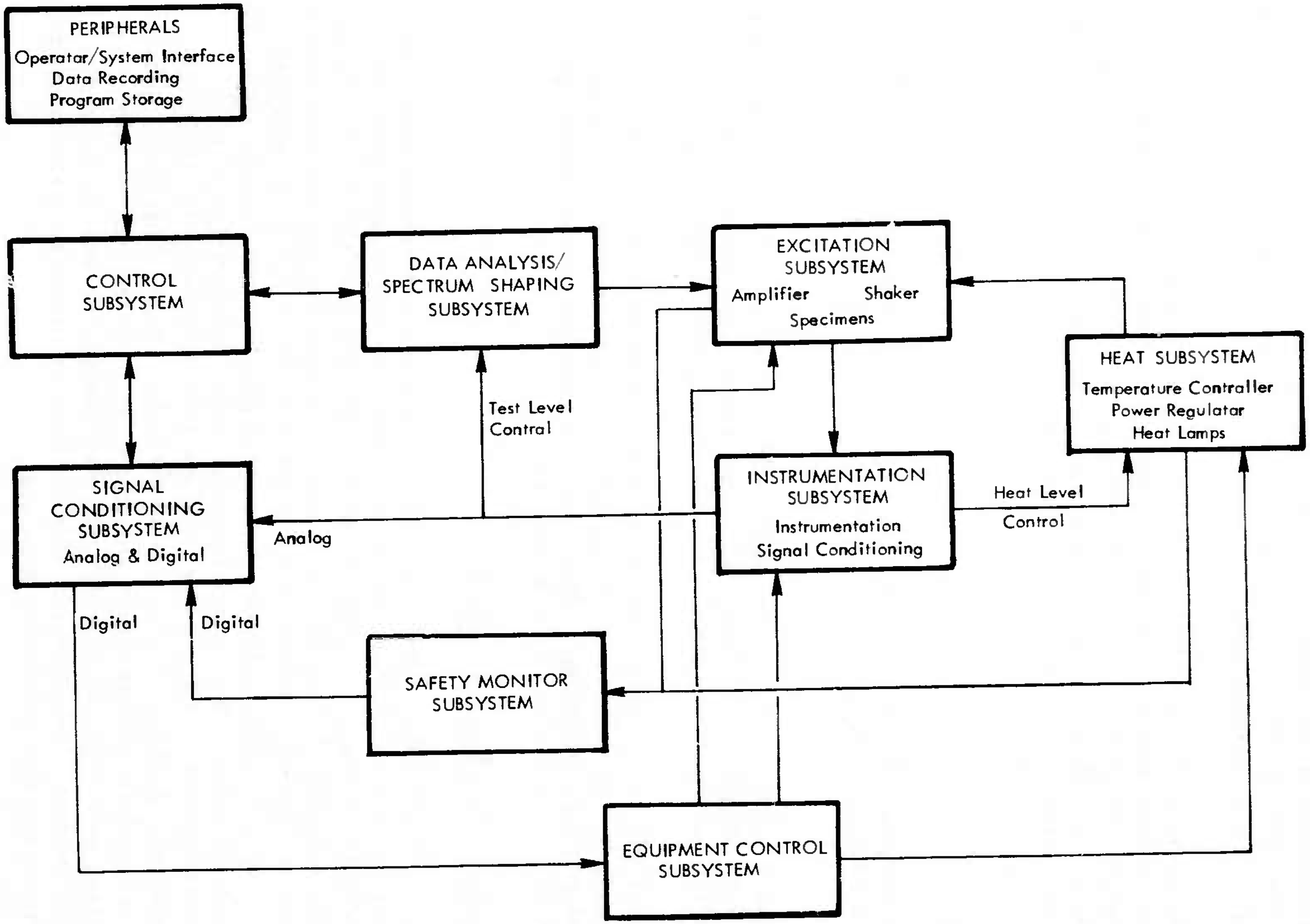


Figure 3. Functional Diagram of Test System

for permanent record or later data analysis. The controller will output all vital data to retrievable storage in the event of line power failure to prevent loss of information. This data transfer will occur simultaneously with shutdown of the test system. The controller will provide a restart capability to resume testing from an interim shutdown situation; this restart capability is to be initiated only by the test operator, and will then be automatic, as discussed previously.

The control computer interface will have sufficient capacity to operate with a variety of input/output devices, some of which may be added after initial system installation. The control computer will communicate with the test operator via a high-level language, such as Fortran. In addition to space requirements for the input/output device, interface software, data monitoring and recording, extra storage space will be required for user generated programs to analyze the data.

Peripherals

The control computer will interface with a variety of input/output devices. The primary means of operator communication with the computer will be via a teletype or CRT terminal.

The computer interface will also be compatible with other peripherals to store and input programs, to run program verification, and to store and/or output test data. The computer interface will be capable of accepting future peripheral additions without modification.

All peripherals will be compatible with the control computer software and will include all software required for operation of the peripheral. Control computer peripherals to be included are cartridge disc storage, magnetic tape storage, X-Y plotter, paper tape reader, and analog and digital signal conditioning.

Data Analysis/Spectrum Shaping Subsystem

This subsystem will provide data analysis, signal generation and spectrum shaping capability. Sinusoidal and random signal generation capabilities will be provided in the computer software package. Sinusoidal signal generation and amplitude control may be alternatively accomplished via analog equipment. Shaping of the input spectrum will be accomplished for finite-width frequency bands, not wider than 5 Hz, by acceleration feedback control of the band amplitude. Existing computer software packages are available to accomplish both sine and random signal generation and control of level(1). These packages typically use Fast Fourier Transform (FFT) and Inverse FFT (IFFT) techniques to generate a drive signal correction for the shaker. Figure 4 depicts a typical spectrum shaping scheme used for digital vibration control. A detailed discussion is not included herein, since there are several off-the-shelf systems available to accomplish the necessary functions. The papers presented in Reference 1 provide a good source for signal generation and spectrum shaping techniques.

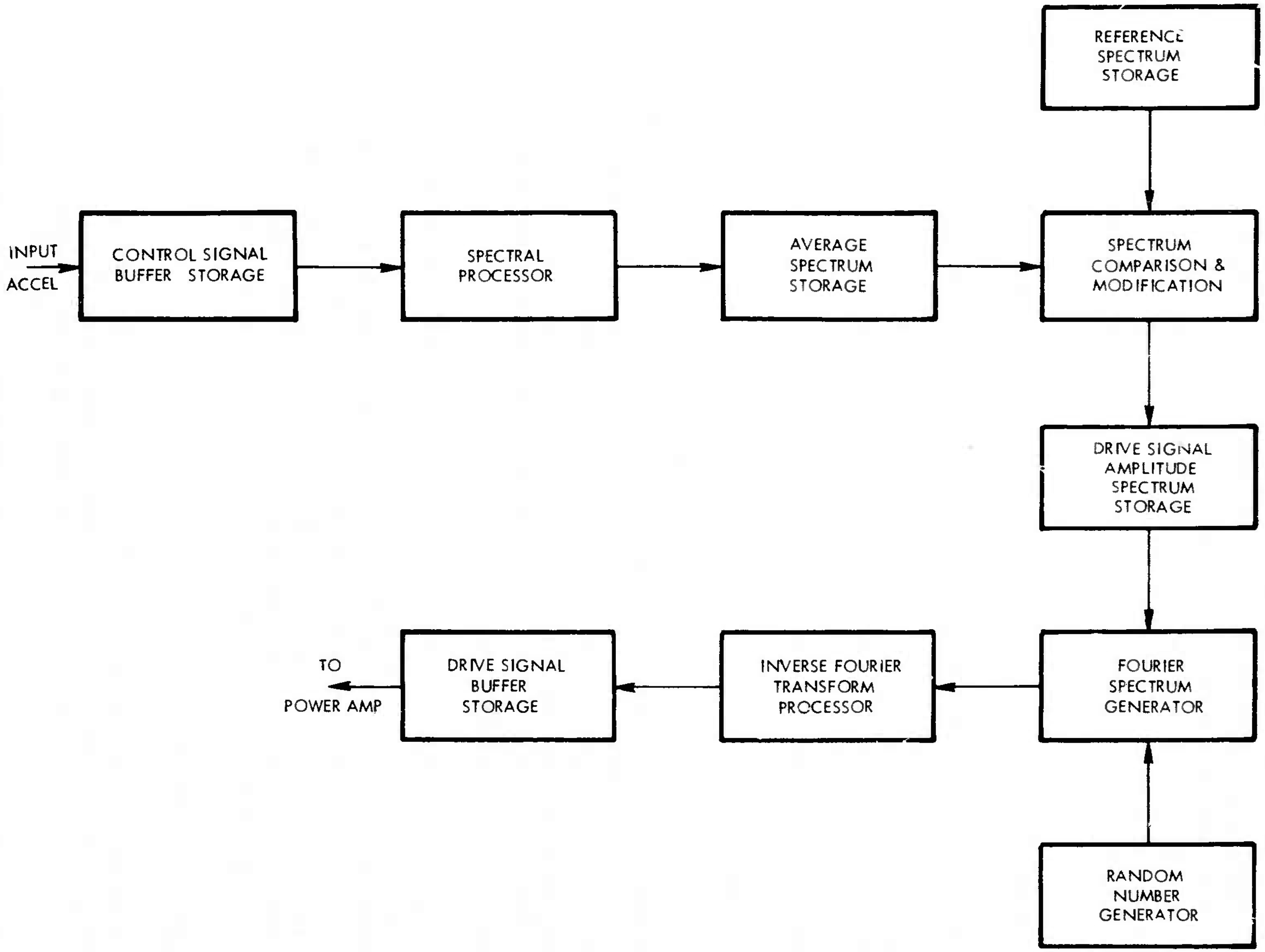


Figure 4. Typical Digital Signal Generation and Spectrum Shaping

Narrow-band random excitation with Gaussian amplitude distribution will be used to control the test level. The input signal will be controlled to the desired mean test level between the lower and upper frequency cutoff points, as illustrated in Figure 5. Excitation band levels which exceed variable alarm limits will trigger a warning to the test controller, and the condition will be recorded. Excitation band levels which exceed the alarm limits by a certain increment for an excessive time interval will cause the controller to shut down the excitation system due to excessive input. Loss of the input signal will also cause the control computer to shut the excitation system down.

If multiple shakers are used in the excitation subsystem, the data analysis subsystem software will provide time sharing of the data analysis and spectrum shaping capabilities to permit use of a single data processor. The input to each shaker subsystem will be a continuous signal, updated periodically via the acceleration feedback/spectrum shaping loop. Figure 6 illustrates a possible control loop timing scheme to meet spectrum shaping and data analysis requirements for a multi-shaker system. This scheme requires that each Digital-to-Analog Converter (DAC) have a memory for storage of the output signal between signal update cycles.

Excitation Subsystem

The excitation subsystem will consist of the power amplifiers, shakers, test fixtures, and test specimens. The number of each will depend on the selected system design. The power amplifier/shaker combination will be compatible in power-force capabilities and will be interconnected for protective features such as shaker overtravel, armature overtermperature or overcurrent, etc. The power amplifier will be solid-state to increase reliability and life, reduce cooling requirements, reduce maintenance and minimize floor space requirements.

The test fixture will mount directly to the shaker head and will include provisions for water cooling to prevent excessive heat flow into the shaker head during elevated temperature fatigue tests. The test fixture will also include provisions for applying a mean stress to the test specimen--either an axial load or bending moment. Fixtures and lamp reflectors will be designed to support the heat lamps; a thermal enclosure will be designed to maintain a uniform thermal environment. Detailed design of these fixtures will be accomplished after selection of the shaker system concept.

Instrumentation Subsystem

The instrumentation subsystem includes all transducers and transducer signal conditioning instrumentation. This includes strain gages and strain gage signal conditioners and amplifiers, accelerometers and accelerometer charge amplifiers, and thermocouples.

The transducer signals will be connected to the test control computer, the data analysis computer and to the heat controller. Both static and dynamic strain instrumentation, ten channels of each, will be required to measure thermal or mean stresses concurrent

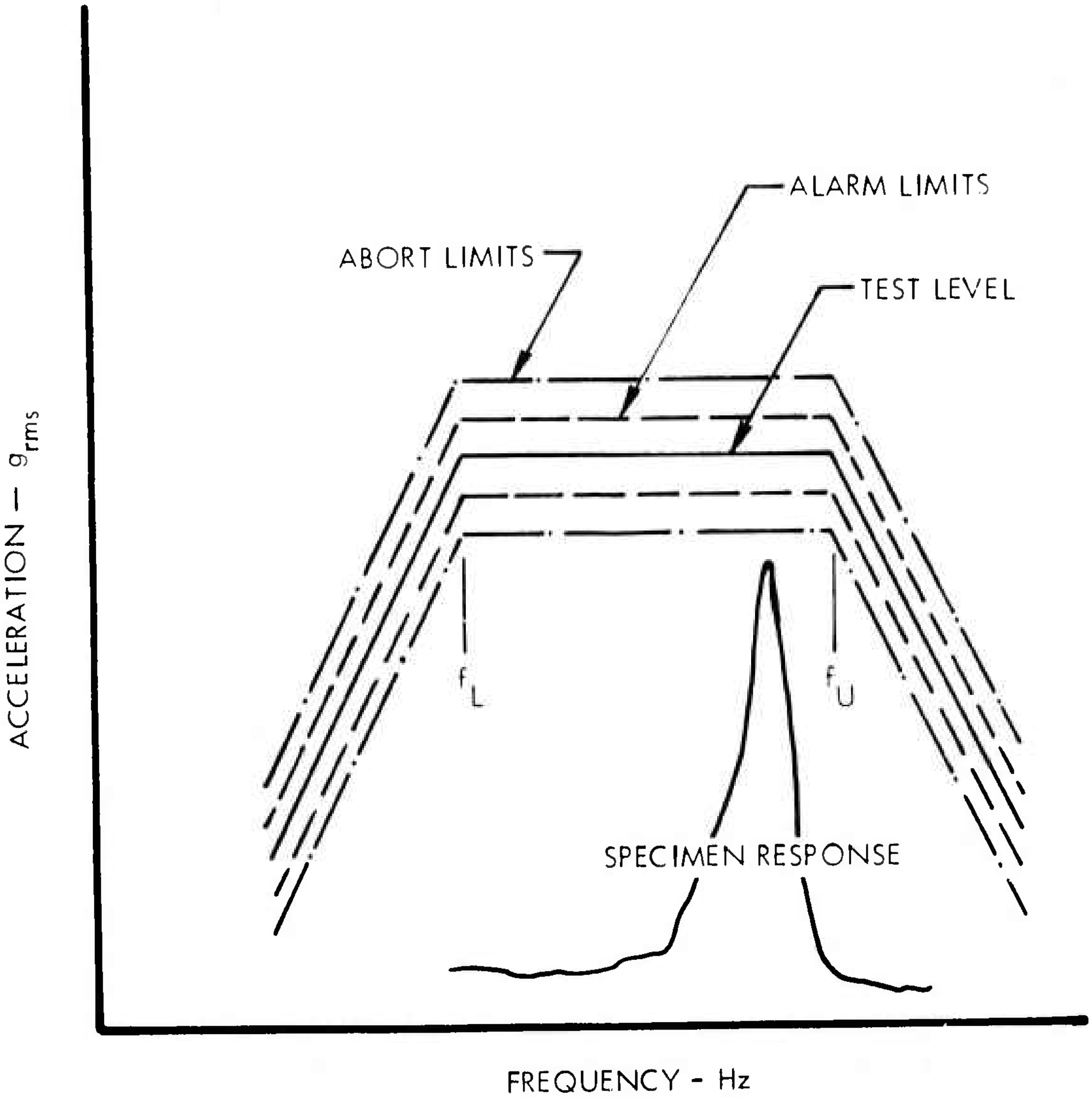


Figure 5. Typical Excitation Spectrum, With Alarm And Abort Limits

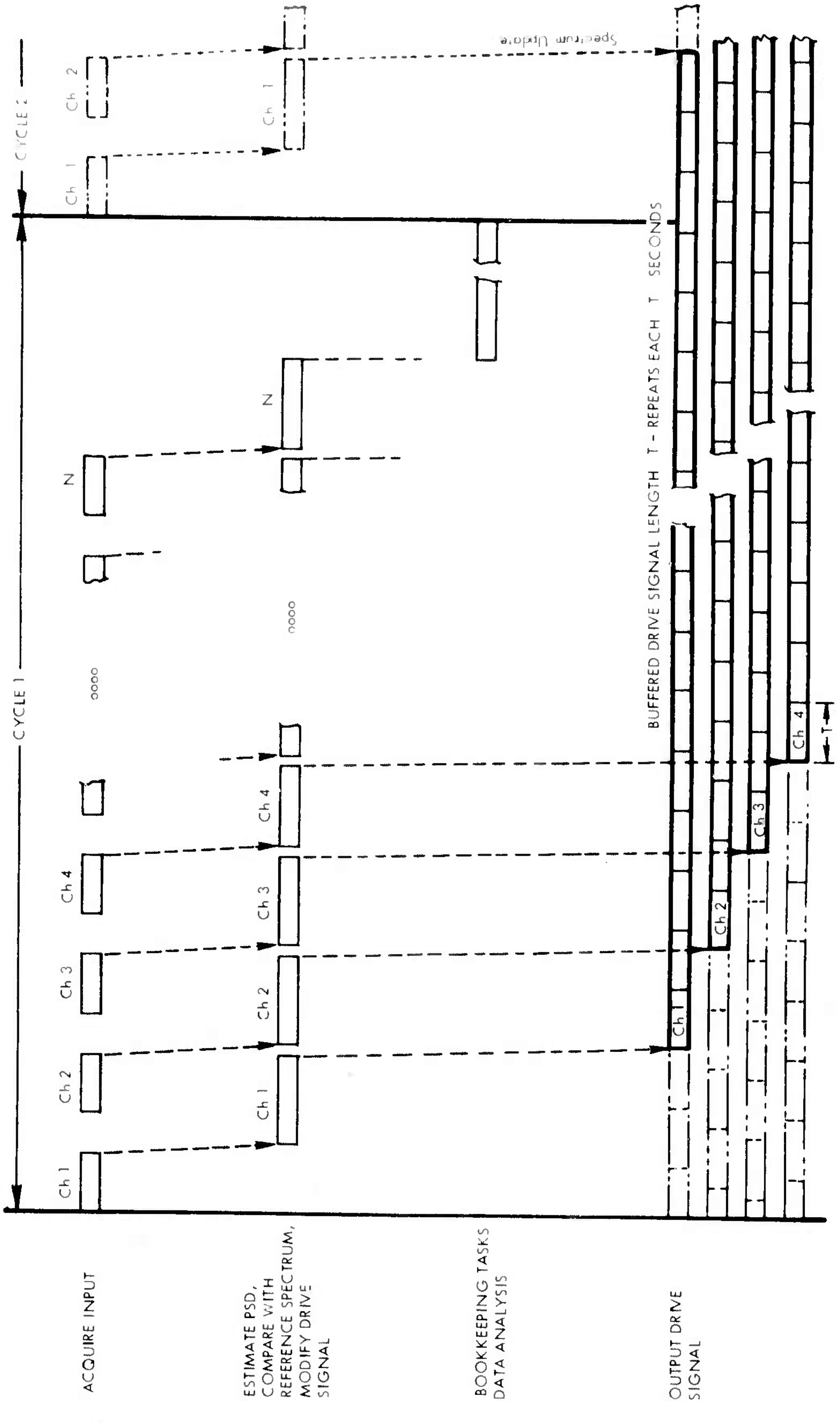


Figure 6. Control Loop Timing Scheme For Multiple Shaker System

with vibratory stresses. From one to ten channels of acceleration instrumentation will be required--dependent on the selected system concept. Ten channels of temperature measurement transducers will be required, consisting of foil thermocouples. The remainder of the temperature measurement/control instrumentation is included in the heat subsystem, since this is an existing system at AFFDL.

Heat Subsystem

This subsystem includes automatic temperature controls and power regulators for ten channels of temperature regulation. An existing AFFDL 10-channel temperature control system will be used for this function. Heat lamp fixtures will be designed, or selected from commercially available fixtures, to provide uniform heating of the specimen, particularly in the specimen attachment region.

The heat controller will provide a separate temperature signal to the test control computer for test documentation.

Signal Conditioning Subsystem

An Input/Output (I/O) signal conditioning subsystem will be used to provide data multiplexing prior to input into the control computer. Two basic types of input signals will be used--analog data from accelerometers, strain gages, etc., and digital signals from switch closures. All analog data will be converted to digital format, with at least 12 bit resolution, by an Analog-to-Digital Converter (ADC). All data channels will be matched to the input signal level. Digital inputs (switch closures) shall be monitored by the subsystem and input into the control computer only when an event, or switch closure, occurs. These digital event sense channels are part of the safety monitor system and will cause the controller to initiate action as dictated by the event priority.

Equipment Control Subsystem

This subsystem will provide on/off control for the excitation and heat subsystems. Digital signals from the I/O subsystem, initiated by the control computer, will activate remote relays to start or shut down the proper system. Provisions will be included for all power amplifier functions (including the amplifier gain) required to start or stop the shaker as well as on/off control of the heat system controller and power regulator. Remote calibration and zero of the strain gages is provided under this subsystem via relays in the signal conditioning package.

Remote on/off control of other instrumentation can also be provided, if desired, to facilitate removal of unused components from on-line status to reduce power consumption. However, it is doubtful that the extra hardware and software complexity is justified, since these instruments can be turned off manually.

Safety Monitor Subsystem

This subsystem will include all instrumentation necessary to monitor performance and operation of the entire test facility. All high power and high temperature equipment will be continuously monitored by the signal conditioning subsystem and the control computer. Doors of the high power and temperature equipment will be interlocked with the power amplifier and the test controller to automatically shut down the system in the event of accidental or unauthorized opening.

4. FACILITY DESIGN

The preceding functional requirements are generally applicable regardless of the number of shakers involved. In conformance with the Phase I results, two alternative system concepts were used throughout the Phase II study. These were a single shaker gang testing concept and a multi-shaker, single specimen concept. During this phase, a tradeoff was made of shaker/power amplifier cost versus number of shaker systems. The results of this study, shown in Figure 7, reveal the single shaker system to be the least expensive, while a 10 shaker system is the most expensive. A multi-shaker system employing only five shakers proves to be an attractive tradeoff from a cost standpoint as well as versatility, floor space required, power and cooling required, and operator work load.

The last item, operator work load, was found to be an important consideration during the Phase III fatigue testing. Two shaker systems were used to conduct room and elevated temperature fatigue tests, using equipment and test techniques similar to those envisioned for the AFFDL facility. Operator work load during the daily startup sequence (for a continuing test) was high, with many different steps to be followed to start the system and reestablish the proper test level. While the Lockheed system is manual, the observation will still be valid, although to a lesser degree, for an automatic control system with multiple shakers. Therefore, it is advantageous to minimize the number of shaker systems while retaining the versatility of multiple shaker systems--the five shaker system is nearly optimum in this respect.

The operator work load aspect also points out the need for completely automatic restart procedures following an interim shutdown. This has been incorporated into the functional requirements as discussed previously.

This facility design section is divided into separate sections to discuss each of the above three concepts. These facility designs are generalized and are intended to establish the operational characteristics for each function. Specific manufacturer equipment was studied to assure the feasibility of each design concept; however, these data are not included in this report.

NO. SHAKERS & AMPLIFIERS	NO. SPECIMENS PER SHAKER	TOTAL SPECIMENS	SHAKER FORCE lb-sine	RELATIVE COST SHAKER/AMP	
				UNIT COST	TOTAL COST
1	10	10	15,500	1.00	1.00
2	5	10	9,000	0.76	1.51
3	4	12	8,000	0.65	1.96
4	3	12	5,500	0.44	1.74
5	2	10	4,000	0.28	1.41
10	1	10	2,000	0.24	2.44

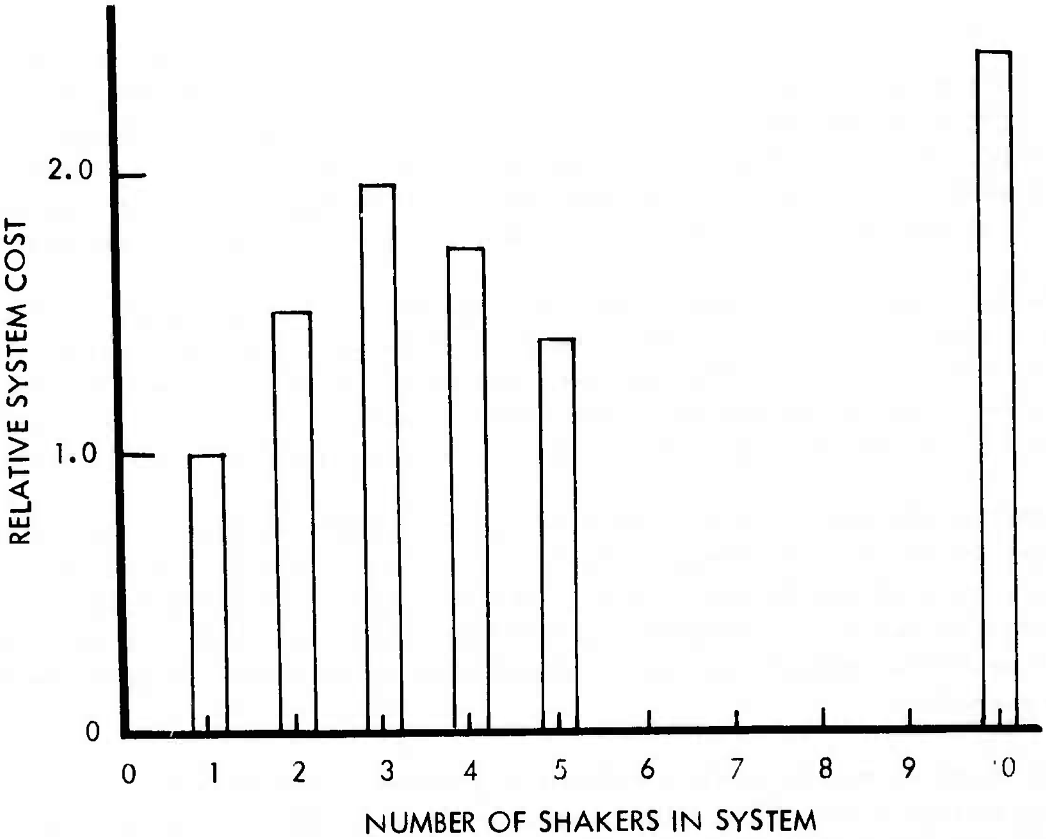


Figure 7. Power Amplifier/Shaker Quantity And Cost Tradeoff

Single Shaker Test Facility

A single shaker facility for gang testing up to 10 test specimens is shown in the functional diagrams of Figures 8 and 9. The system is built around two minicomputers, each with a minimum 32 K memory size. The computers are interfaced together to allow control and data exchanges by direct memory access, thereby permitting use of a single operator terminal. The hardware items shown on these figures perform all of the functional requirements depicted in Figure 3. The control computer operates as a real time executive to provide overall test control and data analysis functions. All data will flow through the control computer.

The primary computer control is a CRT terminal, coupled to a hard copy unit to obtain a permanent record. A teletype can be used to perform I/O functions; however, due to the high usage, a heavy duty teletype terminal would be required--this would be only marginally cheaper than the CRT/copier combination. The CRT is capable of providing a graphic display (X-Y plot) of the data as well as the program and command excitation. Plots can be obtained in a fraction of the time required for the X-Y plotter. These plots are normally adequate for working data--an X-Y plotter is also included for report quality plots, generally only a small percentage of the total number of plots generated during a test.

In addition to test and data control, the control computer will monitor the facility operations via analog and digital inputs from the various components. Analog signals from strain gages, accelerometers, and thermocouples will be converted to digital format in the ADC. The ADC will provide at least 12-bit resolution and will have a minimum of 30 channels, plus spares. The ADC electronics will be required to be compatible with the signal level from the transducers, which will likely be in the millivolt range.

Switch closures, such as shaker overtravel, amplifier door interlocks, etc. will be input to the computer via the digital I/O subsystem. Event sense electronics will be used to minimize the work load on the computer. The digital I/O subsystem will monitor the switches and provide an interrupt signal to the computer upon closure of a switch. The computer can then take appropriate action to correct the problem or terminate the test.

A cartridge disc memory, with a minimum of 2.5 megawords storage, is used for program storage and interim data storage. On short duration tests, the disc can be used as the primary means of data storage. For long duration tests, the data will be stored on digital magnetic tape at 800 characters per inch (cpi) density to reduce tape consumption. The tape can be replayed into the control computer or into another computer for later data analysis.

A high speed paper tape reader is utilized for program loading and program verification. The paper tape reader will be interchangeable with the analysis computer to permit loading and checkout of programs on that computer.

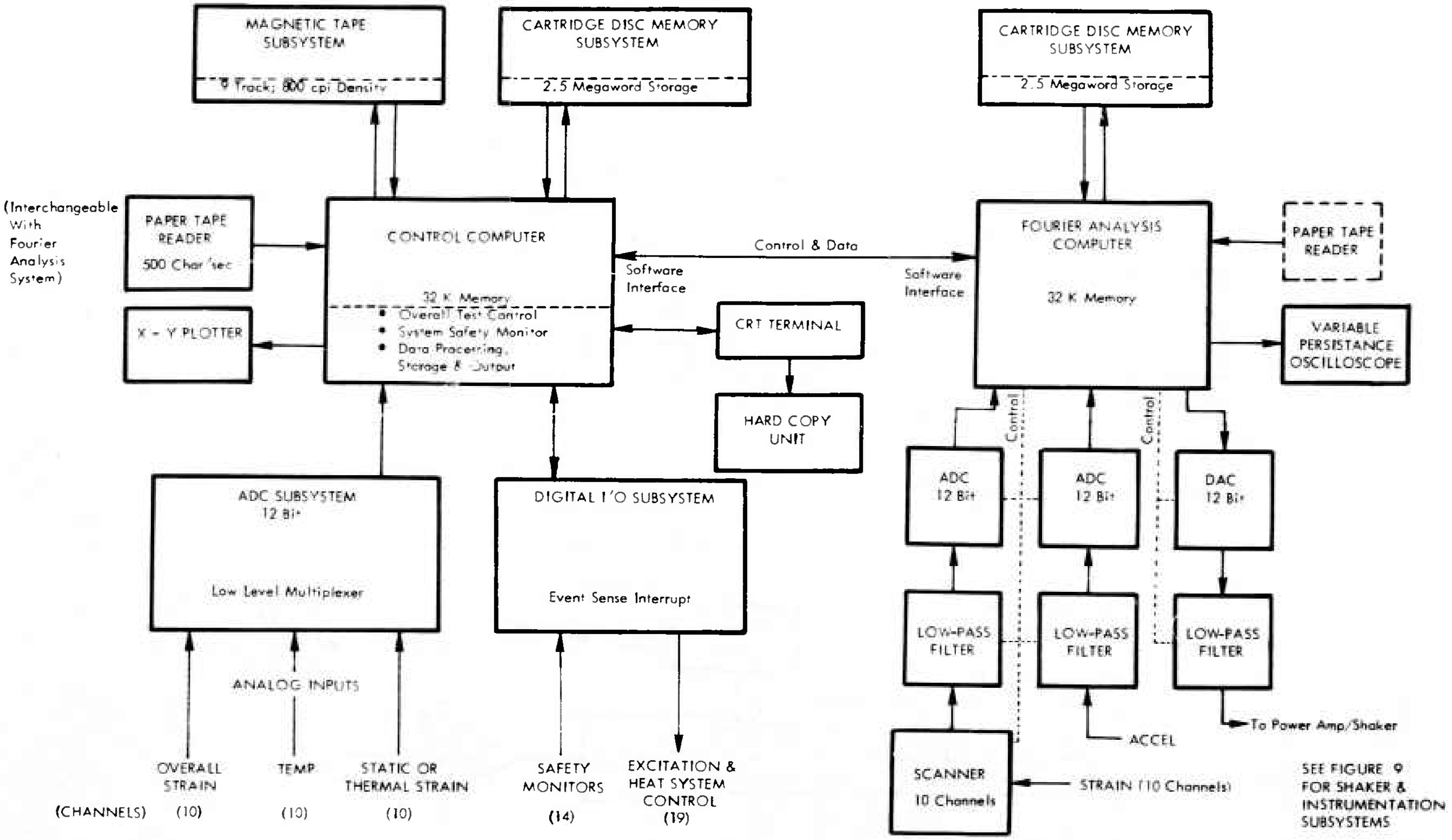


Figure 8. Single Shaker Test Facility Control System

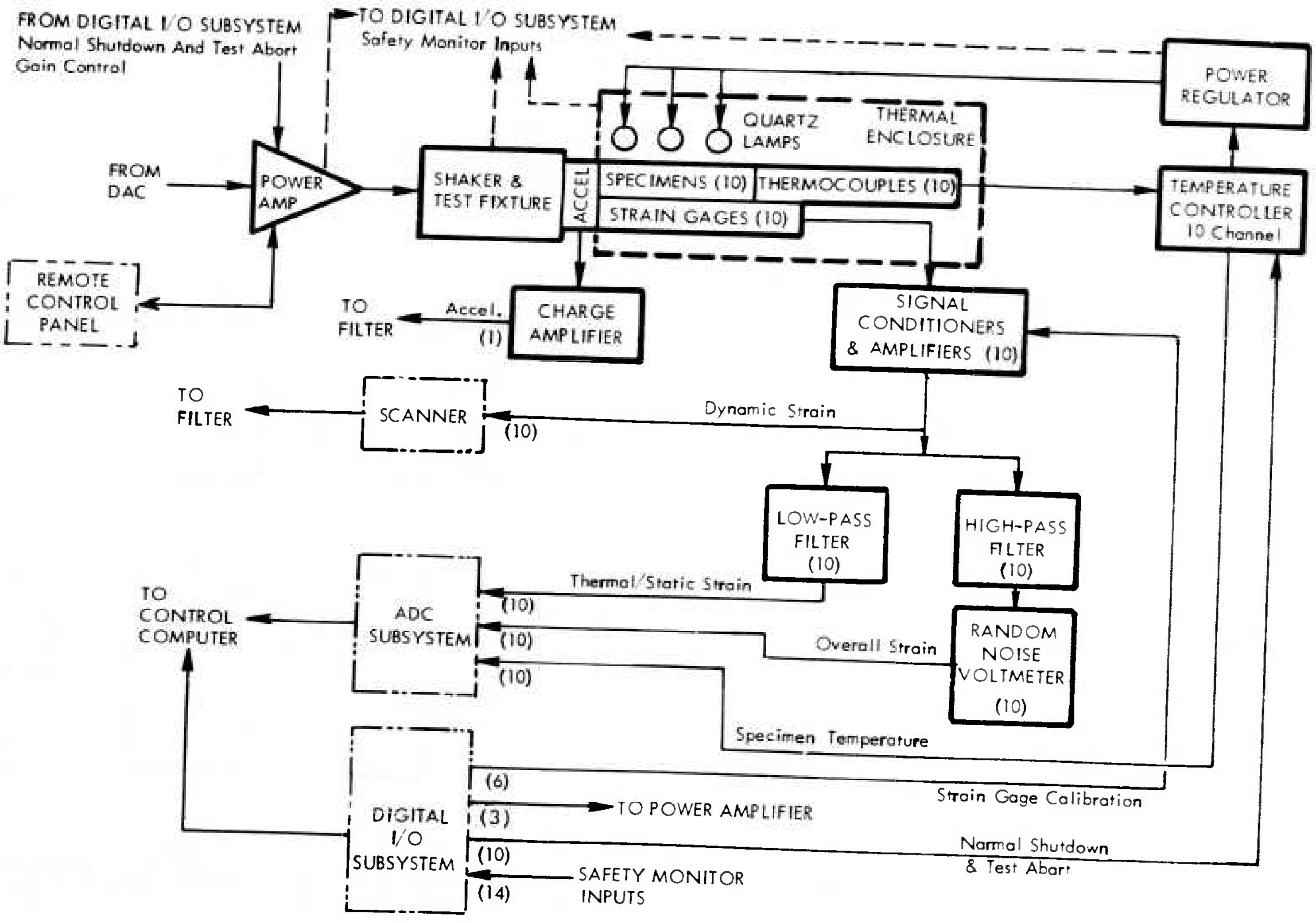


Figure 9. Single Shaker Test Facility Excitation And Instrumentation

Other peripherals could be added to this list to enhance the overall system operation. A high speed line printer or paper tape punch would provide alternate methods of output. However, these are not necessary for most tests, since output speed will not be a problem during long duration tests.

Test Data - The data recorded by the computer will consist of the following minimum items for each test specimen:

- Date, time of day
- Specimen identification
- Test level, overall acceleration
- Incremental test time (since last update)
- Accumulated test time
- Test temperature
- Response frequency
- Spectrum strain
- Overall strain
- Static or thermal strain
- Incremental cycles of stress reversal (since last update)
- Accumulated cycles of stress reversal

The above data can be readily converted to engineering units from the measured voltages and recorded on magnetic tape for future retrieval. A line printer could also be employed to tabulate the data each time a data record is made--however, this extra expense is not felt to be warranted due to the high reliability of the magnetic tape.

All of the data will be stored on either magnetic tape or the control computer disc at intervals selected in advance by the test operator. These time increments will be not greater than 5% of the total expected life to assure a minimum of 20 data points for each variable during the test. After the test, the above data can be replayed into the computer and analyzed. The control computer will have sufficient memory capacity to permit the data to be processed while fatigue tests are concurrently being controlled. While the tape recorder is being used for data playback, the ongoing test data will be temporarily stored on the disc, and later transferred to tape. Alternatively, this data analysis can be accomplished on a separate computer facility.

Typical test data to be plotted are shown in Figure 10. These data will normally be used only as working data to obtain a graphic test history, and can therefore be plotted on the CRT terminal using library plotting routines. A hard copy can then be obtained, if desired, in a few seconds via the hard copy unit. Report quality plots can be obtained on the digital X-Y plotter, which requires substantially more plotting time than the CRT.

Data Input - Data is input to the control computer via an Analog-to-Digital Converter and Digital I/O subsystem. A 12-bit ADC operating at a maximum sampling rate of at least 20 KHz is required to provide adequate dynamic range and data resolution. Thirty channels are required for overall and static strain and temperature data (10 channels each). The input data will be discussed in more detail subsequently.

The Digital I/O subsystem will be used to monitor switch closures and to control remote relays for safety requirements. This subsystem will contain event sense interrupt logic, such that the computer is notified only when switch contact is made. Approximately 14 channels will be required to monitor switch closures--these will be identified in a later section. Approximately 13 channels will be required to output signals to the excitation and heat systems. These output channels will provide on/off control of system components for normal test shutdown and test abort; six output channels are required to control strain gage calibration. Other instrumentation could also be controlled in this manner, but the added expense of hardware (relays, digital I/O electronics) and software is not felt to be justified in the initial system.

Signal Generation/Spectrum Shaping - The data analysis system uses a 32 K, 16-bit minicomputer, which must be hardware and software compatible with the control computer. The analysis computer commands normally come through the control computer. The high speed paper tape reader can be used for initial program loading or program verification. A cartridge disc memory system with 2.5 megaword storage and appropriate controller software is used to store the operating programs and for temporary data storage. This disc will be identical to the control-computer disc to minimize spares provisioning.

The random output signal is generated in the analysis computer using existing software packages as described previously. The excitation signal will be wide-band Gaussian random noise, which will be filtered and shaped to provide a flat, narrow-band input acceleration spectrum on the shaker head (see Figure 5). Both line-by-line spectrum and overall control will be utilized for shaping the spectrum. The line-by-line frequency alarm limits will be continuously variable from 0 to ± 40 dB; abort limits will be continuously variable from the alarm limits to 80 dB.

A programmable low-pass filter will be used in the feedback loop (acceleration input to the analysis computer) to minimize aliasing errors. The low-pass frequency ranges will be selected by the test operator, during test setup, to be compatible with

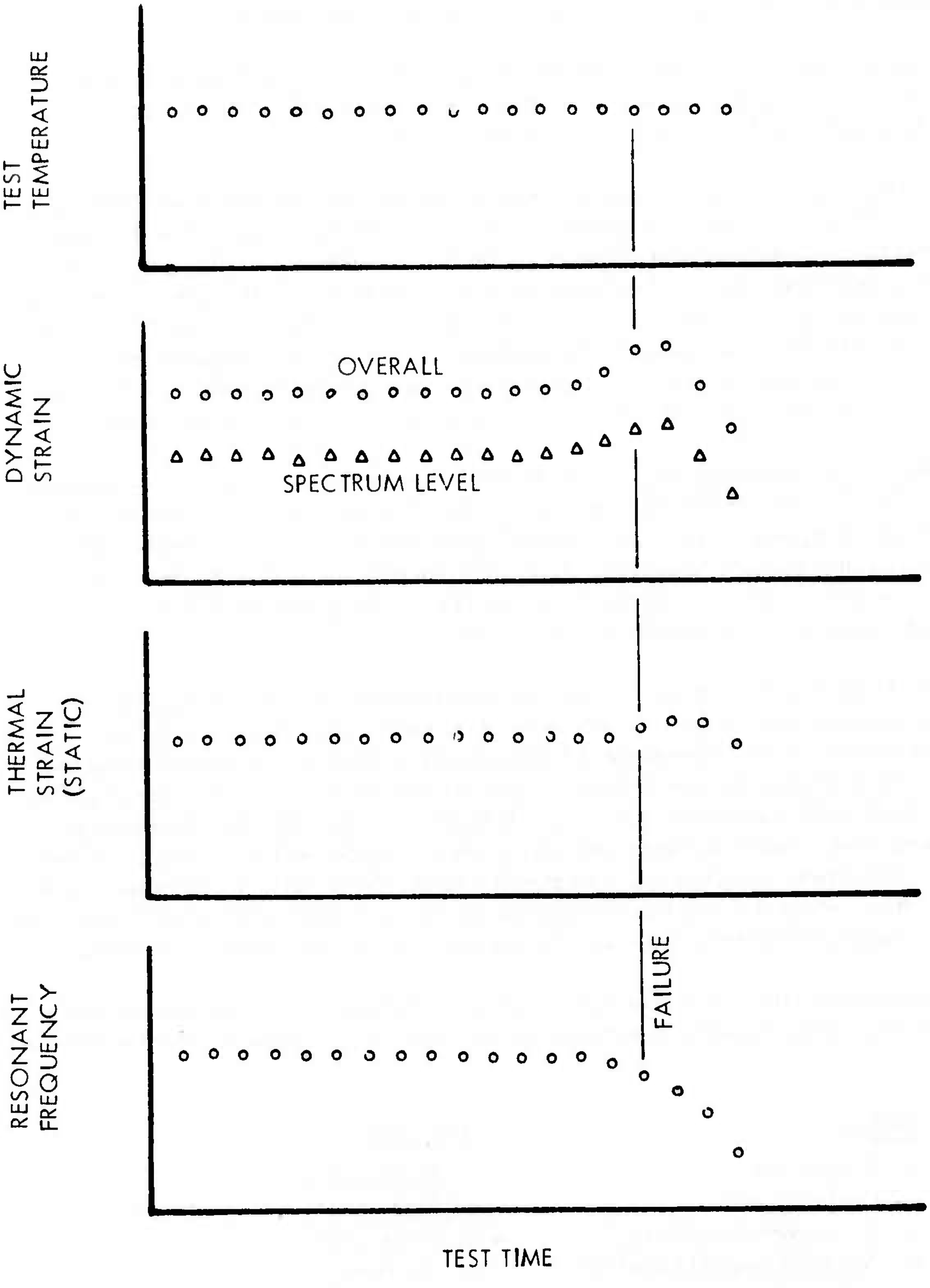


Figure 10. Typical Test Data Output

the shaker input spectrum. The input filter will be an 8-pole butterworth filter with a minimum rolloff of 48 dB per octave. A 12-bit (minimum) ADC is required to provide adequate digital data resolution for spectrum shaping.

The drive signal to the power amplifier is converted to analog form by a 12-bit Digital-to-Analog Converter. A programmable low-pass filter is used on the output to smooth the drive signal to the power amplifier.

This subsystem will also be employed to analyze and compute the Power Spectral Density (PSD) of the strain response data from the test specimens. This data analysis can be accomplished simultaneously with the acceleration analysis/spectrum shaping functions since most existing analysis systems have dual channel capability. The spectral output of this analysis will be stored on the disc for later plotting, if desired. The spectrum will then be transferred to the control computer and analyzed to determine the resonant frequency and spectrum strain level--these values will then be stored for later use and the remainder of the spectrum discarded.

Excitation and Instrumentation - As shown in Figure 9, the single power amplifier and shaker can be controlled from a remote panel which will be located near the computer controller. Amplifier voltage/current meters will be provided on the remote control console to provide visual status monitoring of the shaker system. Separate abort/shutdown commands are provided to the power amplifier from the control computer to automatically stop the test.

Figure 11 defines in more detail the interfaces between the control computer, power amplifier and shaker. It was determined during the Phase I study that approximately 12,000 pounds force (random) will be required to provide adequate specimen excitation for the majority of possible test conditions. A power amplifier with 45-50 KVA continuous duty output is required to develop this force rating. The amplifier, shaker and specimen base plate all require water cooling to dissipate heat. The power amplifier and shaker will require 30-40 gallons-per-minute (gpm) water flow, while the specimen base plate requirement will be less than 5 gpm. No water cooling of the base plate will be required during room temperature tests.

The power amplifier and shaker require certain interlocks for system and personnel protection. These interlocks between the two units will include at least the following:

Shaker

- Overtravel
- Coolant flow
- Field overtemperature
- Armature overtemperature

Amplifier

- Master gain
- Open door
- Overcurrent
- Air flow
- Coolant flow/overtemperature

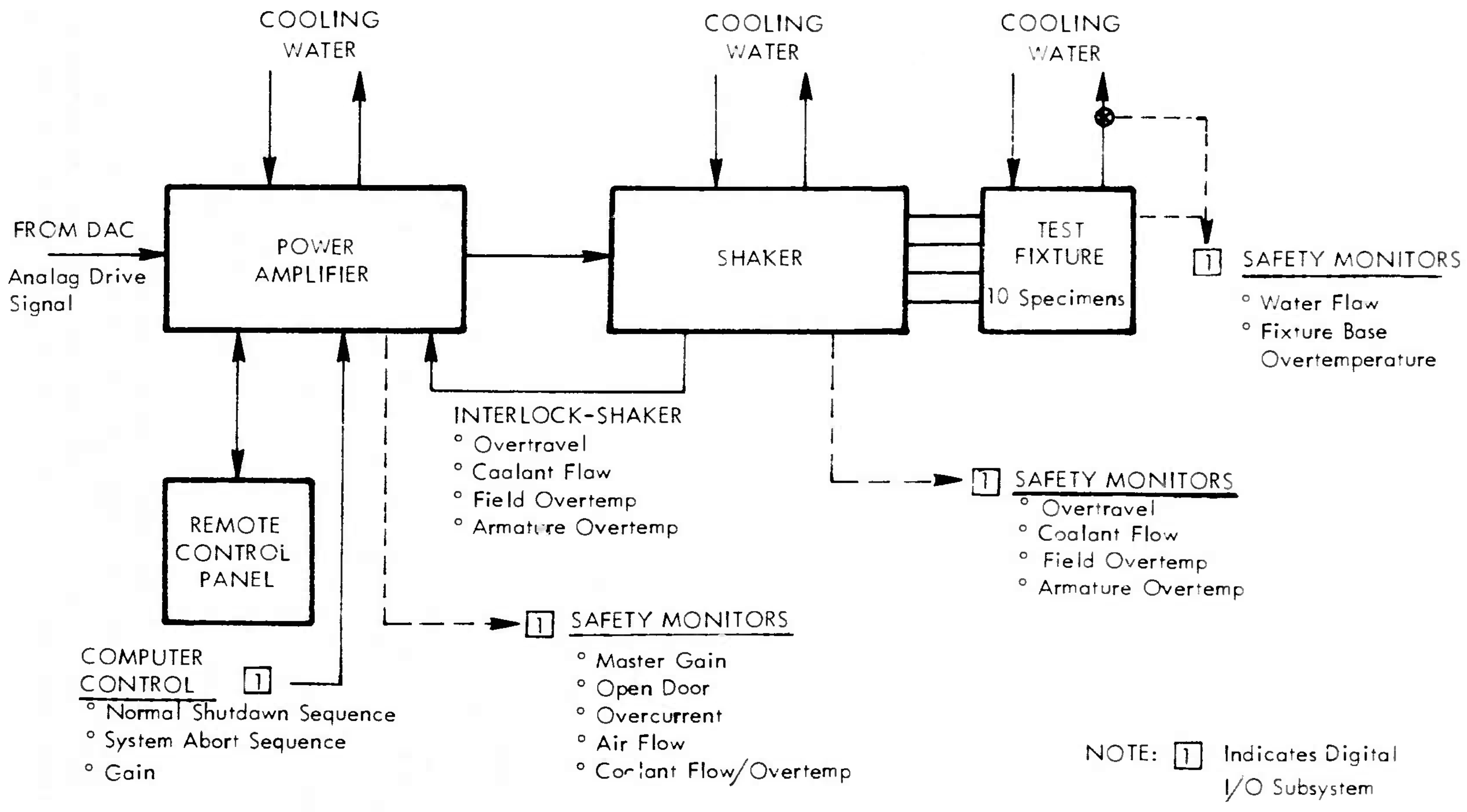


Figure 11. Excitation Subsystem For Single Shaker Facility

Exceedance of preset values or switch closure will cause the amplifier to automatically terminate the test and shut down the high voltage sections of the amplifier. These interlocks will also be monitored by the control computer to provide immediate fault identification. In addition, sensors will be required for measuring the flow rate of the cooling water from the specimen base plate to prevent damage to the shaker in the event of coolant loss. A thermocouple will be used to measure fixture temperature. These sensors will be connected to limit switches that make contact when preset limits are exceeded. The safety monitoring circuits for the shaker and amplifier can, in almost all cases, be connected to the existing relays in the power amplifier or shaker. Amplifier gain control will be provided by programmable resistance output cards in the digital I/O unit. Sensors and switches will need to be provided for the base plate temperature and coolant flow monitoring. These should be included in the test fixture design effort.

The test fixture will need to be designed to match the shaker table to minimize fixture overhang. The test fixture will be attached directly to the shaker table, and should be capable of accepting a wide variety of specimen mounting blocks for a maximum of 10 individual specimens. Separate specimen mounting blocks will be required for zero mean stress and applied mean stress tests. Each specimen will have a minimum of one strain gage and one thermocouple (for elevated temperature testing only) bonded to the surface at the point of expected failure. When static or thermal strains are to be measured, a compensating strain gage will be installed on a piece of identical material in the vicinity of the active gage but will not be strained or vibrated. Figure 12 shows a schematic of the strain gage instrumentation required to measure static (or thermal) as well as dynamic strain. The scanner output is connected to a low-pass filter and ADC, thence to the analysis computer to provide narrow-band analysis capability. This data will be processed to determine resonant frequency and spectrum strain data, as described previously. The signal conditioner and amplifier shall have a flat frequency response (less than ± 5% variation) from DC to 5000 Hz to provide capability for measuring both static and dynamic stress. A high-pass filter, with a lower frequency cutoff of approximately 20 Hz, is used to block the DC from the AC voltmeter. A voltmeter with variable averaging time, up to at least 100 seconds, is required to smooth the fluctuations in the overall level. For simplicity, the voltmeter shall have a DC output, which is then input to the ADC as a voltage proportional to the overall strain level.

Static, or thermal strains, are obtained from the same strain gage by using a low-pass filter, with a 2 Hz cutoff frequency, to eliminate the AC signal. This DC signal can then be input directly to the ADC. Time averaging of the signal, by the computer, may be required to smooth fluctuations in the strain level.

Alternatively, the low- and high-pass filters can be eliminated and the static and dynamic strains determined by the computer. The signal would be digitized and averaged by the computer, then separated into the DC and AC components to yield the static and spectrum strains. The overall level could then be computed from the

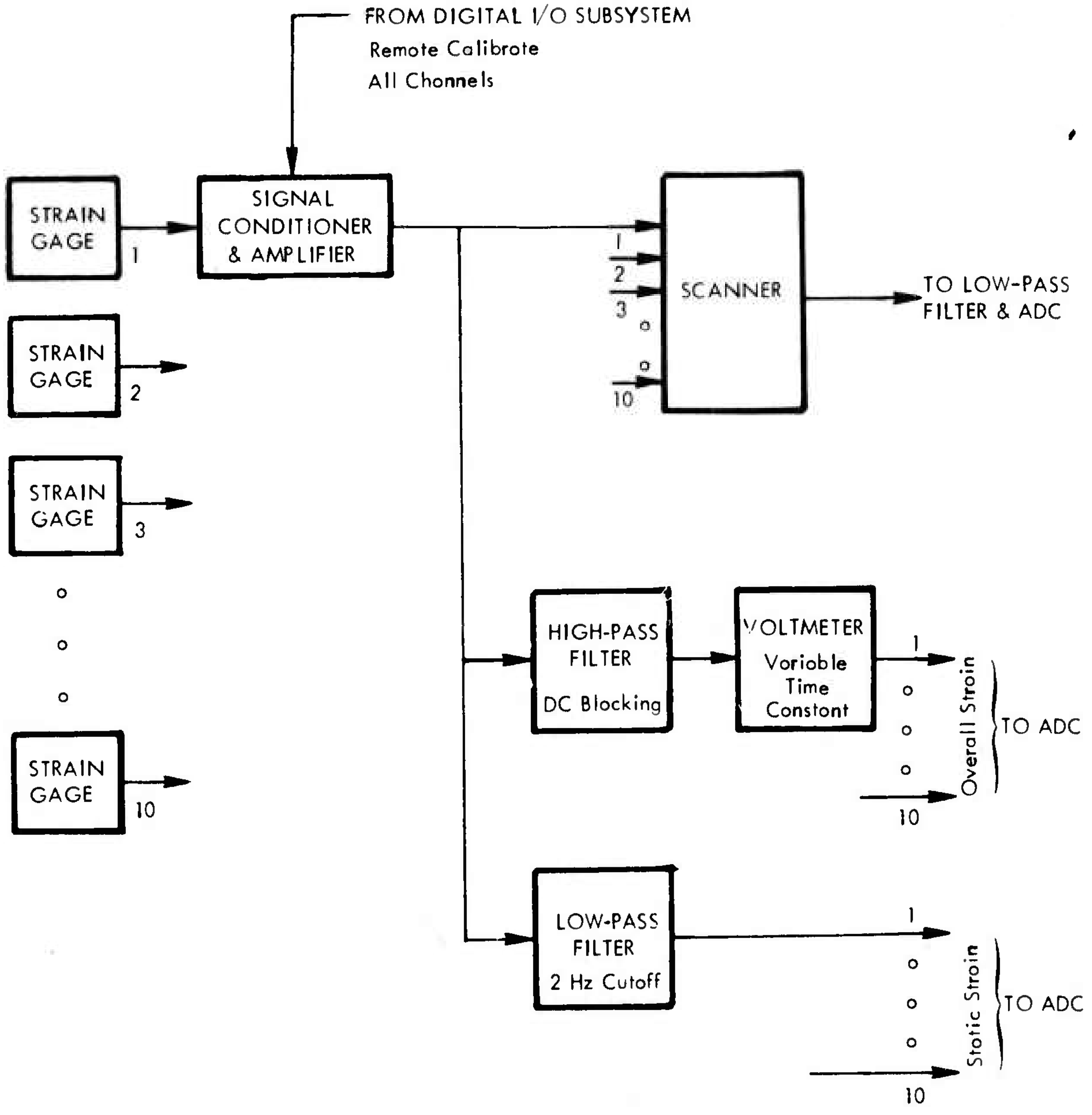


Figure 12. Strain Instrumentation Schematic

strain spectra. Although considerable computer core will be required to perform this continuous computation, it can probably be accomplished without increasing the core size since the control computer is not normally being used to capacity during test monitoring.

Calibration of the strain gages can be accomplished remotely under control of the computer, using remote calibrate relays in the signal conditioner. For instance, if four calibrate steps are available, two each can be used for static and dynamic strain calibration steps. Zero level calibration is also required for static and thermal strain measurements.

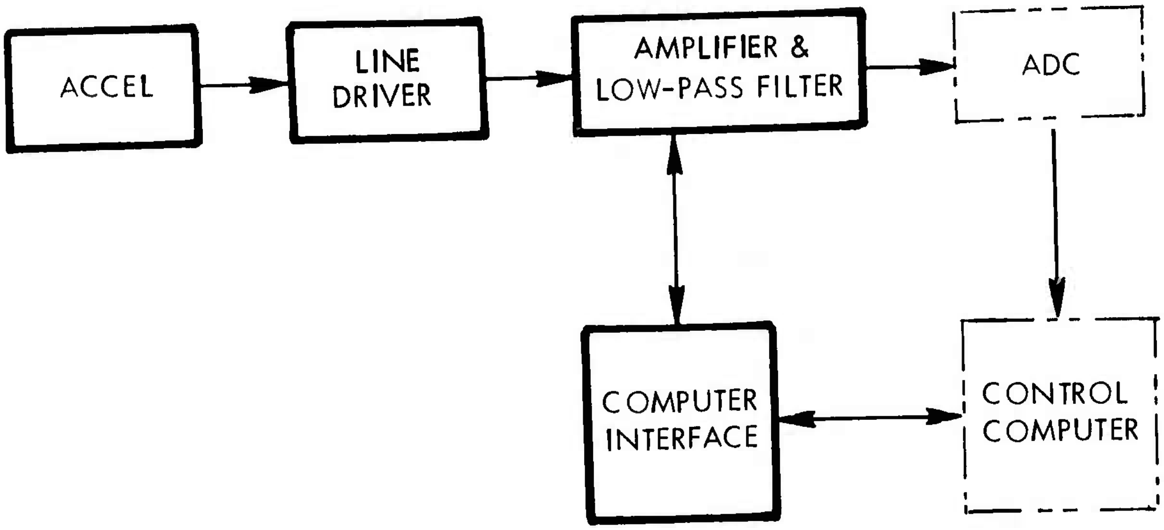
Test level will be controlled by means of an accelerometer mounted on the shaker table. Figure 13 shows two alternative methods of signal conditioning for the single control accelerometer. The automatic gain-ranging and programmable filter cutoff frequency are recommended if new instrumentation is to be purchased. This automatically provides the computer with amplifier and filter settings. If existing signal conditioning instrumentation is to be employed, a charge amplifier can be used in conjunction with a separate low-pass filter for anti-aliasing (this can be either manual or programmable). Analysis of the accelerometer signal, and spectrum shaping, have been discussed previously.

Figure 14 summarizes the analog data channel requirements for this facility. Ten analog channels each are required for overall (dynamic) strain and thermal or static strain. An additional ten channels are required to measure specimen temperatures. All of these data channels will be DC voltages proportional to the desired quantities. An additional 2-4 channels should be provided for spares and future additions.

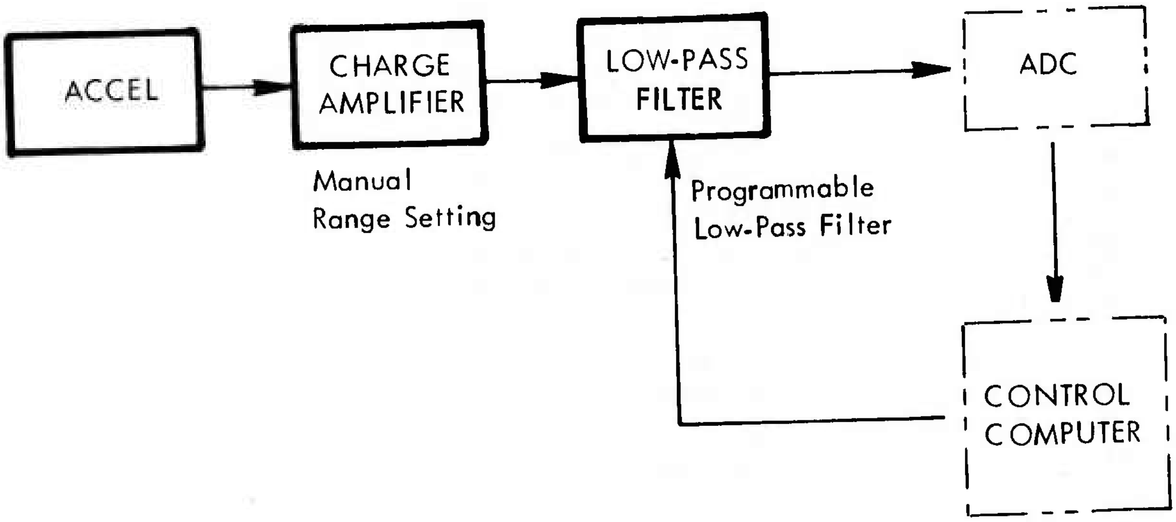
Heat Subsystem - The heating subsystem is shown schematically in Figure 15. AFFDL has an existing 10-channel temperature control system which meets the design requirements; therefore, this system has been depicted on the figure. The heating system, manufactured by Research Incorporated, consists of four major components:

- Remote Control Station, Model 4082
- Controller/Recorder, Model 4080
- Thermocouple Reference Junction Compensator, Model 4081
- Power Regulator, Model 4078

Some modification of the system will be required to meet the automation and safety criteria. The temperature recorders will not be required for long duration, high temperature tests; therefore, the recorder input will be used to obtain temperature input data for the control computer.



A. Automatic Amplifier Gain-Ranging & Programmable Filter Cutoff



B. Manual Amplifier Gain

Figure 13. Accelerometer Signal Conditioning For Single Shaker Facility

ANALOG DATA CHANNELS
INPUT TO CONTROL COMPUTER

Channel No.	Quantity Recorded	Test Specimen No.
1	Test Specimen Overall Strain	1
2	Test Specimen Overall Strain	2
3	Test Specimen Overall Strain	3
4	Test Specimen Overall Strain	4
5	Test Specimen Overall Strain	5
6	Test Specimen Overall Strain	6
7	Test Specimen Overall Strain	7
8	Test Specimen Overall Strain	8
9	Test Specimen Overall Strain	9
10	Test Specimen Overall Strain	10
11	Test Specimen Static or Thermal Strain	1
12	Test Specimen Static or Thermal Strain	2
13	Test Specimen Static or Thermal Strain	3
14	Test Specimen Static or Thermal Strain	4
15	Test Specimen Static or Thermal Strain	5
16	Test Specimen Static or Thermal Strain	6
17	Test Specimen Static or Thermal Strain	7
18	Test Specimen Static or Thermal Strain	8
19	Test Specimen Static or Thermal Strain	9
20	Test Specimen Static or Thermal Strain	10
21	Test Specimen Temperature	1
22	Test Specimen Temperature	2
23	Test Specimen Temperature	3
24	Test Specimen Temperature	4
25	Test Specimen Temperature	5
26	Test Specimen Temperature	6
27	Test Specimen Temperature	7
28	Test Specimen Temperature	8
29	Test Specimen Temperature	9
30	Test Specimen Temperature	10

Figure 14. Analog Data Input To ADC For Single Shaker Facility

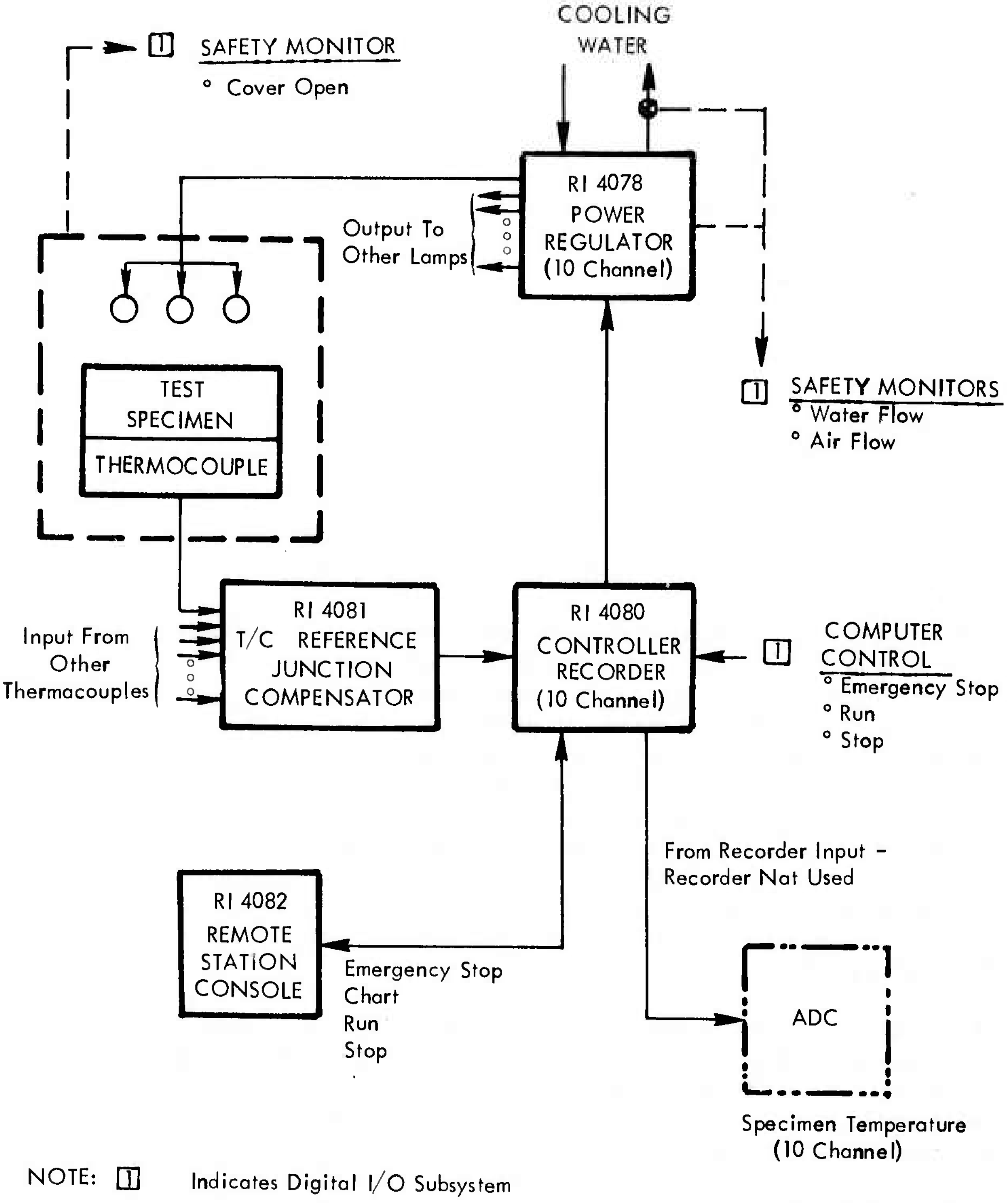


Figure 15. Heat Subsystem

Sensors and switches will be required to monitor the water and air flow in the power regulator chassis to allow the computer to shut down the system in the event of coolant loss. These switch closures will be monitored by the Digital I/O subsystem. The Digital I/O subsystem will also provide output signals to the temperature controller for run, stop and emergency stop. These functions parallel those on the remote control station, which will be located adjacent to the computer controller and shaker remote control panel.

While the existing temperature control system has 10 channels of temperature regulation, not all of these will be required for temperature control due to the confined space over the specimens. Four channels will probably prove sufficient to provide zone control of specimen temperatures with Tungsten-filament quartz lamps. The arrangement of these lamps, and the quantity required, will be dictated by the fixture design. Lamp holders and reflectors should be designed concurrent with the fixture design, or selected and procured from available equipment.

The test fixture and heat lamp fixture design effort will also include design of a thermal enclosure around the test specimens to maintain uniform specimen temperatures. The enclosure should be readily removable for specimen replacement and should have a removable cover for ease of specimen inspection. The cover will have an interlock switch connected to the control computer to indicate removal when the heat lamps are on--this will initiate shutdown of the test system.

Safety Monitoring - The test facility operation is intended to be completely automatic after the initial startup, as specified in the design requirements. In order to minimize the probability of personnel danger (whether or not the personnel are authorized to be in the vicinity) and of specimen or equipment damage, it is necessary to monitor specific functions of the system, particularly for the high power and temperature components. The safety monitor provisions have been mentioned briefly in discussing each subsystem function. The operations and quantities to be monitored by the Digital I/O subsystem are itemized in Figure 16. Status monitoring requires a minimum of 14 channels--at least 2-4 extra channels should be provided as spares for future expansion or for use in case of malfunction of a module in use. The parameters shown will, in most cases, be quantities measured on the purchased equipment.

The output requirements for the Digital I/O subsystem are also itemized in Figure 16. These output signals will activate remote relays in the affected component to shut down the system for normal test termination or for emergency abort. Six output channels are used to activate remote relays in the strain gage signal conditioner to obtain strain calibration and zero levels.

System Calibration - The equipment in the system will be required to undergo periodic laboratory calibration to verify that the measured parameters are accurate. The control accelerometer shall also be subject to this periodic calibration. These

SAFETY MONITORING AND CONTROL CHANNELS
DIGITAL I/O SUBSYSTEM

Channel No.	Input or Output	Component	Operation Or Quantity	Indication Or Action
1	Input	Power Amplifier	Master Gain	Gain On/Off
2			Doors	Door Open
3			Armature Current	Overcurrent
4			Air Flow	Loss of Air Flow
5			Coolant Flow/Temp	Loss of Coolant Flow
6		Shaker	Overtravel	Armature Overtravel
7			Coolant Flow	Loss of Coolant Flow
8			Field Temperature	Overtemperature
9			Armature Temp	Overtemperature
10		Test Fixture	Coolant Flow	Loss of Coolant Flow
11			Fixture Temperature	Overtemperature
12		Heat Regulator	Coolant Flow	Loss of Coolant Flow
13			Air Flow	Loss of Air Flow
14		Thermal Enclosure	Cover	Cover Open
15	Output	Power Amplifier	Test Shut Down	Normal Shut Down
16			Test Abort	Abort Sequence
17-26		Heat Controller	Test Shut Down	Normal & Abort
27-32		Instrumentation	Strain Gage Signal Conditioner	Remote Calibration & Zero
33		Power Amplifier	Master Gain Control	Gain Variation

Figure 16. Safety Monitoring Requirements For Single Shaker Facility

calibration intervals should be scheduled at increments of less than three months. Preventative maintenance and repair can be conducted during these periods to minimize system downtime.

The test facility will have a built-in calibration capability for the strain gages. Remote calibrate relays in the strain gage signal conditioner will be activated through the control computer to provide DC voltage levels proportional to strain. A zero strain level is also required for static strain calibration. The voltage/strain relationships provided by this calibration will then be used to compute dynamic or static strain and stress.

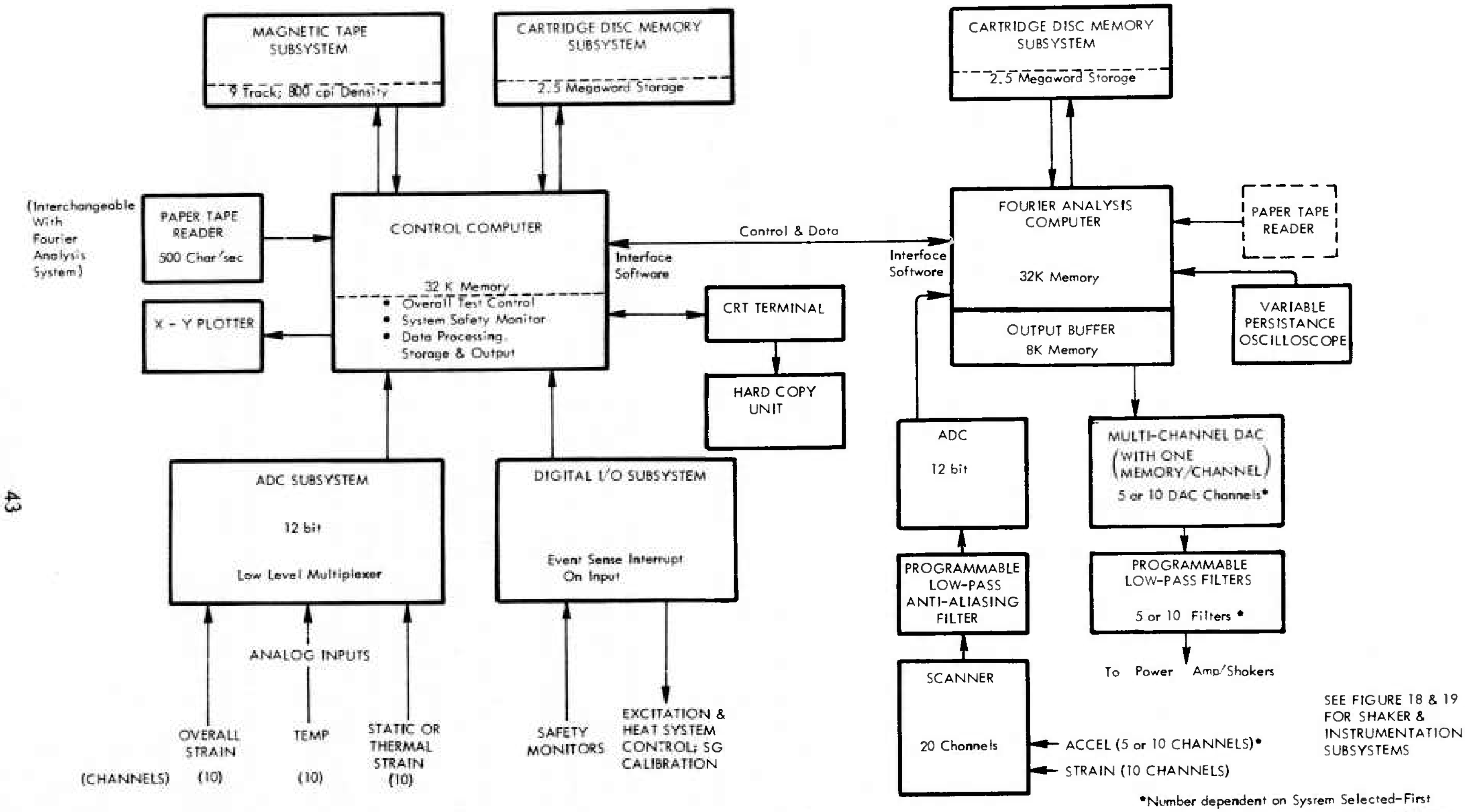
Accelerometer and temperature data will be converted to engineering units by entering the calibration data (i.e., mv/g) into the computer, since it is not practical to provide voltage insertion calibration steps for these transducers.

Other data parameters, such as time and frequency, will be generated by computer devices which will require checking during the periodic calibrations.

Multi-Shaker Test Facility

Two multi-shaker facility concepts are covered in this subsection, one using five and the other ten independent excitation subsystems. Since the control and instrumentation requirements are basically similar, both will be discussed together. Figure 17 shows a functional diagram for the control and analysis subsystems for the multi-shaker concept. The control computer and peripherals are the same as for the single shaker facility, the only difference being in the number of digital input and output channels required, and in the software for controlling the excitation subsystems. Test data will be identical since the data are accumulated separately for each of the test specimens. Hence, all of the discussion from the preceding section (for the single shaker facility) is pertinent to the control computer for the multi-shaker test facility.

Signal Generation/Spectrum Shaping - The same size computer is used for this system as for the single shaker concept--the peripherals will be basically the same except that a single input channel is used. Spectrum shaping techniques for the acceleration spectrum will also be identical. However, instead of simply shaping a single drive spectrum, either five or ten independent drive spectra must be shaped and controlled to different reference spectra. Periodic update of the spectrum shape is satisfactory since the fatigue tests to be conducted will be comparatively long in duration with steady-state vibration inputs, and the resonance change will be gradual. This allows a single analyzer to control and shape multiple spectra. When the spectrum is not being updated, the system will operate in an open-loop mode, whereby the stored drive spectrum is continuously fed to the power amplifier. The drive signal spectra are fed to an interim buffer which consists of an 8K minicomputer. This frees the analysis computer from data storage/sequencing functions. However, there will be a significant amount of software development required to sequence, store, and feed the spectrum update data to the DAC. A multi-channel DAC is required to convert the digital drive signal to analog form. Each



SEE FIGURE 18 & 19
FOR SHAKER &
INSTRUMENTATION
SUBSYSTEMS

*Number dependent on System Selected-First quantity for five shaker system; Second for ten shaker system

Figure 17. Multi-Shaker Facility Control System

DAC channel will require an individual memory to store the drive signal while the computer updates the other channels. Multiple low-pass filters are used to smooth the drive signals to the shaker; these filters are programmable to provide frequency cutoff variation under computer control.

The analysis computer will not be required to have dual channel analysis capability since strain spectrum analyses will be conducted sequentially with spectrum shaping. Otherwise, the strain analysis and data handling requirements will be identical to those described for the previous system.

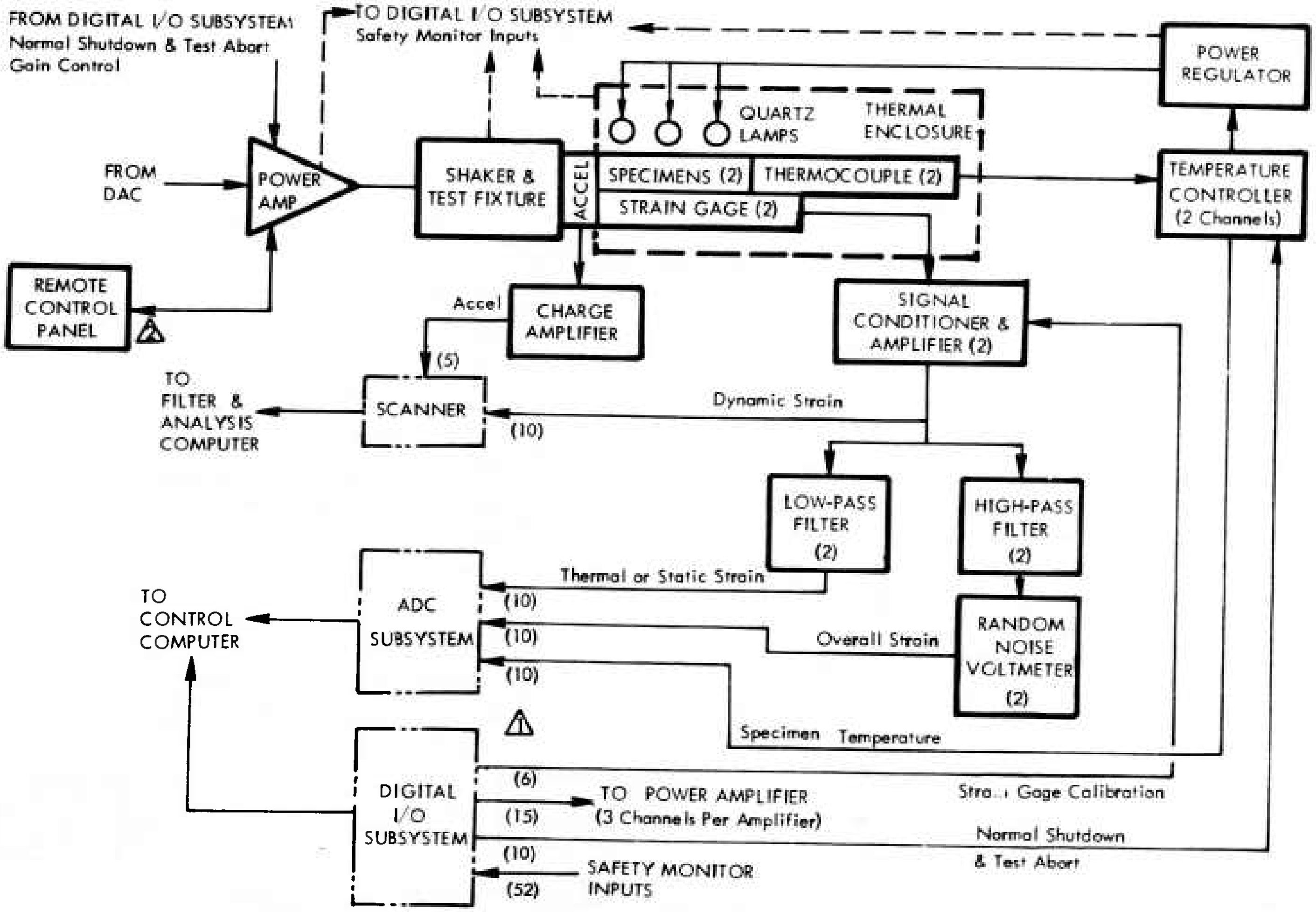
Excitation and Instrumentation - The excitation subsystems for the two multiple shaker systems are shown in Figures 18 and 19. The two schematics are similar--the basic difference being that the five shaker system will excite two specimens per shaker while the ten shaker system will excite a single specimen per shaker. The quantities of strain instrumentation and heat control channels are different for each system since only a single shaker channel is shown in the figures. However, the total number of channels required remains the same as for the single shaker system--ten channels each of static strain, dynamic strain, overall dynamic strain and temperature. The only real difference in the instrumentation is in the number of acceleration channels required; one acceleration feedback channel is required for each shaker.

Each power amplifier will be connected to a master remote control console located adjacent to the computer controller. Amplifier status meters and controls will be provided on this panel. These control functions will be duplicated by the control computer, which will have separate shutdown/abort capability as well as operating control of the amplifier gain.

The shaker force requirements will be approximately 2500 pounds (random) for the five shaker facility and approximately 1000 pounds (random) for the ten shaker facility. These shakers require amplifiers with 16 and 8 KVA output, respectively, to develop the required force ratings.

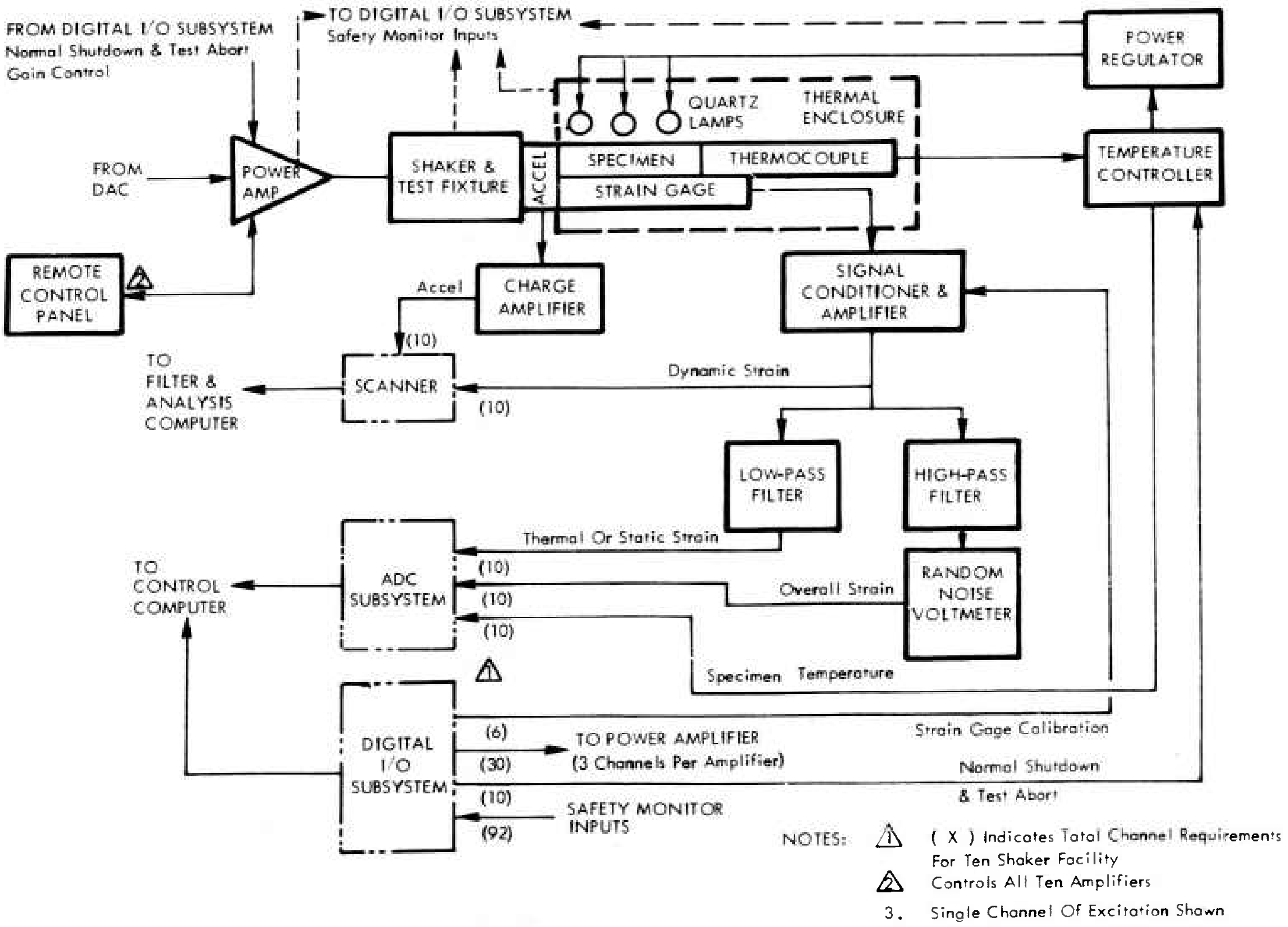
Figures 20 and 21 define the excitation subsystem interfaces for the two alternate multi-shaker systems. The power amplifier for the large shakers will likely require water cooling, as well as internal air cooling, as shown in Figure 20. The amplifier for the ten shaker system can be cooled by forced air. The shakers for both systems will likely be forced-air cooled. Both concepts require water cooling of the fixture base plate during elevated temperature tests to prevent excessive heat flow into the shaker head.

Interlocks will be provided between the power amplifier and shaker to shut down the system in case of malfunction or personnel error. These interlocks will include at least the following for both concepts:



NOTES: 1. (X) Indicates Total Channel Requirements For Five Shaker Facility
2. Control: All Five Amplifiers
3. Single Channel Of Excitation Shown

Figure 18. Five Shaker Test Facility Excitation and Instrumentation



NOTES:

⚠1 (X) Indicates Total Channel Requirements For Ten Shaker Facility

⚠2 Controls All Ten Amplifiers

3. Single Channel Of Excitation Shown

Figure 19. Ten Shaker Test Facility Excitation And Instrumentation

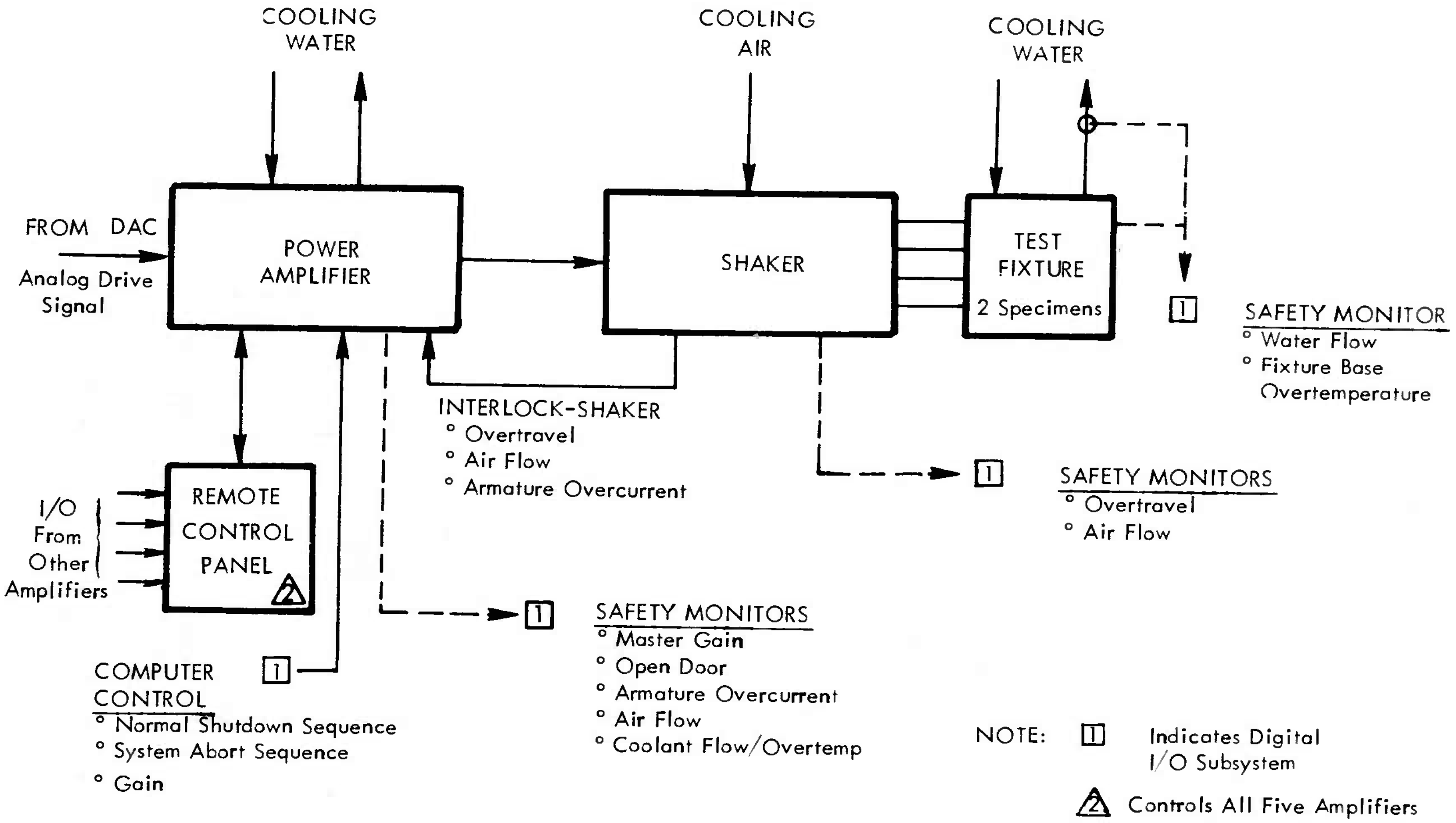


Figure 20. Excitation Subsystem For Five Shaker Facility

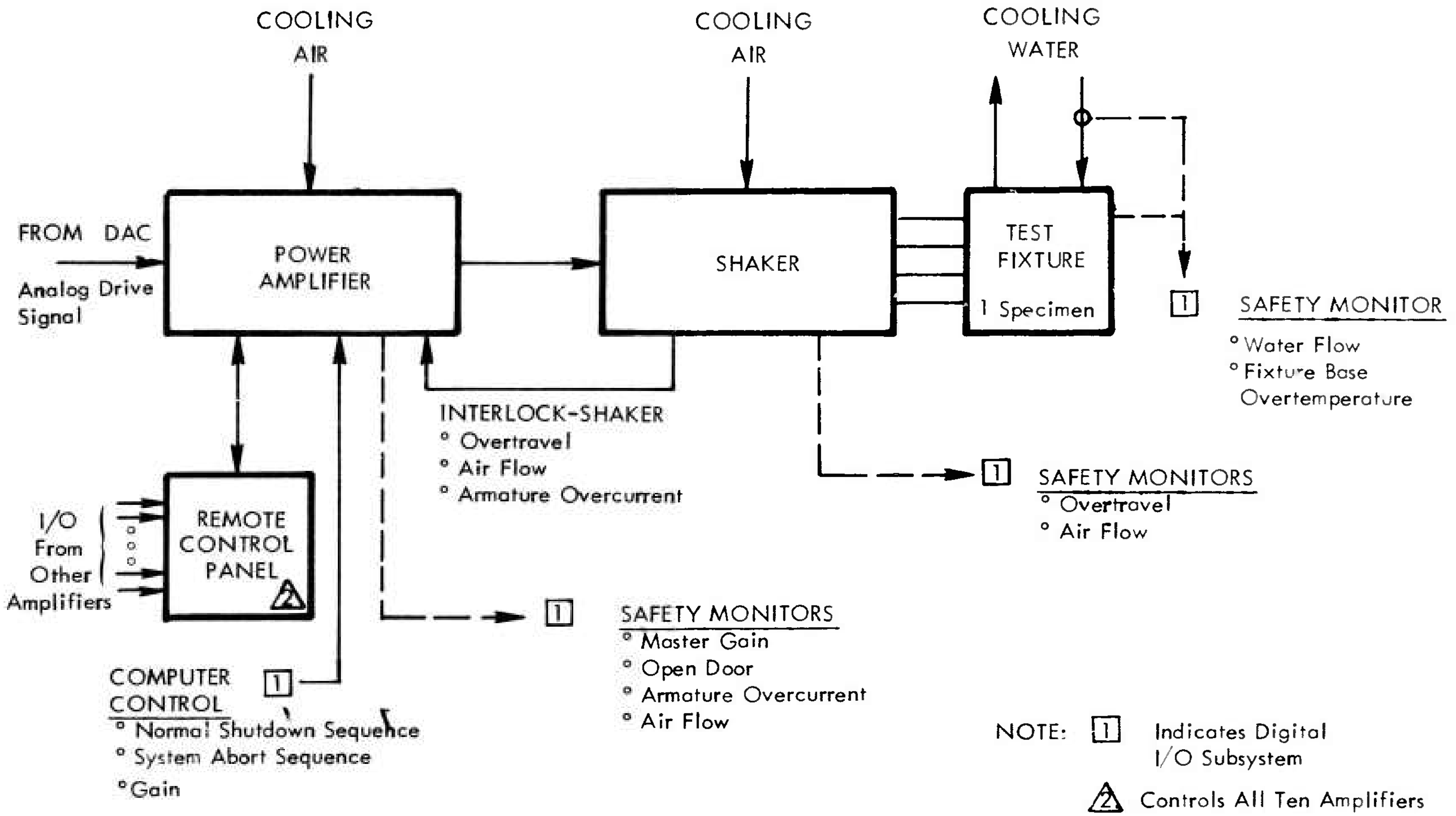


Figure 21. Excitation Subsystem For Ten Shaker Facility

Shaker

- Overtravel
- Air flow

Amplifier

- Master gain
- Open door
- Armature overcurrent
- Air flow
- Coolant flow/Overtemp (five shaker system only)

Exceedance of preset values or switch closure will automatically terminate the affected test and shut down the high voltage section of the appropriate power amplifier. These interlocks will also be monitored by the control computer to provide immediate fault identification. In addition to the above, sensors will be required for measuring the flow rate of the cooling water from the specimen base plate, as well as the temperature of the plate, to prevent damage to the shaker in the event of coolant loss. These sensors will be connected to limit switches that make contact whenever a preset value is exceeded. The safety monitoring circuits can, in most cases, be connected to existing relays in the power amplifier or shaker. Sensors and limit switches will need to be provided for the base plate temperature and coolant flow monitoring. These should be included in the test fixture design effort.

The test fixture must be designed to match the shaker table to minimize fixture overhang. The test fixture will be attached directly to the shaker table, and shall be capable of accepting a wide variety of specimen mounting blocks. The test fixture for the five shaker system will include provisions for installing two test specimens while the fixture for the smaller shaker shall include provisions for a single specimen.

Specimen instrumentation (strain gages and thermocouples) will be identical to that for the single shaker system, described in the preceding section. The strain gage signal conditioning requirements are identical to those shown previously in Figure 12.

Test level control for the multi-shaker concept is also provided by means of an accelerometer mounted on the shaker table. The signal conditioning requirements for a single channel are the same as those shown in Figure 13 and described previously for the single shaker system. The only difference in the three concepts is the total number of acceleration measuring channels required, since each shaker requires a single control accelerometer.

Test instrumentation channel requirements are dependent only on the total number of test specimens; hence, they remain unchanged from those described previously and shown in Figure 14.

Heat Subsystem - The heat subsystem remains the same as that described previously since an existing AFFDL system is to be used. The only differences in the heat subsystem, shown in Figure 15, will be in the number of channels of heat lamp control required. Whereas approximately four channels will be required for the gang-testing system, the multi-shaker systems will require at least one channel per shaker. Each of the control channels can power multiple quartz lamps to attain uniform heat distribution. Thermal enclosure requirements remain as previously discussed.

Safety Monitoring - Safety and status monitoring of the system operation is required to minimize the probability of personnel danger and of specimen or equipment damage. Specific functions of the high power and temperature components will be continually monitored by the control computer, and the affected subsystem will be shut down in the event of malfunction. Figures 22 and 23 itemize the operations and quantities to be monitored by the Digital I/O subsystem. Status monitoring of the system operation requires a minimum of 52 and 92 input channels for the five and ten shaker systems, respectively. Digital output requirements total 31 and 46 channels for the respective systems. An additional 10% of the input and output channels should be provided as spares and for future expansion.

The input parameters are those provided on most available components as standard equipment. The digital output subsystem will activate remote relays in the component to shut down the system under normal and abort situations. Six output channels are used to obtain remote calibration and zero levels for the strain gages, as discussed for the single shaker facility.

System Calibration - Calibration requirements for the sensors and equipment are independent of the test concept. Hence, the discussion of the preceding section is applicable to all of the systems.

5. POSSIBLE FACILITY DESIGNS

The efforts discussed in the foregoing sections defined the functional and interface requirements for single and multiple shaker test systems. In order to assure that each concept can be assembled from existing hardware, discussions were held with several equipment manufacturers. There are five major manufacturers of digital control systems for shakers; each of these offers systems tailored to control a single shaker. These systems are oriented toward conducting multi-level "Mil-Spec" type tests, either swept sine, resonant dwell, or random environmental tests. Most have disc storage capability for saving test data and for storing operating programs and diagnostic routines. However, none of these, in their standard configuration, can control the heat system, monitor the system operation and record the strain and temperature data required. Since all of the systems investigated are built around a minicomputer, it would be possible to interface a second control computer with the analysis computer. This would require software development for both computers.

SAFETY MONITORING AND CONTROL CHANNELS

DIGITAL I/O SUBSYSTEM

Channel No.	Input or Output	Component	Operation Or Quantity	Indication Or Action
1-5	Input	Power Amplifier	Master Gain	Gain On/Off
6-10			Doors	Door Open
11-15			Armature Current	Overcurrent
16-20			Air Flow	Loss of Air Flow
21-25			Coolant Flow/Temp	Loss of Coolant Flow
26-30		Shaker	Overtravel	Armature Overtravel
31-35			Air Flow	Loss of Air Flow
36-40		Test Fixture	Coolant Flow	Loss of Coolant Flow
41-45			Fixture Temperature	Overtemperature
46		Heat Regulator	Coolant Flow	Loss of Coolant Flow
47			Air Flow	Loss of Air Flow
48-52		Thermal Enclosure	Cover	Cover Open
53-57	Output	Power Amplifier	Test Shut Down	Normal Shut Down
58-62			Test Abort	Abort Sequence
63-72		Heat Controller	Test Shut Down	Normal & Abort
73-78		Instrumentation	Strain Gage Signal Conditioner	Remote Calibration & Zero
79-83		Power Amplifier	Master Gain Control	Gain Variation

Figure 22. Safety Monitoring Requirements For Five Shaker Facility

SAFETY MONITORING AND CONTROL CHANNELS

DIGITAL I/O SUBSYSTEM

Channel No.	Input or Output	Component	Operation Or Quantity	Indication Or Action
1-10	Input	Power Amplifier	Master Gain	Gain On/Off
11-20			Doors	Door Open
21-30			Armature Current	Overcurrent
31-40			Air Flow	Loss of Air Flow
41-50		Shaker	Overtravel	Armature Overtravel
51-60			Air Flow	Loss of Air Flow
61-70		Test Fixture	Coolant Flow	Loss of Coolant Flow
71-80			Fixture Temperature	Overtemperature
81		Heat Regulator	Coolant Flow	Loss of Coolant Flow
82			Air Flow	Loss of Air Flow
83-92		Thermal Enclosure	Cover	Cover Open
93-102	Output	Power Amplifier	Test Shut Down	Normal Shut Down
103-112			Test Abort	Abort Sequence
113-122		Heat Controller	Test Shut Down	Normal & Abort
123-128		Instrumentation	Strain Gage Signal Conditioner	Remote Calibration & Zero
129-138		Power Amplifier	Master Gain Control	Gain Variation

Figure 23. Safety Monitoring Requirements For Ten Shaker Facility

Since most of the control/spectrum shaping systems store data which is of no use on the long duration fatigue tests, some reprogramming would be required to make the computer operation more efficient and to free space on the disc for the necessary test data.

To illustrate that these existing systems could be adapted to both the single and multiple shaker applications, actual conceptual designs were laid out with detailed equipment data and costs included. These designs are omitted here in order to avoid implied endorsement of particular manufacturers.

These designs clearly illustrated the availability of off-the-shelf equipment to fulfill the design requirements. Approximate cost data were included to provide realistic data for planning purposes. The cost data were for purchased equipment only and did <u>not</u> include the following items:

- Temperature controller, power regulator and other components of the existing AFFDL temperature control system.
- Remote control panels and controls for power amplifiers.
- Transducers (i.e., strain gages, accelerometers, thermocouples).
- Test fixture or water cooling provisions for the fixture base plate.
- Heat lamps, lamp fixtures, thermal enclosure, or cover interlock switch.
- Installation, external water or air cooling equipment, electrical power provisions.
- Software development.
- Spares.

All of the initially established general design criteria were incorporated into these systems. Maximum use was made of solid-state technology, where available, to improve reliability. Every effort was made to minimize the number of different manufacturers involved and to utilize equipment from a single manufacturer for the control system.

Experience with similar testing during Phase III of the current contract and previous programs (i.e., Reference 4) has shown that the power amplifiers are high-maintenance items. The current generation of all solid-state amplifiers greatly improves the reliability of the power amplifiers, but there will still exist a requirement for adequate spares provisioning and periodic scheduled preventative maintenance. For the multi-shaker systems, it would be beneficial to procure one extra power amplifier simply as a spare--so that the test can proceed while repair and/or maintenance is being conducted on a malfunctioning amplifier.

All components will require investigation during the system design to identify critical spares items, and these should be purchased and stocked for immediate use. All instruments with plug-in cards should have at least one extra card provided as a spare--these could be purchased with the initial order and, in most cases, simply left in unused slots in the mainframe.

Figure 24 shows a relative cost comparison of the alternative facility concepts. While this shows the single shaker system to be somewhat lower in total initial investment, this system presents several procurement and technical problems. For instance, a single "lump-sum" procurement would be required to obtain the shaker and control system. Heating and test fixture design problems will be much greater than for either of the multi-shaker concepts.

On the other hand, the multi-shaker system, with one specimen per shaker, represents a much more complex software and hardware system and imposes a much higher work load on the test operator.

6. RECOMMENDED SYSTEM

After a reexamination of all of the advantages and disadvantages of the various alternatives, it was decided that a multi-shaker facility with five amplifier-shaker systems most closely matches all of the initial requirements. This system, schematized in Figures 17 and 18, is therefore recommended to the AFFDL. This system can be purchased incrementally to spread the capital outlay over two or more budget years. A recommended minimum test system for initial procurement is shown in Figure 25. The magnetic tape system and X-Y plotter can be omitted initially--these are not necessary for software development or program checkout. The Digital I/O subsystem can also be temporarily omitted during system installation and program development since this component is used primarily for system monitoring. However, this subsystem should be added concurrent with the second shaker system or the start of unattended operation. Only three of the 35 ADC channels will be required initially, but the additional cost to procure the full required capability is minor so all cards should be purchased with the mainframe.

Disc storage is necessary for both the control and analysis computers to provide data and program storage. The analysis computer programs, most of which will be existing, are normally loaded into the computer from the disc. The paper tape reader will be required initially for program verification and checkout of both computers.

The analysis computer input/output peripherals will be required with the initial purchase. Again, several of these have plug-in cards, and the full complement should be purchased with the mainframe.

	Single Shaker System	Multi-Shaker System	
		Five Shakers	Ten Shakers
Control System	.27	.28	.29
Spectrum Shaping & Data Analysis System	.26	.42	.43
Power Amplifier, Shaker & Instrumentation	.47	.75	.90
Total Cost	1.00	1.45	1.62

NOTES:

1. Costs are relative to single shaker total cost.
2. Temperature control system, installation, test fixture, transducer, software development costs not included.

Figure 24. Relative Cost Comparison for Alternative System Concepts

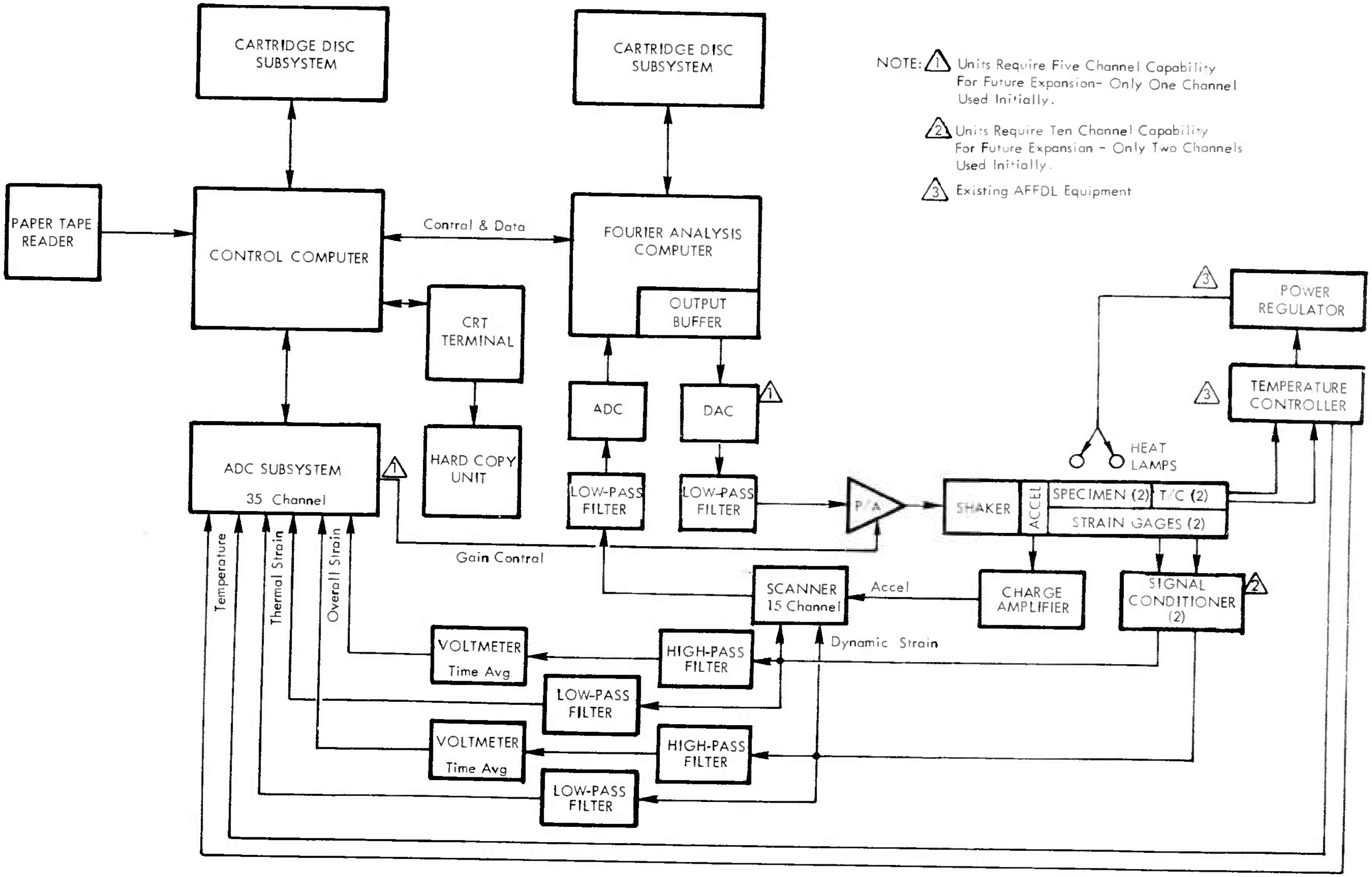


Figure 25. Recommended Test System - Initial Procurement

The major saving in startup cost is in the power amplifier and shaker system since it is necessary to purchase only a single shaker and amplifier in the initial procurement. In fact, the first shaker and amplifier purchase could be deferred since the AFFDL currently has at least one amplifier and shaker. This existing system could be used during the initial software development phase. However, due to the limited force output of the existing shaker, interim test and heating fixtures would be necessary.

Much of the acceleration and strain signal conditioning instrumentation may be available at AFFDL, and procurement of a full system could be deferred until later.

The initial system would not include a remote monitoring and control panel for the power amplifier. This should wait until at least two amplifier/shaker systems are installed, and the panel should then be designed to include controls and meters for the remaining systems.

Tentative Procurement Specification

The design criteria and component specifications for the recommended five shaker system were incorporated into a tentative procurement specification for the control system. Only the control system was included since all of the control equipment can be purchased through a single supplier. The excitation and instrumentation subsystems will, of necessity, be purchased through different suppliers and separate procurement specifications will be required for these. These systems will be hardware only and can therefore be selected and more readily procured from the existing alternatives.

The control system specification defined all of the design criteria and requirements for the system operation. The specifications for the system components were purposefully general--no attempt was made to define all component performance specifications in detail since this could possibly eliminate one or more of the available systems.

Problem Areas

The recommended system design will provide a large improvement in the test capabilities for high cyclic fatigue testing. Data accuracy will be enhanced while the amount of data obtained can be increased many times over current test methods. Automatic spectrum shaping provides a degree of test level control not attainable with previous analog equipment. Setup errors can be virtually eliminated and individual test conditions can be readily duplicated.

It should be borne in mind that the systems presented herein represent conceptual designs to accomplish automated random test control for multiple test specimens. The systems have been formulated to take advantage of existing hardware and software packages where possible, and the component functions have been generalized to include a wide selection of equipment. The use of existing or available equipment "off-the-shelf" was a design restriction. Equipment alterations or modifications were not considered. Therefore, it is likely that during detailed design of the system, minor modifications to existing equipment to increase or extend capability, particularly in the areas of signal conditioning, amplification, filtering, and averaging, will be found to be more cost effective than the conceptual designs shown. The possibility also exists that the application of a specific vendor component and/or software package to fulfill the system functions may present unanticipated interface problems. Computer space limitations, when all peripheral software interfaces are incorporated, will require detailed study. The drive signal buffer for the multi-shaker system will require development of appropriate software to sequence the data block updates as well as rapid data output to the DAC's, since the DAC memory will be very limited. Interaction of the DAC gain and the power amplifier gain is a potential problem area--it may be necessary to limit the power amplifier gain to an on/off function only to prevent signal instabilities. However, it is desirable to maintain computer control of the amplifier master gain since the amplifier must not be started with the gain on.

There are still other problems inherent to the test method. The more serious of these is the ability to maintain strain gages on the test specimen for long durations under extreme temperature environments. The same is true for thermocouples. Anticipated long duration tests will be longer than the strain gage element fatigue life in some cases, requiring gage replacement during the fatigue test. If a rigid fixture is used, and the specimen is removed to reinstall the strain gage or thermocouple, the specimen will likely have a different response after reinstallation unless extremely accurate specimen and fixture tolerances are maintained. Gage placement must also be extremely accurate to preclude error.

The adhesives normally used to bond strain gages and thermocouples are only good to 600-650°F for short periods. Since the strain is used to determine resonant frequency shift, and the thermocouple is used to maintain temperature control, a suitable method of attaching these transducers must be utilized. Optical tracking of the specimen tip is not practical for the high temperature environment and is very expensive, particularly since a single unit would be required for each specimen. Miniature accelerometers located on the specimen or proximity transducers at the tip would be suitable for the ambient temperature but have not been proven for the high temperature environment.

The thermocouple can be swaged into holes in the specimen (away from the stress concentration) and the temperature at that point calibrated against the temperature at the stress concentration. This either places the thermocouple in a high displacement region where the wire is subject to fatigue, or in the region of specimen fixity where the heat sinks make calibrating to another thermocouple unreliable.

Hence, there will be some experimentation and development required in the area of transducer attachment and life prior to the start of high temperature or long duration automatic testing.

These problems and the potential equipment/interface problems will require careful attention during the detailed design of the test facility.

IV. PHASE III - HIGH CYCLE FATIGUE TESTING

1. OBJECTIVE

These tests were designed to provide high cycle, random loading, reversed bending fatigue data for use in formulating S-N curves over the range of 10^6 to 10^9 cycles to failure, for 2024-T81 bare aluminum at room temperature and 250°F, and for 6Aℓ-4V annealed titanium at room temperature and 600°F.

2. SCOPE

A minimum of 3 coupon type beam specimens were tested at each of 4 strain levels for each material and each temperature. In some instances, more than the minimum were tested; the total quantity tested was 62 specimens. The test strain levels were chosen to be commensurate with specimen lives of 10^6, 10^7, 10^8, and 10^9 cycles to failure.

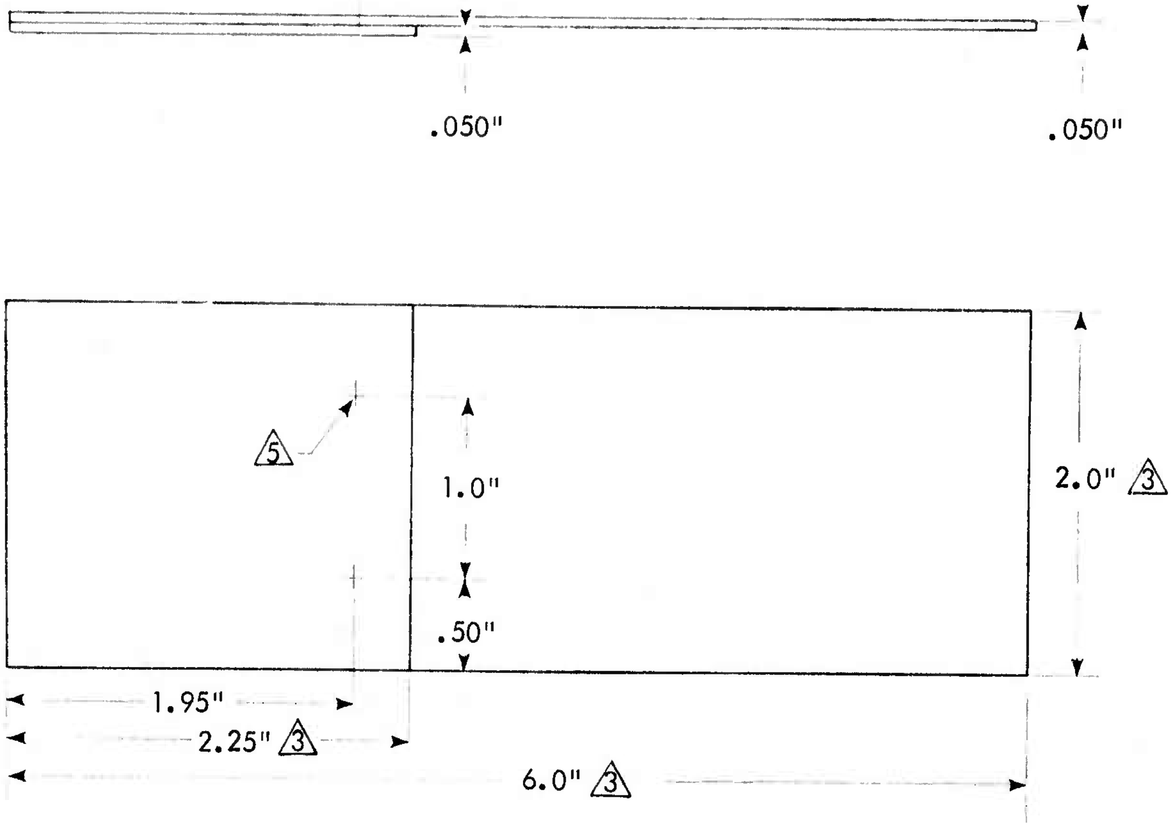
These tests consisted essentially of resonance endurance tests of approximately 2" x 6" sections of aircraft skin/stiffener structure. A specimen consisted of a section of skin panel and a section of the stiffening substructure, assembled and attached to an electromagnetic vibrator. The beam type specimen was then vibrated with narrow-band random excitation so as to induce a bending resonance of the specimen at deflections sufficient to ultimately cause cracking, in simulation of the flexural strain environment frequently realized by jet aircraft surface structure.

3. DESCRIPTION OF TEST SPECIMENS

Aluminum and titanium test specimens, designed in accord with criteria formulated from the initial program requirements and from the results of the Phase I analytical studies, are shown in Figure 26. The aluminum and titanium specimens are identical in configuration and dimension; only the riveting and cleaning processes differ. In order to increase the utility of the test data, the fasteners and edge distances were made identical to the design tested by Schneider [4].

While all specimens were fabricated the same length, the lengths tested varied from a maximum of six inches (four inches overhang) to a minimum of three inches (three-fourths inch overhang). In the majority of tests, the overhang length was shortened from the original four inches in order to increase resonance frequency.

Front and back views of a long and a short specimen with uniaxial strain gages and foil thermocouples in place (after testing) are shown in Figure 27.



NOTES:

1. All aluminum assemblies made from same mill run of 2024-T81 bare sheet; all titanium assemblies from same mill run of 6Aℓ-4V annealed sheet.
2. Thicknesses shown are nominal.
3. All specimens and stiffeners rough cut 1/2" oversize, then machined to obtain dimensions shown.
4. All edges deburred prior to assembly.
5. Rivet, two places, flush with sheet surface; buck on stiffener side; use MS20426(AD)(4)-(5) rivet for aluminum specimens; MS20427M4C-5 rivet for titanium specimens.
6. Chemically clean all titanium parts before assembly.

Figure 26. Test Specimen Design

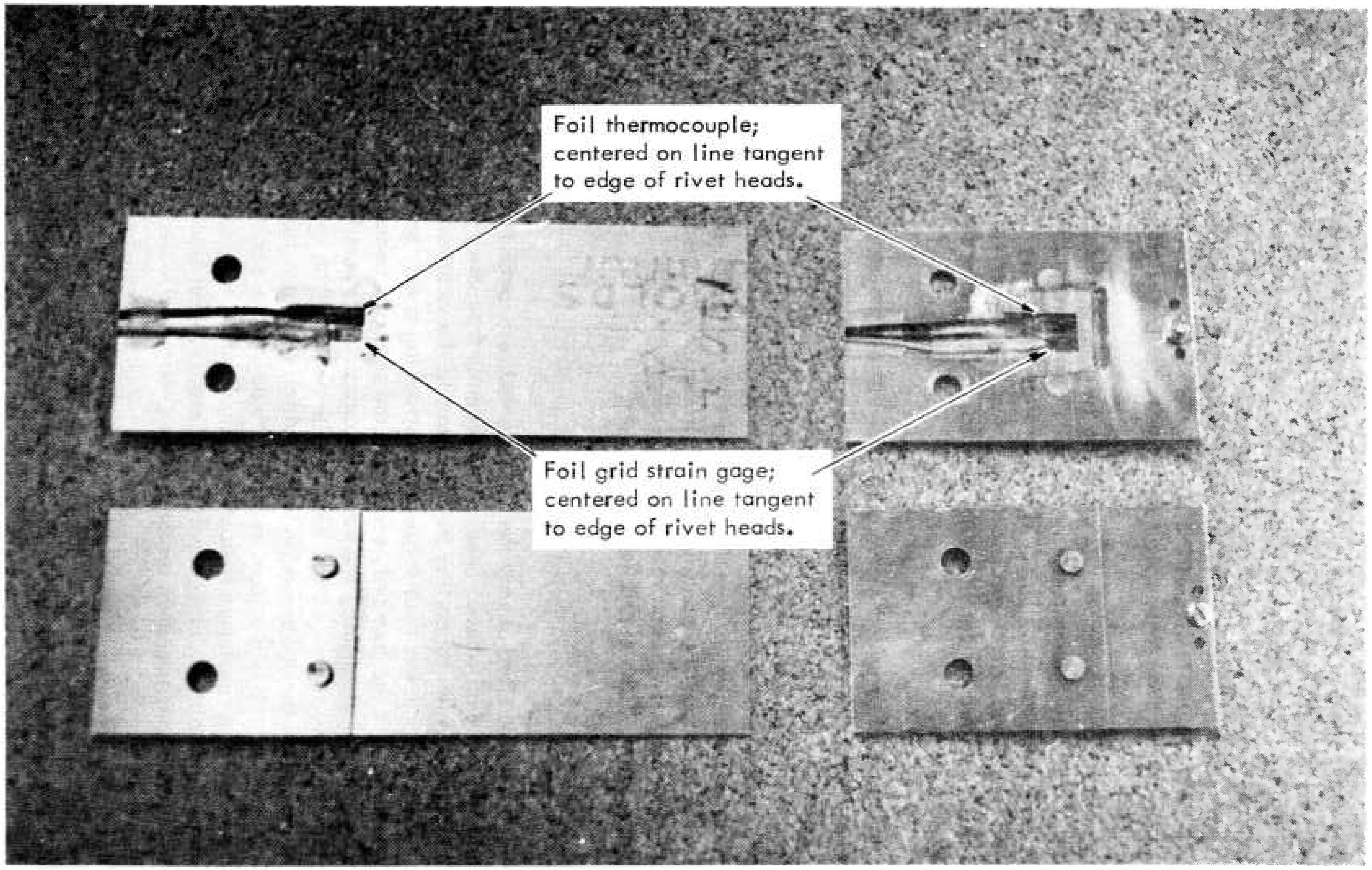


Figure 27. Strain Gage And Thermocouple Installations On Long And Short Specimens

4. TEST SETUP

The test specimens were vibrated at flexural resonance as clamped-free cantilever beams. The excitation was applied at the clamped end with conventional electromagnetic vibrators. The specimens were usually tested in groups of three, using two independent exciter systems to test two groups simultaneously. One exciter was used for room temperature tests, the other for elevated temperatures. In the case of room temperature testing at low stress levels (commensurate with 10^9 cycles to failure), six rather than three specimens were tested simultaneously.

The arrangement of the specimens and clamping fixtures on the exciter are shown in Figures 28 and 29 for the room temperature case. An identical setup was used for elevated temperature testing. Standard analog type laboratory instruments were used for generating and filtering random and sinusoidal electrical signals to the vibrator amplifiers, and for conditioning and processing the acceleration, strain, and temperature data.

Specimen heating was provided by tungsten filament quartz lamps arranged to heat both the clamping fixture and the test specimens. The general arrangement was as shown in Figure 30. An enclosure was placed over the specimens and the quartz lamps as shown in Figure 31, in order to maintain surrounding air temperature close to the desired specimen temperature. Each elevated temperature specimen was fitted with a thermocouple to detect temperature at the region of maximum strain. The thermocouple output was continuously monitored on a strip-chart recorder. Specimen temperatures were controlled to $\pm 6\%$ of programmed levels by regulating the electrical power to the quartz lamps.

5. TEST PROCEDURE

The specimens were excited at only the fundamental resonance frequency using narrow-band random excitation. Specimen resonance frequency was set at approximately the desired value by cutting the specimen to the required length. Minor adjustment in frequency was then obtained by attaching a very small mass (1/16 inch screw and nut) to the free end, and filing the screw as necessary to make all specimens resonant at essentially the same frequency. This permitted setting the upper side of the excitation spectrum close to the peaks of the specimen response spectra, to maximize the lower margin within which specimen frequency could shift as failure progressed. It was seldom necessary to adjust the excitarion spectrum downward or specimen resonance frequency upward during the course of testing a group of specimens, although this capability existed. When it was necessary, care was taken to insure that specimen response levels were unaffected.

Each group of three specimens was tested at a strain level calculated to produce failure at either 10^6, 10^7, 10^8, or 10^9 cycles. The specimen strain level was sensed by a uniaxial strain gage arranged as the active resistor in a balanced four-arm

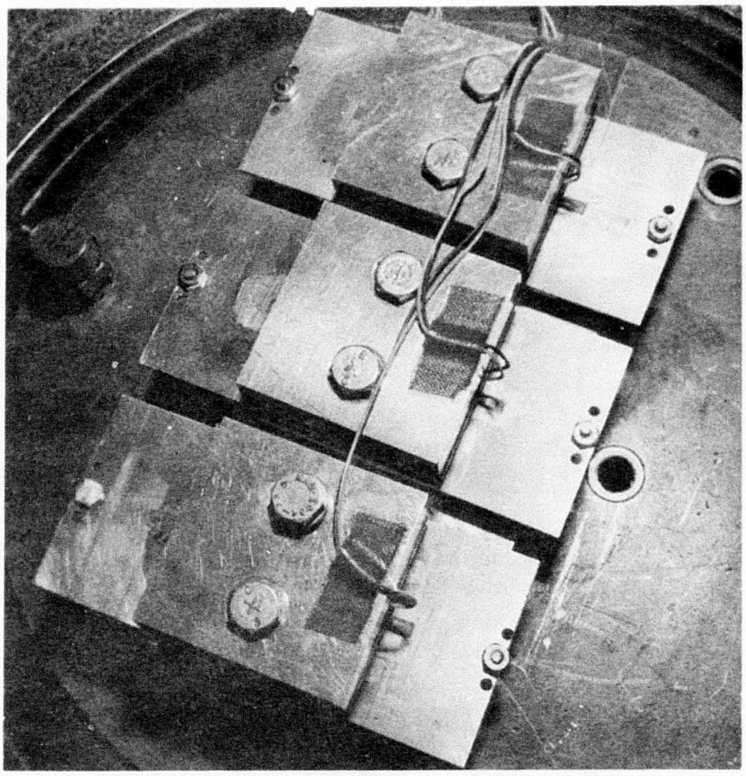


Figure 28. Six High Frequency Test Specimens Mounted For Room Temperature Fatigue Testing

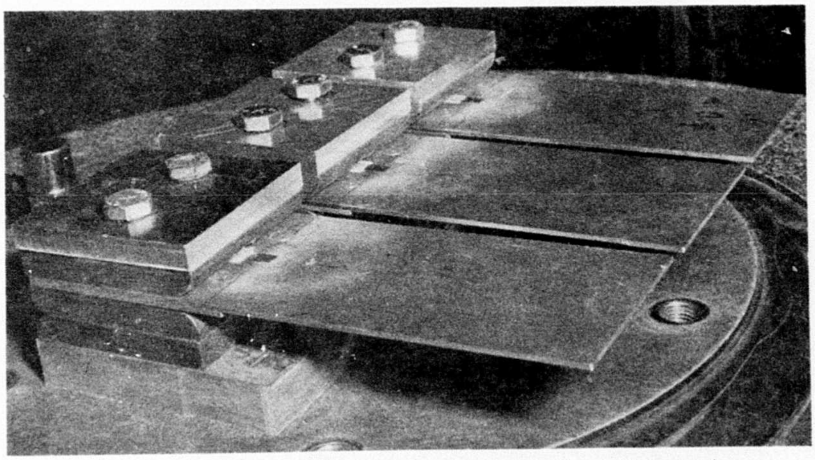


Figure 29. Three Low Frequency Test Specimens Mounted For Room Temperature Fatigue Testing

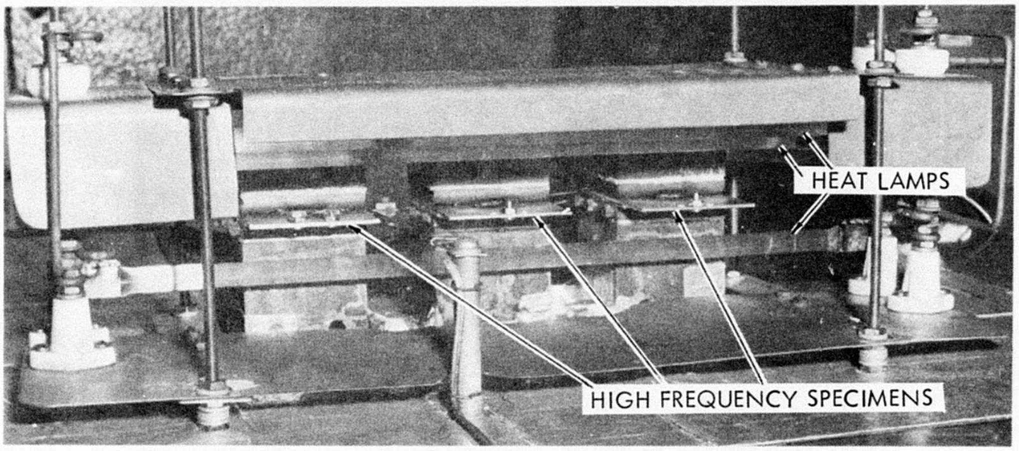


Figure 30. High Frequency Test Specimens Mounted For Elevated Temperature Fatigue Testing - Enclosure Removed

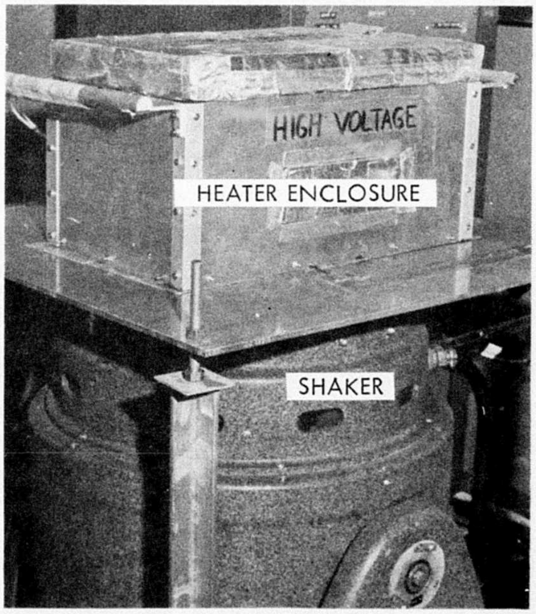


Figure 31. Elevated Temperature Fatigue Test Setup

bridge; the root-mean-square voltage change across the bridge then being proportional to the rms strain in the specimen. This rms level was monitored on a meter having a very long averaging time, suitable for the specimen response frequency and bandwidth. An accelerometer was installed on the exciter head near the specimen clamp blocks for measuring and controlling excitation level.

The test cell was airconditioned throughout the tests in order to maintain 75° to 80°F in the room temperature specimens. The elevated temperature specimens were heated to the correct temperature and allowed to stabilize before beginning the random excitation.

Resonance scans were made at frequent intervals to determine specimen resonance frequency, and to identify changes in frequency with cumulative test time. Spectrum analyses were also made regularly to determine response frequency. The resonance scans were usually made at increments of about 5 percent of specimen life. Since the random response was sometimes nonlinear, the sinusoidal excitation level used for the resonance scans was initially chosen so as to yield the same response frequency as was obtained from the spectrum analyses, and then kept the same for all resonance checks.

The strain cycles induced during each interval were obtained from the products of response frequency and elapsed time. These were accumulated as the tests progressed, to maintain a cumulative total of the strain cycles for each specimen. The tests were continued until failure was either visable or evident from the degree of frequency change.

6. SUPPLEMENTARY TEST RESULTS

Prior to beginning the coupon fatigue tests, limited investigations were made to validate the test procedures. One set of 3 specimens was fitted with strain gages and thermocouples, and vibrated at various combinations of resonance frequencies and amplitudes in order to determine temperature rise attributable to working. It was found that temperature rise was negligible; that additional cooling would not be necessary for high frequency room temperature testing. The maximum temperature rise was less than 10°F, as measured at the surface of a titanium specimen with a 1/8" x 3/8" thermocouple grid.

The degree of torsional response expected to be encountered was checked on another set of 3 specimens. The specimens were fitted with a strain gage at each side, and excited at resonance for various lengths with distributed mass and concentrated mass. Resonance frequency ranged from 80 Hz to 1670 Hz. Phase angle between the two gage signals was observed with sinusoidal excitation, and level ratio was observed with random excitation. The maximum phase deviation was 15°, the maximum variation in level ratio was 4.5%, both being negligible. This does not attest to an absence of torsional resonance; it simply shows that very little rocking motion was present at the exciter head to induce torsional response, and that bending and torsional resonance were uncoupled.

The variation in temperature among the three specimens in a set was checked for aluminum at 250°F, and titanium at 600°F. It was found that temperatures varied considerable from one set to another, with the same heater arrangement and power setting. This was found to be due to variation in heat transfer at the mating surfaces between the specimens and clamp blocks. Balanced specimen temperatures were obtained by insulating the specimens from the clamp blocks with asbestos.

Amplitude probability distribution analyses were made of excitation and response signals for both high and low frequency specimens to verify test consistency. The excitation signal amplitude distribution was determined to be correctly gaussian or "normal" and consistent for all test levels and frequencies. The response signal amplitude distribution was also found to be consistent with level and frequency, and was reasonably "normal" with a small degree of bias due to the one-direction "spring hardening" effect of the doubler.

Upon completing these and other validation tests and investigations, the high cycle fatigue tests were begun. Examples of the excitation and response spectra obtained "on-line" during the course of fatigue testing are shown in Figures 32 and 33. These examples are typical of all spectra. The excitation spectra were essentially flat, and exciter motion was nearly pure vertical translation. Despite these ideal conditions, there was always some vairation in strain level among the specimens in any given set, due to normal assembly, instrumentation, and installation tolerances. Thus each specimen was strain gaged and monitored. The desired test strain level was established at the start of each test, and correlated with excitation level after response level and frequency had stabilized. Thereafter, excitation level was held constant, and response was allowed to vary as the test progressed. A sample plot of specimen strain versus number of cycles is shown in Figure 34. Response frequency of course decreased as fatigue damage accumulated, as also shown in Figure 34 for the same specimen. Usually, the region of constant strain was consistent with the region of constant frequency, as exemplified in Figure 34. A reduction in frequency often occurred first, and was soon followed by an increase in strain. The "test" strain level for which fatigue life was ultimately plotted, was that "constant" strain level (calculated average of the values) that existed until the frequency began to decrease.

In most cases, the specimens were tested until a fatigue crack was visible on the exposed surface using 10X magnification. All failures consisted of cracks in the skin sheet on the rivet row, usually originating at the rivet holes. No cracks occurred in the substructure (doubler); no rivets failed; no cracks occurred in the sheet at the end of the doubler. This type of riveted structure in flexure incurs the highest tensile strain during the half-cycle of bending away from the supporting substructure, so failure initiates in the concealed side of the specimen, usually at the rivet hole, and progresses through to the opposite surface. Thus, the fatigue damage is relatively extensive by the time it becomes visible, and a criteria more realistic than visual observation was needed to define failure. Since frequency was observed

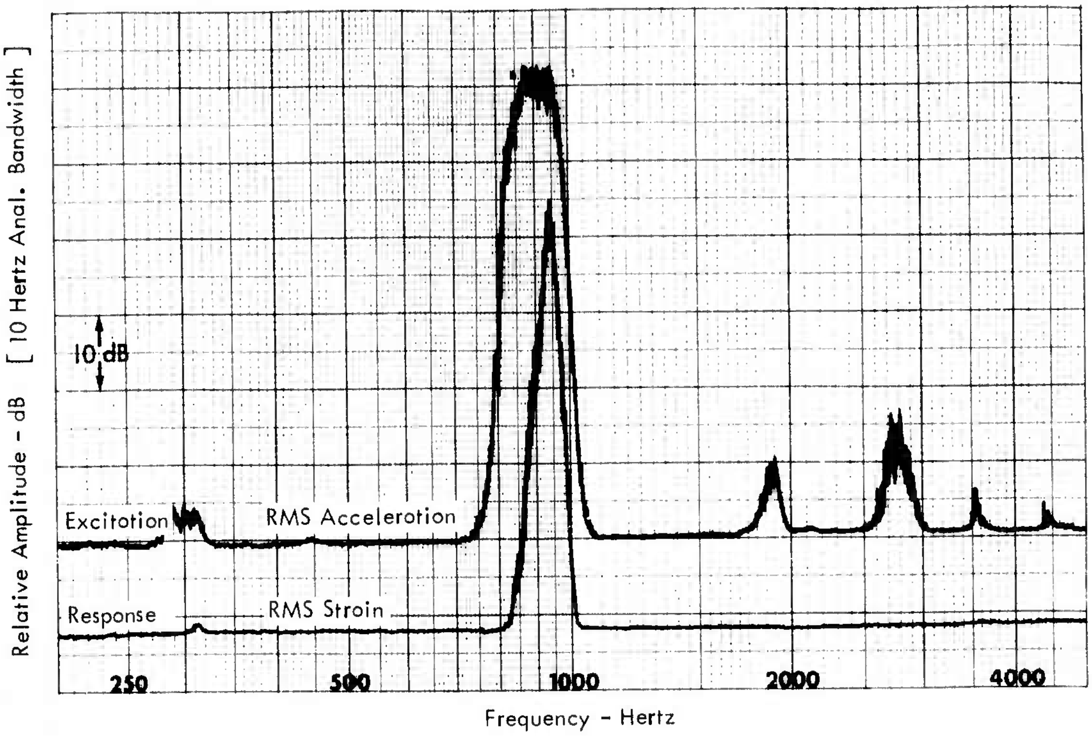


Figure **32**. Typical Excitation and Response Spectra For High Frequency Specimens

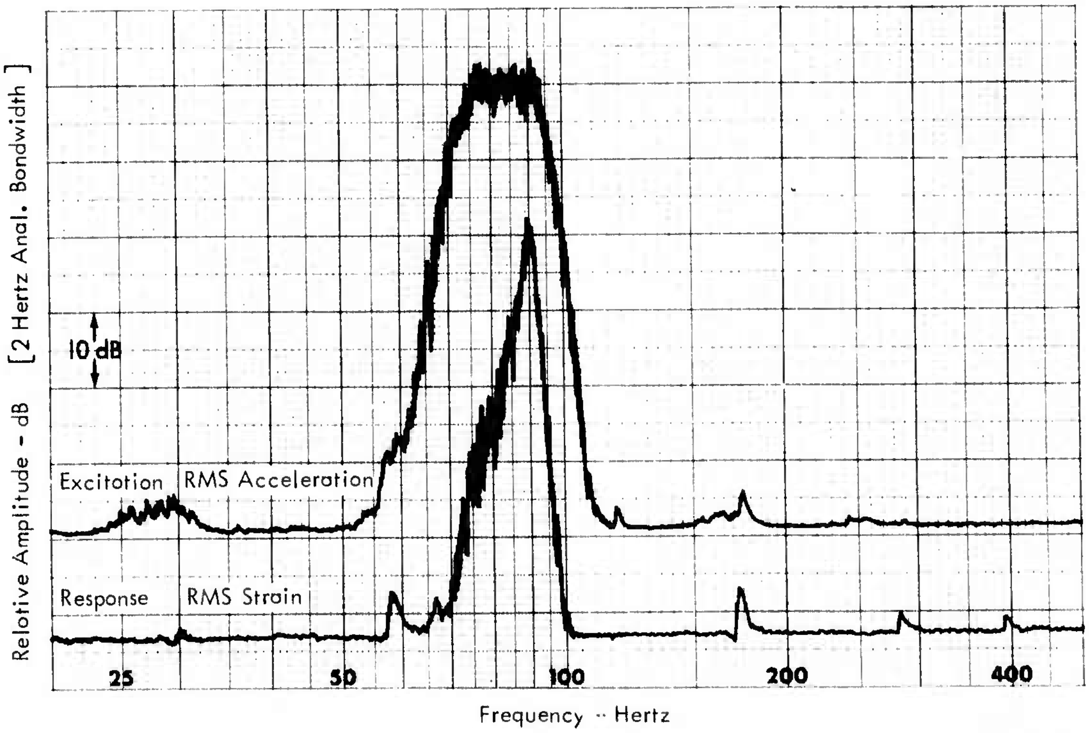


Figure **33**. Typical Excitation and Response Spectra For Low Frequency Specimens

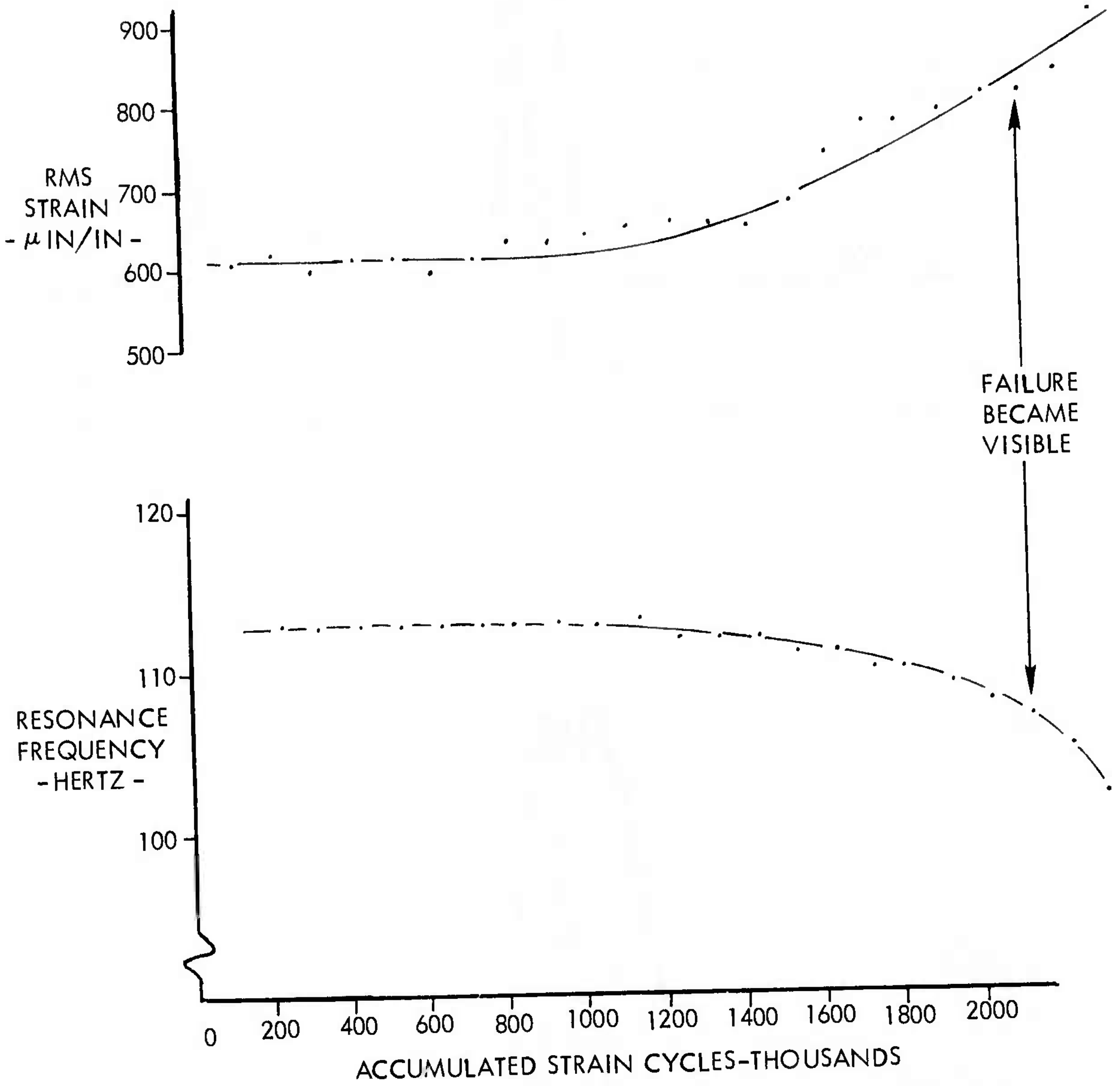


Figure 34. Effect of Accumulated Cycles On Resonance Frequency and Response Strain

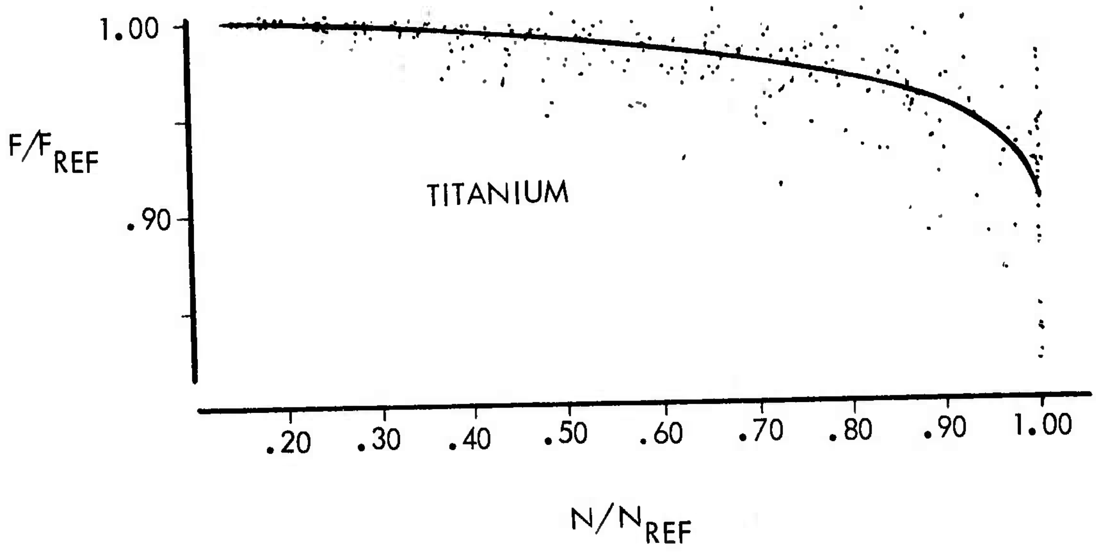
to be more sensitive to damage accumulation than was strain level, it was used as an indicator of failure. Other alternate methods of quantifying cycles to failure, and failure itself, were considered but not used because of the cost and complexity they would have added to the program.

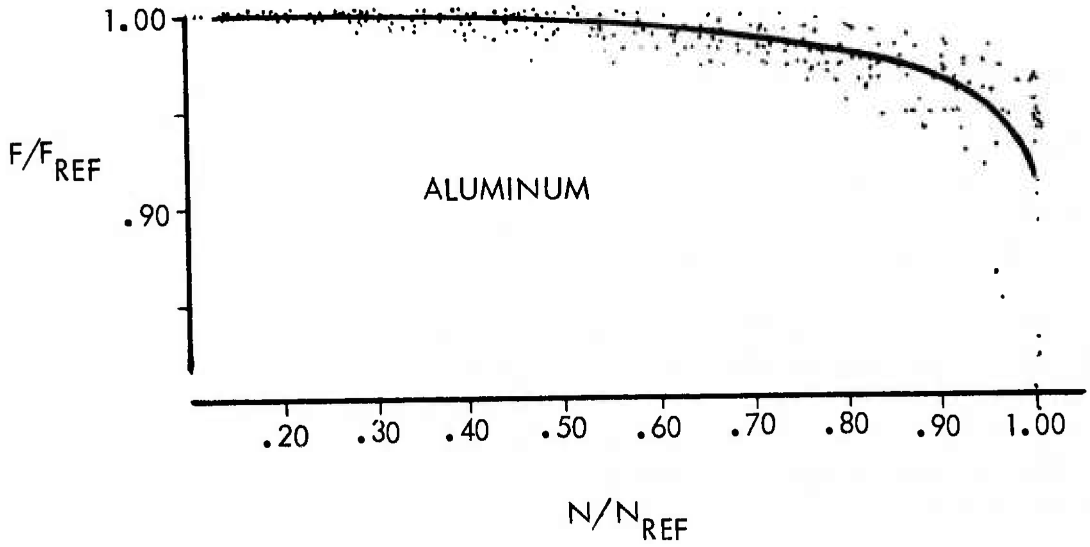
Having selected resonance frequency change as an indicator of damage accumulation, it then remained to quantify the degree of frequency change which constituted specimen failure. A plot of frequency versus strain cycles was made for each specimen, and the "heel" or "knee" of the curve was identified where the rate of failure progression was obviously increasing. This point, in terms of frequency ratio (percent change in frequency), was found to vary widely among specimens, and was therefore unsatisfactory for quantifying failure on an individual specimen basis. These values of frequency ratio were then averaged for all specimens of like material. The results indicated that the average "knee" in the frequency versus cycles curve occurred at a frequency of 96% of the initial frequency for titanium, and at 97% of the initial frequency for aluminum. These values were considered conservative indicators of failure, because the "heel" in the curves occurred well before cracking was visible. And since cracks originating at one rivet hole were often already visible before cracking had originated at the other hole, the structure was still far from catastrophic failure. Thus, on the liberal side, a case could be made for using the frequency change corresponding to visible crack detection as the failure criterion. Using this approach, the mean frequency at which cracking became visible was 90.2% of starting frequency for titanium and 93.2% for aluminum.

A compromise approach is plausible - establishing failure as the frequency change corresponding to some lesser probability of visibly detecting failure. Assuming a normal distribution of frequency ratios about the mean value at visible detection of failure, the frequency change corresponding to 80% confidence (20% probability that failure would be visible) was computed to be 94.4% of starting frequency for titanium, and 96.4% for aluminum.

Another approach to quantifying failure involved plotting all resonance frequency data on a single conglomerate plot of the type shown in Figure 35, establishing a mean line through the data, and selecting the point on the mean line which constituted failure. It was determined that on the average, resonance frequency was nearing an abrupt change when frequency ratio was about .94 for aluminum, and .93 for titanium.

As a result of all of these exercises in establishing a reasonable criterion for failure, the best compromise was concluded to be: define failure as the point at which resonance frequency has decreased to 96% of initial frequency for aluminum, and 94% of initial frequency for titanium, or the point at which cracking was visible, whichever occurred first.





Note: $F/F_{REF} = \frac{\text{Resonance Frequency at N Cycles}}{\text{Initial Resonance Frequency}}$

$N/N_{REF} = \frac{\text{Accumulated Strain Cycles}}{\text{Strain Cycles to Failure}}$

Figure 35. Composite of Resonance Frequency Change With Strain Cycles, For All Test Specimens

7. PRINCIPLE TEST RESULTS

The significant data for all specimens tested is summarized in Figures 36 and 37. The stress levels in these figures are the product of strain and modulus of elasticity, the latter obtained from MIL-HDBK-5B.(5) Fatigue curves developed from these data are shown in Figures 38 and 39, and are conventional in all respects. The mean line (method of least squares) and statistical confidence limits (Student's T distribution) are provided in each case. The S-N curves show clear evidence of flattening in the region of 10^9 cycles. However, further testing beyond 10^9 cycles would be necessary to establish the random flexural endurance limits, and whether they exist. A summary comparison of the mean lines for the four test cases is shown in Figure 40.

From the aluminum S-N curves it is clear that the effect of 250°F temperature is slight. This might be expected if elevated temperature effects on fatigue life were expected to be similar to the effects of elevated temperature on yield strength. The effect of temperature on yield strength is shown in Figure 41 for 2024-T3 (from MIL-HDBK-5). From Figure 41, 2024-T3 yield strength is reduced about 8.5% at 250°F and fatigue strength is reduced about 20% at 250°F.

For 2024-T81, yield strength at 250°F is reduced about 6%, and if the trend is similar to that for T-3, fatigue strength would be expected to be reduced about 14%. From Figure 40, the reduction in fatigue strength (at 10^7 cycles) is noted to be only about 5%. Thus the fatigue strength of T-81 is apparently following the trend of the yield strength curve more closely than is the T-3 material. This indicates that temperatures between ambient and 250°F have negligible effect on fatigue life. However, above 250°F the fatigue strength could be expected to deteriorate more rapidly with temperature, as evidenced by the slope of the T-81 yield strength curve. However, this is conjecture and should be validated by test. For 6Aℓ-4V titanium, the effect of 600°F temperatures on fatigue life is more pronounced, as would be expected from Figure 41, which shows temperature effects on yield and fatigue strengths for both annealed and solution treated/aged titanium. (In both the aluminum and titanium cases, the fatigue strength data is for constant amplitude axial load conditions.) While Figure 41 shows a reduction in fatigue strength at 600°F of about 12%, the random flexure test data in Figure 40 show a reduction of about 22%. However, if the trends are similar, the effect of temperature on fatigue strength would be expected to be appreciable at any temperature above ambient, and increasingly significant above 600°F. Here again, this conjecture should be validated.

In Figures 38 and 39, the various test frequencies have been identified, and no appreciable effect of frequency is evident. Evidence is available in the literature to either support or refute the argument that test frequency should affect fatigue life. However, such an exercise or discussion is beyond the scope of this report. It should be noted that while no frequency effect is obvious, small effects, if present, would not be discernible.

ITEM	TEST TEMPERATURE	TEST FREQUENCY	TEST STRAIN	MODULUS OF ELASTICITY	TEST STRESS	CYCLES TO FAILURE
#	°F	Hertz	μ in./in.	10^6 lbs./in.^{2}	lbs./in.^{2}	Quantity N
1	80	113	892	10.5	9370	5.49×10^5
2	80	109	882	10.5	9260	4.15×10^5
3	80	111	863	10.5	9060	5.89×10^5
4	80	112	637	10.5	6690	1.50×10^6
5	80	113	608	10.5	6380	1.74×10^6
6	80	109	608	10.5	6380	2.15×10^6
7	80	111	597	10.5	6270	1.64×10^6
8	80	113	560	10.5	5880	2.56×10^6
9	80	112	532	10.5	5590	4.04×10^6
10	80	479	250	10.5	2630	4.7×10^7
11	80	473	244	10.5	2560	5.7×10^7
12	80	472	210	10.5	2200	9.02×10^7
13	80	898	150	10.5	1550	2.04×10^9
14	80	881	142	10.5	1490	8.95×10^8
15	80	894	134	10.5	1410	1.04×10^9
16	80	866	131	10.5	1380	2.0×10^9
17	80	897	127	10.5	1330*	$2.04^{*} \times 10^9$
18	80	877	113	10.5	1190	1.80×10^9

* Specimen did not fail.

Figure 36. Test Data Summary - Aluminum Specimens (Sheet 1 of 2)

ITEM	TEST TEMPERATURE	TEST FREQUENCY	TEST STRAIN	MODULUS OF ELASTICITY	TEST STRESS	CYCLES TO FAILURE
#	°F	Hertz	μ in./in.	10^6 lbs./in.^{2}	lbs./in.^{2}	Quantity N
19	250	106	837	10.1	8450	6.44×10^5
20	250	109	756	10.1	7640	8.34×10^5
21	250	111	663	10.1	6700	6.66×10^5
22	250	109	447	10.1	4510	5.25×10^6
23	250	112	425	10.1	4290	1.16×10^7
24	250	111	358	10.1	3620	1.43×10^7
25	250	735	250	10.1	2530	1.63×10^8
26	250	745	217	10.1	2190	6.65×10^7
27	250	758	203	10.1	2050	1.12×10^8
28	250	944	150	10.1	1510	2.02×10^9
29	250	920	130	10.1	1310	6.59×10^8
30	250	943	128	10.1	1290	3.94×10^8
31	250	948	125	10.1	1260	2.14×10^9

Figure 36. Test Data Summary - Aluminum Specimens (Sheet 2 of 2)

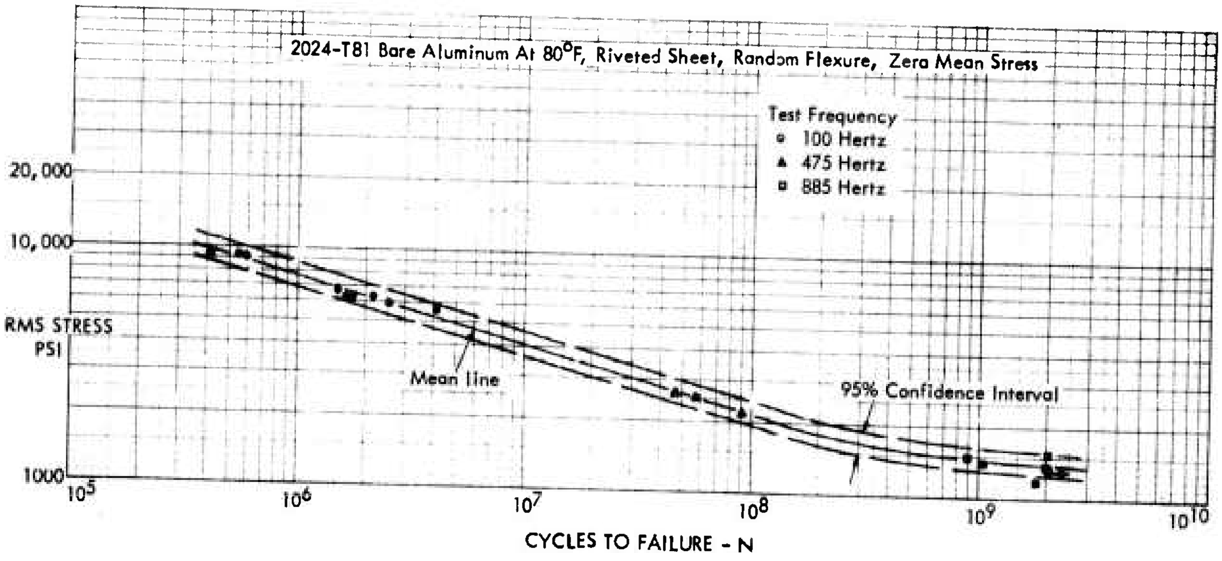
ITEM	TEST TEMPERATURE	TEST FREQUENCY	TEST STRAIN	MODULUS OF ELASTICITY	TEST STRESS	CYCLES TO FAILURE
#	°F	Hertz	μ in./in.	10^6 lbs./in.^{2}	lbs./in.^{2}	Quantity - N
1	80	117	1113	16.0	17,800	1.04×10^6
2	80	116	1094	16.0	17,500	1.3×10^6
3	80	118	994	16.0	15,900	8.3×10^5
4	80	95	662	16.0	10,600	7.9×10^6
5	80	94	625	16.0	10,000	5.8×10^6
6	80	94	625	16.0	10,000	6.4×10^6
7	80	517	407	16.0	6,510	3.6×10^7
8	80	517	397	16.0	6,350	3.3×10^7
9	80	700	257	16.0	4,110	2.59×10^8
10	80	647	247	16.0	3,950	1.11×10^9
11	80	717	246	16.0	3,930	6.07×10^8
12	80	645	239	16.0	3,830	1.92×10^8
13	80	723	239	16.0	3,820	1.61×10^8
14	80	708	214	16.0	3,420	2.83×10^8
15	80	737	197	16.0	3,150	1.67×10^9
16	80	739	193	16.0	3,090	9.83×10^8

Figure 37. Test Data Summary - Titanium Specimens (Sheet 1 of 2)

ITEM	TEST TEMPERATURE	TEST FREQUENCY	TEST STRAIN	MODULUS OF ELASTICITY	TEST STRESS	CYCLES TO FAILURE
#	°F	Hertz	μ in./in.	10^6 lbs./in.^{2}	lbs./in.^{2}	Quantity - N
17	600	102	1031	13.1	13,500	1.21×10^6
18	600	103	893	13.1	11,700	1.94×10^6
19	600	105	855	13.1	11,200	2.22×10^6
20	600	102	541	13.1	7,090	1.25×10^7
21	600	106	449	13.1	5,880	1.80×10^7
22	600	102	384	13.1	5,030	3.62×10^7
23	600	460	335	13.1	4,390	4.3×10^7
24	600	458	313	13.1	4,100	2.56×10^8
25	600	479	311	13.1	4,080	1.22×10^8
26	600	698	231	13.1	3,690	1.71×10^8
27	600	665	211	13.1	3,370	1.56×10^8
28	600	692	192	13.1	3,070	1.33×10^9
29	600	687	183	13.1	2,930	8.81×10^8
30	600	702	150	13.1	2,400 *	$1.36^* \times 10^9$

* Specimen did not fail.

Figure 37. Test Data Summary - Titanium Specimens (Sheet 2 of 2)



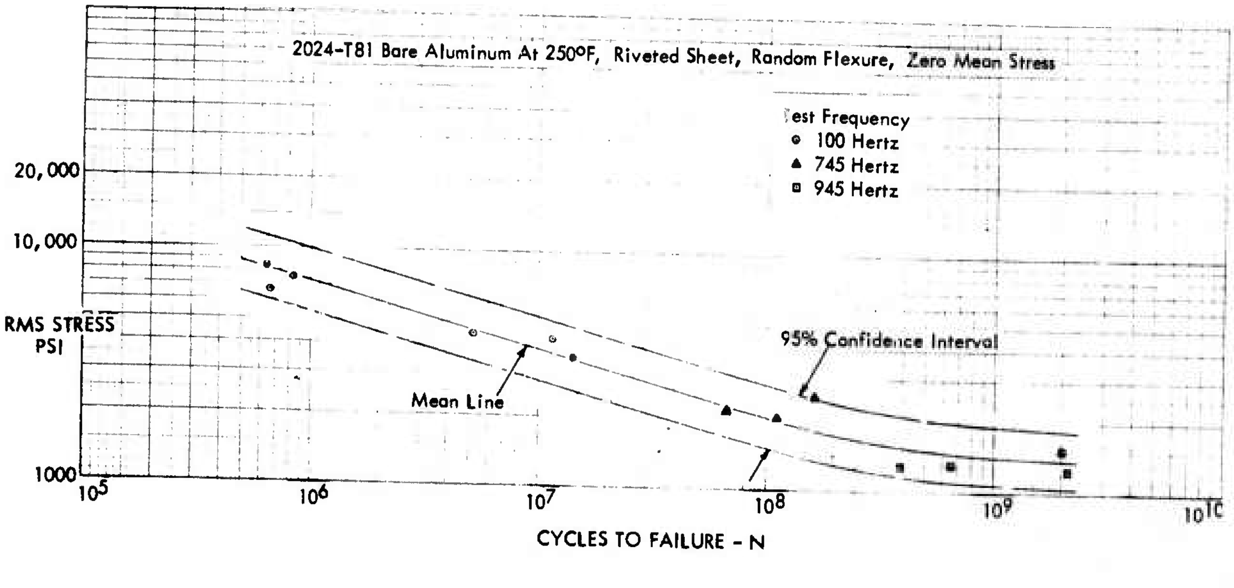


Figure 38. Fatigue Test Results For Aluminum

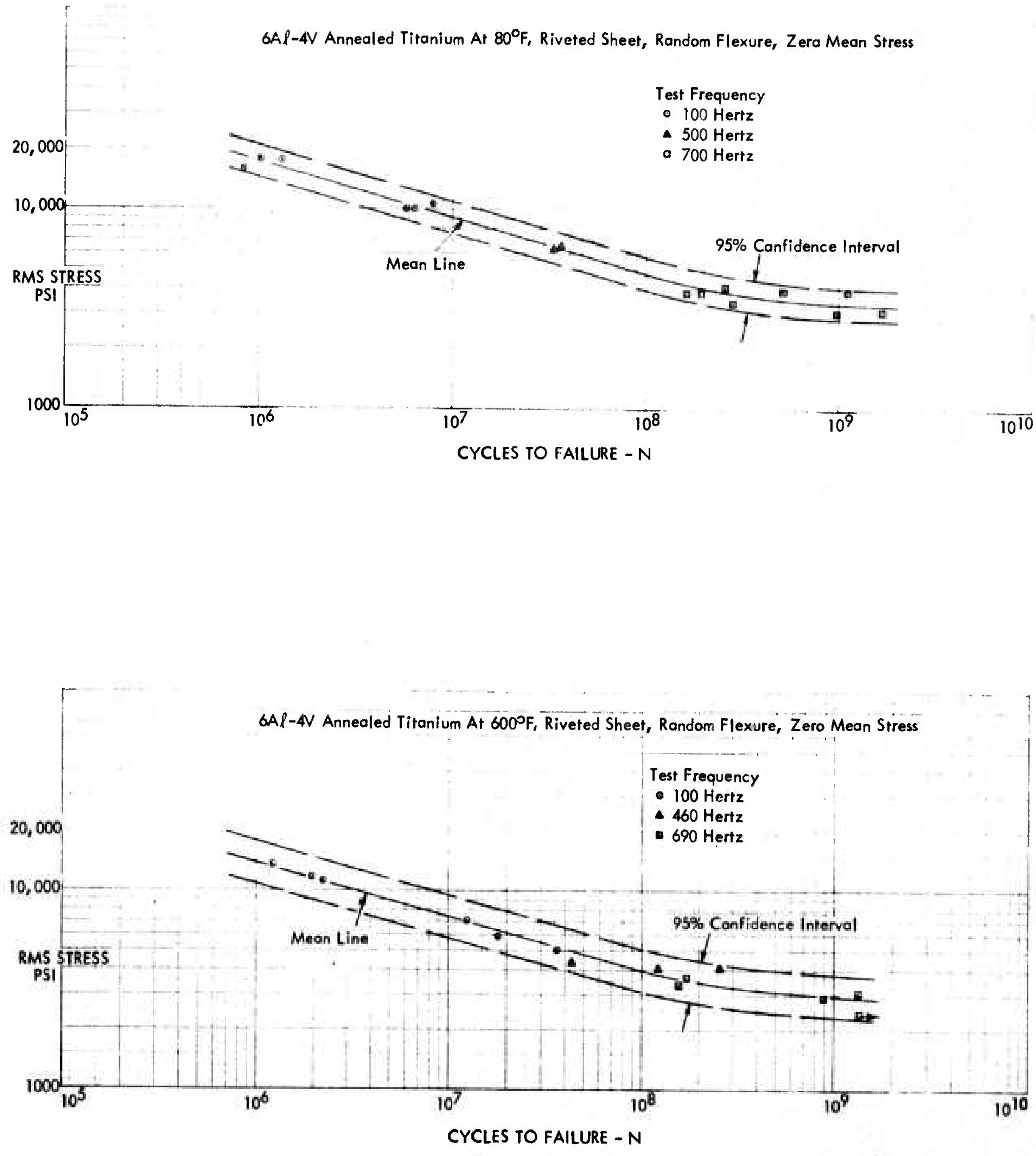


Figure 39. Fatique Test Results For Titanium

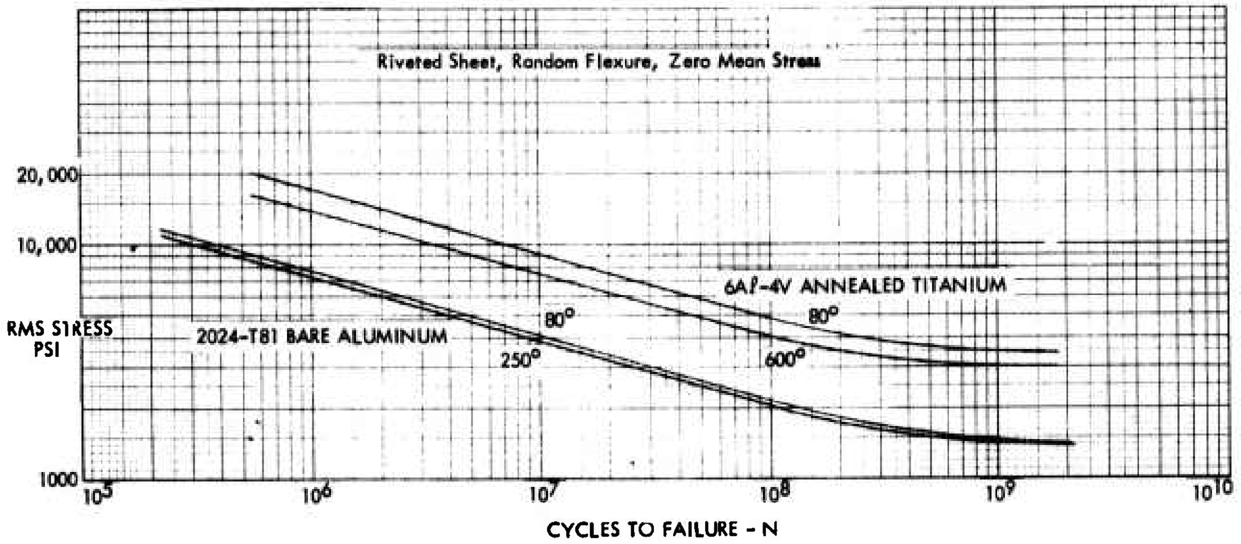
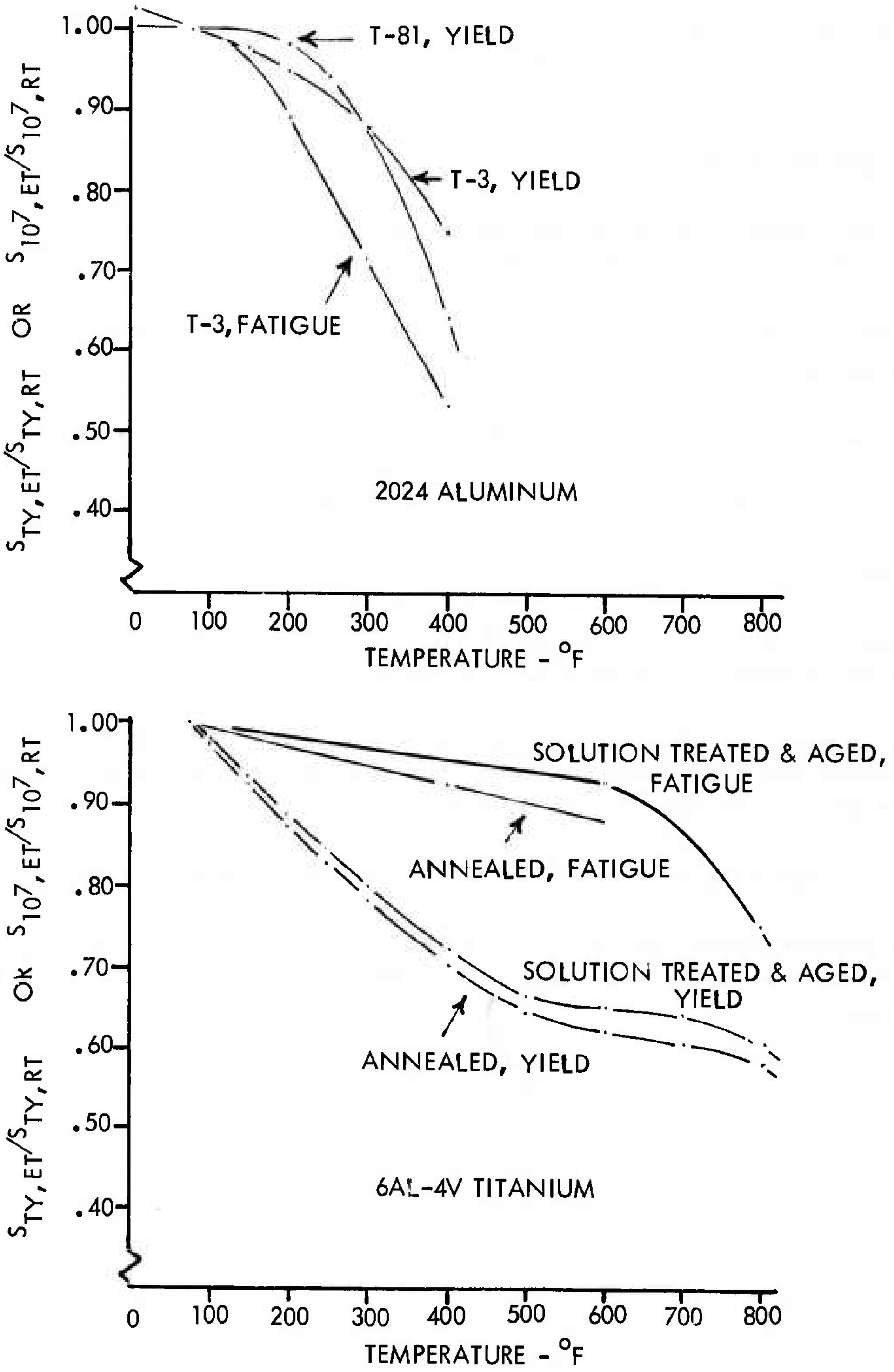


Figure 40. Summary Comparison of Fatigue Curves



Note: $S_{TY,ET}/S_{TY,RT} = \dfrac{\text{Tensile Yield Strength at Elevated Temperature}}{\text{Tensile Yield Strength at Room Temperature}}$

$S_{10^7,ET}/S_{10^7,RT} = \dfrac{\text{Fatigue Strength at } 10^7 \text{ Cycles for Elevated Temperature}}{\text{Fatigue Strength at } 10^7 \text{ Cycles for Room Temperature}}$

Figure 41. Comparison of Temperature Effects on Yield and Fatigue Strengths

In the interest of extending the range of the test results, the S-N data have been combined with the relatively meager data available from other sources, and the mean line and statistical confidence limits recomputed, as shown in Figures 42 and 43.

8. OBSERVATIONS

There is evidence of an endurance limit in both the aluminum and titanium S-N curves, but the curves are still trending downward at 2 x 10^9 cycles.

The slopes of the S-N curves were approximately the same for aluminum and titanium, and on a log-log basis, were about -0.28.

There was no obvious effect of test frequency evident in the S-N curves.

After initial stabilization, a four percent reduction in resonance frequency was judged to constitute failure for the aluminum specimens; a six percent reduction for titanium.

The normal variation in response level among three to six specimens in a gang test was found to necessitate a strain gage on every specimen.

It was necessary to tailor the heat sink insulation for each elevated temperature specimen in order to balance specimen temperatures. This also dictated a thermocouple on each elevated temperature specimen.

There was negligible influence of torsional motion on specimen response.

It was observed during the high cycle fatigue tests that the largest increase in mean surface temperature due to flexure was less than 10°F in the high strain region of the specimen.

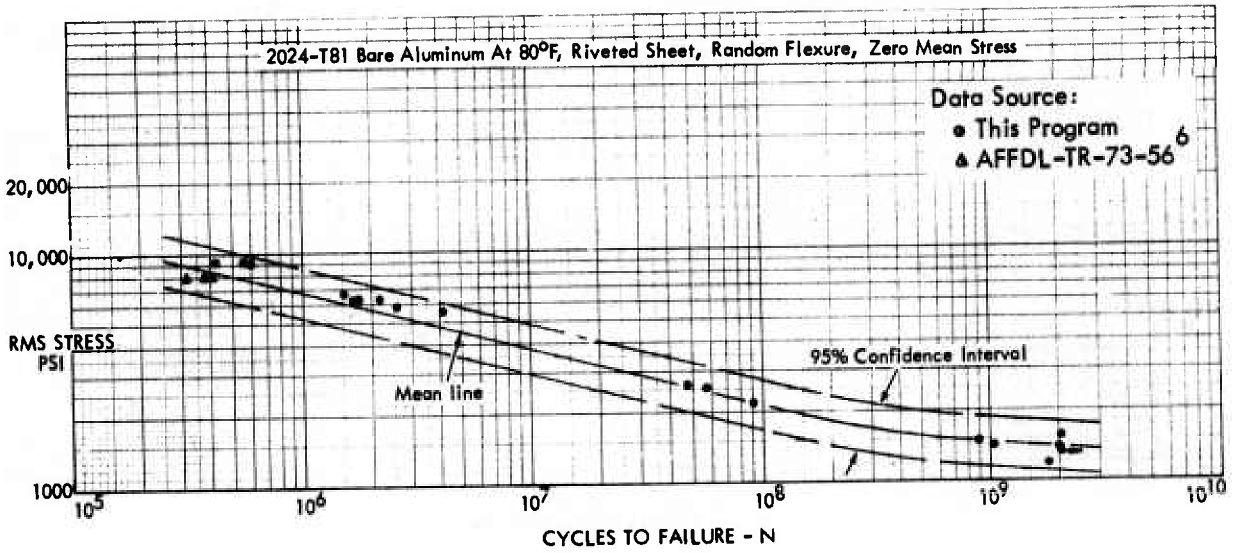


Figure 42. Combined S-N Data For Aluminum

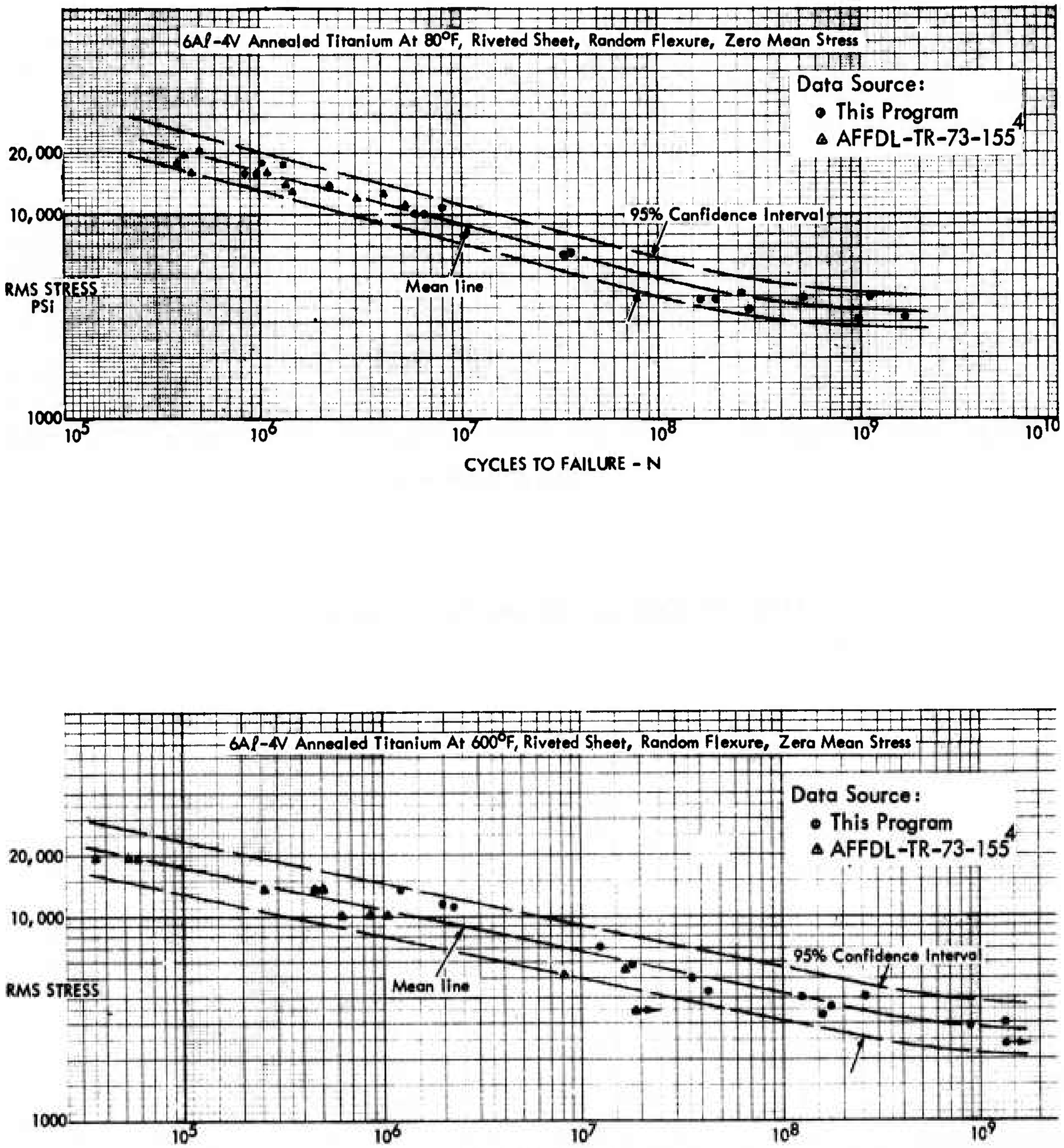


Figure 43. Combined S-N Data For Titanium

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