29 February 1968

Materiel Test Procedure 5-2-586
White Sands Missile Range

U. S. ARMY TEST AND EVALUATION COMMAND
COMMON ENGINEERING TEST PROCEDURE

CENTRIFUGE TEST PROCEDURES

1. OBJECTIVE

The objective of this (MTP) is to investigate the basic considerations and procedures to be followed in conducting a centrifuge test program.

2. BACKGROUND

The advent of high performance weapon systems and space programs in which components are subjected to sustained acceleration levels in combination with numerous other environmental conditions has caused centrifuge testing to become increasingly important. Test engineers are required to obtain answers to a multitude of problems in the laboratory before the flight or final test stage because of demands that program objectives be accomplished in the most expedient manner, and because of a lack of knowledge as to material and equipment response to complex environments and new areas of investigation.

Centrifuge testing is performed on components of a missile system to determine the effects of sustained acceleration forces. The forces to be applied must be comparable to, or in excess of, the forces the component will experience during flight. Performance characteristics and the tendency toward temporary or permanent failure from exposure to specified acceleration conditions may be primary objectives of a centrifuge test. Whether an item is to be tested to a brief, simple set of specifications or is to be subjected to a complex investigation in which the operational mode of the item and test conditions are programmed, careful consideration should be given the test objectives and the method by which they are to be attained.

3. REQUIRED EQUIPMENT

a. Applicable Centrifuge Device
b. Applicable Manufacturer's and Military Instructions and/or Specifications for Centrifuge and Test Specimen
c. Rigid Fixtures to attach test specimen to the centrifuge
d. Recording Systems
e. Signal Conditioning Equipment
f. Various Transducers for measurement of accelerations, strains, and Relative Displacement if needed
g. X-ray Machine, if needed

4. REFERENCES

A. Kaufman, A. B., Acceleration Generators, Instruments and Control Systems 33:240-5 F, 1960

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B. G-Accelerators, Handbook of Operation, Service and Maintenance, Genisco, Incorporated
C. Institute of Environmental Sciences, 1959 Proceedings, Annual Technical Meeting, April 22, 23, 24, 1959
D. Rogers, A., Physiological Effects of Acceleration, Scientific American, Feb. 1962
E. Harris, C. M. and Crede, C. E., Shock and Vibration Handbook, Vol. 2, McGraw-Hill Book Co., Inc.
F. Brown, R., Testing with a G-Accelerator, Instruments & Automation 28, 29 Sept. 1955
G. The Diesel-Powered Ballistic Centrifuge, ABL/X-69, Oct. 1961
H. Sources of General Reference Material:

1) Proceedings of the Institute of Environmental Engineers Symposia
2) Bulletins of Shock and Vibration Symposia
3) Technical Publications listed by Armed Services Technical Information Agency (ASTIA), Arlington Hall Station, Arlington 12, Va.

I. MTP 5-1-025, Structural Data Analysis Methods
J. MTP 5-1-028, Telemetry Methods
K. MTP 5-2-587, Photo-Stress Method of Structural Data Acquisition
L. MTP 5-2-506, Shock Test Procedures
M. MTP 5-2-507, Vibration Test Procedures

5. SCOPE

5.1 SUMMARY

This procedure describes the necessary particulars to be performed when a test specimen is subjected to steady state accelerations.

5.2 LIMITATIONS

None

6. PROCEDURES

6.1 PREPARATION FOR TEST

6.1.1 Preparation of Test Equipment

a. Determine the required test specifications to be applied to the test specimen (see Appendix A).

b. Determine the centrifuge to be used (see Appendix B).

c. Determine the type and instrumentation required and the appropriate calibration as described in references 4A and 4F and Appendix C.

d. Determine the extent of testing to be performed as described in Appendices A, B, and C using the criteria of Appendix D.

6.1.2 Preparation of the Test Item

a. Ascertain that the test specimen's physical characteristics are in accordance with specified requirements, and visually inspect the test item for physical damage or corrosion.

b. Fasten the test item to the centrifuge by means of fixture as described in Appendix E and record the distance from the specimen centermass to centrifuze center.

c. Mount the required instrumentation.

6.2 TEST CONDUCT

Centrifuge tests shall be conducted as follows:

a. Operate the test specimen in a normal manner, when applicable.

b. Apply power to the centrifuge and record the following, versus time in seconds, from the start:

1) Angular velocity indicated
2) Angular velocity corrected by means of calibration factor
3) Tangential acceleration produced by centrifuge at center of mass of the test specimen, computed using the corrected angular velocity
4) Normal acceleration produced by centrifuge at the center of mass of the test specimen, computed using the corrected angular velocity

c. Measure the test specimen's response using the criteria that the specimen continues to perform, as designed, satisfactorily.

d. Put test specimen in a non-operating state, when applicable, and record any unsatisfactory results.

e. At completion of centrifuge test, examine the test specimen for evidence of intermittent or catastrophic failure and record all observations (See Appendix F)

NOTE: In the case of complex test specimens visual inspection can be misleading and x-ray and/or other types of inspection may be necessary to detect catastrophic failure.

f. Steps a through d shall be repeated, as necessary to obtain maximum data completeness.

NOTE: This repetition must be performed if an intermittent failure is suspected (See Appendix F)

6.3 TEST DATA

6.3.1 <u>Preparation of Test Equipment</u>

a. Record the following:

1) The centrifuge used (manufacturer, model number, serial number, etc.)

2) Type and location of instrumentation for the test
3) Category of testing (centrifuge only, combined with environmental, vibration etc.)

b. Retain the centrifuge's calibration curve.

6.3.2 Preparation of the Test Item

Record the following for a test specimen:

a. Nomenclature
b. Model number
c. Serial number
d. Deviations from specifications
e. Observed physical damage
f. Method of mounting the specimen to the centrifuge
g. Distance from center of specimen mass to center of centrifuge

6.3.3 Test Conduct

Record the following:

a. Ambient temperature in °F
b. Indicated angular velocity in radians/sec
c. Corrected angular velocity in radians/sec
d. Tangential acceleration if ft/sec^2
e. Normal acceleration in ft/sec^2
f. Duration of centrifuge operation in minutes
g. Type of failure, if any (intermittent, catastrophic)
h. Response of specimen
i. For combined testing, as applicable:

1) Vibration data collected as described in MTP 5-2-507
2) Shock data collected as described in MTP 5-2-506

6.4 DATA REDUCTION AND PRESENTATION

Prepare a log book or folder for each system tested and record the results of the centrifuge test. Enter all pertinent data in this log such as mathematical calculations, test conditions, test parameters, intermittent or catastrophic failures, etc., that were obtained during the test. The log must be complete, accurate, and up-to-date, as the log may be used for future analysis of missile system components.

Upon completion of the test or termination due to failure, test results should be studied to arrive at conclusions and recommendations regarding the suitability of the test specimen for service use, or compliance with test specifications. (See Appendix F).

In this event of structural failures, the data obtained during the conduct of this procedure shall be analyzed and presented as described in MTP 5-1-025.

The extent of evaluation with respect to the centrifuge forces usually will be limited to comparing the actual or theoretical estimations with the manufacturer's specifications and/or the military requirements imposed by the intended usage.

GLOSSARY

1. Acceleration: A vector quantity specifying the time rate of change of velocity.
2. Acceleration Buildup: A change of acceleration with time in which the acceleration is increasing.
3. Acceleration Decay: A change of acceleration with time in which the acceleration is decreasing.
4. Acceleration Envelope (Profile): A portrayal of acceleration conditions in which a line is used to describe acceleration versus time characteristics (a profile line).
5. Acceleration, Normal: The time rate of change of the direction of velocity.

$$a_n = \frac{V^2}{r} = V\frac{d\theta}{dt} = r\left(\frac{d\theta}{dt}\right)^2$$

where:

θ = angular displacement of the rotating centrifuge arm

$\frac{d\theta}{dt} = \omega$ = centrifuge arm rotational velocity

r = radius of gyration

V = tangential velocity

6. Acceleration Range: The range through which the centrifuge can be operated and controlled to supply sustained acceleration.

7. Acceleration, Tangential: The time rate of change of the magnitude of velocity.

$$a_t = d\frac{(r\omega)}{dt} = r\left(\frac{d\omega}{dt}\right) = r\alpha$$

(r and ω are defined under the definition of normal acceleration).

8. Balancing: The procedure for adjusting the mass distribution of a rotor so that the forces on the bearings are reduced or controlled. The centrifuge design may provide for static balance only, or it may include automatic dynamic balance, a feature by which the forces due to the masses at opposite ends of the rotating beam are adjusted to lie in the same plane.

9. Barricade: The enclosure within which a centrifuge arm rotates. The barricade may be for safety and/or for reducing aerodynamic effects.

10. Bracketry: The means by which the test object and associated equipment are supported on the centrifuge.

11. Center of Rotation: The axis about which the centrifuge arm rotates.

12. Centrifugal Force: The force tending to make rotating bodies move away from the center of rotation.

13. Counterweights: The weights which are used to obtain static balance of the centrifuge arm when a test item is installed at one end of the arm. On some centrifuges, static unbalance is indicated by illumination of a lamp.

14. Test Fixture: The means by which a test item is supported on the centrifuge.

15. Test Specimen, Test Item, or Test Object: A structural assembly of physical (mechanical, hydraulic, electrical, etc.) components. It may consist of a relatively simple configuration which performs a single function or it might consist of several components, each responsible in some way for the performance of the unit to be tested.

16. G: The gravitational unit which indicates the number of gravities of acceleration (acceleration in $\frac{ft/sec^2}{32.2}$ or acceleration in $\frac{in/sec^2}{386.4}$

17. Indicator Lamps: Lamps which indicate the equipment condition of operation.

18. Instrumentation: The use of, or work with, scientific devices associated with a test. Frequently used in the laboratory in conjunction with the installation and preparation of electrical equipment for a test.

19. Interlock Switches: Series connected electrical switches in the system to prevent the centrifuge rotor assembly from being started inadvertently.

20. Mounting Base or Leg Assembly: The supporting structure upon which the centrifuge rotor assembly rests.

21. Mounting Platform: The part of the centrifuge upon which the test object is installed. Sometimes referred to as a mounting pad or mounting plate.

22. Radius of Gyration: The distance from the axis of centrifuge arm rotation to the location on the test object where acceleration is required.

23. Radius of Gyration Chart or Conversion Chart: A chart which provides information on the rotational speed at which the centrifuge should be operated to produce a desired acceleration or G value on the test item when the radius of gyration is known.

24. Sliprings: Means by which electrical signals and power are transmitted between conductors on the rotating centrifuge arm and conductors on the centrifuge mounting base or supporting structure. They provide electrical connections between the test object and a stationary terminal board.

25. Tachometer Indicator: That part of the instrumentation for monitoring centrifuge arm rotational speed from which a visual indication of rpm may be obtained.

26. Test Parameters: The test conditions to which an object is exposed while being tested.

27. Transducer: A device which transmits power from one system into another system. Occasionally referred to as a pickup in the laboratory in the sense that the device converts a monitored action such as acceleration, velocity, or displacement into an intelligible signal, usually of the electrical type which is proportional to the parameter of interest.

28. Weight Capacity: The maximum dead weight recommended for installation on a centrifuge.

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APPENDIX A

TEST CONSIDERATIONS

1. TEST SPECIFICATIONS

The basic centrifuge test specifications may be originated by an agency responsible for the performance of an item, or by an agency responsible for investigating performance for acceptance or for other purposes. The nomogram shown in Figure A-1 is one of several methods of presenting acceleration, radius of gyration, and rotational speed so that centrifuge operating conditions may be selected to produce specified acceleration values. The specifications may define an acceleration value considered adequate for component proof testing or conditions may be required such that certain parameters are simulated. The generation of test specifications for a go, no-go type of test may be accomplished considering the test object as a black box about which little is known except the input and output requirements; however, the development of specifications for a test to determine optimum performance characteristics is enhanced by a knowledge of the construction and operational qualities of the item to be tested, as well as an appreciation of the degree of exposure of the item to environmental conditions experienced in actual use. The specifications for a centrifuge test usually include the operating conditions of the test item and the acceleration conditions to which the item may be exposed on a time basis. For simple tests, the g level may be stated as one or a series of sustained acceleration values required during specified periods of time. Specifications for more complex acceleration tests may define the g level versus time history for a period when the acceleration may vary at a specified rate.

Acceleration information is frequently presented in the form of an acceleration envelope or profile as shown in Figure A-2. By use of the profile, complex acceleration versus time histories may be shown in simple, easy to read, form. In addition to showing the basic acceleration characteristics, the profile may include tolerances associated with test conditions.

Test conditions such as those required for the simulation of flight environments experienced by missile components are often difficult or impossible to produce in the laboratory. (Figure A-3 shows the occurrence of sustained acceleration during flight.) The selection of equipment to produce these conditions may require careful consideration of the specified acceleration-time history and the associated tolerances since the specification may define test conditions which cannot be accomplished by use of the ordinary centrifuge. A machine not capable of producing and maintaining the g level within acceleration and time tolerances, specified for a particular test would not be acceptable. A quick inspection of an acceleration-time history such as that depicted by Figure A-2 may be sufficient for experienced personnel to determine whether the conditions can be met with existing equipment. The ability of centrifuge equipment to produce and maintain within specified limits, nonchanging sustained acceleration of the type depicted by the 6-g part of Figure A-2 may be determined easily by reference to performance data supplied with the centrifuge.

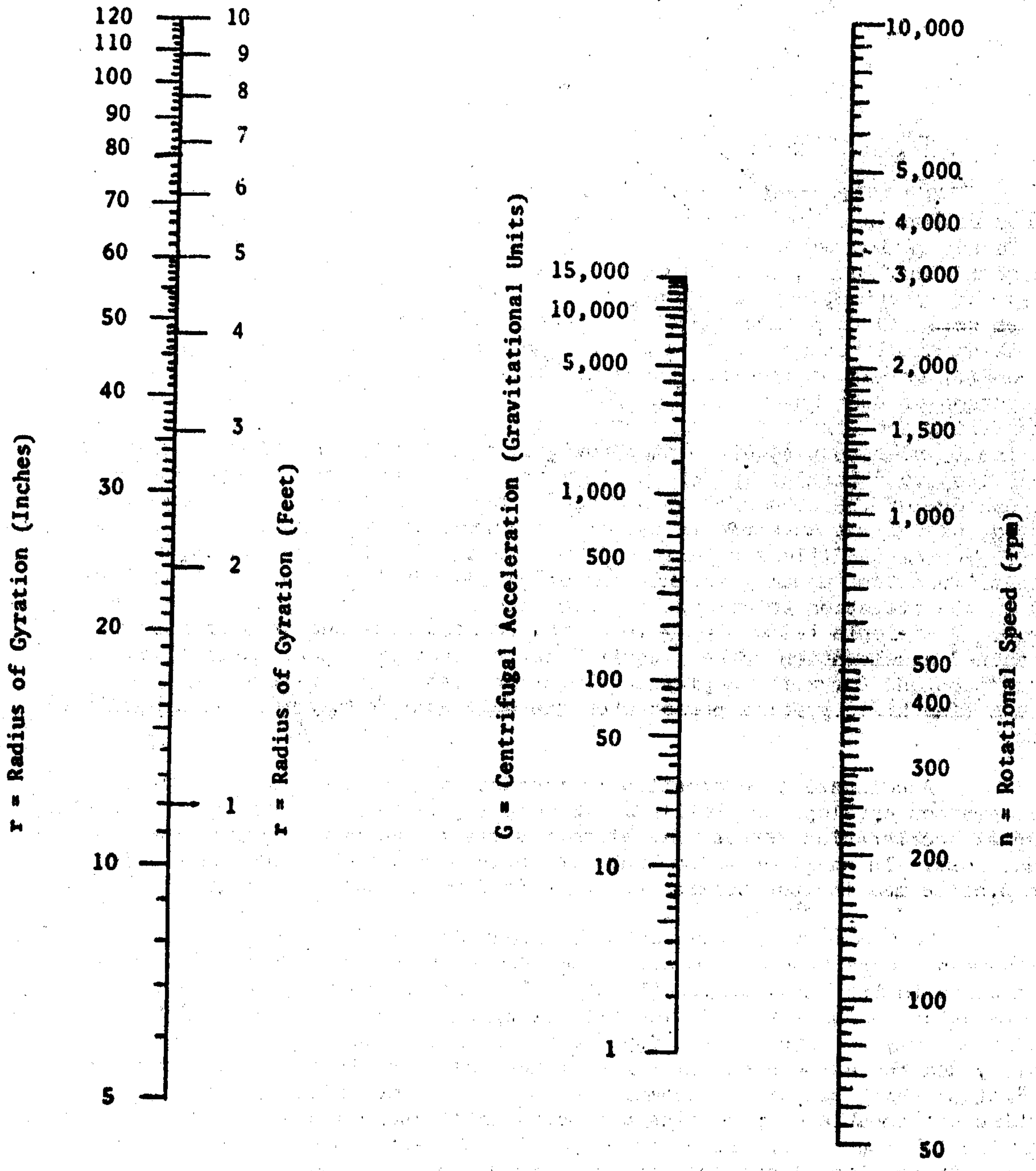


Figure A-1. Nomogram for Determining Centripetal Acceleration

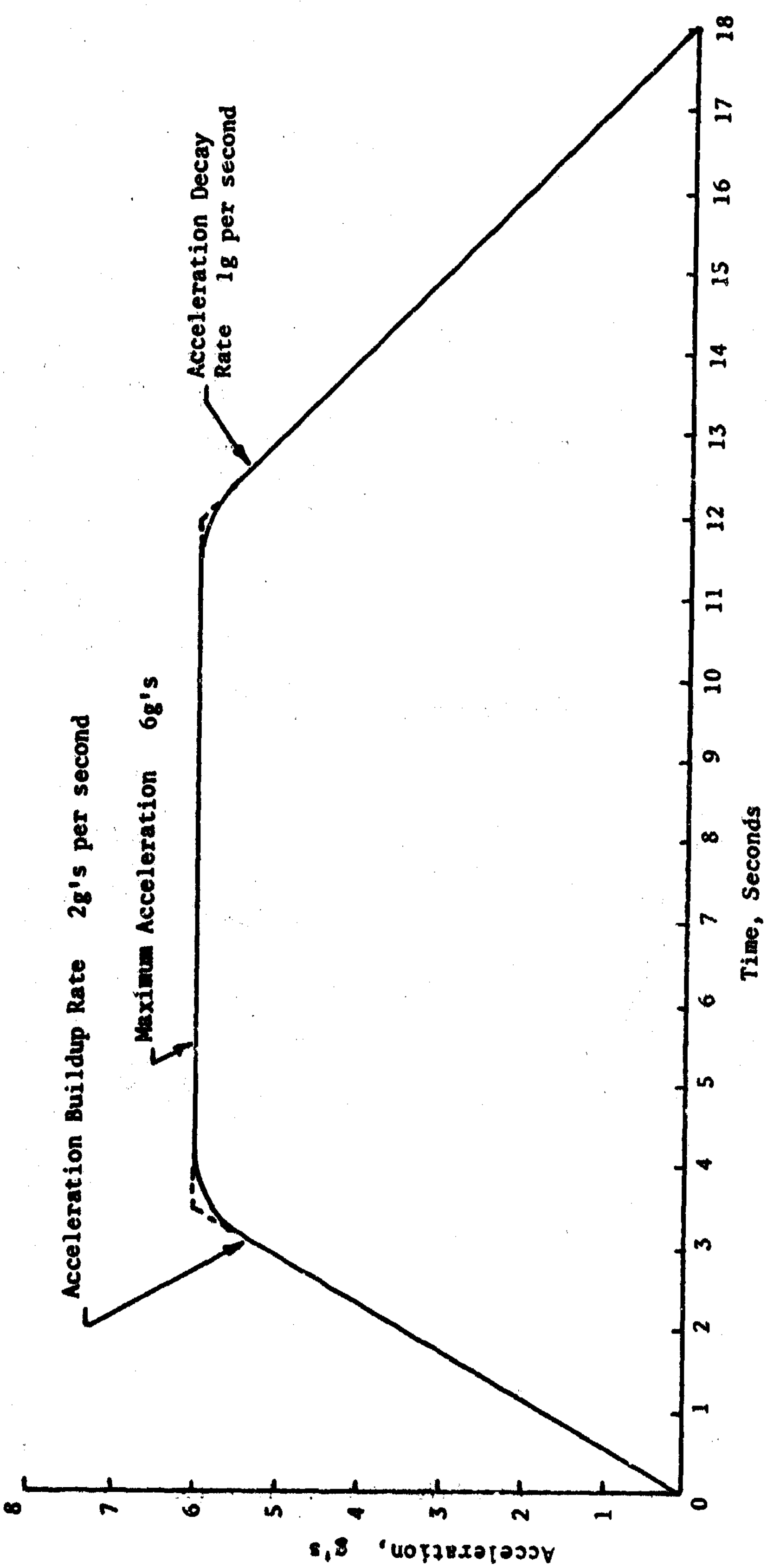


Figure A-2. Acceleration Profile

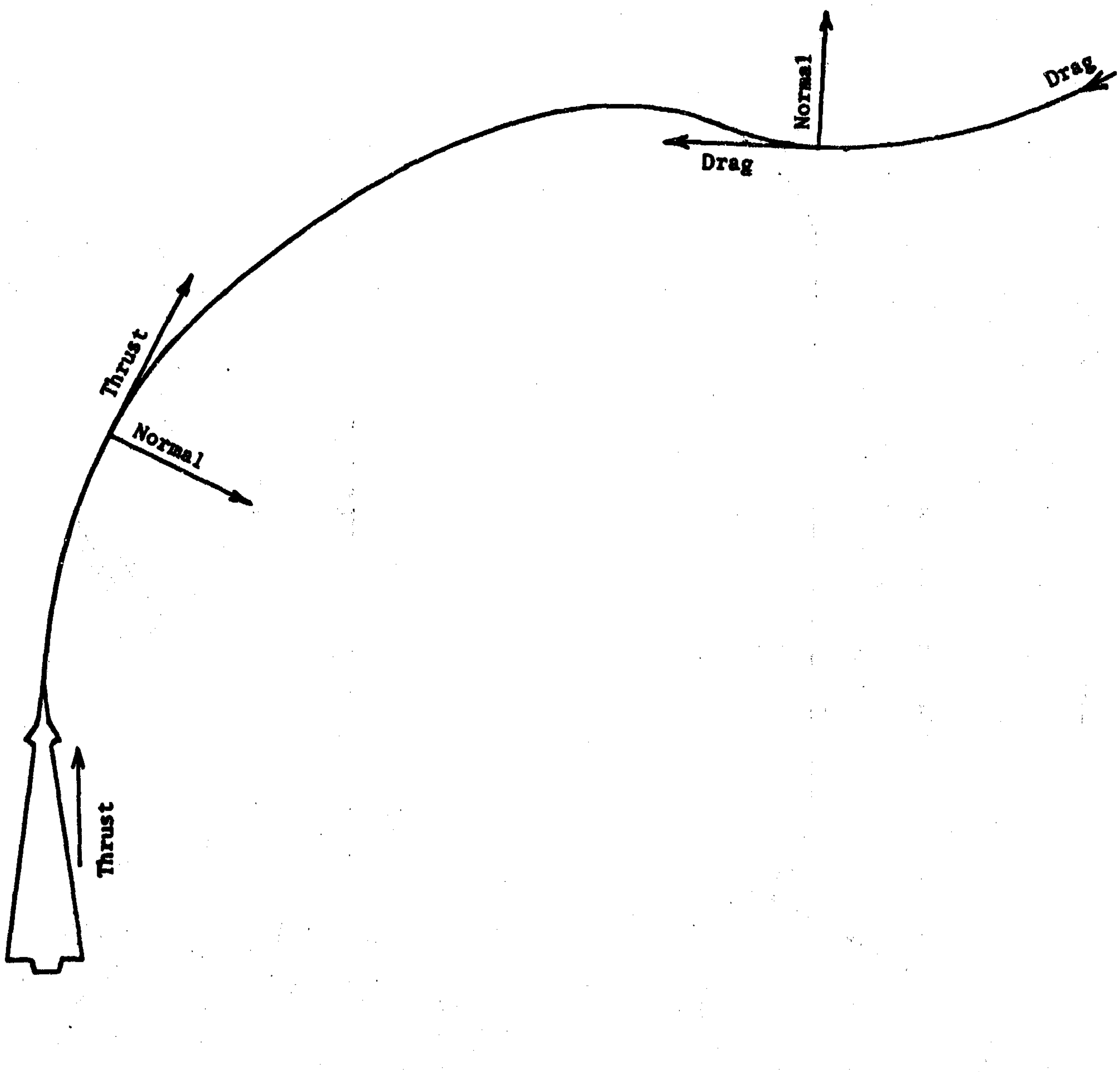


Figure A-3. Typical Missile Sustained Accelerations

On the other hand, specifications which prescribe tolerances in conjunction with changing acceleration should be examined carefully, as this condition must be obtained through manual control of the centrifuge if the centrifuge is not equipped so that the acceleration profile may be programmed. Manual control under such conditions, even by experienced personnel, allows relatively large variations of acceleration.

2. COMBINED TESTING

In combined testing, numerous problems in the installation and operation of equipment on the centrifuge as well as limitations on centrifuge performance may occur. The power requirements of equipment added to the centrifuge for combined environmental testing may exceed the capacity of the centrifuge circuitry. The voltage and current requirements are important considerations since the centrifuge sliprings may limit the power supplied. The installation of equipment on the centrifuge to combine other environmental conditions with sustained acceleration may result in a reduction of equipment capacity. Also, an increase in operational problems may be expected. Typical operational problems encountered are those which result from operating equipment under a condition (sustained acceleration) other than that for which it was designed. Malfunctions of automatic equipment, spring loaded valves, blowers, or other equipment sensitive to sustained acceleration are typical of the operational problems which might be expected. Problems associated with the operation of a vibration exciter installed on the centrifuge as shown in Figure A-4 are cited as an example of the difficulties encountered in the combining of test conditions. Difficulties may be experienced with vibration exciter field windings which become damaged because of a lack of support against sustained acceleration loads. Operational problems in conjunction with the armature assembly may be experienced, if the assembly design is inadequate under conditions where sustained acceleration might be applied along, or perpendicular to the armature axis. Further, the operation of a vibration exciter installed on a centrifuge can cause severe loads in centrifuge bearings and structural members and excite structural resonances in the centrifuge boom.

Figure A-5 depicts a means of combining sustained acceleration and climatic conditioning. On larger centrifuges, the conditioning enclosure may be attached to the end of the centrifuge arm. An application such as this, of course, depends upon the size of the item being tested. Weight and aerodynamic drag of the configuration at the mounting table location may affect centrifuge performance.

Frequently, complex environmental conditions are separated into single (or a limited number of) test parameters. The omission of an environmental condition, which is desired but cannot be simulated, raises a question as to the effect of the omission of that parameter on test results and how this is to be considered in the final evaluation. If, under normal operating conditions, a component is exposed to a complex environment of shock, vibration, temperature, and pressure in addition to sustained acceleration, the applied stress may vary to a large degree with time. Further, the

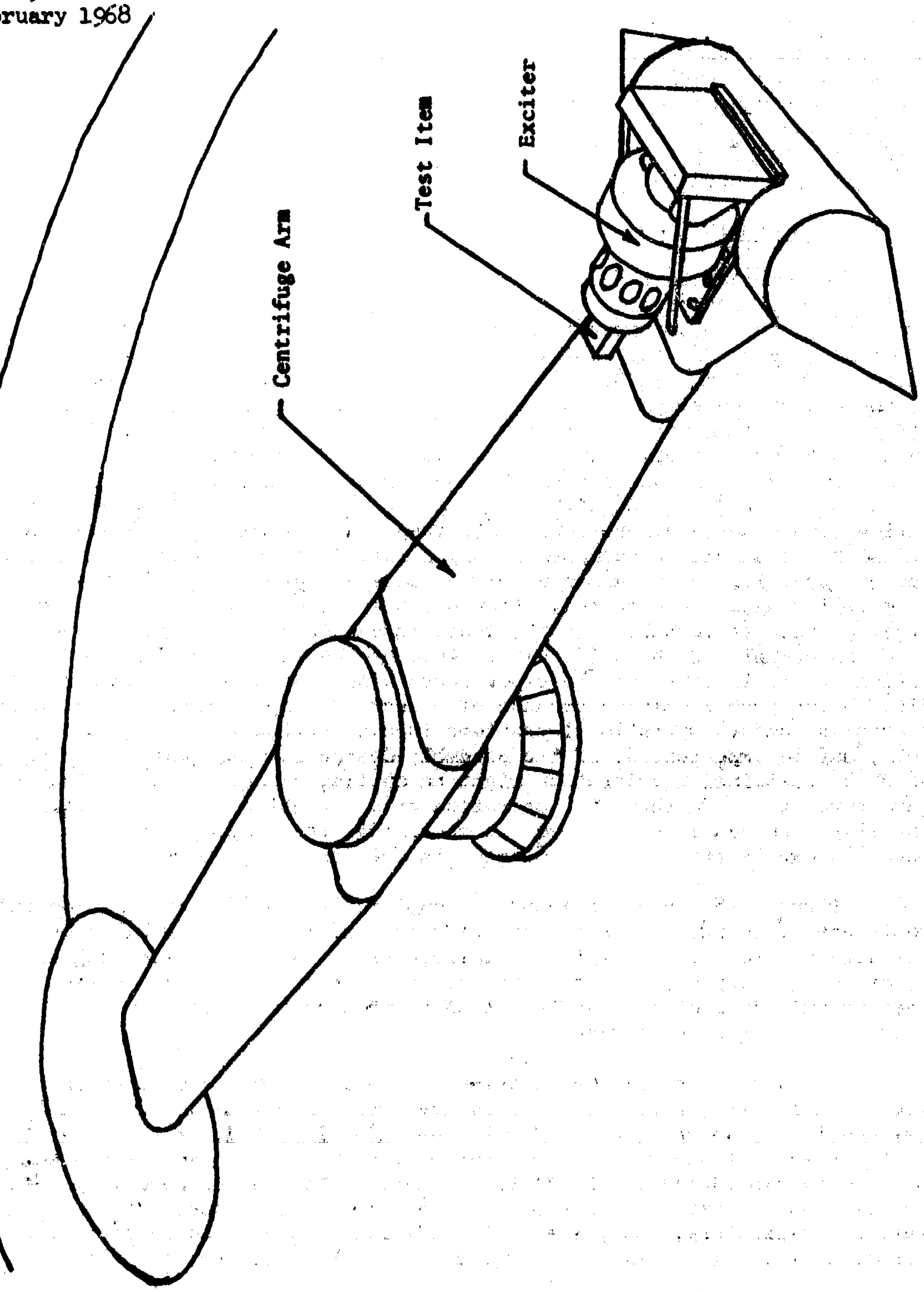


Figure A-4. Combined Environment Testing (Vibration Exciter on Centrifuge) failure pattern for an item exposed to one or a minimum number of test parameters may vary considerably from that which might occur in actual use. The ability of an item to pass a test sucessfully in which it is exposed to one or a limited number of parameters is no guarantee that the item will perform as well under actual operating conditions. To increase the reliability of hardware exposed to complex conditions, test specifications have been utilized requiring exposure to obtainable environmental parameters at an elevated level. This procedure, unless used with discretion, may introduce performance difficulties which result from over testing or over exposure of sensitive items.

3. PROBLEMS IN CENTRIFUGE TESTING

Although testing by means of the centrifuge appears to be simple when compared with other types of testing, the test engineer may encounter numerous problems which vary in magnitude depending upon the complexity of the test. Typical problem areas encountered are those associated with the generation of required test conditions, data acquisition, test item servicing and handling, and miscellaneous support of the type supplied at the test site.

The generation of other than the required acceleration conditions at the test item location may be objectionable. An acceleration gradient along the axis of the centrifuge arm and a tangential acceleration exist at the test item location in varying degrees of intensity during the operation of a centrifuge.

Centrifugally produced forces are not uniform along a test specimen on a centrifuge because of the proportionality of acceleration to the radius. The normal acceleration (along the length of the centrifuge arm) varies directly with the radius and by the square of the angular velocity ($a_n = r\omega^2$). The effect of the incremental variation of acceleration along the radius of a centrifuge arm may be undesirable if a test item is required to be subjected to an acceleration value within specified tolerances at more than one location and test item dimensions along the centrifuge arm are such that the difference in acceleration between these locations is excessive. The importance of a centrifuge with a large radius is appreciated in such a situation, since the incremental variation of acceleration over the above test item is less if the item were installed at the end of a centrifuge arm of greater length.

In tests requiring acceleration values to be maintained within close tolerances on a large object, it may be desirable to adjust the centrifuge rotational speed so that the required acceleration is obtained at the location (radius of gyration) of a critical test item component.

The effect of tangential acceleration ($a_t = r\alpha$) on the resultant acceleration vector should not be overlooked. This acceleration occurs in a direction perpendicular to that of the normal acceleration and may be large enough to cause a considerable change in direction and magnitude of the resultant acceleration vector. Because of centrifuge design and power requirements, the tangential acceleration usually encountered on a large centrifuge is relatively low; however, the tangential acceleration generated by changes in rotational speed of smaller centrifuges may become significantly large. If test specifications require a rapid g-level buildup within the limits attainable on a centrifuge, it may be necessary to provide a means of accounting for a large tangential acceleration values at the test item location. There have been designs which allow the test item to be rotated relative to the centrifuge arm in such a way that the resultant of the normal and tangential acceleration vectors remains orientated along the desired axis of the test object during periods when a change in centrifuge rotational speed occurs. Figure A-6 depicts the forces due to rotation and change in rotational speed of the centrifuge.

The capability of the centrifuge circuitry (including the sliprings) to handle the electrical power required for operation of test items and associated equipment should be investigated prior to a decision to utilize a centrifuge for a test. Maximum slipring voltage and current ratings frequently are limiting factors in the planning of a centrifuge test.

The quality of electrical power available at the test site is an important consideration to be made in planning. Occasionally, power conditions which appear to be basically satisfactory are a source of trouble or prove to be intolerable for test purposes. Such may be the case where it is determined that d-c power of sufficient quantity is available, but during the test run, it is found that the d-c voltage contains a ripple which cannot be tolerated. Power characteristics such as voltage ripple, voltage variation, and frequency variation may be important considerations when the equipment to be used is sensitive to conditions of this type.

Electrical power to drive the test item during a centrifuge test may be obtained from batteries installed on the centrifuge if it cannot be supplied through the centrifuge sliprings. The design of a battery installation should include provisions against loss of electrolyte, failure of battery case, and the collection of toxic and/or explosive products in the test area.

Other means of driving the test item while it is installed on the centrifuge may include the application of hydraulic, pneumatic, and hot gas sources of power. Because of limitations in the use of swivel connections through which a source of energy might be conducted from the centrifuge base to the item on the rotating arm a pressurized container may be installed on the centrifuge. This procedure allows direct connection to the test item. The design of an installation which utilizes hydraulic, pneumatic, or hot gas power sources requires consideration of centrifugal force effects on high pressure lines and equipment and the associated operational and personnel safety problems.

The data desired from a particular test may be affected by the choice of a centrifuge. The centrifuge circuitry may not provide the number of channels of information required; the signal from an item to be tested may be of such a frequency that the signal would be attenuated by the centrifuge circuitry, or excessive noise may be introduced into the data channels by sliprings or nearby electrical equipment. A discussion of instrumentation and the associated problems will be found in Appendix C.

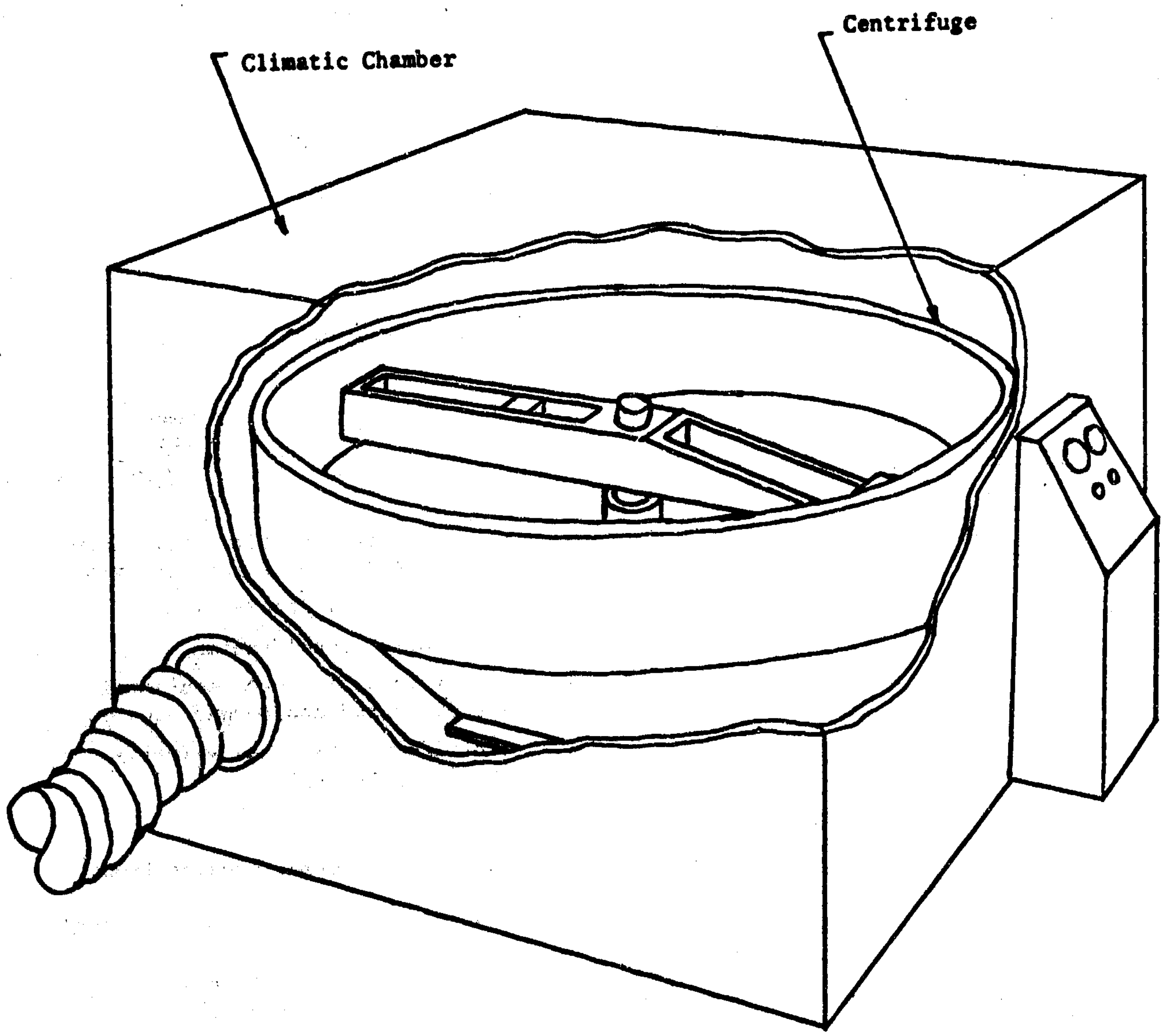
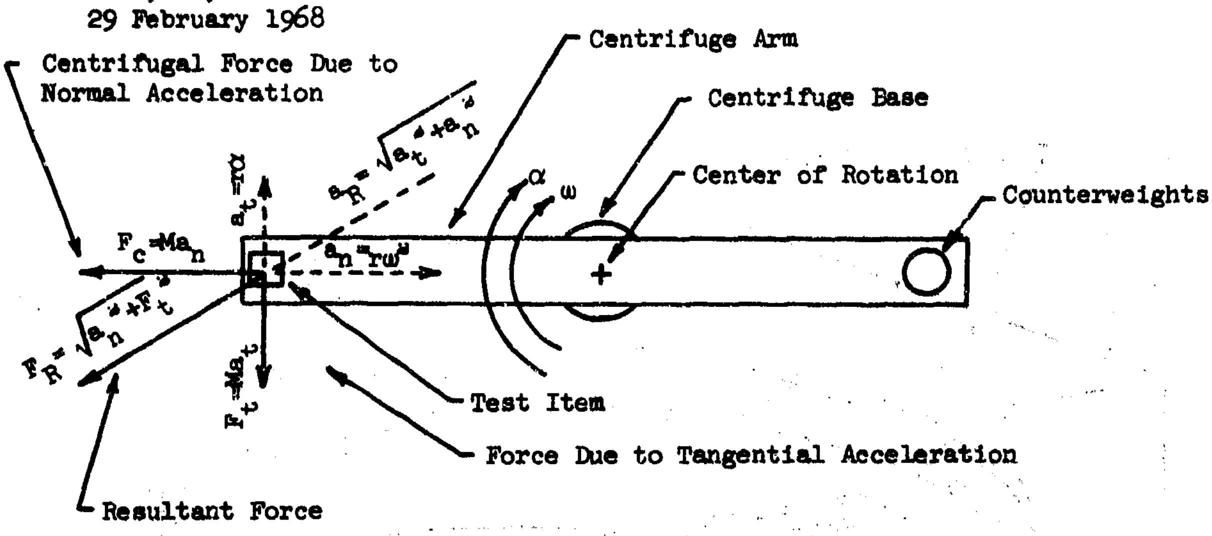


Figure A-5. Combined Environment Testing



Acceleration Equations

$$a_R = \sqrt{a_t^2 + a_n^2}$$

a = resultant acceleration where normal and tangential acceleration exist

a = $r\alpha$, tangential acceleration

a = $r\omega^2$, normal acceleration

α = change in centrifuge rotational velocity (radians/second squared)

ω = centrifuge rotational velocity (radians/second)

General Expression $$g's = \frac{\pi^2 N^2 r}{900 G}$$ (Derived from equation for normal acceleration, a = $r\omega^2$)

g = acceleration as a number of gravity units

G = gravitational unit of acceleration (32.2 Ft/Sec² or 386.4 In/Sec²)

π = 3.14159+

N = revolutions per minute

r = radius of gyration (feet or inches)

Inch Units $$g's = 0.2838 \times 10^{-4} rN^2$$

Feet Units $$g's = 0.3406 \times 10^{-3} rN^2$$

Figure A-6. Basic Forces Imposed on Test Item Due to Accelerations Produced by Centrifuge

Structural design problems associated with test installations on the centrifuge may be static and/or dynamic in nature. Structural components exposed only to sustained acceleration may require investigation as to their ability to withstand loads due to acceleration along the axis of the applied load. Rapid changes in centrifuge rotational speed, centrifuge fixtures such as swingout devices, test items which include moving components, and parameters of shock and vibration are typical conditions which may require consideration of dynamic effects in centrifuge bracketry design.

The application of the centrifuge to the calibration and evaluation of accelerometers used in inertial guidance systems requires a centrifuge capable of producing and holding specified accelerations to extremely close tolerances. Associated with this area of testing are a number of problems in measurement accuracy, control of acceleration within specified limits, and the minimization of conditions which may cause undesirable test results. For details concerning centrifuge applications of extreme precision, see reference 4 C and the literature of manufacturers of precision centrifuges.

4. MISCELLANEOUS SPECIFICATION CONSIDERATIONS

After the required test conditions have been determined, a decision as to the necessary test support and equipment is made. The selection of a site or facility at which to conduct centrifuge testing may be affected by various considerations.

The need and availability of support in conducting a test is important. This support from within or from without the agency may include manpower (engineers, technicians, equipment operators, etc.) and test equipment (instrumentation or other special equipment required in conjunction with a test). Shop facilities for assembly, repair, and inspection of test items as well as storage facilities for equipment and supplies associated with test will influence the decision to use a test facility. Further, the availability of special services such as computers, data processing, and calibration may influence the decision to conduct tests at a given installation.

Specifications requiring the simulation of combined environments in conjunction with centrifuge testing should be examined closely in making estimates for a test program. The ability of existing equipment to produce the specified test conditions is a primary consideration. If available centrifuge equipment must be modified or if additional test equipment must be obtained to perform a test, the cost and schedule may be expected to vary accordingly. A requirement for the combining of attainable test parameters may result in unforeseeable difficulties. The section on problems in centrifuge testing discusses some of the difficulties that may be encountered in combined testing.

APPENDIX B

THE CENTRIFUGE

1. INTRODUCTION

The centrifuge shown in Figure B-1 (also referred to as a rotary accelerator or g-accelerator) is a device for producing steady-state or sustained acceleration under laboratory controlled conditions. It consists of the centrifuge arm (beam) supported by a bearing so that the arm may rotate about an axis perpendicular to the longitudinal axis of the arm. A drive mechanism applies power to cause continuous rotation of the arm and allows control of the rate of rotation. At the end of the centrifuge arm is located a mounting table or other means of attaching the item to be tested to the centrifuge arm. The centrifuge usually includes a barricade within which the rotating arm is enclosed. This enclosure is primarily for personnel safety and/or reduction of aerodynamic drag effects on the centrifuge. The centrifuge normally is driven by electrical power. Rotation of the centrifuge arm may be accomplished by electric motors which drive the arm through a clutch and drive mechanism, or by an arrangement of electrically driven hydraulic pumps and motors. Rotation of the arm about its axis results in generation of the sustained acceleration to which the test specimen mounted on the centrifuge arm is exposed. The magnitude of the acceleration produced depends upon the rotational speed of the centrifuge arm about its axis and the radius at which the test item rotates about the centrifuge rotational axis. In a typical centrifuge test, the rotational speed of the centrifuge arm is allowed to increase to the value necessary to produce the required acceleration (g) level at the test specimen location on the arm. The rotational speed may be maintained or varied as necessary to produce the specified acceleration conditions. Numerous data may be required on test item operational characteristics as well as on the test conditions to which the item is exposed.

2. TYPES OF CENTRIFUGES

A large number and variety of centrifuges are in existence. Test specifications, test objectives, and the size of test items are the important parameters in the selecting of a centrifuge.

Large accelerators are used primarily in the laboratory for testing electronic packages and components, guidance systems, fire control systems, gyro packages, servo motors or systems, guns, motors, missiles, or similar objects used in rocketry and flight.

Smaller accelerators are used for testing relays, electron tubes, capacitors, subassemblies, valves, and other equipment which must function in an acceleration environment.

In this section, some of these centrifuges will be described and discussed. The following is not a complete list of centrifuges; it is included to provide a brief introduction to the characteristics of some typical equipment.

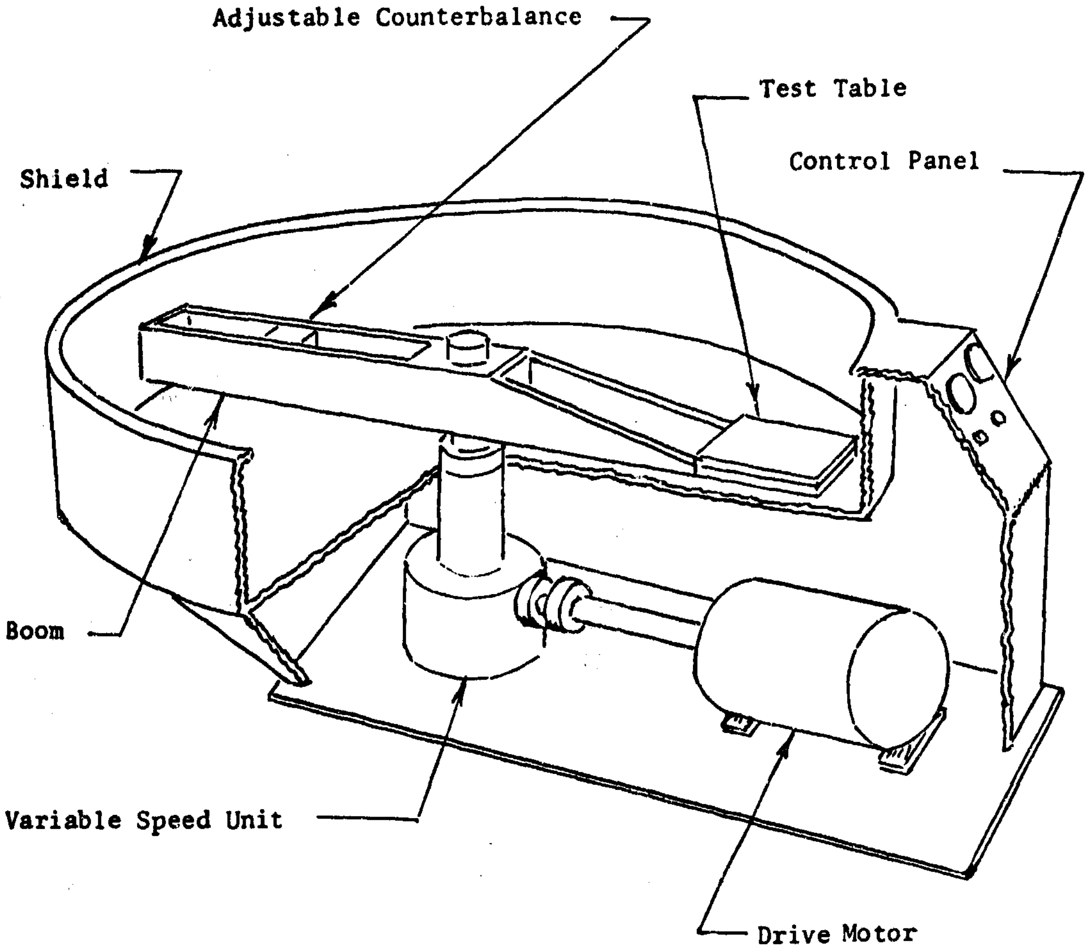


Figure B-1. Typical Centrifuge

2.1 GENISCO CENTRIFUGES

The Genisco Model E185 is a large centrifuge capable of steady state acceleration testing of complete electronic and mechanical packages under g loadings that simulate those experienced in actual flight operation. Two test objects weighing up to 300 pounds each can be tested simultaneously. The maximum acceleration is approximately 100 g's. The intrinsic accuracy of the machine provides reliable values below one g. The machine is driven by a variable-speed hydraulic drive system consisting of a variable delivery pump and a constant displacement motor, and it provides rotational stability, minimum hunting, and constant torque characteristics. The boom consists of two symmetrical cantilever arms and adjustable 30-inch square cradle type mounting platforms. Tapped mounting holes facilitate emplacement of test objects on the platforms. The platforms can be locked into the horizontal, 45-, 90-, 135-, or 180-degree positions, permitting test objects to be subjected to g loadings in several different directions by changing the attitude of the platforms. Static balancing is achieved if identical objects are to be tested. If a single object is to be tested, counterweights are provided. An automatic dynamic balancing feature of the machine eliminates the necessity for static balancing to a differential of less than 10 pounds on the mounting platforms. Dynamic balance is accomplished automatically by vertical displacement of the two arms of the boom until the centers of gravity of the opposing masses lie in the same plane. Full compensation requires approximately 20 seconds. Dynamic unbalance generates a couple moment to the fulcrum assembly causing it to tilt about its pivot point. A total of 44 sliprings provide electrical connections between the test object and a stationary terminal board.

The model B is a machine for applying a steady force of variable magnitude to instruments and component parts of aircraft and guided missiles. The accelerator is used for calibrating acceleration equipment and for functional testing of apparatus under predetermined acceleration forces to simulate operating conditions. The boom is 50 inches long and has an acceleration range of 120 g's. The acceleration arm assembly is mounted on the vertical main shaft inside the guard-rail well. The arm is mounted on a tee clamp assembly which permits a slight amount of movement about a horizontal axis for static balancing prior to operation. At one end of the arm is a rigid pad to which the test item is secured. On the arm assembly, opposite the mounting pad, a counterbalance system is provided to achieve static balance of the rotary arm assembly. Test objects weighing up to 25 pounds can be tested. The prime source of power is one horsepower (HP) electrical motor at 1750 revolutions per minute (rpm). A Vickers 3/4 HP variable speed transmission is used to couple the power from the motor to the drive shaft. The transmission consists basically of a variable displacement hydraulic pump and a constant displacement hydraulic motor. To increase the versatility of the model B, a symmetrical acceleration, a turntable and a mounting stand could be added at any time. The turntable would provide an additional rotating platform for mounting test objects.

Genisco also has produced smaller centrifuges (12-, 24-, 38-inch radius) which can provide up to 10,000 g-pounds (40-pound load to 250 g's). Model A-1030 has a 93-inch arm and will take an 18-inch cube of 100 pounds weight to 175 g. A small centrifuge developed for production line acceleration testing ranges from one to 800 g's with capacity of 100 g-pounds. American Bosch Arma has installed a Genisco centrifuge to test a highly accurate accelerometer. This instrument has a range of about plus or minus ten g's and can detect accelerations as low as five millionths of one g.

2.2 SCHAEVITZ CENTRIFUGES

Standard rotary accelerators manufactured by the Schaevitz Machine Works include eleven models, ranging from three to 500 pounds capacity and to 1000 g's. The model C-1-A has a nominal radius of nine inches and develops up to 250 g's. It takes test objects weighing up to three pounds. Size limit is a five-inch cube. The speed is continuously variable from zero to 1000 rpm. The largest standard accelerator is the T-16-A with a 500-pound capacity at 100 g's on each end of a nominal radius of five feet six inches. Maximum size of the test object is a five-foot cube; 50 silprings are provided. An optical system for continuous observation of the test object is available.

2.3 STATHAM CENTRIFUGES

The Statham RA-1 centrifugal-table acceleration generator provides up to 500 g's at 1725 rpm. The model RA-2 provides 1000 g's at 1740 rpm and a nine-inch radius within a controlled environment that can be varied from minus 90 to plus 350 degrees Fahrenheit (°F). Rotation can be monitored to plus or minus one percent. The model 2B utilizes a one HP, 120-volt, direct current (d-c), shuntwound, direct coupled motor to spin a 20-inch diameter table at usable rates between 100 and 1940 rpm. With a 9-inch maximum effective radius, the table will accommodate a 5-pound test unit occupying up to a four square inch table area.

2.4 ALLEGHENY BALLISTICS LABORATORY - THE DIESEL POWERED BALLISTIC CENTRIFUGE

Reference g describes the centrifuge equipment in operation at the Allegheny Ballistic Laboratory (see Figure B-2). This centrifuge is used in ballistic and physical testing of rockets and rocket components. Certain flight conditions can be simulated by centrifuging a rocket either ignited or unignited. Forces up to 50 g's can be applied. The centrifuge is designed to withstand a maximum horizontal force of 200,000 pounds. That is, when a rocket is being fired during centrifuging, if the centrifugal force of the rocket and its attachments is balanced by that of the counter-weight, the permissible inward thrust of the rocket would be 200,000 pounds. If the unit is centrifuged and not fired, the total weight is counterbalanced. If the rocket is to be fired during centrifuging, all the inert weight plus half of the propellant charge weight is counterbalanced. All tests are made at a constant boom speed corresponding to a constant flight acceleration.

2.5 QUICK STARTING CENTRIFUGE

A quick starting centrifuge as described in Reference 4E is used to attain operating speed quickly and maintain an acceleration for a long

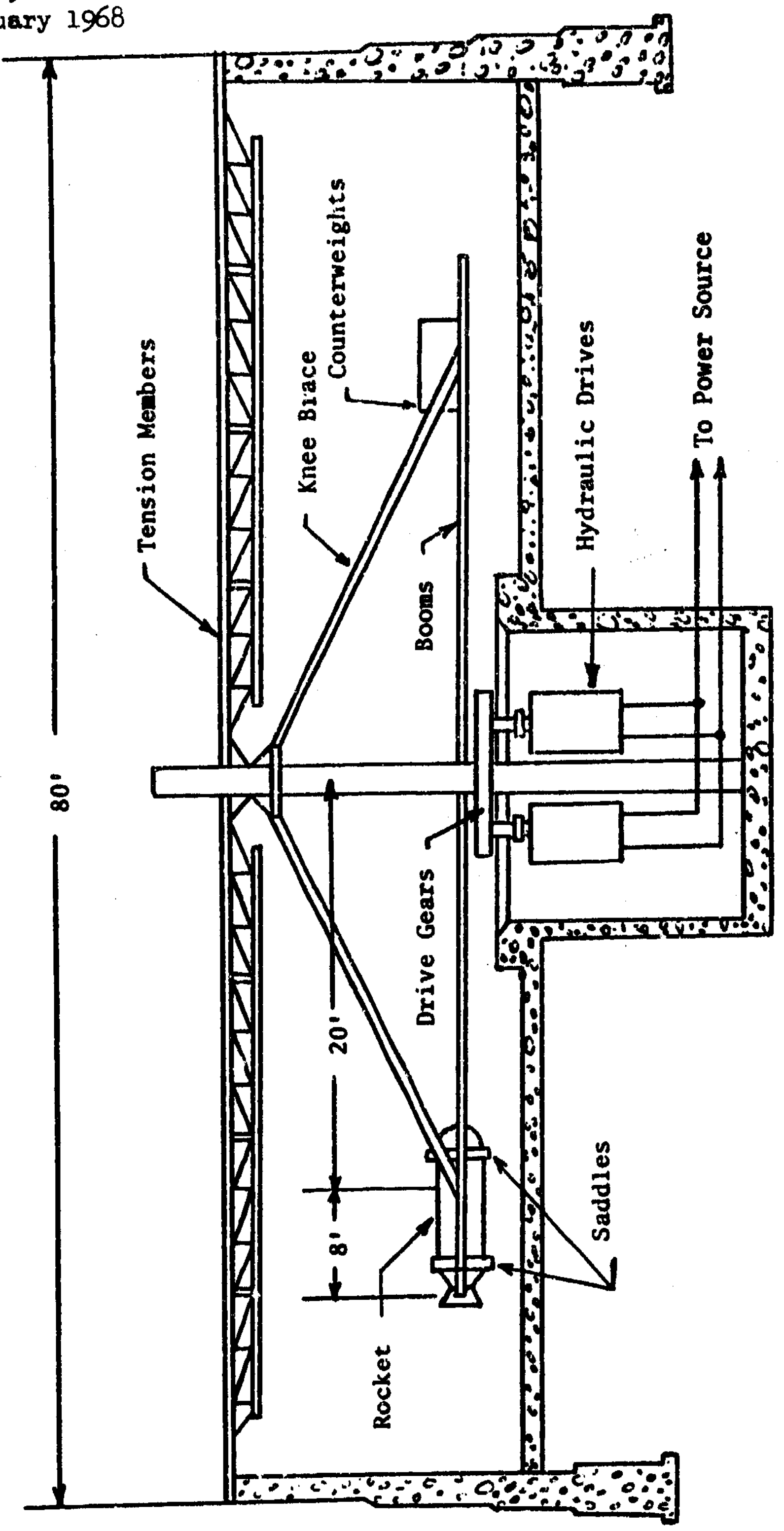


Figure B-2. Diesel Powered Ballistic Centrifuge period of time. The accelerator consists of a rotating arm which is set into rotation suddenly by an air-operated piston assembly. The test object is mounted on a table attached to the outer end of the arm. The table swings on a pivot so that the resultant direction of motion is caused largely by angular acceleration of the arm. As the centrifuge attains a constant speed, this acceleration axis assumes a radial direction. These machines are built in several sizes. They require from five to 60 milli-seconds to reach the maximum value of acceleration. For small test items (eight pounds), a maximum acceleration of 450 g's is attainable; for heavy test items (100 pounds), the maximum value is 40 g's.

2.6 HYDRAULIC CENTRIFUGE (SANDIA CORPORATION)

This centrifuge is installed in an area where hazardous testing may be conducted. It is used in physical testing of rockets and rocket components. The centrifuge arm is 56 feet long. The distance between the mounting plates is 74 inches. The arm is made of a pipe 16 inches in diameter with a wall thickness one-half inch. The unit is propelled hydraulically by seven Denison hydraulic pumps, each driven by a 100 HP electric motor. These pumps supply fluid to the five hydraulic motors which drive the centrifuge at a pressure of 5000 pounds per square inch. The design is such that the driving motors act as brakes when it is necessary to stop centrifuge rotation. The original capacity of this unit allows an acceleration of 100 g's with a specimen weight of 1100 pounds and an acceleration of 25 g's with a specimen weight of 9000 pounds. A large centrifuge is also installed which will allow combined vibration and acceleration.

3. CENTRIFUGE SPECIFICATIONS

A decision in favor of a particular centrifuge for a test program depends upon the ability of the centrifuge to produce and maintain test conditions within specified limits. Characteristics typical of those requiring consideration are as follows:

a. Acceleration range
b. Mounting table weight capacity
c. Mounting table size
d. Centrifuge arm length
e. Centrifuge arm width
f. Centrifuge arm height
g. Dimensions between centrifuge and enclosure
h. Speed control; in steps or infinite
i. Speed range
j. Operational stability characteristics
k. Control accuracy and operational tolerances; manual or automatic control.
l. Instrumentation for monitoring centrifuge rotational speed
m. Time required to bring centrifuge to specified rotational speed and to stop it.
n. Adjustability of mounting table with test item installed
o. Centrifuge electrical circuitry including the number of power and signal channels and the power handling capacity (maximum current and voltage).

Also, frequency limitations in conjunction with test requirements.

p. General characteristics of electrical power available at the centrifuge site

q. Means of supplying hydraulic or pneumatic power to item being tested

r. Visual means of monitoring test item physical response while test is in progress (optics installed in centrifuge, strobe light, closed circuit television, etc.)

s. Isolation of test item from extraneous vibration

t. Centrifuge drive component mechanical and electrical characteristics

u. General safety provisions associated with the centrifuge installation (i.e. interlocking circuitry to prevent inadvertent starting of centrifuge, safety barricade, precautions against electrical, hydraulic, and/or other hazards, centrifuge structural safety features, location of centrifuge in area frequented by personnel or in a hazardous test area, and alarm system to indicate faulty operation)

v. The capability of existing centrifuge test equipment to generate the complete test condition

w. The necessity of designing and fabricating special fixtures to allow test conditions to be accomplished

APPENDIX C

CENTRIFUGE CALIBRATION AND INSTRUMENTATION

After a centrifuge has been installed, it should be calibrated to ascertain the capability of the machine and to ensure its compliance with the specifications. Moreover, the instrumentation used to measure precision centrifuge speed should be calibrated at regular intervals depending on equipment use.

To perform a calibration, the accelerometer is mounted on the centrifuge with its axis of sensitivity aligned along a radius of the circle of rotation as shown in Figure C-1. If the centrifuge rotates with an angular velocity of ω radians per second, the acceleration acting on the pickup is $r\omega^2$ where r is the distance from the center of gravity of the mass element of the pickup to the axis of rotation. Where the exact location of the center of gravity of the mass in the pickup is not known, mount the pickup with its positive sensing axis first outward and then inward, then compare the average response with the average acceleration acting on the pickup.

The calibration factor is determined by plotting the output of the pickup as a function of the acceleration given by $r\omega^2$ for successive values of ω and determining the slope of the straight line fitted through the data. Error results primarily from difficulty in measuring the angular velocity accurately and in holding the angular velocity constant during the time required to take a reading.

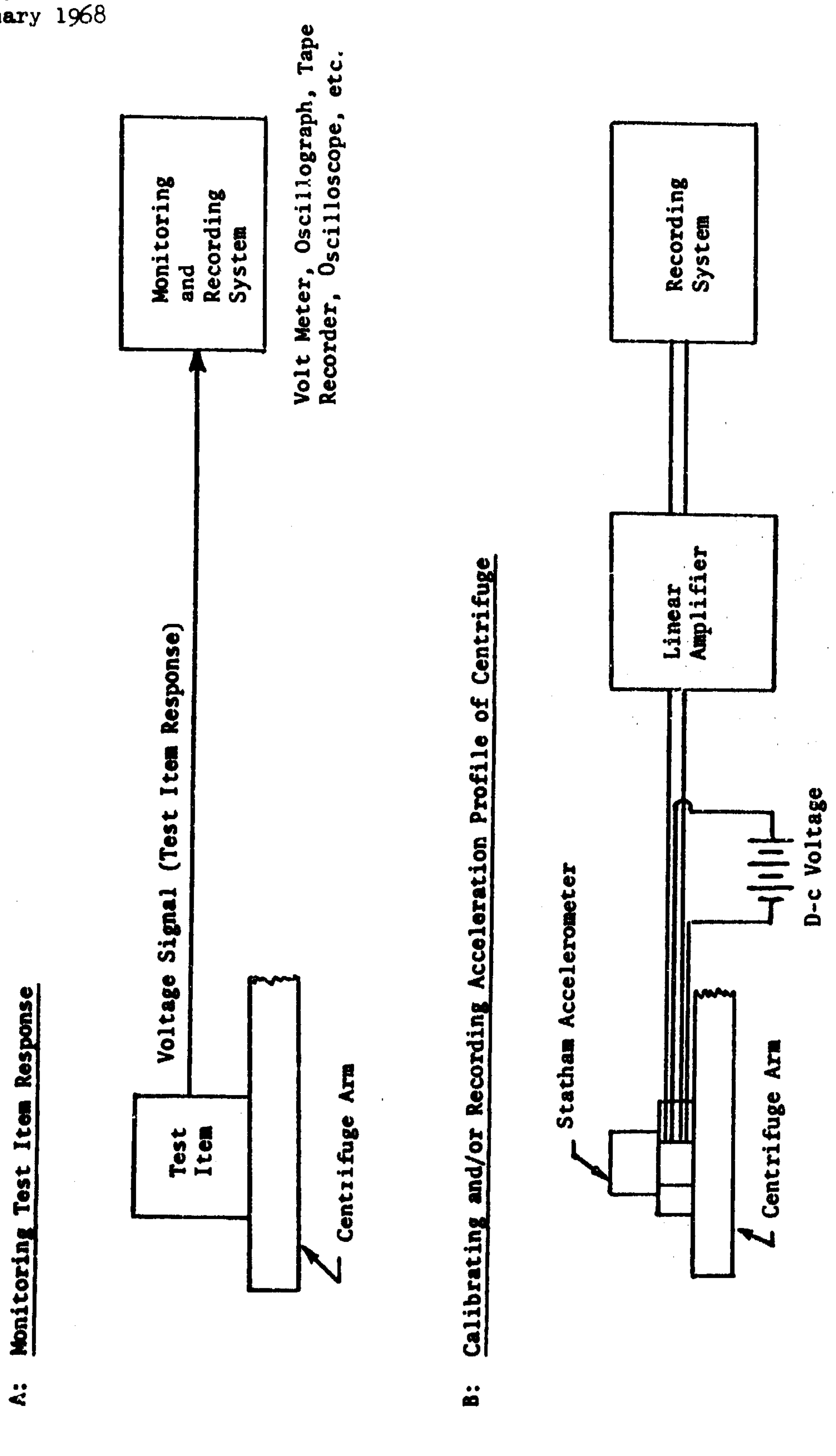


Figure C-1. Typical Data Acquisition Systems

APPENDIX D

TEST PROGRAM PLANNING

To realize worthwhile information from a centrifugal test program, it is necessary to have a test procedure that will provide adequate information to attain the test objectives. The procedure may be part of a plan which considers all activity in conjunction with a test program from its inception through the final report. Costly delays may be avoided by careful planning of a test. In addition to the familiarity of the test engineer with environmental test requirements, a knowledge of the basic design and operational modes of the test item frequently is necessary for good planning. The selection of test objectives may be influenced by the availability of centrifuge equipment capable of producing the required test conditions. After the test objectives, test conditions, and data requirements for a centrifuge test have been established, areas typical of those requiring consideration include the rate of testing, test schedule, centrifuge availability, supplies, test item power requirements, and the test equipment and instrumentation necessary to obtain data. If other agencies are to participate in a test, the extent of participation and responsibilities of each should be known, since the progress of testing and consequently the schedule may be affected.

In areas which require consideration in centrifuge testing, it is found that test planning, test philosophy, specifications, design, and the accumulation of data are each important. Planning requires, as in other environmental testing, that the engineer be acquanted with the design of the test item. A knowledge of design characteristics may aid the engineer in predicting test item response to certain test conditions and will be of further assistance in design of the test setup.

There is some philosophy associated with all testing. Centrifuge testing is not excluded even though it is not as complicated as the means of obtaining test item response to other mechanical inputs. Many centrifuge tests are conducted according to standard contractor or Government Specifications developed in conjunction with a project. The engineer must be aware of the responsibility he is assuming when he interprets, changes, or produces specifications for test conditions, especially if the specifications are for combinations of environments. The engineer should have a working knowledge of the test environment and the mechanism of failure.

Although centrifuge test conditions appear to be simple, there are areas which might cause difficulties and/or result in undesirable test results. Centrifuge characteristics such as those listed in paragraph 3 Appendix B, should be considered in the planning of a test. The maximum and minimum accelerations, the variation of acceleration versus time, and the tolerances required to be held for acceleration-time values may require careful consideration if a complex acceleration profile is required. The engineer should be aware of the existence of the acceleration gradient along the axis of the centrifuge arm and of the existence of tangential acceleration and their effects on test results.

Problems may be encountered in supplying power to the test item and in obtaining signals from the item for test purposes. The characteristics of power required versus the power available and the means of supplying that energy to the test item are important considerations in the centrifuge test.

The design of fixtures and bracketry should allow data to be obtained accurately and economically. The design load conditions to be considered may be simple tensile, compressive, or shear conditions, or they may be complex depending on the installation design and test specifications.

Where extreme accuracy of centrifuge performance and data is required, an intimate knowledge of centrifuge performance characteristics is necessary. Tests to determine this information, centrifuge calibration, and additional instrumentation to determine test performance data may be required.

APPENDIX E

TEST ITEM MOUNTING FIXTURE

1. FIXTURE DESIGN CONSIDERATIONS

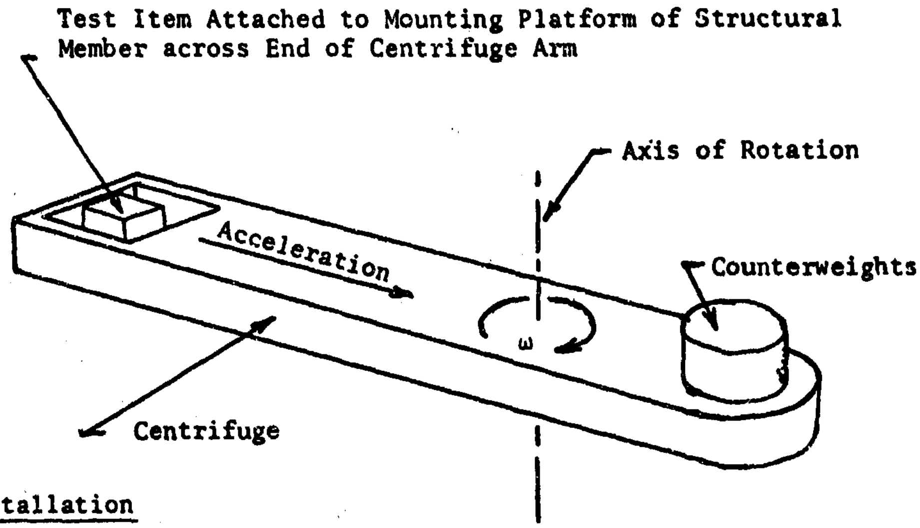
An installation design in which centrifugal force tends to hold the test item against the machine or fixture as shown in Figure E-1 and E-2 is generally preferred for unusually severe acceleration conditions, since this type of installation tends to minimize the possibility of accidential loss of the test item during a test. In this case, a compressive stress at the test item attachment location results from the normal or centripetal acceleration. A centrifuge equipped with an adjustable mounting table has definite advantages over a machine with a fixed mounting surface as the quality of being adjustable means greater versatility in the test installation. For example, an adjustable mounting table which may be rotated relative to the axis of the centrifuge arm might allow a test installation of the type referred to above, or allow a choice of more than one test item axis for exposure to the acceleration vector without detaching the test item to reorientate it for each axis tested. Difficulties in such operations as installation, checkout, servicing, and removal of the test item can be reduced by using a mounting table which allows a change in position relative to the centrifuge arm.

The testing of small items, or items which are difficult to set up, may be expedited by using a fixture which allows exposure of each axis to the acceleration vector without removal of the test item from the fixture. In this procedure, the fixture (with the test object attached to it) is reorientated. One of the simpler fixtures of this type holds the test item at a central location so that any number of fixture faces may be attached to the centrifuge mounting table depending upon the item orientation required. Installations of this type usually are bolted to the centrifuge. At centrifuge sites where numerous tests requiring reorientation of the test object are conducted, fixture versatility means reduced costs in test programs and less time to complete tests.

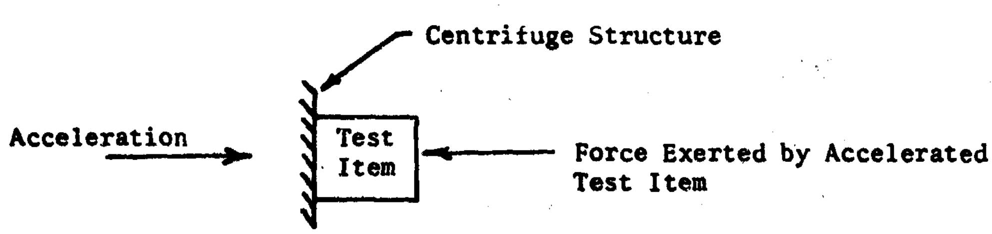
The decision in favor of a particular fixture design may be affected by such considerations as:

a. The scope of the test program
b. The complexity of test requirements
c. Physical characteristics of the test item
d. Centrifuge design

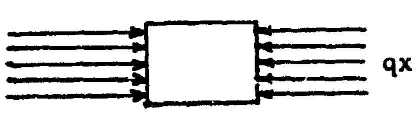
The economics of conducting a centrifuge test often are primary considerations. If the test program is a large one requiring a test to be duplicated for a number of like items, an elaborate fixture design which minimizes the installation and test time for each item may be required. The design and cost of the fixture in this case might be justified by a reduction in the cost of the program such that the cost of fixture design and fabrication is a fraction of the total amount saved. Conversely, a small number of tests might be conducted more economically by using a simple installation in which the item is unfastened from



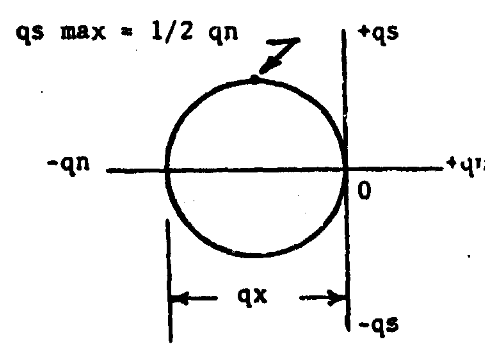
Typical Installation



Direction of Acceleration and Force Vectors Acting at Mounting Location to Produce Compressive Load Condition

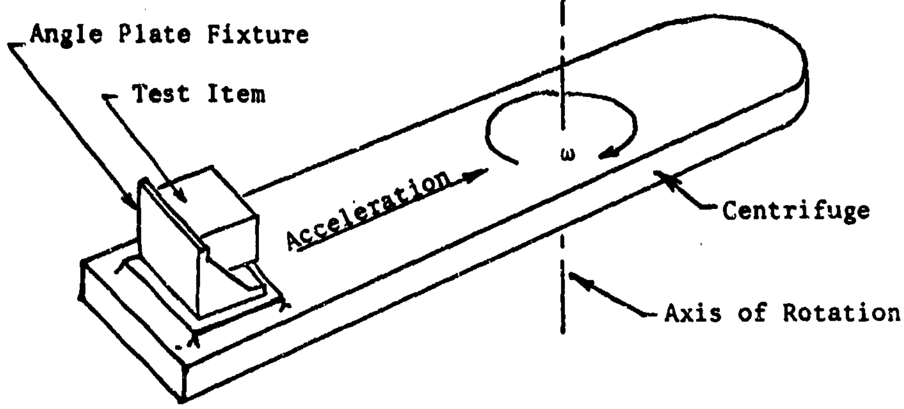


Element in Compression Field

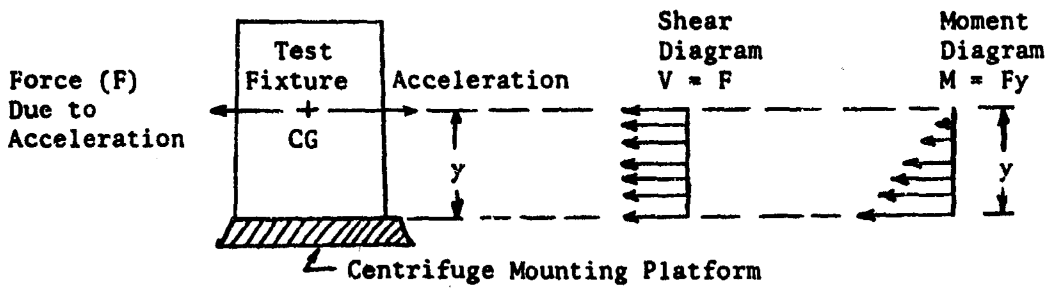


Mohr's Circle for Simple Compression

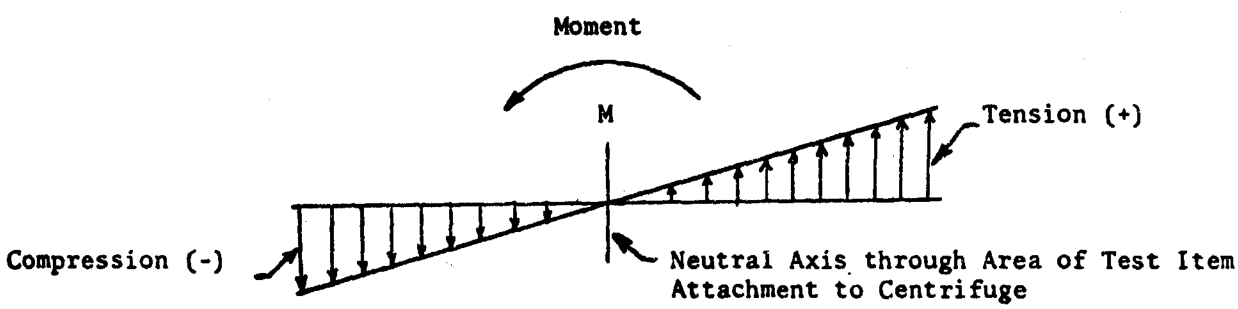
Figure E-1. Basic Centrifuge Test Installation Resulting in Compressive Load Conditions



Typical Installation Utilizing a Fixture



Representation of Fixture As a Simple Cantilever Beam with Load Applied at Center of Gravity



Linearly Distributed Force Field on Mounting Platform Due to Moment

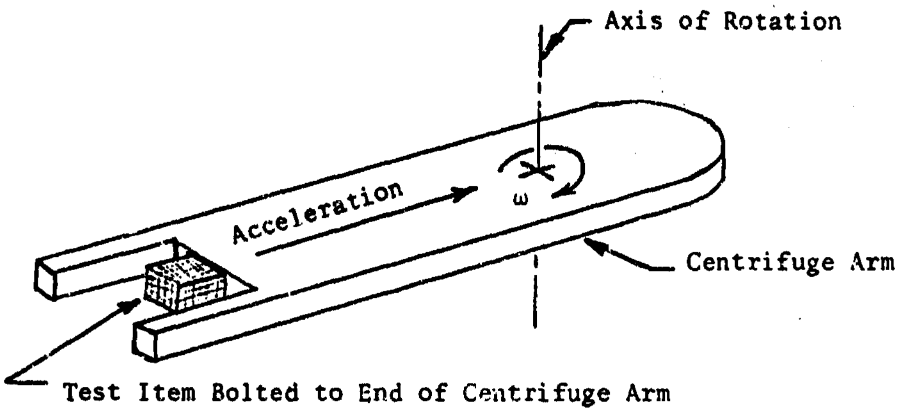
Figure E-2. A Typical Centrifuge Test Installation Requiring Consideration of Moment Effects in Installation Design the centrifuge and reorientated for each part of a test.

A knowledge of the ability of supporting bracketry to carry the required loads is an important factor in the preparation for a centrifuge test. A detailed analysis may not be necessary, if a previously used mounting bracket is to be exposed to loads known to be less severe than those for which it was designed; however, a preliminary design investigation, including a force and stress analysis, usually is required in conjunction with a new test installation. Basic forces imposed on the test item by centrifuge accelerations are shown in Figures E-1,E-2, and E-3. Free-body diagrams showing the forces at critical locations under various load conditions commonly are used in making the force analysis. After the forces have been identified as to point of application, direction, and magnitude, the stress analysis is undertaken. The analysis may require consideration of as many as four separate loading cases: axial force, transverse force (shear), bending, and torsion. In a bracket under complex loading conditions, it is possible that more than one of these conditions will exist. Loading conditions which appear to be relatively simple sometimes are required to be broken down into idealized conditions. After each loading condition has been analyzed to determine stresses and deflections, the results are combined to determine total strength and deflection characteristics.

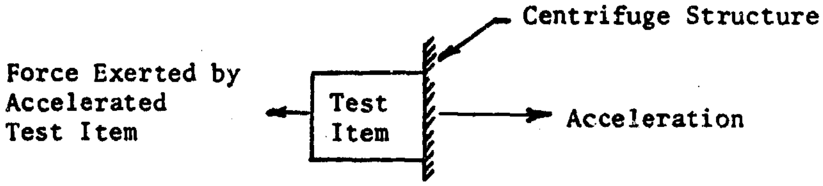
Occasionally, the design of a centrifuge test installation may require that the bracketry weight be kept at a minimum so that the total installation load does not exceed the centrifuge load limits. This, as in other areas of structural design, may require a careful investigation of various combinations of stress at critical locations. The complexity of the load conditions is dependent upon the centrifuge test requirements as well as the configuration of the test item and the bracketry by which the test item is attached to the centrifuge. Test conditions and the installation may be such that only simple bracketry loading involving shear, tension, or compression requires consideration or the test may be such that various loading conditions exist with combined stresses which vary with time. An analysis of the more complex loading conditions may require investigation of the state of stress and strain and the deflection due to distributed forces or force fields. The use of experimental as well as analytical analysis tools may be necessary to obtain an analysis in sufficient detail. Standard strength-of-materials references are adequate for most of the structural design required in conjunction with centrifuge testing. Some typical centrifuge test item installations and the basic bracketry load and stress considerations are shown in Figures E-1, E-2 and E-3.

2. FIXTURE MATERIALS AND CONSTRUCTION

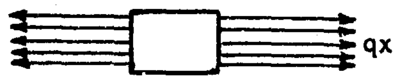
In selecting the material for a fixture, two important factors to be considered are the stress to which the fixture will be subjected and the weight the centrifuge arm can support. Other factors that should be taken into account are machinability and fabrication qualities. The material giving the lowest cost, yet having the properties needed, generally is considered the best engineering material; however, test schedule and material availability influence the choice of materials to be used. Aluminum and magnesium combining lightness with good mechanical properties to give a high strength-to-weight ratio are frequently used for centrifuge test fixtures. Both metals are available in a variety of forms including standard sheet, plate, bar stock, and



Typical Installation



Direction of Acceleration and Force Vectors Acting at Mounting Location to Produce Tensile Load Condition



Element in Tension Field

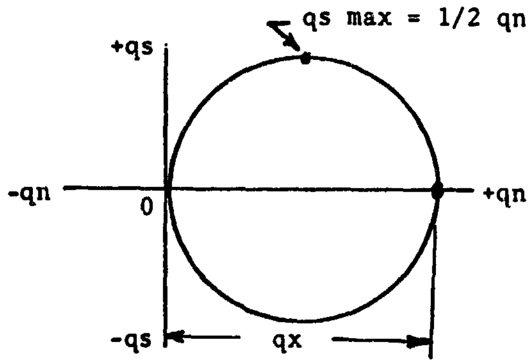


Figure E-3. Basic Centrifuge Test Installation Resulting in Tensile Load Conditions miscellaneous shapes, and both have generally desirable fabrication qualities. Most of the fusion and mechanical fastening methods common to the metal working trades may be utilized in the fabrication of fixtures; however, the designer should be aware of the characteristics of each material under his design conditions. Inserts may be used to reinforce the fixture base metal. In bolted connections they increase the resistance to severe loading conditions and/or to thread wear due to repeated use of the fixture. A bolted fixture design may be found desirable because of the versatility offered by this method of fabrication in new fixtures, as well as in the adaption of fixtures previously used for other tests. The fixture may either be bolted directly to the centrifuge platform or, if necessary, to an adapter plate which in turn is bolted to the centrifuge arm.

APPENDIX F

FAILURE DETECTION PROBLEMS

During a centrifuge test, the detection and analysis of the cause of failure may be difficult. For example, during a centrifuge test, an electronic circuit in a component under test might fail due to a capacitor short. This failure might have occurred regardless of the test, or might have been a direct result of the test. Other possibilities exist, and a conclusion that the capacitor failed as a result of the test is extremely uncertain without additional evidence. Careful technical consideration must be given to the cause and effect relationship of each failure to prevent erroneous conclusions and unnecessary redesign efforts. There is no definite procedure for failure investigation or troubleshooting, except that drawings, system specification documents, operating instructions, and good engineering practices should be used. Failure may be classified as intermittent, catastrophic or fatigue. An intermittent failure is one that occurs during the test but disappears when the equipment returns to normal operation after the causitive influence is removed. Catastrophic or fatigue failure is one which results in the structural failure of a component of the equipment and can be detected by inspection of instrumentation after the test is concluded.