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AEROSPACE INFORMATION REPORT

SAE AIR560 | REV. B

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MISSILE HYDRAULIC PUMPS

1. SCOPE:

1.1 Missile pumps are categorized by a moderate testing life and a relatively short operational service life. Generally, the pumps are operated at higher speeds, temperatures, and pressures than those used in manned aircraft systems, yet reliability must be extremely high, since there rarely is a redundant system aboard the missile.

1.2 Missile pumps must be compatible with very severe environmental conditions during the service life. In general, the temperature, vibration, shock, and acceleration encountered are more severe than those met in manned aircraft.

1.3 This SAE Aerospace Information Report (AIR) will be confined to describing missile environments and pump usage that differ significantly from those normally encountered in manned aircraft. Since missile pumps are usually driven by a secondary power source, and since this AIR is intended for use by systems designers, as well as pump designers, a brief description of some of these sources and some potential problem areas associated with each are included for reference. A more detailed treatment of auxiliary power sources can be found in AIR744.

1.4 Detailed test requirements are not included in this AIR since a wide variation exists between those operating conditions and environments that might be encountered on an air-to-air missile, hung beneath the wing of a fighter aircraft, and that of an ICBM, launched from an environmentally controlled silo. Missile pumps frequently have their genesis in standard aircraft pumps, however, what distinguishes them from manned aircraft pumps is that they are usually operated outside of, or at the extreme of their long-life design parameters. Therefore, if a new design pump is being proposed for a missile application, environmental conditions referenced in this AIR should be considered, as opposed to long-life operation and environmental requirements of a manned aircraft, engine-driven pump.

1.4 (Continued):

Appendix A is intended to indicate typical environments for several different types of missiles. The actual requirements for a given system should be used and specified in the detailed specification.

1.5 Purpose:

1.5.1 This AIR delineates those factors in which the requirements of hydraulic pumps for use in missiles differ from the requirements of hydraulic pumps for use in manned aircraft.

1.5.2 It is intended that this AIR shall alert both the pump designer and systems designer to these differences and thus achieve lighter, simpler and more reliable hydraulic pumps which are particularly suited for missile use.

2. REFERENCES:

2.1 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

ARP598 The Determination of Particulate Contamination in Liquids by the Particle Count Method
AIR744 Auxiliary Power Sources for Aerospace Applications
AIR974 Long-Term Storage of Missile Hydraulic Systems
AS4059 Aerospace - Cleanliness Classification for Hydraulic Fluids

2.2 U.S. Government Publications:

Available from Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

MIL-STD-8-10 Environmental Test Methods and Engineering Guidance
MIL-H-5440 Hydraulic Systems, Aircraft, Types I and II, Design and Installation, Specifications For
MIL-H-8609 Motors, DC, 28 Volt System, Aircraft, General Specifications For
MIL-P-19692 Pump Units, Hydraulic, Electric Motor Driven, Variable Delivery, General Specifications For

3. REQUIREMENTS:

3.1 Materials:

3.1.1 All materials shall be carefully chosen for chemical and dimensional stability when subjected to extremes of temperature and varieties of hydraulic fluids.

3.1.1.1 The choice and installation of elastomeric materials are particularly strongly affected by ranges of temperature and pressure and the chemical nature of the hydraulic fluid. Careful attention must be paid to the requirements of the detailed specification.

3.1.1.2 Chemically active materials such as cadmium, zinc, and silver whose reactions with other materials are accelerated by high operating temperatures shall not be used in contact with the operating fluid. In elevated temperature applications (fluid or ambient), consideration should also be given to the stress alloying with steel components. In particular, cadmium shall not be used at temperatures conducive to stress alloying of steel parts.

3.2 Design and Construction:

3.2.1 All dynamic spring-mass systems in the pumps shall be damped to an extent that assures no adverse operation under the specified vibrational requirements. Insure that acceleration forces will not adversely affect the compensator control (variable pumps).

3.2.2 All compliant members shall be chosen, designed, or installed such that any changes in strength and/or modulus of elasticity caused by changes in the temperature environment will not affect the operating characteristics of the pump.

3.2.3 Insofar as possible, the pump design shall minimize the effect of changes in fluid viscosity, density, and compressibility caused by changes in temperature.

3.2.4 If cooling circulation ports are used, the flow passages in the pump should be designed so that they will not add additional pressure drop (heat) in the circulation process. In applications where the pump is contained in a reservoir, the reservoir shall be capable of heat radiation. In cases where the reservoir radiation is insufficient, the downstream leakage and/or system bleeds can be considered for heat dissipation.

3.2.5 The pump drive shaft shall not incorporate a shear section and have at least the capability of withstanding the torque of the internal pump drive mechanism. This precludes premature failure in rapid start-ups, or high pressure surge conditions.

3.2.6 It is desired that provisions for the automatic purging of gases entrained within the fluid be included in the pump design. This frequently may not be possible, and therefore, care must be exercised in the filling and bleeding procedures used. Where possible, vacuum filling shall be considered.

3.2.7 The reduction of weight is of extreme importance. This shall include consideration of enclosed fluid as well as the weight of the pump structure. Use of "plug-in" pumps, manifold porting, and nonstandard mounting flanges should be considered.

3.2.8 Because of the stringent reliability requirements, a very high quality of workmanship shall be used in fabricating the pumps. In particular, great care must be exercised to avoid free particles, hanging burrs, or other contaminants that may dislodge during operation and initiate a malfunction within the pump or within the system in which the pump will be used.

3.2.9 Where pumps are to be operated at high temperatures, nameplates, identification tags, inspectors' marks, etc. should be of thermally inert materials and attached in a manner that will not be affected by high temperature. For pumps submerged in oil, minimum external marking should be permitted. All marking should be either of a permanent nature or by nameplates securely attached to the pump body.

3.2.10 It is desirable that pumps be designed so that the effects of variation in inlet pressure are minimized. System designers should be aware of the effects of variation in inlet pressure on discharge pressure and design accordingly.

3.2.11 The overall efficiency of the pump shall be as high as possible, consistent with the requirements of the missile and cost-effectiveness. The low flow losses may be more important than the full flow losses. Sometimes, trade-offs in these areas are possible, for example, with DC motor driven pumps, it may be possible to improve the partial flow efficiencies at the expense of full flow efficiency by modifying the electric motor characteristics, to minimize the total watt-hour drain.

3.2.12 The pump shall not be subjected to testing in which a design misalignment between the base of the pump mounting flange and the test mounting fixture exists unless such a possibility also exists in the actual application.

3.2.13 Shaft seal leakage, especially during storage, is frequently a problem. Storing pumps in systems with 1 to 5 psig (7 to 35 kPs) inlet pressure requires careful design in the shaft seal area. Typical allowable leakage is 13 drops (0.05 in^3) (818 mm^3) per year, static; 1 drop per 5 min, operational. However, some systems specify zero leakage.

Provision should be made for visually determining if leakage has occurred and for suitable ways of measuring any leakage without disassembly of the unit.

3.2.14 Rapid start-up of the pump with only low reservoir storage inlet pressure (especially at cold temperature) can cause pump damage and/or inability to meet initial flow/pressure requirements in some systems. Influencing factors are acceleration time, choice of fluid, reservoir type and initial pressure, pump design, and operating speed. Prefiring warm-up time and/or heater blankets are additional considerations in very low temperature start environments.

3.2.15 Many hydraulic pumps can operate for one-duty cycle well above the rated temperature. For example, MIL-H-5440 Type II pumps 275 °F (135 °C), can reliably perform one terminal cycle up to 350 to 400 °F (177 to 204 °C). Temperatures from -65 °F (-24 °C) to over +700 to 800 °F (371 to 427 °C) are being considered for missile pumps. Operation at extreme elevated (over design) temperatures must consider the limited volume of fluid in the system and relate this to limited fluid leakage requirements.

3.2.16 Contamination control is a major problem in aircraft hydraulic systems. It is even more critical in missile systems. Pumps should be examined for contamination-generating chracteristics and also for the ability to survive in a contaminated environment. In systems where contamination is critical, a patch test should be established; the wear-out characteristics and performance degradation of the pump with oil contaminated to the level expected in the missile should be explored. Almost all systems incorporate a filter in the outlet of the pump. Filters usually are between 3 to 10 μm, nominal, depending on the dirt sensitivity of the system and the contamination level expected. It is good practice to use a "clean-up" filter during initial system operation, and replace it with a clean unit prior to delivery. If contamination levels cannot be accurately estimated, ARP598 can be used as a guide to determine contamination levels. AS4059, Class 5, is a suggested acceptance level for contamination.

3.2.17 Indications are that pumps can operate satisfactorily after up to 5 to 15 years or longer in storage, depending on the environment, frequency of exercise, etc. Refer to AIR974 for additional information.

3.2.18 Because missiles operate in small, tight systems, control stability of variable displacement pumps shall be explored in the early stages of system development. Functional test stands for production pumps shall simulate, as nearly as possible, the line sizes and lengths expected in the missile system.

3.2.19 The maximum speed at which a pump can reliably operate is a function of displacement (the lower the displacement, the higher the maximum speed), and to a lesser degree, temperature, and pressure. Speed can also be limited by inlet pressure or ability to load. For the smaller piston pumps, speeds up to 30 000 rpm are feasible. Efficiency tends to fall off at the higher speeds, primarily due to windage losses. Centrifugal pumps can be operated at much higher speeds, but efficiencies tend to be low.

3.2.20 Missile pumps tend to be used over a much wider range of pressures than an aircraft pump, and because each missile generally has much of its hydraulic equipment especially designed for it, and weight and space are at a premium, rated pressures tend not to be the conventional 1500/3000 psi (10 300/20 700 kPs) but whatever pressure is found to be optimum for a particular system (e.g., 3400 psig/23 400 kPs).

3.2.21 Although the pump itself is generally insensitive to the nature of the duty cycle (as long as operating conditions stay within design parameters), this is frequently a critical design problem to the supplier of the power source that drives the pump. This appears to be one of the most difficult areas to pin down and frequently results in underdesigned or overdesigned power sources with its attendant reliability and/or weight penalties. An early effort to define the duty cycle in realistic terms is well worthwhile.

4. DRIVING SOURCES:

4.1 A number of auxiliary power sources may be used to drive the pump. In this AIR, some of the more common power sources that drive missile pumps will be briefly described, and some of their characteristics that interrelate with pump characteristics will be discussed. Refer to AIR744 for a more detailed discussion of some of these power sources.

4.1.1 DC Electric Motors (28 and 56 V and Higher): Use of a DC motor for a missile hydraulic pump drive will usually require an aircraft-quality type motor per MIL-M-8609. The design considerations, although quite similar to many aircraft applications, are generally more restrictive. Weight, size, and available power are especially critical, and dynamic environmental requirements such as acceleration, shock, and vibration may be more severe. Although end usage may only be a one-shot duty cycle of only a few minutes duration, the operational life requirements will usually specify many repeated cycles that may accumulate a total life of 50 h or up to 100 times operating life. Since the energy stored in the battery becomes the limiting factor for the total mission, the battery characteristics and the detail duty cycle profile should be specified if maximum usage is to be obtained from the available energy. If the time the motor operates at light load is much greater than at full load, the efficiency of the motor at light load may become more important with respect to total power consumption than the full load efficiency. Motor characteristics can be adjusted somewhat to improve the partial load efficiency at the expense of full load efficiency.

Minimum weight for the motor will be obtained where it is sized for a speed that will provide the required output and where the total losses (motor), at the most adverse environmental condition, result in the maximum safe motor temperature for the limited life required.

This is an ideal condition for the motor pump unit (MPU) and in practice is generally compromised. If the battery is marginal and the greater total efficiency required of the MPU is obtained by a reduced speed, the weight of the MPU will be increased and the maximum temperature will be reduced. If a reduced speed is required because of pump limitations, the effect will be the same.

The choice of battery may impose a starting current limit that is far below the motor full voltage stalled current. The MPU must be capable of starting at a current level far below the limit value so that, when the battery is activated, it will start at low voltage and accelerate with the increasing battery voltage without exceeding the current limit value.

The need for an electromagnetic interference (EMI) filter may impose a significant weight penalty. Rather than imposing a standard MIL-STD-461 requirement, a significant weight saving might be obtained if tests could be made to determine the real EMI requirements.

4.1.2 AC Electric Motors 400 HZ, 3-Phase, 115/200 V Standard: AC Power is not too common for missile pump drives, but may find application on larger cruise type missiles where it may be available. AC Power may be lighter than DC power for equivalent horsepower. Speed may be limited with AC power since speed is a function of frequency and number of motor poles. 24 000 rpm is considered maximum for 400 Hz motors. Speed is inversely proportional to the number of poles. Weight and size increase with number of poles for the same horsepower. 6600, 7600, and 11 400 rpms are most common speeds. Motors have good speed versus torque characteristics and, generally, have high reliability and efficiency. Problems are in the areas of mismatch of starting torque requirements, especially with wide variations in voltage/frequency conditions, sensitivity to duty cycle overloads as compared to DC motors, and temperature/altitude requirements.

4.1.3 Ram Air Turbines: Ram air turbines are axial flow turbines (windmill) that convert airstream kinetic energy to useful shaft horsepower. High power levels can be attained by a relatively small turbine blade tip diameter compared to the familiar ground windmill type installation. Ram air turbine power capability is proportional to the true relative wind velocity raised to the third power, the air density, and the blade swept area.

Ram air turbines capable of generating up to 100 shp are currently in use. Ram air turbine-governor systems provide a power-to-weight ratio of approximately 3.0 hp/lb (4.9 kW/kg).

Ram air turbine governors provide shaft speed control operating ranges which rarely exceed 13 500 rpm. However, special systems have been designed that operate at shaft speeds exceeding 50 000 rpm. Conventional systems employ governors which provide accuracy of ±3 to ±12.5% of nominal shaft speed. High nominal shaft rotational speeds are desirable for purposes of minimum size and weight. Care must be taken to assure that maximum anticipated speeds are compatible with pump life and reliability requirements. There are large variations in types of mechanical and hydraulic governors. Control characteristics and shaft speed transients must also be evaluated for system compatibility.

Emergency ram air turbines can be extended into high Mach number air speeds. The pump designer shall be aware of possible high shaft accelerations when evaluating both inlet pressure and mechanical requirements. Such accelerations can be in the order of 14 700 rad/s^2.

Ram air turbines have relatively low starting torque characteristics. Fast running turbines have low solidity (fewer blades) and starting torque is less than for a slow running turbine having high solidity (many blades). The difference in acceleration characteristics may influence the overall design when evaluating weight differences and cost required to achieve low acceleration times using special devices. Low starting torque considerations are primarily limited to the minimum airspeed portion of the flight envelope. Starting characteristics quickly improve with increases in true air speed.

4.1.3 (Continued):

To improve starting characteristics, ram air turbines have been designed with turbine blades positioned at improved incidence angles which move to the normal design position during initial rotational acceleration. Conventional improvements in starting characteristics are accomplished by reducing the driven load during the initial acceleration period.

Hydraulic units using fixed displacement pumps normally employ flow sensitive pressure regulators that limit the maximum pump discharge pressures as a function of fluid flow. Low flow demands at very low air speeds, or excessive loads, or combinations of both, can cause reduced revolutions per minute and eventual stall. The flow sensitive pressure regulator is a device that limits pump output pressure to a value compatible with turbine torque characteristics. Unfortunately, turbine torque characteristics also vary with altitude and care must be taken to ascertain that valve operation matches also the altitude performance requirements.

Flow sensitive pressure regulator performance is also affected by fluid temperature variations. As a result, all parameters affecting fluid flow must be evaluated with respect to system performance requirements. In particular, flow variations with low volumetric efficiencies, resulting from extreme operating temperature and degradations due to wear, must be considered.

4.1.3.1 Pump Flow Controls: Variable displacement pumps are also used with ram air turbines. The obvious advantage is improved efficiency with minimum heat rejection to the system during periods of minimum fluid flow demand.

Standard variable volume, constant pressure pump controls without other aids normally are not compatible with turbine performance. Because of limited power at low air speed, there usually is insufficient turbine torque to maintain operation at a constant 3000 psi (20 700 kPa) compensator level without experiencing turbine stall.

Additional controls that reduce pump displacement as a function of flow when operating below the compensator setting provide an ideal performance match.

An additional control is required to drive the pump towards minimum displacement to unload the system for initial starting.

4.1.4 Turbine: Turbine drives have good power-to-weight ratio. Turbine drives are typically used for applications requiring moderate to high power output. They can use compressor bleed air or self-contained stored energy from a liquid or solid propellant. They operate at high speed. Positive displacement pumps generally require a reduction gearbox. Some work is being done on high speed centrifugal, gear and ball pumps that can be directly driven on the shaft at speeds up to 100 000 rpm. Turbine drives are adaptable to variable power demand. Some are speed controlled; others are torque balanced with the driving load. Turbine drives are generally more complex and therefore more expensive than other drives.

4.1.5 Positive Displacement Motors: These motors have the following advantages when considered for missile pump drives: very high torque to inertia; good rapid start-up capability, far exceeding the acceleration capabilities of either gas turbine or electric motors. This high acceleration capability also makes them usable for demand type systems, eliminating the need for variable displacement pumps, particularly if there is an accumulator in the system. This is an important cost and reliability advantage. Size and weight are generally very competitive with other pump drives.

High efficiencies can be obtained at moderate speeds, by contrast to gas turbines. For example, a rotary vane type expansion motor with an expansion ratio of 3:1 has demonstrated adiabatic efficiencies of approximately 70% at 4000 rpm, when operated with 1000 °F (538 °C) gas. Weight was 1.8 lb. Output horsepower was 2.5. This allows for direct drive or simple gearing as compared with gas turbines, which cannot approach these efficiencies even at very high speeds.

For warm or cold gas operation, there are cost advantages to the system employing the positive displacement motor. If operation with high temperature solid propellants is required, the advantages of the positive displacement motor would appear to reduce or perhaps disappear. It would appear that the high temperature, contamination, long life, and reusability problems are more readily resolved with a turbine.

If a relatively constant speed is required, the inherent fly-wheel energy advantage of the high speed turbine would appear to make it a better choice.

Production costs of positive displacement motors are reasonable, but development costs high, since few off-the-shelf devices exist. Check out generally limited to cold gas operation.

5. ENVIRONMENTAL CONDITIONS:

5.1 Temperature:

The nominally rated temperature of missile pumps should be in accordance with Table II of MIL-P-19692. Missile pumps and systems generally are capable of short duration operation at temperatures considerably in excess of their rated temperatures. For example, a Type II pump can usually be reliably operated to terminal temperatures of 400 °F (204 °C) or higher for periods of 5 to 10 min or more. Because of the seals, this should be considered to be a "one shot - end of flight" condition. The ambient temperature should be -65 to +160 °F (-53 to +71 °C), unless otherwise indicated in the detail specification. High ambient temperatures appear to have little effect on pump performance as long as they are lower than the maximum rated temperatures. Ambient temperatures higher than rated fluid temperatures can be tolerated for short periods due to the slow transfer from ambient to fluid.

Low ambient soak temperatures are more critical in design considerations in that they influence start-up time, starting torque and ability to load, especially in systems with low initial reservoir pressure, which in turn can cause cavitation damage.

5.2 Vibration:

Missle pumps seldom exhibit problems associated with sinusoidal vibration. Missile pumps are frequently exposed to severe random vibration resulting from operation in or near such propulsion devices as ramjet engines and rocket motors, the missile pump, in order to withstand the high pressures, temperatures and speeds that is its normal environment, seldom exhibits problems associated with vibration. Problems associated with vibration are more apt to be found on the next higher assemblies, e.g., electric motors, hydraulic power supplies, etc. Also, because of the wide variation in vibration requirements that are encountered between, for example, a turbojet powered cruise missile and a rocket powered ICBM, it is difficult to establish any parameters that would be meaningful, without imposing restrictive penalties.

Therefore, although the designer should be aware of the vibration environment, no specific values will be specified in this document as applicable to missile pumps. However, a typical set of values for several classes of missiles, which can be used for reference, can be found in Appendix A.

5.3 Shock:

Comments made under 5.2 concerning the wide variation between the various types of missiles equally apply here. Again, typical values are included in Appendix A for reference.

5.4 Acceleration:

Comments made in 5.2 concerning the wide variation in specific values also apply here. However, unlike the vibration and shock requirements, which seldom have any influence on pump performance, acceleration can affect such things as the pump compensator control, cylinder block, shaft seal, loading, etc. and an early examination of these potential problem areas should be made. A table of typical values is included in Appendix A.

6. TEST REQUIREMENTS:

6.1 A missile hydraulic pump is usually incorporated into another component or subsystem. Any detailed qualification tests that needs to be performed should be conducted on the higher subsystem, since in many cases the characteristics of the subsystem will strongly influence the pump's performance and reliability. Prior to subsystem qualification, however, it is desirable to have the pump supplier run a first article inspection test which can include the type of tests discussed in 6.2 and 6.3.

6.2 Endurance:

Missiles are inherently one-way, single mission, airframes. This requirement should dictate testing procedures. The operating life of the pumps should be consideered to consist of two portions:

a. A ground condition test that simulates ground check-out and testing prior to flight. This test can be from 5 to 50 h, depending on the receiving test time, missile check-out time and frequency, and numbers of captive flights.

b. A terminal test period that simulates severe operational environmental conditions. This test period should be representative of the extremes of the actual duty cycle in the live firing of the missile, and should cover the actual duration and number of hot cycles the pump will see in service. If this is a nondestructive test, the cycle may be repeated two additional times to establish a confidence level. Disassembly between cycles should be permitted to replace "O" ring seals, if this test includes a high temperature (beyond normally rated) run.

6.3 Low Temperature Testing:

A total of five starts shall be made at the applicable low temperature specified in the detailed specification. Every effort should be made to simulate start-up acceleration characteristics of the intended driving source, and the reservoir type, inlet line sizes, and length to the pump. Missile pumps are usually required to develop full flow and pressure immediately after activation, yet they normally are used with some sort of boot-strap reservoir. The purpose of this test is to insure that the pump is capable of starting cold, and that it can develop sufficient flow and pressure to charge the reservoir, and thus meet the system flow and pressure requirements in the time allotted.

PREPARED BY SAE COMMITTEE A-6,
AEROSPACE FLUID POWER, ACTUATION, AND CONTROL TECHNOLOGIES

APPENDIX A
TYPICAL ENVIRONMENTS

A.1 GROUND TO GROUND MISSILE:

A.1.1 Shock:

a. Operating: Per Figure A1, opposite directions in each of three axes
Duration: 10 to 30 ms

b. Nonoperating: Per Figure A2, in each of the three axes
Duration: 5 to 80 ms

A.1.2 Acceleration (Linear):

a. Operating: 21 g: longitudinal axis
4 g: all other directions

b. Nonoperating: None

A.1.3 Vibration:

a. Vibration-operating

b. Combined Sine Random

The unit shall be designed to operate within performance tolerances during vibration levels specified below:

TABLE A1

Sinusoidal g rms	Gaussian Random g^2/cps
8 g @ 5 to 300 cps	0.3 g^2/cps @ 15 to 300 cps
10 g @ 300 to 2000 cps	0.6 g^2/cps @ 300 to 2000 cps

The unit shall be designed to operate within performance tolerances after vibration levels specified below:

TABLE A2

Sinusoidal g rms	Gaussian Random g^2/cps
12 g @ 5 to 300 cps	0.6 g^2/cps @ 15 to 300 cps
18 g @ 300 to 2000 cps	1.5 g^2/cps @ 300 to 2000 cps

The sinusoidal vibration of the combined sine-random tests shall be swept at a constant 1/2 octave/min sweep rate and be limited to 0.4 in double amplitude.

A.1.3 (Continued):

Roll off random vibration at 12 db/octave (on an acceleration basis) from 1500 to 2000 Hz.

Limit Gaussian random vibration to 0.1 g^2/Hz below 25 cps.

A.1.2 Sine

The unit shall be designed to operate within performance tolerances while being subjected to a vibration of 25 g rms from 50 to 150 Hz.

The unit shall be designed to operate within performance tolerances after being subjected to a vibration of 50 g rms from 50 to 150 Hz.

A.1.3 Vibration-Nonoperating:

Sinusoidal vibration of the following frequencies and magnitudes shall be applied to the unit.

TABLE A3

Frequency	Magnitude
5 to 50 Hz	3.5 g
50 to 300 Hz	1.5 g

A.1.4 Maximum Amplitude: Figure A1 and Figure A2 0.4 in (1.02 cm) (double amplitude)

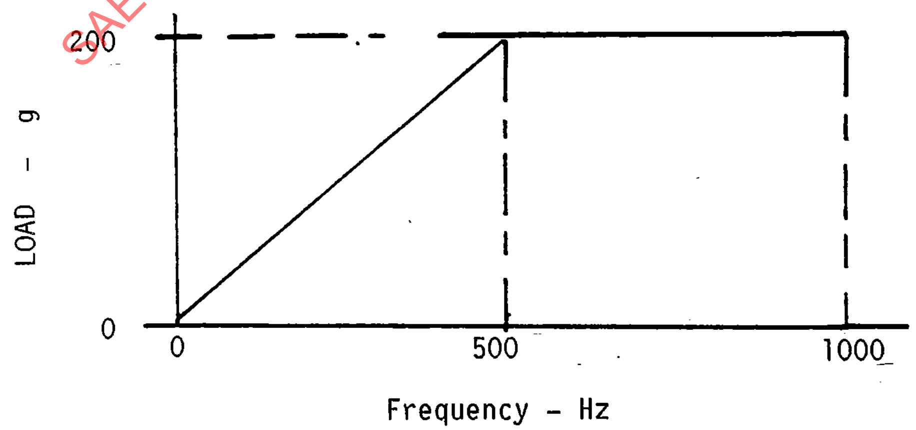
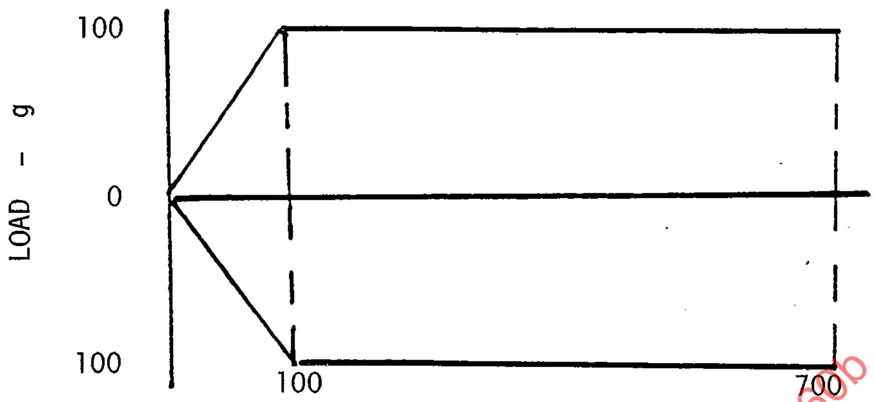


FIGURE A1 - Shock Spectrum-Operating



Primary Spectrum Tolerances:
±10 g of -30% to +50% for the 0 to 100 cps frequency range
-10% to +50% for the 100 to 200 Hz frequency range
-30% to +50% for the 200 to 700 Hz frequency range

Residual Spectrum Tolerances:
As above except ±50% for the 200 to 700 Hz frequency range

FIGURE A2 - Shock Spectrum-Nonoperating

A.2 GROUND TO AIR MISSILE:

A.2.1 Shock:

a. Operating Shock: The unit shall be capable of meeting its performance requirements during or after application of high impact shock along each of three mutually perpendicular axes. Each shock shall be a terminal peak sawtooth with a linear rise time of 6 ms and a peak amplitude of 100 g.

b. Nonoperating Shock: The unit shall sustain no damage and shall be capable of meeting its performance requirements after application of railroad transportation and rough handling shocks along each of three mutually perpendicular axes. The railroad transportation shock shall be a half-sine pulse of 30 g amplitude and 11 ms duration. The rough handling shock shall be the drop test specified in MIL-STD-810A, Method 516.1, Procedure 111.

c. Acceleration: The unit shall be capable of meeting its performance requirements after application of sustained acceleration of 27.5 g along the longitudinal axis, 31.2 g on the horizontal axis and 31.2 g along the vertical axis. The acceleration may be applied for 200 s along any axis. The pump shall be capable of being started and brought to rated speed during application of the acceleration load.

A.2.1 (Continued):

d. Vibration:

TABLE A4 - Operating

Frequency Range	Vibration Amplitude
5 to 18 Hz	0.2 in (5 mm) double amplitude or ±1.0 g, whichever is less
18 to 400 Hz	0.06 in (1.5 mm) double amplitude or ±10 g, whichever is less
400 to 3000 Hz	0.001 in (0.25 mm) double amplitude or ±20 g, whichever is less

TABLE A5 - Nonoperating

Frequency Range	Vibration Amplitude
2 to 28 Hz	±1.3 g
28 to 500 Hz	0.035 in (0.89 mm) double amplitude or 5 g, whichever is less

A.3 UNDERWATER TO GROUND MISSILE:

A.3.1 Shock:

a. Nonoperating (Simple Pulse): One-half sinewave as follows, in any direction, 12 occurrences:

1) Not greater than 25 g peak to peak amplitude
2) Pulse width of 30 ms

Complex wave - any direction

TABLE A6

Frequency (Hz)	Response (g)
20	25
230	130
2000	550

A.3.1 (Continued):

b. Operating (Simple Pulse): One-half sinewave $+Z_m$ direction; one occurrence as follows:

1) Not greater than 17 g peak amplitude
2) Pulse width of 30 ms

Complex wave - any direction

TABLE A7

Frequency (Hz)	Response (g)
50	35
60	100
150	250
420	250
550	170
2000	130

A.3.2 Acceleration:

a. Nonoperating:

1) Not greater than 2.3 g, any direction, duration 10 years
2) Not greater than 9 g, any direction, duration 1 min

b. Operating:

1) 3.5 rad/s about the center of gravity of the component, any axis; intermittent
2) Velocity in any direction will not exceed 120° (2.09 rad/s)
3) Not greater than 17 g in the Z_m direction duration 1 min
4) Not greater than 4.0 g in 2 mutually perpendicular axes normal to the Z axis duration 1 min each axis

A.3.3 Vibration:

a. Nonoperating: Discrete frequency sinusoidal, any axis, intermittently over a period of 7 years, with peak amplitude as follows:

1) Not greater than 0.040 in (1 mm) single amplitude from 5 to 16 Hz
2) Not greater than 1.0 g peak from 16 to 33 Hz