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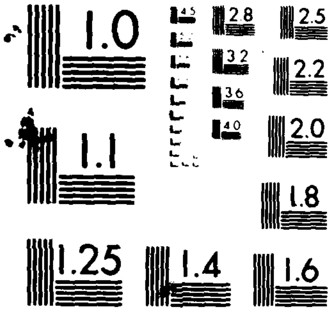

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Preliminary Design of a Hydraulic Power Supply for a Laminar Jet Angular Rate Sensor

by T. R. Small, W. O. Wilkinson,
F. F. Mark, and R. A. Makofski

Prepared by

The Johns Hopkins University
Applied Physics Laboratory
Laurel, Md. 20707

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Also presented are a test plan for measuring the performance of the proposed power supply and a limited literature review of potential hydraulic fluids.

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The preliminary design of a hydraulic power supply for a laminar jet angular rate sensor is described. The requirements upon which this design was based are that the power supply provide stable pressure and flow rates (of the order of 10 psi and 1ℓ/min) over the military temperature range (-60°F to 180°F). Reliability, safety, small size, and low cost are also factors that were considered. State-of-the-art equipment and passive control are specified.

Also presented are a test plan for measuring the performance of the proposed power supply and a limited literature review of potential hydraulic fluids.

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1. INTRODUCTION

The implementation of laminar jet angular rate sensors (LJARS) in field equipment requires that a reliable, low-cost power supply be available to provide stable pressures and flow rates over the military temperature range. These requirements are imposed by the sensor requirements for a constant (or predictable change in) Reynolds number, very low noise due to pressure, flow, or temperature fluctuations, and a contaminant-free, nontoxic fluid.

Although there are no fundamental differences in the operation of an LJARS using hydraulic or pneumatic techniques, the need for a closed recycling system with hydraulics does provide an additional complication, which, however, may be offset by the capability to use supply pressures that are within the range of available pumping equipment. In order to explore the potential of LJARS using both hydraulic and pneumatic techniques, Harry Diamond Laboratories has begun an effort to develop power supplies using both techniques. The current report is devoted to a preliminary design of a hydraulic power supply.

The technical approach employed in the preliminary design of the hydraulic power supply consisted of a review of available equipment (pumps, motors, sensors, heaters, control components, etc.) to identify those components that appeared to most closely satisfy the design goals cited in Section 2 and the conduct of design analyses and layouts with these components to project the power supply performance and cost. In order to minimize cost and complexity, the design approach used passive control to the maximum extent possible to satisfy design criteria. Active control would be incorporated only as necessary.

Concurrent with the design effort, a limited review was conducted of potential hydraulic fluids; the results are given in Section 3. The preliminary design is described in Section 4. Finally, a test plan to measure the performance of the proposed power supply is presented in Section 5.

2. DESIGN GOALS

The requirements to be imposed upon the power supply are dictated by sensor considerations of operating range, sensitivity, offset, drift, and noise. These considerations can be translated into power supply operating range for supply pressure, flow rate, and temperature and in the allowable operating limits for these parameters. Furthermore, the power supply must be capable of operation (although not at specification) over the military temperature range (-60°F to 180°F) and with an electrical input of 28 ± 10 Vdc.

The specifications for the hydraulic power supply were based on the following LJARS specifications:

Supply pressure, P_s	3 to 12 psi
LJARS gain, G_p	10
LJARS sensitivity, S	0.5×10^{-3} to 3×10^{-3} psi/deg/s
Null offset, $\partial(\Delta P_o)/\partial P_s$	0.02
Ratio of maximum differential pressure to centered pressure recovery, $\Delta P_o/P_{rec}$	2
Maximum rate, θ_{max}	550 deg/s
Threshold rate, θ_{min}	0.02 deg/s
Dynamic range, D_R	32,000
Common mode rejection ratio, CMRR	400

Based upon the relations provided in Ref. 1 and discussions with Harry Diamond Laboratories personnel, the design goals shown in Table 1 were established for the hydraulic power supply.

Table 1.

Design goals:
Hydraulic power supply for three-axis LJARS.

Parameter	Range	Operational variability
Supply pressure (psi)	3 to 12	Less than ±0.1%
Flow rate (ℓpm)	Note 1	Note 1
Environmental temperature (°F)	-60 to 180	
Warm-up time from -60°F	30 min or less	
Input voltage	28 Vdc	± 10 V
Reynolds number (LJARS)	500 to 1000	Note 2
Sensitivity (psi/deg/s)	0.5×10^{-3} to 3×10^{-3} (preferably $< 10^{-3}$)	Note 2
Hydraulic fluid: Nontoxic, noncorrosive, nonflammable, low variation of viscosity with temperature.		
No free surfaces within systems.		
Minimize cost, volume, and weight.		

Notes: 1. As dictated by Reynolds number and pressure requirements.
2. To be determined.

The design goals for Reynolds number and sensitivity variations were not specified but are to be kept to a minimum within the capabilities of the state-of-the-art equipment. Since these parameters are dependent on the fluctuations in pressure, flow rate, and temperature of the working fluid, a tentative design goal specified that these fluctuations should be less than the measurement capability of current state-of-the-art instrumentation.

The suggested design approach to achieving these goals is given in Section 4.

3. REVIEW OF POTENTIAL LJARS HYDRAULIC FLUIDS

A limited literature and catalogue search (Refs. 2 through 10) was conducted in order to identify liquids that would be suitable for use in an LJARS system. In addition, critical fluid factors involved in the design of an LJARS hydraulic power supply were defined, and fluid-property values required for preliminary design work were obtained.

Information was gathered on inorganic and organic (including petroleum-based and silicone) fluids. On comparing the characteristics of the fluids, it was decided that a silicone would be the best fluid for the LJARS application.

As a baseline for this review of fluids, the Dow Corning DC-200 silicone (dimethyl polysiloxane) fluids, which span a range of viscosity grades, were taken to be representative of liquids that could be used for LJARS. Other fluids were then compared with the DC-200 series. The text, tables, and graphs that follow present both general and specific information on hydraulic fluids considered in this evaluation.

Table 2 lists the factors that were used to evaluate hydraulic fluids. The first two groups (P: Primary and S: Secondary) include those factors that are important in the design of the LJARS power supply. The third group consists of those that are used generally to describe requirements for an ideal hydraulic fluid. Factors in the first and second groups are weighted, with 1 indicating the highest weighting, and are used to rate the fluids listed in Table 3.

Part a of Table 3 lists those fluids whose specifications, according to the rating scheme, best meet the primary criteria in Table 2. Part b lists fluids that were considered but rejected, primarily because their specifications did not meet the primary criteria of Table 2. The inorganic fluids are included principally for reference information. A dagger indicates those fluids from both groups whose viscosity-temperature curves are given in Fig. 1. These viscosity-temperature variations are presented as being characteristic of the available fluids.

Table 4 is a compilation of characteristics obtained for representative hydraulic fluids; part a lists silicones, part b other fluids. These characteristics are those that relate to the

Table 2.

Hydraulic-fluid factors.

a. Primary Importance (P)	
P-1.	Wide operating temperature range with fluid remaining liquid with stable properties. LJARS operating range: -60° to 180°F, fluid: 60° to 240°F (maximum temperature of fluid heater.)
P-2.	Nonflammable or fire resistant.
P-3.	Moderate nominal viscosity (value about 77°F), range of viscosity grades available.
P-4.	Comparatively insensitive viscosity-temperature characteristic.
P-5.	Possesses lubricating properties.
P-6.	Compatible with system materials, noncorrosive.
P-7.	Nontoxic.
b. Secondary Importance (S)	
S-1.	Moderate-to-high density, low expansion coefficient.
S-2.	Relatively incompressible.
S-3.	Resists shear breakdown, liquid is newtonian.
S-4.	Resists oxidation and gumming, contamination, and sludge formation.
c. Least Importance	
1.	Low air/water absorption, hydrolytic stability.
2.	Low temperature expansion coefficient.
3.	Good heat transfer properties.
4.	Low volatility.
5.	Low foaming.
6.	No handling and storage problems.
7.	Good service life.
8.	Electrically nonconducting.
9.	Average value of surface tension.
10.	Radiation resistant.

Table 3.

Hydraulic fluids with primary and secondary factor ratings.

Fluids	Factor rating: P: Primary, S: Secondary* Fluids meet factors: Well	 Less well	 Poorly (or insufficient data)
Conditionally acceptable for LJARS use:			
Phenylmethyl polysiloxane (silicone), DC-510+	P: 1 to 7 S: 1 to 4		
Dimethyl polysiloxane (silicone), DC-200+, DC-210H	P: 2 to 7 S: 1 to 4	P: 1	
Chlorophenylmethyl polysiloxane, DC-560	P: 1,2,5,6,7 S: 1 to 4	P: 3,4	
Polyaryl based blends MCS-310+ (Monsanto)	P: 1,2,5,6,7 S: 1,2,4	P: 3,4	S: 3
Conditionally rejected for LJARS use:			
Inorganic			
Water+	P: 2,4,6 S: 1 to 4		P: 1,3,5,7
Mercury+	P: 2,4,6 S: 1,2,3	S: 4	P: 1,3,5,7
Petroleum based			
Hydraulic fluid Mineral oil (MIL H5606)+ SAE motor oils	P: 5,6 S: 2	P: 3 S: 1,3,4	P: 1,2,4,7
Silicone			
Chlorosilicone polymers	P: 1,3 S: 1		P: 2,4,5,6,7 S: 2,3,4
Disiloxane	P: 6	P: 3	P: 1,2,4,5,7 S: 1 to 4
Disiloxane, dibasic acid ester	P: 6	P: 3	P: 1,2,4,5,7 S: 1 to 4
Fluorosilicone polymers, DC-FS-1265	P: 2,5,6 S: 1 to 4	P: 1	P: 3,4,7
Phenylmethyl polysiloxan			
DC-550,	P: 2,5,6,7 S: 1 to 4	P: 1,3	P: 4
DC-710	P: 2,5,6,7 S: 1 to 4		P: 1,3,4
Organic			
Chlorether			P: 1 to 7 S: 1 to 4
Chloronaphthalene	P: 5		P: 1,2,3,4,6,7 S: 1 to 4
Cyclicfluorinated ether	P: 1,2	P: 6	P: 3,4,5,7 S: 1 to 4
Dibasic acid ester (MIL-L-7808)	P: 1,7	P: 3,5	P: 2,4,6 S: 1 to 4
Fluorinated ether	P: 1,2,5	P: 6	P: 3,4,7 S: 1 to 4
Organophosphorus compounds		P: 3	P: 1,2,4,5,6,7 S: 1 to 4
Perfluoralkyl	P: 2 S: 1		P: 1,3,4,5,6,7 S: 2,3,4
Phosphate ester (Skydrol 500-A)	P: 2,6,7	P: 3,5	P: 1,4 S: 1 to 4
Polyphenyl ethers			P: 1 to 7 S: 1 to 4
Polytrifluorochloroethylene polymers		P: 3	P: 1,2,4,5,6,7 S: 1 to 4
Silicate esters+	P: 4,7	P: 1,3,6	P: 2,5 S: 1 to 4
Trimethyl propane ester		P: 3	P: 1,2,4,5,6,7 S: 1 to 4

*Factors defined in Table 2.
+Viscosity-temperature curves given in Fig. 1.

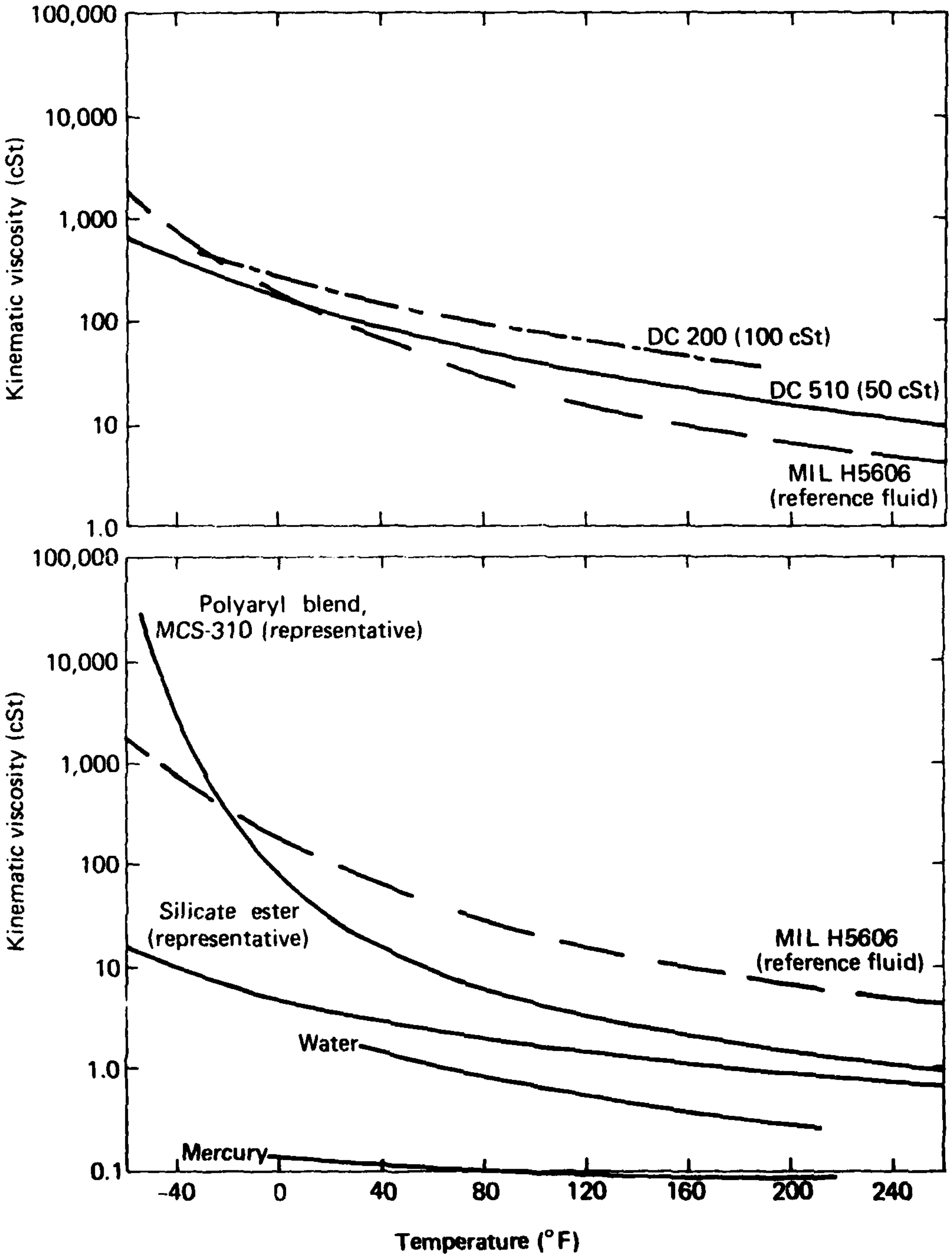


Fig. 1 **Viscosity-temperature characteristics.**

Table 4.

Comparison of fluid characteristics

Fluids (Note 1)	Chemical classification	temperature range (°F)	Thermal expansion ---------- Flash point (°F)	Viscosity at 77°F (vcSt)	Viscosity temperature-coefficient, C_T (Note 2)	Lubricity (see notes)	Specific gravity ---------- Compressibility (% at 10,000 psi)	Other
a. SILICONES:								
1. **DC-200 (DC-210H)**	**Dimethyl Polysiloxane**	-40 low, 329 high operation	9.6×10^{-4} /°C ---------- 572	100 Blendable, 0.65-2.5 x 10^6 cSt	(.60	3	0.968 ------- 6	Nontoxic, inert, stable shear, and oxidation resistant. DC210H: higher shear and oxidation resistance.
2. **DC-510**	**Phenylmethyl polysiloxane**	-70 low 400 high operation	9.6×10^{-4} /°C ---------- 527	100 Blendable, 0.65- 50 to 30,000 cSt	0.62	3	0.992 ------- 4.6	Nontoxic, inert, stable shear, and oxidation resistance.
3. **DC-550**	**Phenylmethyl polysiloxane**	-40 to 450	7.5×10^{-4} /°C ---------- 572	125 Single grade only	0.76	3	1.07 ------- ---	Nontoxic, inert, stable, resists oxidation and gumming; primarily a heat transfer fluid.
DC-710	**Phenylmethyl polysiloxane**	0 to 500	7.7×10^{-4} /°C ---------- 572	500 Single grade only	0.84	3	1.11 ------- ---	
4. **DC-560**	**Chlorophenyl methyl polysiloxane**	-65 to 550	9.5×10^{-4} /°C ---------- 550	75 Single grade only.	0.71	3	1.04 ------- ---	Nontoxic, inert, stable shear, and oxidation resistant.
5. **FS-1265**	**Fluorosilicone**	-40 to 400	9.5×10^{-4} /°C ---------- 500	300 Single grade only.	0.84	3	1.25 ------- ---	Toxic at elevated temperatures.
b. OTHER:								
1. **MCS-310 (Monsanto)**	**Halogen-polyarly blend**	-40 to 250	7.4×10^{-4} /°C ---------- 335 High temperature, fire resistant	6.3 Blendable	0.69	4	1.4 ------- 1.9 (7000 psi)	Toxicity: irritant, stable.

Table 4.

Comparison of fluid characteristics (cont'd).

Fluids (Note 1)	Chemical classification	temperature range (°F)	Thermal expansion ---------- Flash point (°F)	Viscosity at 77°F (cSt)	Viscosity temperature-coefficient, C_T (Note 2)	Lubricity (see notes)	Specific gravity ---------- Compressibility (% at 10,000 psi)	Other
2. **Silicate ester**	**Silicate esters**	**-142 pour point; low temperature use**	--- ---------- 180 Flammable	2.1 Higher values obtainable	0.52	5	--- -------- ---	Primarily heat transfer fluid.
3. **Hydraulic fluid SAE 10 Oil MIL H 5606**	**Petroleum/ mineral oils**	**-15 minimum -15 minimum -60 minimum**	--- ---------- --- Flammable	30 85 30	0.82 0.86 0.70	6 6 6	--- <1 SG 0.85 SG	**Oxidation and gumming problems. *MIL H 5606 specification* listed in hydraulic power supply work statement, also serves as a comparison standard, nontoxic, corrosive.**
4. **Water**	**Inorganic**	**32 to 212 (FP to BP)**	2.1×10^{-4} /°C ---------- --- Nonflammable	0.89	0.60	7	1.0 -------- 3	Corrosive
5. **Mercury**	**Inorganic**	**-38 to 674 (FP to BP)**	1.8×10^{-4} /°C ---------- --- Nonflammable	0.11	0.10	7	13.6 -------- 0.26	Toxic, corrosive.

NOTES:

1. **The first five entries are Dow-Corning fluids.**
2. $C_T = 1 - \frac{\nu_{210°F}}{\nu_{100°F}}$**, lowest value, most insensitive** (defined in the silicone literature.)
3. **Good, but depends upon system material** combinations and fluid blends.
4. **Depends on blend; good to poor.**
5. **Fair to poor.**
6. **Good.**
7. **Poor.**

more important factors selected for fluid evaluation. Moderate values of viscosity (at 77°F reference temperature) are desirable, since the LJAR sensor Reynolds number must also be moderate and since pumping efficiency is lowered if the viscosity is extremely high or low. Reference 2 states that experience indicates that a viscosity of 4000 centistokes (cSt) represents a maximum figure for pump and system operability. This value may be taken as a measure of an allowable viscosity for cold start-up at the minimum temperature expected and emphasizes the importance of low-temperature factors, such as pour point, in choosing a fluid. Too low a viscosity correlates with poor lubrication, mechanical friction, leakage past seals, and pump wear. In addition, because of the LJARS sensitivity-density dependence, high density would be a desirable fluid property. However, of the fluids that meet the standards set for the LJARS application, all have specific gravities near 1.0. Factors of equal importance are good lubrication properties and system-material/fluid compatibility. It appears from information available that the acceptable fluids meet these requirements.

Based on the ratings of Table 3, and because of its low temperature properties, the Dow Corning 510 silicone fluid (a phenylmethyl polysiloxane) with a kinematic viscosity magnitude of the order of 50 cSt at 77°F was chosen over the Dow Corning 200 fluid for preliminary design of the LJARS power supply. It meets the rating criteria satisfactorily: operating temperature range, stability and inertness, viscosity magnitude and temperature sensitivity, and lubrication properties; it also satisfies the other hydraulic-fluid factors listed in Table 2.

However, according to experiences reported in the references, applicability of a fluid, particularly with regard to its lubricating ability, is difficult to determine and varies with the type of pump, system materials, and fluid blends. Actual tests are required to establish the suitability of any fluid and to define problems connected with its use in a given system.

4. PRELIMINARY DESIGN OF LJARS HYDRAULIC POWER SUPPLY

The approach to the power supply design made maximum use of available equipment and passive control. Recognizing that many of the goals for power supply regulation may be beyond the state of the art, the approach consisted of identifying the available components that operated within the specified range and selecting those that appeared to offer the greatest accuracy or stability. Resolution of the system-related problems would then provide a system with capabilities that would be a measure of the current state of the art. Performance testing of the system would then indicate the need for additional active control and for further design refinements and development.

In pursuing this approach, a limited review was made of the availability of the principal equipment components needed for the power supply; the results are provided in Appendix 1. As can be seen from this review, the number of vendors capable of supplying the needed equipment off-the-shelf is limited, and the cited specifications suggest that the power supply goals may be difficult to achieve, especially with regard to noise and accuracy. Based upon information supplied by the vendors, the major components were selected as discussed below.

A design prerequisite is to establish a uniform environment and to provide a constant Reynolds number. This combination of factors leads to a design in which the components are immersed in the hydraulic fluid, which is maintained at a few degrees above the specified temperature range in order to avoid the need for refrigeration. The resultant design is shown schematically in Fig. 2. The parts list and suggested suppliers are given in Table 5.

The unit consists of a sump filled with Dow Corning DC-510 silicone fluid rated at 50 cSt at 77°F (25°C). The sump is fitted with a metal bellows to compensate for oil-volume changes in order to eliminate air/oil interfaces and is heated by immersion heaters to provide a nominal temperature of 184°F. The oil temperature is sensed by a thermistor and controlled to within 0.036°F (0.02°C). The sump is insulated to reduce heat transfer and to protect personnel.

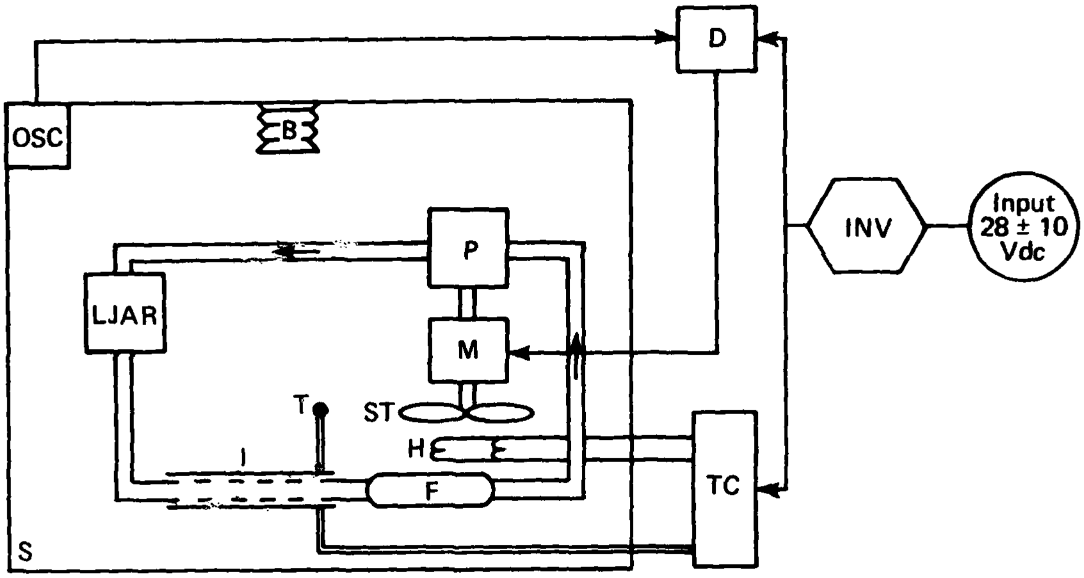
The specified pump is an internal gear hydraulic pump with a displacement of 0.65 in.^{3}/revolution per inch of width and a

Table 5.

Hydraulic power supply component list.

Component	Symbol*	Supplier	Remarks
Hydraulic pump	P	Nichols Gerotor	Mod 4065, Class III
Drive motor	M	Sigma	Mod 20-2220D200-E033
Filter	F	Parr Mfg.	Nondisposable
Stirrer	ST	To be fabricated	Circulates oil in sump
Sump	S	To be fabricated	6 by 6 by 3 in.
Thermistor	T	Cole-Parmer Instrument Co.	Senses oil temperature
Temperature control	TC	Versa-Therm	Mod 2156; sensitivity 0.02°C
Heaters	H	Cole-Parmer Instrument Co.	1 at 50 W; 1 at 400 W
Bellows	B	Metol Bellows Co.	P/N 610-60-3
LJARS	LJAR	Harry Diamond Lab.	3-axis
Isolator	I	To be fabricated	
Solid state inverter	INV	Topaz Electric Co.	500 W ac
Driver	D	Sigma	Mod 29A45
Oscillator	OSC	Texas Instrument Co.	Regulates driver

*Symbols from Figs. 2 and 3.



S = Component symbol from Table 5.

Fig. 2 Schematic of hydraulic power supply.

continuous pressure capability of up to 500 psi. The pump is connected directly to the LJARS input. The LJARS output is connected to an isolator that draws make-up oil from the sump while isolating the working fluid from the turbulence in the sump. The pump is driven by a stepping motor (diameter 2.2 in.; length 2.0 in.) at 200 steps/revolution and with a rated torque of 48 in.-oz. at 50 steps/s.

Power is supplied to the immersion heaters and motor from the primary source at 28 ± 10 Vdc through a 500-W inverter. The motor driver is rated at 50 V at 5 A per phase and is controlled through a stable oscillator, which is also immersed in the sump to maintain constant temperature and, therefore, constant frequency.

Design calculations are provided in Appendix 2. The unit weight including oil is estimated at 18 lb. The pump must supply approximately 8.5 psi at a flow of 0.55 ℓpm. The power dissipated by the electric motor is about 1.3 W. This low power dissipation allows the use of a simplified thermal design wherein heat is added to the oil (and all submerged components) by electric resistance heaters. The rate of heat removal is controlled by choosing the configuration of the sump support structure so that heat is transferred only by conduction to the metal structure of the vehicle in which the LJARS system is mounted. An insulating blanket surrounding the sump effectively eliminates heat losses from radiation and convection, which would have been very difficult to predict and control in field use, and protects personnel from accidental contact with the sump, which operates at 184°F. The make-up heating is provided by a 50-W heating element. To satisfy the condition that the power supply be in normal operation within 30 min following a soak at -60°F, a 400-W immersion heater has been added to the system.

In the proposed design, the only active control is that necessary to maintain sump temperature. Testing of the unit may indicate a need for feedback control on motor speed through pressure and/or flow sensing. However, in the interests of simplicity and cost, these controls have not been included prior to an examination of the test results.

5. TEST PROGRAM AND EQUIPMENT

In this section, a test program is described that has the objectives of determining the capability of state-of-the-art equipment to satisfy the design goals and of identifying further design refinements and developments necessary to attain these goals. The test program will consist of

1. Detailed design, fabrication, and checkout of the power supply,
2. Testing of the power supply to determine performance as related to design goals, and
3. Analysis and documentation of results along with recommendations for design refinement and development.

In addition, the estimated cost is given for conducting the test program. Each phase is described below.

5.1 DETAILED DESIGN, FABRICATION, AND CHECKOUT

Based upon the schematic of Fig. 2, a detailed design including final component selection must be undertaken for the items listed below:

Mechanical

Pump housing

Motor mount

Drive shaft and bearings

Stirrer

Isolator

Sump and insulation

Electronic equipment cabinet

Equipment mounting brackets

Heat sink

LJARS simulator

Electrical

- Control system (pump)
  Oscillator
  Stepping motor drive
  Motor
- Temperature control
  Heater
  Thermistor
  Controller
- Power supply (dc)
  Inverter

The test design will consist of a complete unit with insulated sump mounted through six 1/2-in. studs to a heat sink. The test sump will contain pressure parts for use with the pressure-measuring equipment and two electrical connections — one for main power and operating equipment and one for the bench test equipment. A separate box will contain the driver, inverter, and temperature controller.

The bench test equipment will consist of two pressure gauges, a precision flow meter, and a precision temperature gauge with thermistors. The equipment currently being considered includes:

Pressure. The pressure will be measured by a high-precision gauge to provide a time-average pressure and by a high-frequency response transducer to provide a measure of the pressure fluctuations. The average pressure measurement will be made with a Mensor (Model 300 or 11603) or Texas Instrument (Model 141) quartz coil pressure gauge, both of which have an accuracy of 0.04% full scale (0.002% FS for pressures less than 15 psi). The pressure fluctuations will be measured using a Kistler Instrument quartz transducer Model 606 (or equivalent), which has a range of 30 psi, an output of 5 picocoulombs/psi, and a response of 138 kHz.

Temperature. The temperature at various locations within the sump will be measured by a Hewlett-Packard precision thermometer (Model 2802A) or equivalent having an accuracy of 0.01°C and a response time of about 0.5 s. The time response should be adequate in view of the large thermal inertia of the system.

Flow Rate. The flow rate will not be a primary measurement but will be calibrated against the pressure measurements and a simulated LJARS load (a calibrated orifice to provide the correct pressure drop). This measurement will be made using a Cox flow meter having an accuracy of 0.25% FS, a reproducibility of 0.02%, and a response time of 0.18 s.

Other required test and recording equipment is assumed to be either available or government-furnished equipment (GFE). Vibration tests and tests of extreme temperatures can be carried out in an environmental test chamber. Table 6 indicates what equipment must be purchased or leased and what must be fabricated.

Table 6.

Major procurement and fabrication.

Purchased and GFE components		Fabricated equipment
Nichols gerotor pump	Heater	Pump housing
Sigma motor	Bellows	Motor mounts
Sigma driver	Oscillator	Shaft
Inverter	Heat sink	Stirrer
Bearings	Test equipment	Mounting brackets
Temperature controller	LJARS	Sump
Thermistors		Isolator
		Electrical cabinet
		LJARS simulator

Prior to unit assembly, the components will be assembled and bench-tested to obtain initial operational information and to gross tune the system. After assembly, the normal checkout runs will be made to obtain a relatively fine tuning of the equipment and to obtain estimates of the long-term stability of the sump temperature, the oscillator, and the flow rate and pressure.

5.2 TEST PLAN

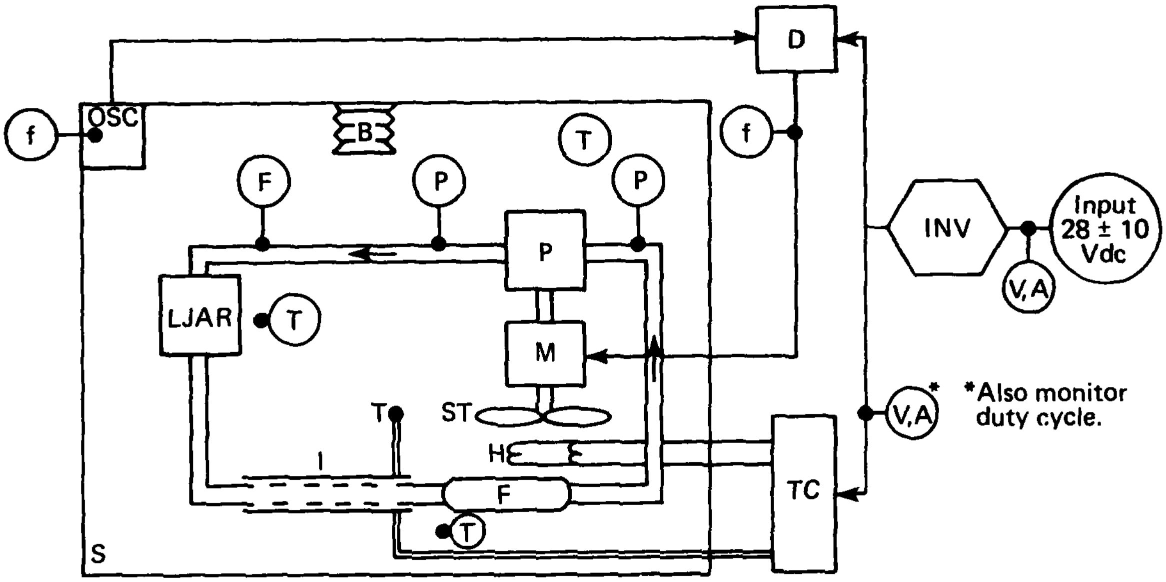
The power supply will be tested under three environmental temperature conditions: normal room temperature and in an environmental chamber at -60°F and at 180°F. The test measurements and test points are given in Fig. 3. Table 7 indicates the testing to be performed.

The locations of the test points are tentative and will be resolved in the final design. The primary measurements for LJARS input will be pressure and temperature. The flow measurement will be calibrated against pressure using a simulated LJARS load since the flow meter as a primary test instrument may provide pressure and flow variations that are untenable in the operation of LJARS. For this reason, if active feedback becomes necessary, pressure will be used as the error variable, and the test program will be expanded to identify the appropriate locations for pressure sensors.

Table 7.

Test plan.

Parameter measured	Ambient test conditions			Comments
	Room temperature	T = -60°F	T = 180°F	
Warm-up time	X	X		From ambient conditions.
Heater power (time and level)	X	X		Measure duty cycle.
Sump temperature	X	X	X	For uniformity.
Pump pressure				
Drift	X	X	X	
Fluctuations	X	X	X	Short-term variations.
Flow				
Drift	X	X	X	
Fluctuations	X	X	X	Short-term variations.
Power to motor	X	X	X	
Frequency to motor	X	X	X	
Oscillator frequency	X	X	X	
DC power				
14 V	X			
28 V	X	X	X	Impact on primary LJARS inputs.
36 V	X			
Step	X			
Vibration				
1 Hz	X			Influence on primary LJARS inputs.
30 Hz	X			



*Also monitor duty cycle.

Measurement test points:

S = Component symbol from Table 5.

ⓕ	Frequency
Ⓥ	Voltage
Ⓐ	Current
Ⓟ	Pressure
Ⓕ	Flow rate
Ⓣ	Temperature

Fig. 3 **Test points on hydraulic power supply.**

5.3 ANALYSIS AND DOCUMENTATION

The results of the test program will be analyzed to provide performance data on the hydraulic power supply with emphasis placed on the LJARS input parameters, i.e., pressure, flow rate, and temperature. The variability of these parameters will be assessed with recognition of the limitations of the measuring equipment.

The differences between power supply performance and the design goals will be discussed, and means to improve performance will be identified. Specific development requirements will be described. Procurement and fabrication costs will also be provided as a measure of the cost of the power supply.

5.4 MANPOWER AND COSTS

The estimated manpower in manmonths (mm) and procurement requirements for the suggested test program are described in this section. The estimated cost for fabrication of the unit is separately identified to provide an estimate for the first unit cost of the hydraulic power supply.

1. Detailed design and component selection

Mechanical design (per Sect. 5.1) . .	2.5 mm
Electrical design and development (per Sect. 5.1)*	4.0 mm
Total	6.5 mm

2. Power supply fabrication (per Table 6)

Component procurement**

Pump	$ 40	
Motor	128	
Drive	91	
Inverter	1,565†	
Bearings	20	
Filter	5	
Temperature control .	175	
Heaters	93	
Bellows	10	
Oscillator	210	
Total	$ 2,337	$ 2,337

(cont'd)

Fabrication (per Table 6) (150 m hrs.)	1 mm	
Assembly and checkout	2 mm	
Total	3 mm	3 mm

3. Test equipment††

Pressure gauges (2)§	$ 3,000	
Flow meter §	710	
Precision thermometer	1,115	
Frequency counter	1,500	
Electrical meters	400	
Total	$ 6,725	$ 6,725

4. Test conduct

Estimated at 2 persons for 3 months	6 mm

5. Analysis and documentation . . . . . . 2 mm

The total cost of the effort is estimated to be 17.5 mm and $9,062 in direct procurement. The procurement cost could be reduced to $6,462 if the pressure and flow measurement equipment were leased. Of this total cost, building the power supply (including direct purchase) is 3 mm and $2,337.

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*These estimates include the work required to develop the control system for the pump, including the integration of the oscillator, driver, and pump.

**Per supplier catalogues or quotations without overhead.

†This cost is primarily due to the wide range of input voltage variation (± 10V). A lower level variation could reduce cost by more than a factor of two.

††Recorders, amplifiers, and certain other equipment are assumed to be available.

§The pressure- and flow-measuring equipment may be leased at 10% of the purchase price per month. For a 3-month lease, the cost would be $1,110 compared with $3,710 if purchased.

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Appendix 1

EQUIPMENT REVIEW FOR LJARS HYDRAULIC POWER SUPPLY

In arriving at the preliminary design layout for the hydraulic power supply for the laminar jet angular rate sensors (LJARS), many manufacturers of components were canvassed through their catalogs and through telephone conversations with their engineering and sales personnel. The more promising of these reviews are tabulated in this appendix with comments regarding the suitability of their standard lines to LJARS needs.

The types of companies reviewed include:

1. DC-to-DC power supply manufacturers.
2. Electric motor manufacturers.
3. Pressure transducer manufacturers.
4. Hydraulic filter and accumulator manufacturers.
5. Hydraulic pump manufacturers.

DC-to-DC power supply manufacturers

Manufacturer	Power supply type	Remarks
Almond Inst.	DC-DC Switch regulated	Probably can do the job.
Alpha Power	AC-DC only	Not suitable for job.
CEA of Berkleonics	DC-DC Switch regulated	Cannot handle input variations with stock unit; probably could with special equipment.
Gould, Inc.	DC-DC Switch regulated	No reply.
Power Mate	DC-DC Switch regulated	45 to 57 Vdc input only.
Elpac Power Systems	DC-DC Switch regulated	Cannot do the job.
ACDC Electronics	AC-DC Switch regulated	Not suitable for job.

Electric motor manufacturers

Manufacturer	Motor type	Remarks
Aeroflex Laboratories	Stepper brushless DC	Linear torque versus speed. Instantaneous value of speed is constant. High cost, but less than brushless DC. Largest size is marginal for projected use.
Warner Elec.	Stepper	Could pot rotor and run submerged; largest in catalogue are suitable but are no longer made.
Sigma Inst.	Stepper	Sigma can provide motor and driver with start-stop ramp cards.
Clifton Precision	DC permanent magnet	None large enough.
GE Co.	DC permanent magnet	Large size, heavy motor (19 lb for 1/4 hp).
Bodine	DC permanent magnet and synchronous	Not powerful enough for projected needs.
Eastern Air Devices	Hysteresis synchronous	To 1/2 hp at 60 and 400 Hz; speed control not exact enough.

Pressure transducer manufacturers

Manufacturer	Pressure gage type	Remarks
Hamilton Standard	"Vibrasense"	Product removed from market.
Gould, Inc. (Statham)	Unbonded strain gage	±0.25% FS accuracy over temperature range. Individual gages can approach ±0.1% accuracy.
Bell & Howell (CEC)	Strain gage (sputtered)	Same as Gould above.
Rosemount	Potentiometer	0.25% FS. Good repeatability.
	Capacitor	0.01% resolution, 0.02% repeatability.
	Variable reluctance	0.05% hysteresis.
Mensor	Digital readout, force-balanced quartz bourdon tube.	0.04% FS accuracy, very expensive laboratory instrument.
Kistler	Quartz piezoelectric	0.005 psi resolution of pressure fluctuations.

Hydraulic filter and accumulator manufacturers

Manufacturer	Power supply type	Remarks
Filterite	Cartridge filters	Large filters with replaceable elements.
Parr Mfg. Co.	Fuel filters	Very small non-replaceable element.
Donaldon Co., Inc.	Fluid filters	Large filters with replaceable elements.
Greer Hydraulics	Pulsation dampers	Very large, heavy equipment for high pressure use.

Hydraulic pump manufacturers

Manufacturer	Pump type	Remarks
Viking	External gear (straight tooth)	Heavy and awkward; probably noisy.
	Internal gear (3 tooth Δ)	Heavy and awkward;
Roper	External gear (helical tooth)	Cast iron housing, steel gears.
	Progressive cavity	Much too large and heavy.
Eastern Industries	External gear (straight tooth)	Aluminum alloy housing; probably noisy.
Tuthill	Internal gear (2 tooth Δ)	Cast iron housings; heavy and awkward.
	Internal gear (1 tooth Δ)	Lightest (we supply housing); hydraulically quiet; drive outer gear.
Nichols	Internal gear (1 tooth Δ)	Drive inner gear; simplest and lightest.
Robbins & Myers	Progressive cavity	Very large and heavy; capacity and power OK.
Sherwood Specialties	Progressive cavity	Capacity too small.
Cherry-Burrell	Progressive cavity	Too large and heavy.

Appendix 2

DESIGN CALCULATION FOR HYDRAULIC POWER SUPPLY*

1. WEIGHTS OF COMPONENTS AND STRUCTURES

The following tabulation provides a weight estimate of the power supply based upon the current design.

Item	Estimated weight (lb)
Sigma stepper motor	1.20
Nichols pump (1.75 OD × 0.543 × 0.283 in.)	0.37
Pump housing	2.00
LJARS (brass) (1 × 1 1/2 × 3/8 in., 0.306 in. thick)	0.17
LJARS housing	0.50
Oil filter	0.50
Electric heaters (2)	2.50
Steel bellows	1.00
Sump (stainless steel) (6 × 6 × 3 in., 1/8 in. thick)	5.10
Steel mounting studs	0.90
Pocket for oscillator	0.90
LJARS pressure sensors	0.50
Tubing (Tygon or polyethylene)	0.50
Total empty weight	16.14
Weight of oil (50 in^3)	1.77
Total weight	17.91

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*Throughout this appendix, except where noted, information used is provided by the supplier of equipment or taken from Marks' <u>Mechanical Engineering Handbook</u>, Sixth Edition.

2. HEAT SYSTEM CONSIDERATIONS

Since the control of oil temperature is of critical importance to the operation of LJARS, and since the operating environment of the unit is not predictable, the heat transfer from the unit will be limited to conduction to the support structure of the vehicle, which is treated as a heat sink. The conduction path from the sump will be through the mounting studs with radiation and convection reduced to negligible levels by thermal insulation (about 2 in. of polystyrene) about the sump. The insulation will also provide for personnel protection.

The calculation of heat transfer is iterative, requiring knowledge of power dissipated, which, in turn, is dependent upon oil temperature (through viscosity). To avoid the iteration, the final design values will be used for certain calculations and verified later.

The power supply support consists of six 0.50 in. steel studs with a heat path length of 2.50 in. The total power dissipated within the sump is 1.31 W. The opertional temperature range is specified as

Minimum:	-60°F
Nominal:	84°F
Maximum:	180°F

These values are used as the temperatures of the vehicle structure for initial operation. The last value (180°F) can be used to estimate the required operating temperature of the oil, i.e., the increment above 180°F that the oil must achieve to transfer the power dissipated in the sump. That is,

$$k\,\Delta T\,\frac{A_s}{L} = q = 1.31\ \text{W} = 4.47\ \text{Btu/hr.}$$

For the steel studs,

$$k = 26.2\ \text{Btu/hr/ft}^2\text{/ft},$$

$$L = 2.5\ \text{in.} = 0.208\ \text{ft},$$

$$A_s = 6\,\frac{\pi(0.5)^2}{4(144)} = 0.00818\ \text{ft}^2.$$

So

$$\Delta T = 4.34°F.$$

The oil sump operating temperature is taken as $T_s = 184°F$.

The nominal and minimum temperatures are used to compute the maintenance and start-up heating requirements. For nominal operation,

$$\Delta T = 184 - 84 = 100°F,$$

$$q_n = 103 \text{ Btu/hr} = 30.2 \text{ W}.$$

For minimum temperature operation,

$$\Delta T = 184 - (-60) = 244°F;$$

$$q_n = 251.3 \text{ Btu/hr} = 73.6 \text{ W}.$$

A 50 W heater should be sufficient for most maintenance heating requirements. Such a heater, along with the power dissipation from the pump, would be sufficient to maintain the oil temperature at 185°F for vehicle sink temperatures as low as 27°F. If lower vehicle operating temperatures are contemplated, a larger heater will be required. In any event, the start-up heater could be used as a gross supplement for lower temperatures.

The start-up heating requirement consists of the heat supplied to heat the oil and the equipment in the sump (mostly steel), and to make up the heat loss to the structure. Thus,

$$q_i = (C_{Pm} W_m + C_{Po} W_o) \frac{dT}{dt} + \frac{kA_s}{L} (T - T_M),$$

where q_i represents the power dissipated by the start-up heater, pump and motor losses being neglected. This equation can be solved to yield

$$q_i = \frac{\beta(T_o - T_M)}{I - \exp\left(-\frac{\beta t_o}{\alpha}\right)},$$

where $\beta = kA_s/L$,

$\alpha = C_{Pm} W_m + C_{Po} W_o$,

T_o = oil operating temperature (184°F),

t_o = specified time to achieve T_o, i.e., 30 min, and

T_M = minimum temperature (-60°F).

For these conditions,

$$q_i = 1326 \frac{\text{Btu}}{\text{hr}} = 388 \text{ W},$$

so a 400 W heater should suffice for start-up heating.

Therefore, heater selection consists of

1. Start-up heater of 400 W,
2. Maintenance heater of 50 W, and
3. Heater switching logic for
   - (a) Gross control of start-up heater with power removed at oil temperature of 180 ± 2°F and
   - (b) Maintenance heater to be operated by fine control to temperature of 184 ± 0.036°F.

3. MOTOR AND PUMPING SYSTEM CONSIDERATIONS

3.1 Pump

For Dow Corning DC-510 silicone fluid rated at 50 cSt at 77°F (25°C), the following properties apply at 185°F (84.5°C):

$\rho = 59 \text{ lb/ft}^3$,

$\nu = 17 \text{ cSt} = 0.183 \times 10^{-3} \text{ ft}^2\text{/s}$, and

$\mu = 23.3 \times 10^{-7} \text{ lb-s/m}^2$.

Harry Diamond Laboratories has specified a LJARS sensitivity of $S = 0.9 \times 10^{-3}$ psi/°/s; from a curve provided by Harry Diamond Laboratories for $S/\mu = 387$, $N_R = 580$.

Assuming the entire velocity heat is lost in the system, the pressure required across the pump is

$$\Delta P = \frac{1}{2}\frac{\rho v^2}{g} = \frac{1}{2}\frac{\rho}{g}\left[\frac{\nu N_R}{b_s}\right]^2 ,$$

$$\Delta P = 1214 \text{ psf} = 8.43 \text{ psi} \quad \text{for } b_s = -0.035 \text{ in.}$$

The flow rate per sensor is computed from the relations

$$\dot{V}_s = C_d\, b_s^2\, \sigma \left(\frac{2}{\rho}\,\Delta p\right)^{1/2} = C_d\, b_s\, \sigma\, N_r\, \nu \text{ and}$$

$$C_d = \left\{\frac{1}{6.6}\, \ell n \left[1 + \frac{\dot{V}_s}{(2.667)(X_{th} + 1)\ (\sigma + 1)^2\ b_s \nu}\right]\right\}^{1/2} ,$$

where C_D is the discharge coefficient relation and is provided by Harry Diamond Laboratories. The relations may be solved iteratively to yield

$$C_d = 0.291 \text{ and}$$

$$\dot{V}_s = 0.000108 \text{ ft}^3\text{/s/sensor},$$

for $\sigma = 1.2$, $X_{th} = 20\, b_s$.

For a three-axis sensor,

$$\dot{V}_s = 0.000324 \text{ ft}^3\text{/s} = 0.55 \ \ell\text{pm} .$$

For a projected pump efficiency of $\zeta_p = 60\%$, the pumping power required is

$$PP = 1.356\, \frac{\Delta P\, \dot{V}_s}{\zeta_p} = 0.89 \text{ W}$$

To size the pump, consider the Nichols Gerotor Model 4065:

Operating speed: 100 rpm

OD: 1.75 in.

Theoretical displacement: 0.65 in^3/rev/inch width

For the current system, $\dot{V}_s = 33.6\ \text{in}^3/\text{min}$, so required displacement is 0.336 in^3/rev, resulting in a theoretical width,

$$W_t = \frac{0.336}{0.65} = 0.517\ \text{in.}$$

Based on the manufacturer's literature, the volumetric efficiency for these conditions is 95%, so the actual width required is 0.544 in.

Summarizing, the pumping requirement can be satisfied by a Nichols Gerotor Model 4065, Class III pump having:

OD:	1.75 in.
Width:	0.55 in.
Operating speed:	100 rpm
Fundamental ripple frequency:	16.67 Hz
Power required:	0.9 W

3.2 Stirrer

The power requirements for the stirrer can be computed using propeller theory. A stirrer that would turn over the fluid every 30 s would require a flow rate of 100 in^3/min (0.0579 ft^3/min). This rate can be obtained by a stirrer with the following specifications:

rpm = 100

Diameter = 2 in.

Chord = 0.25 in.

No. of blades = 2

Blade twist: 6.75° at 20% radius
1.35° at blade tip

Power requirements based upon momentum disk calculations with a propeller efficiency of 50% yield 5×10^{-6} W. Computation of the power based upon blade element considerations provides 2×10^{-5} W. In either case, the power required can be neglected.

3.3 Motor

In addition to the above losses, there will be a loss due to rotor motion in oil. To compute this loss, the rotor will be treated as a bearing with the following dimensions:

Rotor diameter: 1.5 in. ($r = 0.75$ in.)

Rotor length: 2.0 in.

Rotor-to-stator clearance: 0.008 in.

Eccentricity: 0

Clearance ratio: $m = \frac{0.008}{1.5} = 0.005$

Friction coefficient: $k_f = 0.5$

$N = 100$ rpm

Friction force $= \frac{k_f \mu N r \ell}{m} = 0.035$ lb

Power required = 0.031 W

So the total power required is the pump power and the above frictional power or 0.92 W. For a projected motor efficiency of 70%, the motor power required, MP, will be 1.31 W. The motor torque will be

$$T = \frac{MP}{2\pi N} = 0.092 \text{ ft-lb} = 17.7 \text{ in.-oz.}$$

These requirements can be met by the Sigma stepper motor, Model 20-2220D-200-E033:

Steps at 200/rev:

(100 rpm) (200) = 20,000 steps/min

Maximum torque: 48 in.-oz

Unipolar drive circuit (6 motor leads)

Main shaft: 1/4 in., 0.81 in. length
Rear shaft: 1/4 in., 0.75 in. length
OD: 2.25 × 2.25 × 2.0 in.

4. BELLOWS CONSIDERATIONS

To avoid the existence of a free surface, a bellows will be used to accommodate the change in volume with temperature. The Dow Corning 510 fluid has a volume coefficient of expansion of $0.96 \times 10^{-3}/°C$. For a temperature range from -60°F to 184°F, the potential change in volume of 50 in^3 of fluid at 70°F is

$$\Delta V = \begin{Bmatrix} + 3.13 \text{ in}^3 \\ \\ - 3.59 \text{ in}^3 \end{Bmatrix} = 6.72 \text{ in}^3$$

To accommodate this volume change, consider a Metal Bellows Co. 610-60-3 welded stainless steel bellows with the following properties:

Flange OD: 2.687 in.
Bellows OD: 2.55 in.
Effective area: 3.63 in^2
Compressed length: 0.303 in. per capsule
Deflection: 0.71 in. per capsule

The effective change in volume per capsule is $(0.71 \times 3.63) = 2.57$ in^3, so three capsules will be required.

The change in length of the bellows will be

$$\Delta L = \frac{6.72}{3.63} = 1.85 \text{ in.},$$

for a total bellows length of

$$L_T = 3\ (0.303) + 1.85 = 2.75 \text{ in.}$$

When filled at 70°F, the bellows length is

$$L_F = 3\ (0.303) + \frac{3.13}{3.63} = 1.77 \text{ in.}$$

5. REYNOLDS NUMBER AND SENSITIVITY VARIATIONS

The LJARS performance appears to be critically sensitive to small variations in Reynolds number, which, in turn, is affected by fluctuations in pressure, flow rate, and temperature. The sensitivity of the unit to these input parameter fluctuations is best determined by testing, but a first-order estimate may be obtained by considering the possible variation in Reynolds number, N_R, as given by the component specifications.

The change in N_R is given by

$$\frac{\delta N_R}{N_R} = \frac{\delta \dot{V}_s}{\dot{V}_s} - \frac{\delta \nu}{\nu} ,$$

if component dimensional changes are neglected.

But $$\frac{\delta \dot{V}_s}{\dot{V}_s} = \frac{1}{2}\left(\frac{\delta p}{p}\right) - \frac{1}{2}\left(\frac{\delta \rho}{\rho}\right) .$$

For DC-510 to a first approximation,

$$\frac{\delta \rho}{\rho} = -9.6 \times 10^{-4}\ \delta T \quad (T \text{ in } ^\circ C) ,$$

$$\frac{\delta \nu}{\nu} = -4.7 \times 10^{-3}\ \delta T \quad (T \text{ in } ^\circ C) .$$

So

$$\frac{\delta^{N}{}_{R}}{N_R} = \frac{1}{2}\left(\frac{\delta p}{p}\right) + 4.8 \times 10^{-4}\ \delta T\ 4.7 \times 10^{-3}\ \delta T$$

$$= \frac{1}{2}\left(\frac{\delta p}{p}\right) + 0.00518\ \delta T .$$

If $\delta p/p$ and δT are known from experiment, then δN_R can be computed. From the goals for δp and the specification on the temperature controller,

$$\frac{\delta p}{p} \leq \pm\ 0.001 \text{ and}$$

$$\delta T \leq \pm\ 0.02^\circ C .$$

So

$$\frac{\delta N_R}{N_R} \le \pm\, 6 \times 10^{-4} \; .$$

The variation in the sensitivity is given by

$$\frac{\delta S}{S} = \frac{\delta \nu}{\nu} + \frac{\delta \rho}{\rho} + \frac{\delta N_R}{N_R} = \frac{1}{2} \left(\frac{\delta \rho}{\rho} \right) - 4.8 \times 10^{-4} \; \delta T \; .$$

So

$$\frac{\delta S}{S} \le \pm\, 5 \times 10^{-4} \; .$$

Note that the pressure term dominates the values of δN_R and δS, suggesting that the temperature specification can be relaxed. Furthermore, the sensitivity variation is well within the allowable noise, based on a threshold of 0.02°/s, for $\theta < 40$°/s, suggesting that the pressure specification may be relaxed for applications satisfying this condition.

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