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APPLIED SCIENCES DIVISION

INFORMATION REPORT

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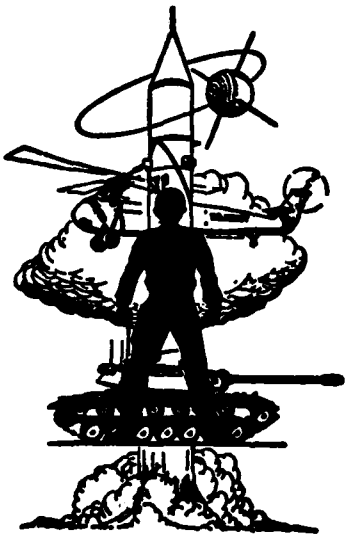
INVESTIGATION OF COMPRESSIBLE FLUIDS FOR USE IN SOFT RECOIL MECHANISMS



LARGE CALIBER WEAPONS SYSTEMS LABORATORY

ARRADCOM - Dover, New Jersey

ASD IR 3-77

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INFORMATION REPORT

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INVESTIGATION OF COMPRESSIBLE FLUIDS FOR USE IN SOFT RECOIL MECHANISMS

By

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September 1977

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WILLIAM J. POWERS

APPROVED BY: [signature]
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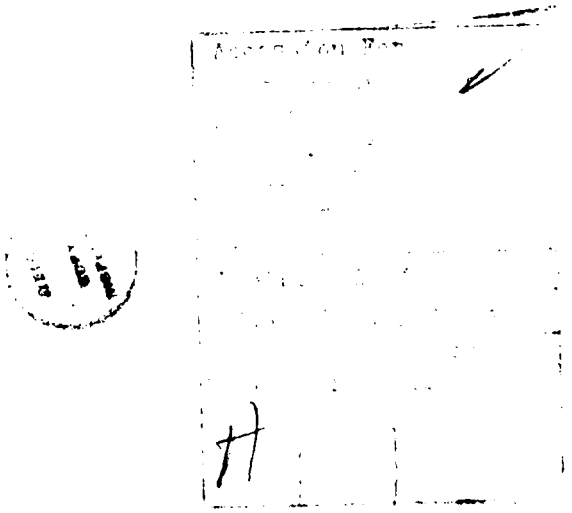

ACKNOWLEDGMENT

Measurements of the sonic compressibility of six fluids were carried out by Dr. Jacek Jarzynski and his staff at the Naval Research Laboratory, Washington, D.C.

OBJECTIVE

Provide compressibility and bulk modulus data for the selection of optimum fluids for the compressible fluid/soft recoil mechanism.

BACKGROUND

An effort on Compressible Fluids for Soft Recoil Systems was initiated by SARRI-LR (currently DRDAR-LCA-O) in October 1975 at the request of SARRI-LA (currently DRDAR-LCW-E). A concept proposal[1] outlined the proposed system and tentative requirements for the fluids to be used. A report by LTC Lyle[2] identified the silicone fluids as the most promising at that time and listed a number of other fluids to be considered. The report pointed out a possible deficiency in compressibility of available fluids at low temperatures and recommended tests to verify this possibility. Accordingly, the Naval Research Laboratory was contacted to carry out compressibility measurements on a silicone oil, Dow Corning (DC) 200-10cs. fluid and several other promising fluids, by the sonic method. Initial results obtained by Dr. Jarzynski of NRL were reported to SARRI-LA on 5 August 1976.[3] These measurements indicated that the compressibilities of five fluids tested were less than initially desired for the CFSR mechanisms, especially at low temperatures.

In spite of the low compressibilities found, the DC200 fluid was selected by SARRI-LA for further testing on several engineering test fixtures. The reasoning was that the test fixture itself had some flexibility and the total system compressibility could be expected to be higher than that for the fluid alone. Initial tests seemed to bear out this concept of the total system compressibility and results of those investigations are being discussed in separate reports by Chin and Drum.[4]

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1. "155mm Howitzer with Compressible Fluid/Soft Recoil (CFSR) Mechanism", prepared by Advanced Concepts Division, Artillery and Armored Weapons Systems Directorate, GEN. Thomas J. Rodman Laboratory, Rock Island Arsenal, Rock Island, IL 61201 October 1975.

2. Lyle, Richard E., "Compressible Fluids for Soft Recoil Systems", SARRI-LR Letter Report 14 November 1975.

3. Hong, Van Y.S. and Bornong, B.J., "Compressibility and Bulks Modulus of Proposed Fluids for Soft Recoil Systems", Research Directorate Laboratory Report No. 76-0991, 5 August 1976.

4a. Chin, V. and Drum, W.R., report in preparation.

4b. Chin, V., "Report on Compressible Fluid Recoil Mechanism for the 105mm M68 Cannon." Report in preparation.

The laboratory phase of this program continued with a search for other promising compressible fluids and the performance of laboratory experiments to obtain compressibility data. A series of engineering experiments carried out by SARRI-LA on a compressible fluid test fixture were monitored by SARRI-LR personnel to determine the behavior of the fluid and to determine the effects of dissolved or entrained air on the compressibility.

This report presents results of the laboratory phase of this program carried out by SARRI-LR from October 1975 to the present time. Work on this task is continuing.

DEFINITIONS

Compressibility data were obtained by two methods. The first series of measurements was made by Dr. Jacek Jarzynski of the Naval Research Laboratory. His laboratory had developed a sonic method for fluid density and bulk modulus measurements.[5,6] The bulk modulus (B_s) is given in this sonic method by the relationship $B_s = \rho C^2$, where ρ is the fluid density and C is the velocity of sound in the fluid. This modulus is the adiabatic or isentropic bulk modulus and it applies under conditions in which no heat is exchanged between the surroundings and the fluid during compression and expansion. These conditions apply in the sonic method because of the rapid compression-decompression cycles of the sound waves.

A second type of modulus is the isothermal bulk modulus, in which heat is exchanged with the surroundings during the compression-decompression cycles to maintain a constant temperature. Several other bulk moduli are defined, and are described in a number of publications.[7,8] Illustrations and definitions of the types of bulk modulus obtained in this program will be given in some detail in the following paragraphs to clarify the data to be presented.

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5. Corsaro, R. D., Jarzynski, J. and Davis, C. M., Jr., "Acoustic Densitometer with Results for Polyethylene Oxide", J. Applied Physics, Vol. 45, No. 1, January 1974, pp. 1 - 8.

6. Davis, C. and Jarzynski, J., Description of densimeter-velocimeter; personal communication to V. Hong.

7. "Engineering Design Handbook-Hydraulic Fluids", AMC Pamphlet No. 706-123, U.S. Army Materiel Command, Washington, D.C., 15 April 1971, pp. 3-44 to 3-51.

8. Wright, W. A., "Prediction of Bulk Moduli and Pressure-Volume-Temperature Data for Petroleum Oils", ASLE Transactions, Vol. 10, 1967, pp.349-356.

Figure 1 illustrates a typical pressure-volume curve for a fluid. The secant isothermal bulk modulus ($\bar{B}_t$) is defined as:

$$\bar{B}_T = \frac{V_o(P-P_o)}{V_o - V} \quad , \tag{2}$$

or

$$\bar{B}_T = \frac{V_o \Delta P}{\Delta V} \tag{3}$$

The volume strain, or volume compression, is $\frac{\Delta V}{V}$: This ratio is the fractional change in the fluid volume as it is compressed from pressure P_o to P. The percent compression as used in this report will be $\frac{\Delta V}{V}$ x 100.

The tangent isothermal bulk modulus (B_t) is defined as:

$$B_T = -V\left(\frac{\partial P}{\partial V}\right)_T \tag{4}$$

and is determined by the slope of the P-V curve at pressure P. The secant bulk modulus is always less than the tangent molulus but it approaches the tangent near P_o, V_o.

The relationships between the isothermal and adiabatic bulk modulus can be illustrated with the aid of Figure 2. Curve OA represents the P-V path followed when the fluid is compressed adiabatically from P_o to P. The tangent bulk modulus at pressure P is defined as:

$$B_s = -V\left(\frac{\partial P}{\partial V}\right)_S \tag{5}$$

In this case a constant entropy (s) condition prevails (no heat exchange). This bulk modulus is the same as the sonic modulus. Now if the fluid which was compressed from point O to point A is allowed to come to thermal equilibrium with its surroundings at pressure P, the volume will change from V_A to V_I and the bulk modulus will become the isothermal modulus defined by equation (3) or equation (4).

A term often used in connection with P-V-T relationships of fluids is 'compressibility'. The coefficient of compressibility (K) is defined as the reciprocal of the bulk modulus:

$$K_T = \frac{1}{B_T} \quad \text{or} \quad K_S = \frac{1}{B_S} \tag{6}$$

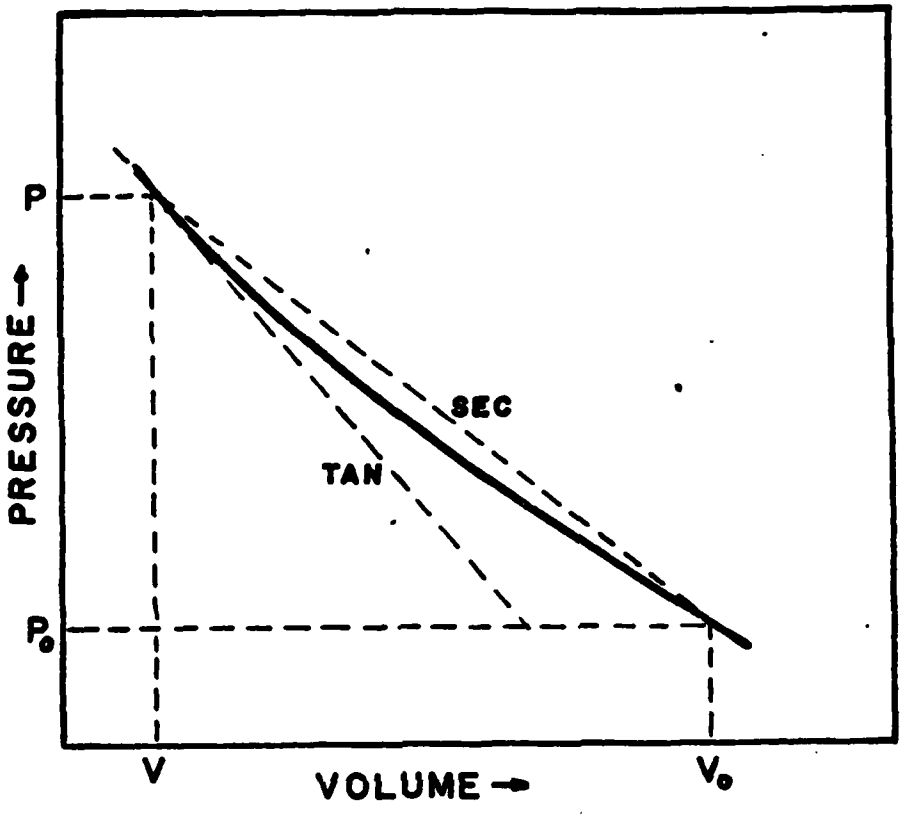


FIGURE 1. Fluid Compression Curve

P = Pressure
P_O = Initial Pressure (atmospheric)
V = Fluid Volume at Pressure P
V_O = Fluid Volume at Atmospheric Pressure
SEC = Secant Line from P_O, V_O to P, V
TAN = Tangent Line at P, V

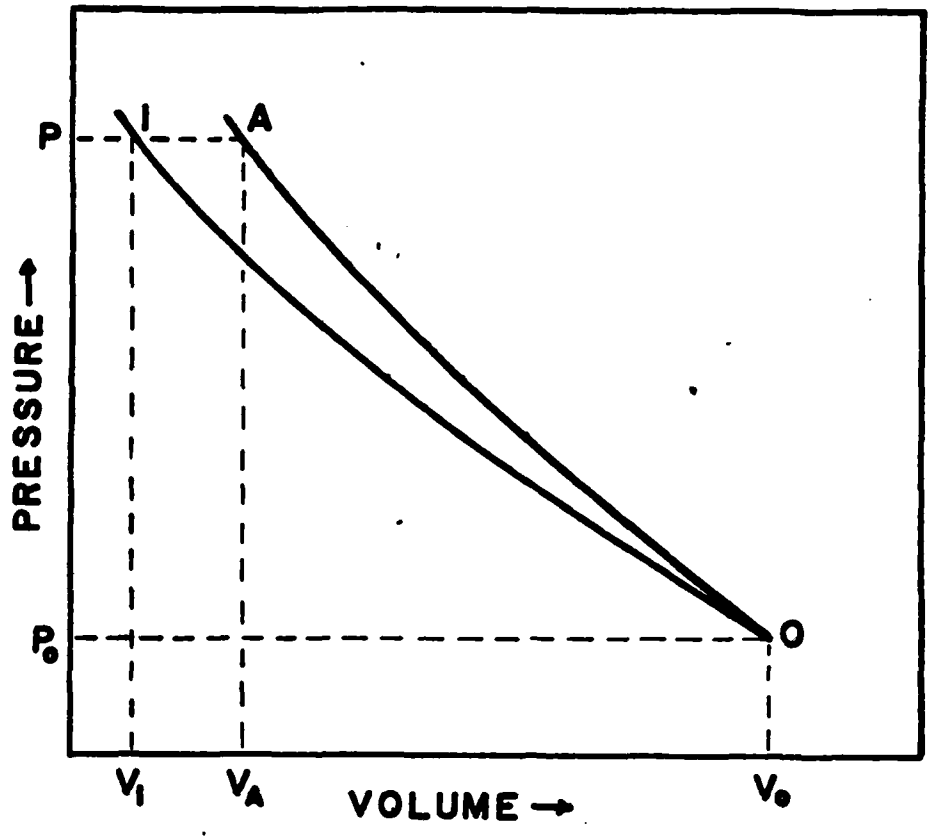


FIGURE 2. Adiabatic and Isothermal Compression Curves

OA = Adiabatic Compression Curve
OI = Isothermal Compression Curve

Relationships between B_s and Bt can be derived from fundamental thermodynamic properties. Using the Bridgman formulas[9] the equation

$$\left(\frac{\partial V}{\partial P}\right)_S = \left(\frac{\partial V}{\partial P}\right)_T + \frac{T}{C_P}\left(\frac{\partial V}{\partial T}\right)_P^2 \qquad (7)$$

relating P, V and T under isothermal or constant entropy (adiabatic) conditions can be derived. Substituting (4) and (5) into (7) gives

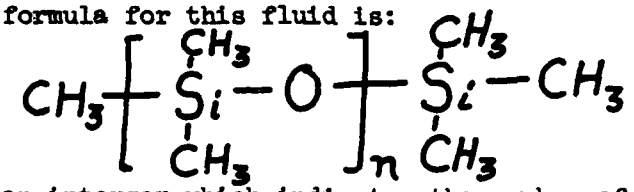
$$\frac{1}{B_S} = \frac{1}{B_T} - \frac{T\alpha^2\bar{V}}{C_P} \qquad (8)$$

where T is the absolute temperature, α is the thermal expansion coefficient, $\bar{V}$ is the specific volume and C_p is the specific heat of the fluid at constant pressure.

MATERIALS

Compressibility measurements were carried out on nine fluids. Six of these were furnished to NRL for sonic compressibility determinations. The fluids tested are listed as follows:

1. Dow Corning 200 Fluid, 10cs. viscosity at 77°F (25°C); a polydimethyl siloxane manufactured by the Dow Corning Corporation, Midland, MI. A chemical formula for this fluid is:



where n is an interger which indicates the number of monomer units making up the polymer; this interger can vary from a relatively small number up to several thousand, giving materials with a wide range of molecular weights and associated properties such as viscosity, flash point, and compressibility.

2. FC75 Fluid, 0.8cs. viscosity at 77°F, 7.4cs. at -65°F; a perfluorinated fluid manufactured by Commercial Chemicals Division, 3M Company, St. Paul, MN.

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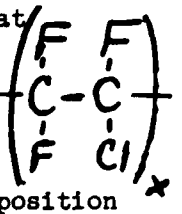
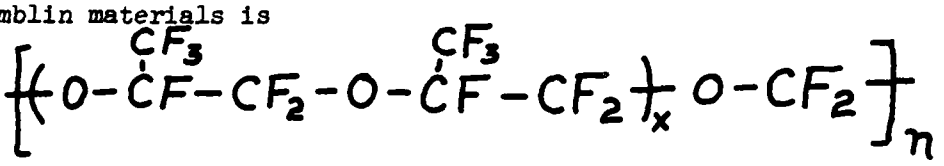
9. Rossini, F. D., "Chemical Thermodynamics", John Wiley & Sons, Inc., N.Y., 1950, Chapter 17.

3. Halocarbon Oil 4-11E, 4.5cs. viscosity at 100°F, 8,000cs. at -65°F; a chlorofluorocarbon polymer of chlorotrifluoroethylene, available from Halocarbon Products Corp., Hackensock, NJ.



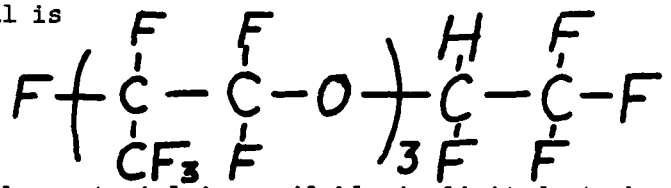
4. Halocarbon Oil 11-14E, 6.5cs. viscosity at 100°F; same composition as no. 3.

5. Fomblin Y04 Fluid, 16cs. viscosity at 100°F; linear perfluoropolyether manufactured by Montecatini-Edison. A chemical formula for the Fomblin materials is



where x and n can vary again to give different products.

6. Freon E3, 1.3cs. viscosity at 77°F; a fluorinated ether manufactured by E. I. duPont deNemours & Co., Wilmington, DE. A chemical formula for this material is



This particular material is available in limited stocks and is no longer being manufactured. However, other Freon materials such as Freon 11 and Freon TA have been recommended.

7. Polygel Hydraulic Elastomer C-151, a silicone gel manufactured by SWS Silicones Division, Stauffer Chemical Co.

8. Halocarbon A0-8/100 Fluid, viocosity 7cs at 100°F. Composition unknown; presumably a fluorinated compound. Same manufacturer as fluids no. 3 and no. 4.

9. Versilube F-50 Fluid, viscosity 52cs. at 100°F, a methyl chlorophenyl silicone fluid manufactured by General Electric Co. This type of chlorinated silicone has better lubricating qualities than the methyl silicones such as the DC 200.

PROCEDURE

A. INDUSTRY SURVEY

Letters of inquiry were sent to fourteen industry, government and academic establishments to determine the availability of fluids suitable for use in the compressible fluid recoil mechanism. Tentative specifications

(shown in Appendix A) were given for the compressible fluid in order to set limits on the types of fluids sought. The establishments contacted were those known to be heavily involved in research and development of lubricants and other mechanical fluids. A list of these establishments is included in Appendix A.

B. SONIC COMPRESSIBILITY MEASUREMENTS

Measurements were made on six fluids by the sonic method. In the apparatus used, ultrasonic pulses are introduced into the fluid and the return echo is detected by means of spring-loaded quartz transducers. The round trip time of flight of a sound pulse over a fixed path length is used to calculate the sound velocity. A second transducer in the lower part of the apparatus measures the fluid volume changes brought about by compression, thus monitoring changes in density. The method is described in more detail in Appendix B of this report.

C. BULK MODULUS BY THE RIA PVT METHODS

While the sonic compressibility measurements were being carried out at NRL, screening tests of compressibility were initiated at Rock Island Arsenal to select promising fluids for use in the proposed recoil mechanisms. The method selected was one commonly used in the petroleum industry:

> To pressurize a known volume of liquid by pumping additional liquid into a container and then measure the volume of fluid expelled when the pressure is released.

Two devices were assembled; one was based on a stainless steel pressure reaction vessel or bomb, which contained approximately 500 cm^3 of fluid and a second, smaller scale apparatus constructed of stainless steel pressure tubing which contained approximately 12 cm^3 of fluid. The larger bomb apparatus is called the RIA Macro PVT (Pressure-Volume-Temperature) apparatus and the smaller scale device is called the RIA Micro PVT apparatus. Diagrams of these devices, descriptions and methods of operation of these devices are given in Appendix C of this report.

D. AIR SOLUBILITY MEASUREMENTS

The procedure for the determination of air solubility was based on a method developed at Rock Island Arsenal by Sass[10]. The modified method, in brief, for the determination of air solubility at atmospheric pressure is to evacuate the oil by means of a vacuum pump, open the container to the atmosphere momentarily to equalize the pressures and immediately connect it through a stopcock to a gas buret to measure the uptake of air. To determine the air content of the fluid in a test fixture, a sampling flask was

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10. Sass, Ronald L., "Method for Determining the Solubility of Nitrogen in Oils Under Pressure", Rock Island Arsenal Laboratory Report No. 54-3529, 21 October 1954.

connected to an outlet valve of the fixture through a rubber plug and hypodermic needle. A sample of the fluid and air were collected in the flask, which was cooled to the room temperature. The flask was then placed in a dry ice bath, transported to the laboratory, connected to the gas buret and allowed to warm to room temperature. The gas volume was measured and corrected for fluid volume and changes in volume due to temperature differences. All volumes are corrected to standard conditions:

Air volume at 0°C and 1 atmosphere pressure; fluid volume at 15.5°C.

The air solubility is expressed as a Bunsen Coefficient at these conditions in cm^3 air/cm^3 fluid/atmosphere. The MIL-H-5606 fluid was included for comparison purposes.

RESULTS AND DISCUSSION

A. INDUSTRY SURVEY

A copy of the tentative specifications for the compressible fluid shown in Appendix A of this report was furnished to the establishments contacted in this survey. Three general types of materials were recommended in the replies received: a) silicones, b) perfluoropolyethers and c) fluorinated hydrocarbons. The lower molecular weight members of these classes of materials must be used to meet the compressibility requirements. However, the lower molecular weight materials will have, in general, higher volatility, lower viscosity and poorer lubricity than the higher members. The low molecular weight silicones have low flash points, while the low molecular weight perfluorinated materials are nonflammable. The low viscosity and high volatility materials may be difficult to retain in the mechanisms and will require excellent sealing. Some of the properties may be improved by blending or by the use of additives. This survey confirmed information available at Rock Island Arsenal from past work on fluid development.

B. SONIC COMPRESSIBILITY MEASUREMENTS

Sonic measurements were carried out on six fluids by the Naval Research Laboratory. Results of all sonic tests are given in Table 1. Original data used in Table 1 and furnished by NRL on three of the fluids is included in Appendix B. These data were obtained after the 5 August 1976 report was submitted to SARRI-LA[3]. The density, sound velocity and compressibility were furnished by NRL in metric units. The bulk modulus calculated from the compressibility is expressed in English units to permit comparison with existing data. The FC75 and Freon E3 materials have the lowest overall bulk modulus and highest volume compression of all the materials listed in Table 1.

Table 1

SONIC COMPRESSIBILITY AND BULK MODULUS OF COMPRESSIBLE FLUIDS

MATERIAL	Temperature °C	Temperature °F	Pressure psig.	Density gm/cm^3	Sound Velocity m/sec.	Adiabatic Compressibility (cm^2/dyne)X 10^{12}	Adiabatic Bulk Modulus psi.	Percent Compression
DC200, 10cs. Silicone Fluid, Dow Corning Corp. (Sample #1)	18.3	65	0 (1 atm)	0.943	985	109.3	132,700	-
	8.8	48	"	0.953	1010	102.7	141,200	-
	- 9.3	15	"	0.969	1066	90.8	159,700	-
	-31.9	-25	"	0.985	1136	78.7	184,200	-
	-52.3	-62	"	0.995	1217	67.9	213,500	-
	22	72	0	-	-	-	130,100	-
	"	"	2000	-	1062	92.6	156,600	1.38
	"	"	4000	-	1134	80.5	180,100	2.52
	"	"	6000	-	1198	71.6	202,500	3.47
	15.5	60	0	0.941	1010	102.6	141,300	-
	"	"	2000	0.954	1084	89.2	162,600	1.31
	"	"	4000	0.966	1151	78.3	185,200	2.42
	"	"	6000	0.977	1213	69.6	208,300	3.37
	4.4	40	0	0.951	1043	95.7	151,500	-
	"	"	2000	0.963	1113	83.7	173,200	1.23
	"	"	4000	0.975	1179	73.8	196,500	2.29
	"	"	6000	0.985	1238	66.0	219,700	3.23
	- 6.7	20	0	0.961	1075	89.3	162,400	-
	"	"	2000	0.973	1143	78.5	184,700	1.15
	"	"	4000	0.983	1207	69.6	208,300	2.15
	"	"	6000	0.993	1265	62.5	232,000	3.04
	-17.8	0	0	0.971	1110	83.1	174,500	-
	"	"	2000	0.982	1175	73.7	196,700	1.07
	"	"	4000	0.992	1237	65.8	220,400	2.02
	"	"	6000	1.001	1292	59.4	244,100	2.86

Table 1

(Continued p. 2)

MATERIAL	Temperature °C	Temperature °F	Pressure psig.	Density gm/cm^3	Sound Velocity m/sec.	Adiabatic Compressibility $(cm^2/dyne) \times 10^{12}$	Adiabatic Bulk Modulus psi.	Percent Compression
	-23.3	-10	0	0.976	1129	79.7	181,900	-
	"	"	2000	0.986	1191	71.3	203,400	1.03
	"	"	4000	0.996	1253	64.0	226,600	1.95
	"	"	6000	1.005	1306	57.8	250,900	2.77
	-23.9	-11	0	-	-	-	175,400	-
	"	"	1000	0.982	1142.9	78.0	185,900	0.55
	"	"	2000	0.987	1177.6	73.1	198,400	1.07
	"	"	3000	0.991	1207.9	69.2	209,500	1.55
	"	"	4000	0.996	1237.2	65.6	221,000	2.01
	"	"	5000	1.001	1265.0	62.4	232,400	2.44
	"	"	6000	1.006	1295.6	59.2	244,900	2.85
	-28.9	-20	0	0.981	1148	77.1	188,100	-
	"	"	2000	0.991	1208	69.0	210,100	1.00
	"	"	4000	1.000	1268	62.1	233,500	1.89
	"	"	6000	1.008	1321	56.4	257,100	2.69
	-34.4	-30	0	0.986	1167	74.2	195,400	-
	"	"	2000	0.995	1225	66.8	217,100	0.97
	"	"	4000	1.004	1284	60.4	240,100	1.66
	"	"	6000	1.012	1336	55.0	263,600	2.61
	-40	-40	0	0.991	1187	71.7	202,200	-
	"	"	2000	1.000	1243	64.7	224,100	0.93
	"	"	4000	1.008	1300	58.7	247,000	1.77
	"	"	6000	1.016	1351	53.7	270,000	2.53

Table 1

(Continued p. 3)

MATERIAL	Temperature °C	Temperature °F	Pressure psig.	Density gm/cm^3	Sound Velocity m/sec.	Adiabatic Compressibility (cm^2/dyne)X 10^{12}	Adiabatic Bulk Modulus psi.	Percent Compression
	-42.8	-45	0	-	-	-	199,900	-
	"	"	1000	0.995	1212	68.4	212,000	0.48
	"	"	2000	0.999	1241	65.0	223,100	0.94
	"	"	3000	1.003	1271	61.7	235,000	1.37
	"	"	4000	1.007	1300	58.8	246,600	1.78
	"	"	5000	1.011	1328	56.0	258,900	2.17
	"	"	6000	1.015	1353	53.8	269,500	2.54
	-45.6	-50	0	0.995	1207	69.0	210,100	-
	"	"	2000	1.004	1261	62.6	231,600	0.90
	"	"	4000	1.012	1317	57.1	253,900	1.72
	"	"	6000	1.020	1367	52.5	276,200	2.46
	-51.1	-60	0	1.000	1227	66.3	218,700	-
	"	"	2000	1.008	1280	60.7	238,900	0.87
	"	"	4000	1.016	1333	55.7	260,300	1.66
	"	"	6000	1.023	1383	51.3	282,600	2.38
Fluorocarbon FC75, 3M Company	25	77	0	-	584	150	97,000	-
	12.3	54	1000	1.976	625	129	112,000	0.95
	"	"	2000	1.991	662	115	126,000	1.77
	"	"	3000	2.007	696	103	141,000	2.48
	"	"	4000	2.023	722	95	153,000	3.16
	"	"	5000	2.038	749	87	167,000	3.72
	"	"	6000	2.051	773	82	177,000	4.15

Table 1

(Continued p. 4)

MATERIAL	Temperature °C	Temperature °F	Pressure psig.	Density gm/cm^3	Sound Velocity m/sec.	Adiabatic Compressibility (cm^2/dyne)X 10^{12}	Adiabatic Bulk Modulus psi.	Percent Compression
	-1.5	31	1000	2.011	674	109	133,000	0.78
	"	"	2000	2.026	707	99	146,000	1.48
	"	"	3000	2.040	736	90	161,000	2.13
	"	"	4000	2.055	764	83	175,000	2.71
	"	"	5000	2.068	791	77	189,000	3.25
	"	"	6000	2.104	815	72	202,000	3.74
	-31.0	-24	1000	2.079	759	84	173,000	0.63
	"	"	2000	2.093	785	78	186,000	1.18
	"	"	3000	2.106	813	72	202,000	1.67
	"	"	4000	2.119	841	67	216,000	2.10
	"	"	5000	2.132	866	63	230,000	2.49
	"	"	6000	2.146	889	59	246,000	2.85
	-44.0	-47	1000	2.102	800	74	196,000	0.53
	"	"	2000	2.115	826	69	210,000	1.02
	"	"	3000	2.129	849	65	223,000	1.48
	"	"	4000	2.143	875	61	238,000	1.90
	"	"	5000	2.156	896	58	250,000	2.30
	"	"	6000	2.170	920	54	268,000	2.68
Halocarbon Polymer Oil 411E (Rust Inhibited) Halocarbon Products Corp.	25	77	15	1.866	880.7	69.1	209,800	-
	14.5	58	1000	1.900	935.6	60.1	241,300	0.42
	"	"	2000	1.908	958.7	57.0	254,400	0.83
	"	"	3000	1.916	979.6	54.4	266,500	1.21
	"	"	4000	1.924	1001.4	51.8	279,900	1.57
	"	"	5000	1.932	1021.4	49.6	292,300	1.91
	"	"	6000	1.940	1041.3	47.5	305,300	2.24

Table 1

(Continued p. 5)

MATERIAL	Temperature °C	Temperature °F	Pressure psig.	Density gm/cm^3	Sound Velocity m/sec.	Adiabatic Compressibility (cm^2/dyne)X 10^{12}	Adiabatic Bulk Modulus psi.	Percent Compression
	- 1.0	30	1000	1.940	978.8	53.8	269,500	0.38
	"	"	2000	1.946	998.8	51.5	281,600	0.74
	"	"	3000	1.952	1018.7	49.4	293,500	1.07
	"	"	4000	1.958	1038.4	47.4	305,900	1.38
	"	"	5000	1.964	1059.9	45.3	320,100	1.67
	"	"	6000	1.970	1079.3	43.6	322,600	1.94
	Tests discontinued; weak signal-excessive sound absorption at lower temperatures.							
Halocarbon Polymer Oil 11-14E (Rust Inhibited), Halo-Carbon Products Corp.	17.5	63	15	1.871	904.7	65.3	222,100	-
	17.5	63	1000	1.879	925.6	62.1	233,500	0.44
	"	"	2000	1.887	946.6	59.1	245,400	0.85
	"	"	3000	1.894	969.5	56.2	258,000	1.25
	"	"	4000	1.901	990.8	53.6	270,500	1.62
	"	"	5000	1.908	1014.1	51.0	284,300	1.97
	"	"	6000	1.916	1033.6	48.9	296,500	2.31
	- 2.0	28	15	1.922	962.8	56.1	258,500	-
	- 2.0	28	1000	1.929	982.2	53.7	270,000	0.38
	"	"	2000	1.936	1002.3	51.4	282,100	0.74
	"	"	3000	1.943	1022.3	49.2	294,700	1.08
	"	"	4000	1.950	1041.3	47.3	306,600	1.41
	"	"	5000	1.957	1060.9	45.4	319,400	1.72
	"	"	6000	1.964	1076.2	44.0	329,500	2.02
	Tests discontinued; weak signal-excessive sound absorption at lower temperatures.							

Table 1

(Continued p. 6)

MATERIAL	Temperature °C	Temperature °F	Pressure psig.	Density gm/cm^3	Sound Velocity m/sec.	Adiabatic Compressibility (cm^2/dyne)X 10^{12}	Adiabatic Bulk Modulus psi.	Percent Compression
Fomblin YO4, Monticatini-Edison Co.	20	68	1000	1.872	695.6	110.4	131,300	0.80
	"	"	2000	1.884	721.9	101.9	142,300	1.52
	"	"	3000	1.895	750.4	93.7	154,700	2.18
	"	"	4000	1.906	778.1	86.6	167,400	2.78
	"	"	5000	1.917	803.5	80.8	179,500	3.35
	"	"	6000	1.928	828.3	75.6	191,800	3.86
	- 3	27	2000	1.920	-	84 *	173,000	-
	"	"	4000	1.941	-	70 *	207,000	-
	-28	-18	2000	1.957	-	70 *	207,000	-
	"	"	4000	1.976	-	63 *	230,000	-
	-46	-51	2000	1.979	-	69 *	210,000	-
	"	"	4000	1.999	-	64 *	226,000	-

* At lower temperatures the absorption of sound was large, the ultrasonic signal was very weak, and the sound velocity could not be measured. These values are isothermal compressibilities determined from static PVT measurements.

Table 1

(Continued p. 7)

MATERIAL	Temperature °C	Temperature °F	Pressure psig.	Density gm/cm^3	Sound Velocity m/sec.	Adiabatic Compressibility $(cm^2/dyne) \times 10^{12}$	Adiabatic Bulk Modulus psi.	Percent Compression
Freon E3, duPont Co.	20	68	0	-	600	162	89,500	-
	"	"	2000	-	689.4	120	120,800	1.88
	"	"	4000	-	754.6	99	146,500	3.26
	"	"	6000	-	811.2	85	170,600	4.32
	-15	+ 5	0	-	718	109	133,000	-
	"	"	2000	-	786	89	162,900	1.35
	"	"	4000	-	842	77	188,300	2.44
	"	"	6000	-	893	68	213,200	3.36
	-36	-32.8	0	-	780	90	161,100	-
	"	"	2000	-	846	76	190,800	1.13
	"	"	4000	-	899	66	219,700	2.07
	"	"	6000	-	947	59	245,800	2.87
	-48	-54.4	0	-	820	80	181,250	-
	"	"	2000	-	878	69	210,100	1.02
	"	"	4000	-	928	61	237,700	1.88
	"	"	6000	-	980	55	263,600	2.64

The percent compression presented in Table 1 was calculated more accurately for this report than it was for the 5 Aug 76 Laboratory report.[3] For the present data, a least squares fit to a quadratic equation was made for B_s as a function of pressure. Thus,

$$B_s = -V\left(\frac{\partial P}{\partial V}\right)_s \quad \text{and} \quad a + bP + cP^2 = -V\left(\frac{\partial P}{\partial V}\right)_s \tag{9}$$

The least squares fit quadratic equations for B_s for the six fluids tested at NRL are given in Table B-1 in Appendix B. Correlation Coefficients for these equations are 0.999 or better. After separation of variables and integration of equation (9):

$$-\ln\frac{V}{V_o} = \int_{P_o}^{P} \frac{dP}{a + bP + cP^2} \tag{10}$$

The integral on the right becomes a logarithm or an arctangent function, depending on the values of the constants a, b and c. This integral can be found in standard integration tables and the equation will then yield $\frac{V}{V_o}$ and $\frac{\Delta V}{V_o} \times 100$, or the percent compression. The values of percent compression obtained in this way express the total change in volume from V_o to V (see Figure 1) rather than the smaller volume change given by the intersection of the tangent line with the horizontal at P_o. The percent compression calculated from V_o more accurately expresses the change occurring when the system is compressed from the initial pressure P_o to the final pressure P. The recoil system operates over a comparatively wide pressure range, for example, from an initial pressure of 2000 psi in a practical recoil system to 6000 psi, rather than in the immediate vicinity of a single pressure P. Therefore, the percent compression calculated according to equation (10) expresses the actual operating conditions of the recoil system more accurately than the tangent bulk modulus at a given pressure P. The difference between the two compression values at the maximum and minimum pressures obtained during recoil would give the actual compression of the fluid during the full recoil cycle.

C. BULK MODULUS BY RIA-PVT METHODS

1. RIA Macro PVT Method:

Results of compressibility measurements by the RIA Macro PVT method are shown in Table 2. These data probably do not represent true isothermal bulk modulus values, because the fluid experiences approximately a 1°C rise in temperature for each 1000 psi pressure increase. A maximum of 15 minutes

Table 2

SECANT BULK MODULUS OF COMPRESSIBLE FLUIDS
RIA MACRO PVT METHOD

MATERIAL	PRESSURE psig.	PERCENT COMPRESSION, x 100					BULK MODULUS, psi				
		70°F (21°C)	0°F (-17.8°C)	-40°F (-20°C)	-40°F (-40°C)	-65°F (-53.4°C)	70°F (21°C)	0°F (17.8°C)	-40°F (-20°C)	-40°F (-40°C)	-65°F (-53.4°C)
		(10)*	(4)			(4)					
MIL-H-5606	1000	0.44	0.34	-	-	0.28	225,000	291,000	-	-	360,000
Hydraulic Fluid	2000	0.87	0.67	-	-	0.55	230,000	296,000	-	-	361,000
	3000	1.26	1.00	-	-	0.81	238,000	299,000	-	-	371,000
	4000	1.64	1.31	-	-	1.07	244,000	305,000	-	-	373,000
	5000	2.00	1.62	-	-	1.33	250,000	308,000	-	-	374,000
	6000	2.36	1.92	-	-	1.58	254,000	312,000	-	-	379,000
		(* Number in parenthesis is the number of repeat measurements at each pressure)									
		(Unswollen condition assumed for Polygel)									
Polygel		(4)	(4)			(6)					
Hydraulic	1000	0.69	0.64	-	-	0.54	145,000	156,000	-	-	184,000
Elastomer C-151	2000	1.25	1.11	-	-	0.95	159,000	181,000	-	-	210,000
SWS Silicones	3000	1.82	1.60	-	-	1.39	165,000	188,000	-	-	215,000
Div., Stauffer	4000	2.43	2.05	-	-	1.79	164,000	195,000	-	-	223,000
Chemical Co.	5000	2.93	2.52	-	-	2.19	171,000	198,000	-	-	228,000
	6000	3.49	2.99	-	-	2.59	172,000	201,000	-	-	232,000
		(67% Volume swell assumed for Polygel)									
	1000	0.59	0.52	-	-	0.44	169,000	192,000	-	-	229,000
	2000	1.10	0.94	-	-	0.79	182,000	214,000	-	-	252,000
	3000	1.60	1.36	-	-	1.16	187,000	221,000	-	-	259,000
	4000	2.12	1.76	-	-	1.51	188,000	227,000	-	-	265,000
	5000	2.57	2.17	-	-	1.86	195,000	230,000	-	-	269,000
	6000	3.06	2.58	-	-	2.19	196,000	233,000	-	-	273,000

Table 2

(Continued p. 2)

MATERIAL	PRESSURE psig.	PERCENT COMPRESSION, x 100					BULK MODULUS, psi				
		70°F (21°C)	0°F (-17.8°C)	-40°F (-20°C)	-40°F (-40°C)	-65°F (-53.4°C)	70°F (21°C)	0°F (-17.8°C)	-40°F (-20°C)	-40°F (-40°C)	-65°F (-53.4°C)
		(2)		(2)	(2)	(2)					
DC200, 10cs	1000	0.77	-	0.57	0.53	0.50	130,000	-	175,000	190,000	201,000
polydimethyl-	2000	1.43	-	1.12	1.00	0.96	140,000	-	178,000	199,000	208,000
siloxane fluid;	3000	2.05	-	1.58	1.35**	1.28**	146,000	-	190,000	222,000	233,000
Dow Corning Corp.	4000	2.66	-	2.09	1.87	1.86	150,000	-	191,000	214,000	215,000
	5000	3.27	-	2.64	2.21**	2.15**	153,000	-	190,000	226,000	232,000
	6000	3.93	-	3.16	2.73	2.68	153,000	-	190,000	220,000	223,000
				** Single measurement							
		(4)									
Halocarbon	1000	0.51	-	-	-	-	195,000	-	-	-	-
AO-8/100 Fluid;	2000	1.00	-	-	-	-	201,000	-	-	-	-
Halocarbon Corp.	3000	1.44	-	-	-	-	208,000	-	-	-	-
	4000	1.85	-	-	-	-	216,000	-	-	-	-
	5000	2.32	-	-	-	-	215,000	-	-	-	-
	6000	2.75	-	-	-	-	218,000	-	-	-	-
		(2)	(1)		(1)	(1)					
Versilube	1000	0.63	0.62	-	0.56	0.54	159,000	159,000	-	180,000	186,000
F-50 Fluid;	2000	1.27	1.07	-	0.98	0.92	157,000	186,000	-	204,000	218,000
General	3000	1.79	1.50	-	1.33	1.28	167,000	199,000	-	226,000	234,000
Electric Co.	4000	2.29	2.03	-	1.76	1.70	175,000	197,000	-	227,000	235,000
	5000	2.77	2.38	-	2.13	2.06	180,000	210,000	-	235,000	243,000
	6000	3.36	2.82	-	2.50	2.38	178,000	213,000	-	240,000	252,000

was allowed between compression and release of excess fluid from the bomb. Therefore, temperatures were probably not at equilibrium and the data would fall between adiabatic and isothermal compressibilities or bulk modulus values. The fluid would experience a similar drop in temperature when the pressure is released. The repeatability of the measurements is very good; the average standard deviation in the measurement of ΔV for MIL-H-5606 was $\pm 0.1 cm^3$. As a screening method for compressible fluids, this method requires simple, inexpensive equipment and the procedure is simple and fairly rapid.

A summary of volume compression data obtained by the sonic and PVT methods is shown in Figure 3. This graph shows that two materials, and possibly three, are superior to the DC200 silicone with respect to compression. As described previously in this report, these are all fluorinated materials. The FC75 fluid is a fluorinated compound of undisclosed composition and is a relatively expensive material. The Freon E3 is a fluorinated ether which is currently out of production but is available in limited quantity. The Fomblin Y04 is a perfluoropolyether which may be difficult to obtain because of its foreign manufacture. However, similar types of material are also available: other Freon-type materials are in production as well as a series of perfluoropolyethers manufactured by the duPont Company under the Krytox trade name. Preliminary Shell Four-Ball wear test results indicate that the fluorinated ethers may be better lubricants than the polymethylsiloxanes. Lower molecular weight polymethylsiloxanes would be expected to have increased compressibility, but their flash points are very low.

The MIL-H-5606 fluid was included here for comparison with published bulk modulus data. Another material evaluated, the Polygel hydraulic elastomer, is a gelatinous silicone material now being used in some automobile safety bumpers. Table 2 shows compression and bulk modulus data for the Polygel in both the swollen and unswollen condition. Figure 3 shows the data for the swollen condition of the Polygel.

The swelling of the Polygel may require some explanation. In order to carry out the compression of this material, chunks of the gel were placed in the bomb and MIL-H-5606 fluid was used as the compression medium. After the tests were completed, the silicone gel was found to be in a swollen condition with a volume 67% greater than the initial volume. For comparison purposes, the compression and bulk modulus were then calculated for both the unswollen and the swollen condition.

2. RIA Micro PVT Method

Results of compressibility measurements by the RIA Micro PVT Method are shown in Table 3. Data provided by the NRL sonic method are shown for comparison purposes. The DC-200, 10cs fluid which was selected by SARRI-LA was used as the primary control fluid for comparison. As shown in Table 3 this material showed reasonable agreement of bulk modulus between the NRL and the RIA test methods. The slightly lower bulk modulus from the RIA test may be due to air contamination. The possibility of contamination will

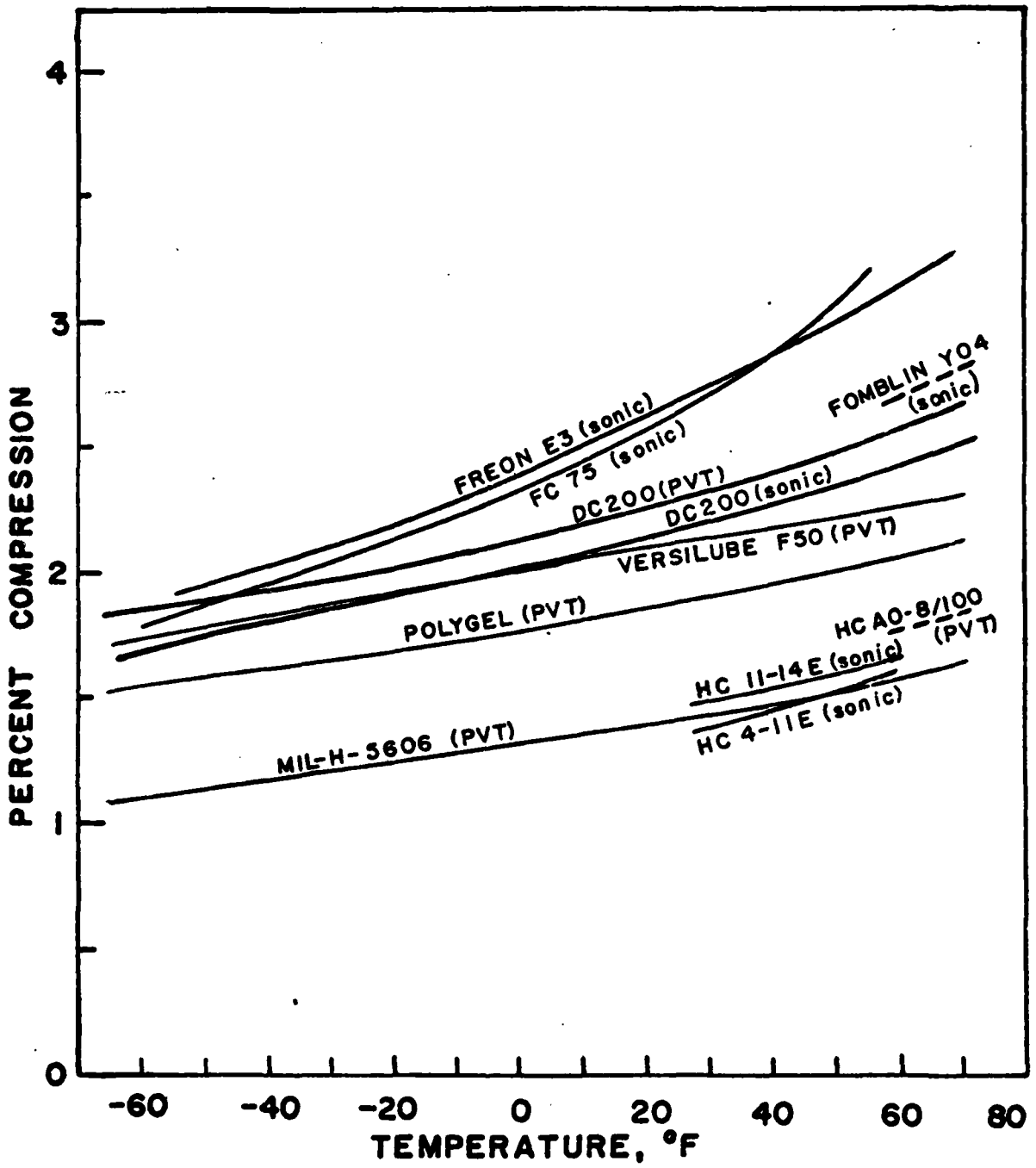
PERCENT COMPRESSION
4
3
2
1
0
-60
-40
-20
0
20
40
60
80
TEMPERATURE, °F
FREON E3 (sonic)
FC 75 (sonic)
DC200 (PVT)
DC200 (sonic)
FOMBLIN YO4 (sonic)
VERSILUBE F50 (PVT)
POLYGEL (PVT)
HC AO-8/100 (PVT)
HC 11-14E (sonic)
HC 4-11E (sonic)
MIL-H-5606 (PVT)

Table 3

SECANT BULK MODULUS OF COMPRESSIBLE FLUIDS

RIA Micro PVT Method
Comparison With Sonic Data

MATERIAL	RIA Micro PVT Method			Sonic Method		
	Temperature °F	Pressure psig.	Bulk Modulus* psi.	Temperature °F	Pressure psig.	Bulk Modulus psi.
DC200, 10cs.	68	2000	157,000	71.6	2000	156,500
	68	4000	175,000	71.6	4000	180,200
	-45	2000	202,000	-45	2000	223,000
	-45	4000	234,000	-45	4000	270,000
Halocarbon Polymer Oil, 4-11E	73	2000	246,900	58	2000	254,000
	73	4000	273,900	58	4000	280,000
	-40	2000	322,580	30.2	2000	281,000
	-40	4000	367,000	30.2	4000	305,000
Fomblin Y04	76	2000	162,600	68	2000	142,200
	76	4000	175,440	68	4000	167,000
	-50	2000	190,500	-50.8	2000	211,000
	-50	4000	201,000	-50.8	4000	226,800
	-60	2000	227,000	-	-	-
	-60	4000	226,000	-	-	-
Freon E3	74	2000	155,040	68	2000	120,800
	74	4000	173,910	68	4000	146,500
	-50	2000	211,640	-48	2000	207,400
	-51	4000	223,460	-48	4000	233,900

Table 3

(Continued p. 2)

MATERIAL	RIA Micro PVT Method			Sonic Method		
	Temperature °F	Pressure psig.	Bulk Modulus* psi.	Temperature °F	Pressure psig.	Bulk Modulus psi.
RIA 1050	72	2000	175,440	-	-	-
	72	4000	186,047	-	-	-
	-55	2000	225,900	-	-	-
	-65	4000	231,220	-	-	-
RIA 1100	72	2000	158,730	-	-	-
	72	4000	171,670	-	-	-
	-61	2000	217,390	-	-	-
	-61	4000	226,000	-	-	-

* Note: To compare these values of secant bulk modulus with those of Table 2, add the value of the pressure (P) to the bulk modulus given by the Micro Method, i.e., B(Macro) = B(Micro) + P. See Appendix C for full explanation.

be reduced when a brass bellows is inserted in the hydraulic line in future improvements of the apparatus (see appendix C).

Contamination and micro leaks are two important errors to consider in this method. However, the errors are easily detected, both visually: The former by the haze in the measured fluid and the latter by the slow dropping of the fluid level in the micro burette. These two errors were kept at a minimum during the testing of the fluids as recorded in Table 3.

The results presented in Table 3 are consistent with those given by the sonic and RIA Macro PVT measurements. Five fluids, including formulations RIA 1050 and 1100 are superior overall in bulk modulus to the DC200. The RIA formulations are blends of fluorinated fluids. The results indicate that fluids may be found and formulations prepared which will approach 3% compressibility at -50°F and 6000 psi.

The five fluids mentioned (Freon E3, FC75, Fomblin Y04, RIA 1050 and 1100) are all nonflammable materials, whereas the DC200 material has a flash point of 320°F. However, some of the nonflammable fluids have low heats of vaporization and may require expecially tight seals and completely closed systems for field applications. An addition to the advantage of nonflammability, the fluorinated fluids may also be better lubricants. The Roxana 4-ball wear tester with test conditions set at 40 Kg., 1200 Rpm, 60 minutes at 167°F and using 52100 steel balls yielded, for the DC200,10cs fluid, a scar diameter of 2.46mm, whereas the 4 nonflammable fluids yielded scar diameters ranging from 0.67 to 1.54mm. However, all the fluids can be fortified with additives to improve the wear property. MIL-H-5606 yielded a wear scar of 0.97mm. in identical test.

The tests conducted indicate that temperature has a considerable effect on compressibility. Although no test temperature higher than 76°F has been used in the RIA-PVT apparatus, higher temperatures can be used. Published literature indicates that some of the nonflammable fluids which have been tested at ambient and lower temperatures can provide, at 150 - 200°F, a bulk modulus of 140,000 at 5000 psi. pressure. This will yield 3-4% compressibility. Therefore, recoil systems can be designed into Automatic cannons used in aircraft, ships and tanks where thermal control of the compressible fluid reservior can be incorporated.

D. AIR SOLUBILITY MEASUREMENTS

Air solubility at one atmosphere pressure is shown in Figure 4 for the DC200 fluid and a MIL-H-5606 fluid at various temperatures. Table D-1 of Appendix D gives the actual values of solubility obtained. The solubilities at 25°C compare favorably with published data. A solubility of 0.109 vol. air/vol. fluid/atmosphere has been reported for an early yersion of the MIL-H-5606 fluid.[11] Solubilities of 0.168 to 0.190 cm^3 air/cm^3 fluid at 25°C for the dimethyl silicone fluids has been reported.[12]

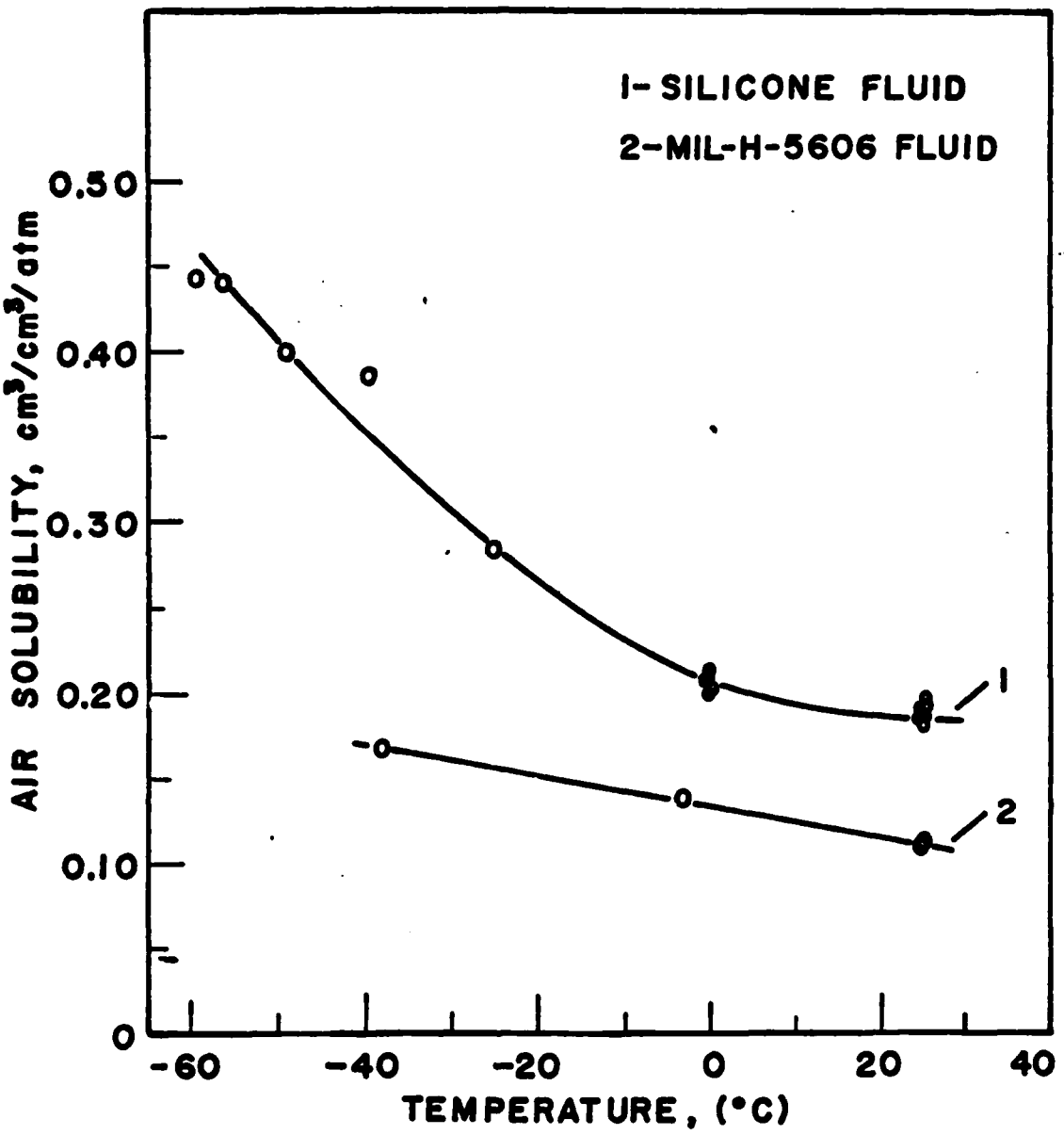

Figure 4. Relationship Between Air Solubility in Fluids and Temperature At One Atmosphere Pressure

(Air volume corrected to 0°C; fluid density to 15.5°C)

The air contents of several fluid samples taken from the compressible fluid engineering test fixture are shown in Table 4. These air content values are also expressed as Bunsen Coefficients with the air volume corrected to 0°C and 1 atmosphere pressure and the fluid volume corrected to 15.5°C. The air/fluid ratio for these samples varied from 26 to 130 volume percent, compared with an air solubility of 19 percent at ambient conditions (Figure 4) and 41 percent at -51°C (-46°F) and one atmosphere pressure. The air content for the last sample taken may be considerably in error, because difficulty was experienced in obtaining the last two samples. Apparently, additional air is being introduced into the fluid, above that which is normally dissolved at the temperatures of the tests. In these tests, the fixture underwent cyclic pressurization in steps of several hundred psi up to 6000 psi. Additional air is introduced in some manner, possibly entrained along the shaft through the seal or through the pump used to fill the fixture with fluid and pressurize it.

The air in these fluid samples taken from the test fixture may have been either entrained (undissolved) or dissolved, because the samples were taken from a valve located at the top of the fixture and some of the air may have collected as a gas pocket at this high point. The location of the sampling outlet was dictated by the requirement to keep openings in the cylinder to a minimum to minimize leakage and the inlet valve was already in place. During the sampling process on all the samples which were taken successfully a uniform stream of fluid was observed issuing from the needle into the sample flask. Immediately therafter, bubbles were observed to form in the fluid as it drained into the flask. The formation of these bubbles indicates that, at the time of sampling, the air was dissolved in the fluid.

Dissolved and entrained gases in recoil fluids have long been known to cause problems due to loss of control when the gas collects in pockets or as foam within the recoil system. The behavior of air in hydraulic systems has been discussed by Magorien.[13] In a test fixture, they obtained a decrease in bulk modulus from 265,000 psi to 132,000 psi when the air content was increased from 0 to 0.17%.

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11. LeMar, R. L., "Compressibility and Solubility Relationships Between Oils, Gases and Gas-Oil Mixtures-Literature Report", Rock Island Arsenal Technical Report no. 59-186, 21 Jan 1959.

12. McGregor, R. R., "Silicones and Their Uses", McGraw-Hill Book Co., N.Y. 1954, p. 41.

13. Magorien, V.G., "How Hydraulic Fluids Generate Air", Hydraulics and Pneumatics, June 1969, pp. 104-108.

Table 4

AIR CONTENT OF FLUID SAMPLES FROM COMPRESSIBLE FLUID TEST FIXTURE;
DC200-10cs Fluid

Run No.	Date	Temperature, °F		Air Content of Sample cm^3 air/cm^3 fluid/atm @ 0°C/15.5°C/1 atm
		Room	Fluid	
After #1	2-9-77	-40	-27	1.00
After #2	2-10-77	-51	-46	0.93
Before #6	2-10-77	-50	-46	1.30
Before #1	2-14-77	-2	+5	1.16
After #2	2-14-77	Air leaked during sampling		
After #4	2-14-77	-2	+7	0.90
Immediately after #1	2-15-77	-40	-34	0.71
2 hours after #1	2-15-77	-40	-34	Air leaked during sampling
2 hours after #1 second attempt	2-15-77	-40	-34	0.26

Calculations were carried out to estimate the effects of a dissolved gas such as nitrogen (N_2) on the compressibility of the DC200 fluid. Sonic compressibility data (Table 1) were used to calculate the expected compression of the fluid when it is subjected to various pressures. The compression of nitrogen was calculated for adiabatic conditions taking the ratio of specific heats ($C_P/C_V = \gamma$) to be 1.4.[14] The equation

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} \qquad (11)$$

gives the pressure-volume relationships for an ideal gas. The compressibility of nitrogen deviates from ideality by up to 25% at 6000 psi. Therefore, the volumes calculated by equation (11) were corrected using the Hougen-Watson-Ragatz chart of compressibility factors.[15] When these calculations were carried out, the data plotted in Figure 5 were obtained. These curves show the expected volume change, or compression, for mixtures of entrained gas and fluid. Curve No. 5 in Figure 5 was calculated for the condition where the gas present gradually dissolves, with all of it being in solution by the time the pressure reaches 6000 psi. The calculated bulk modulus at 4000 psi. of a silicone fluid mixed with various amounts of nitrogen is shown in Figure 6.

Data obtained by Chin and Drum[4] in the engineering tests of a compressible fluid test fixture seemed to indicate a soft initial condition at the beginning of the compression cycle. Data from one of these tests is plotted in Figure 7. This figure compares data obtained with the test fixture (curve 2), sonic compressibility measurements (curve 1) and a curve calculated for a mixture of 1% N_2 and 99% silicone fluid (curve 3). The shape of the experimental curve obtained by means of the test fixture is similar to the calculated curve assuming the presence of gas, with an initial "soft" condition evident. This condition may, however, be explained in other ways; for example, by expansion of the cylinder or movement of the rubber seals in the test fixture. However, except for movements due to looseness in the cylinder or seals these components would probably be at least as stiff or stiffer than the fluid itself. These points need to be further investigated in future work on the development of the compressible fluid recoil mechanism.

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14. Daniels, J. and Alberty, R. A., "Physical Chemistry", John Wiley & Sons, Inc., NY, pp 50-52, 1961.

15. ibid., page 28

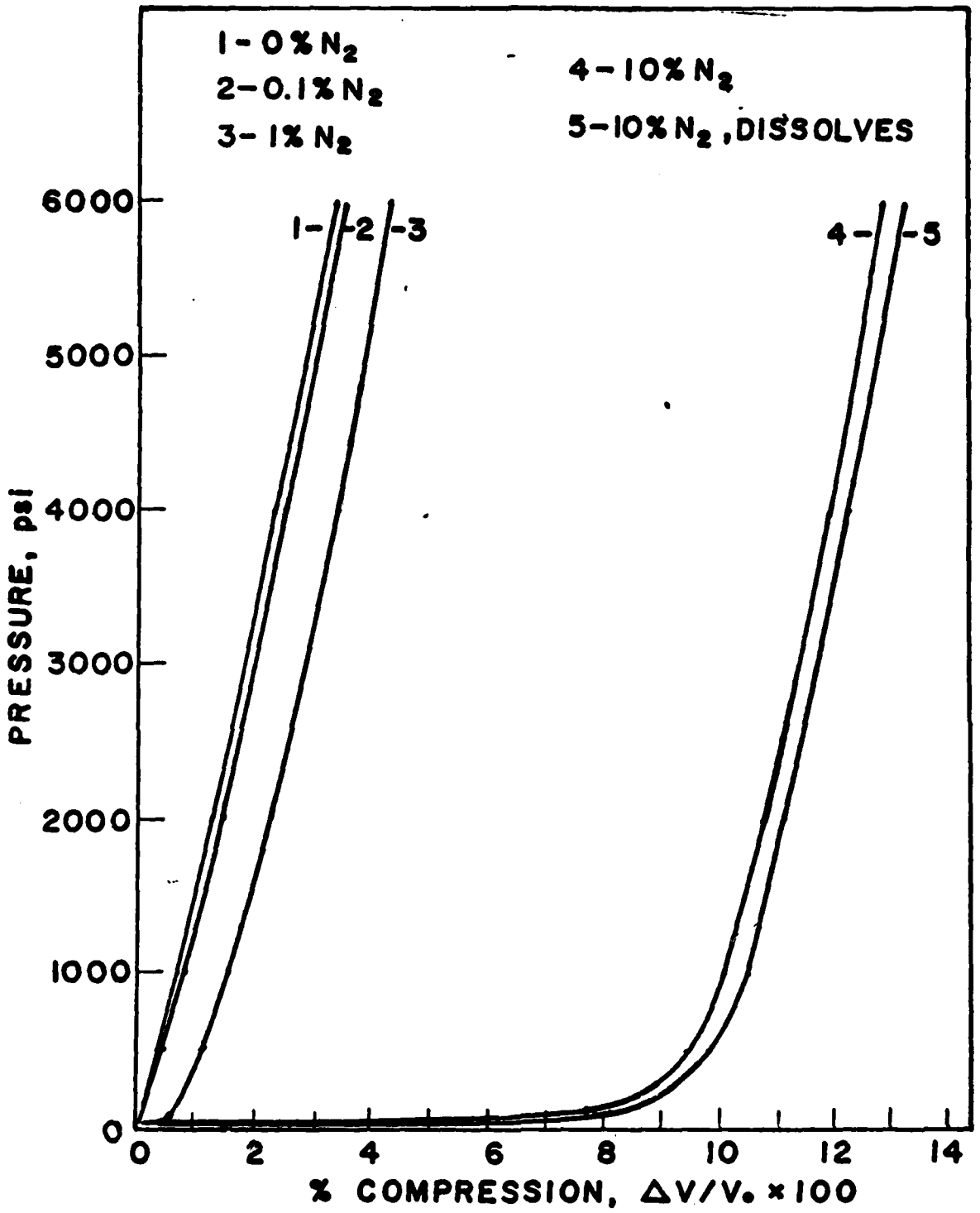


Figure 5. Calculated Volume Compression of Mixtures of Nitrogen and DC200-10cs. Silicone Fluids Under Adiabatic Conditions

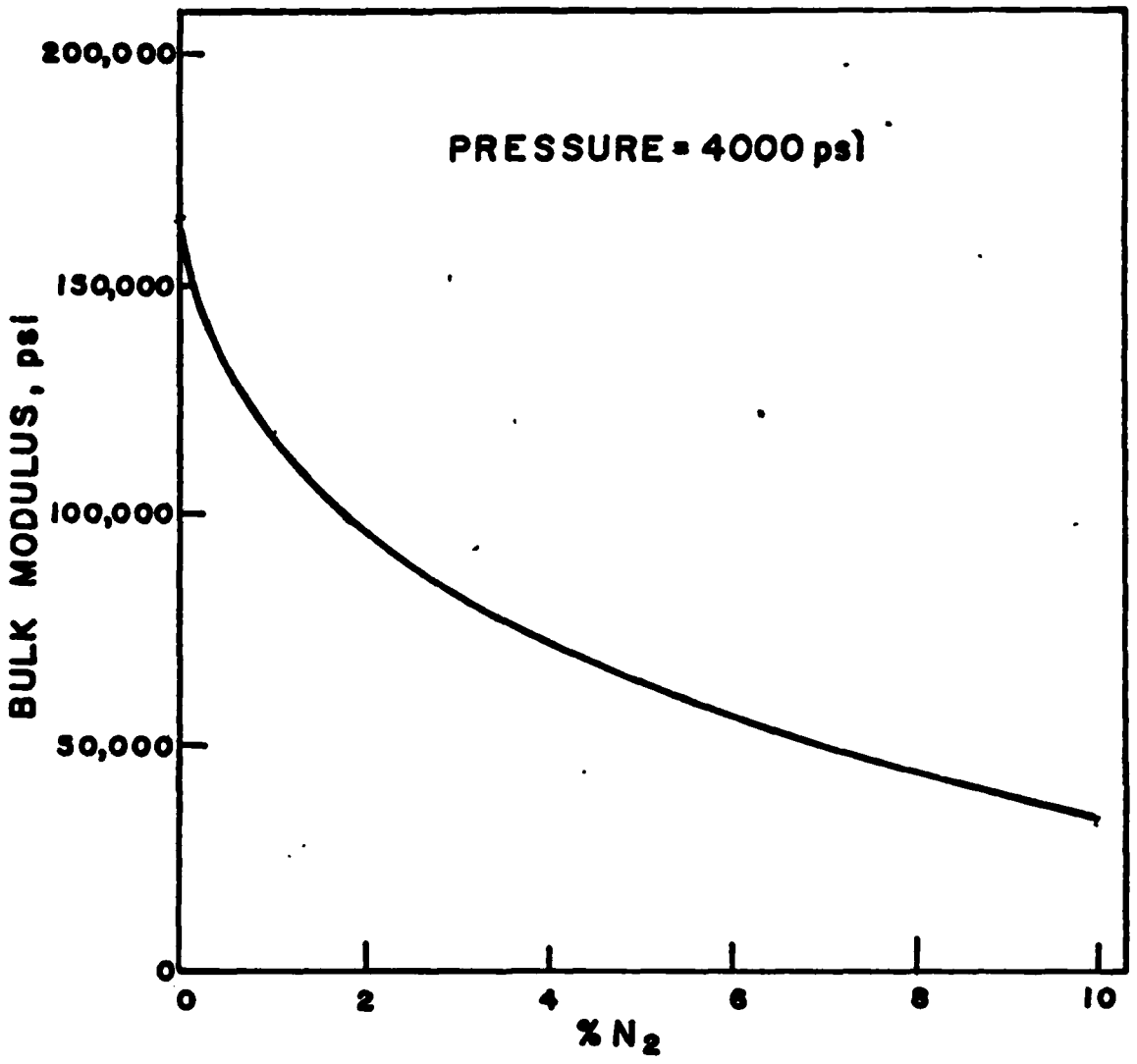


Figure 6. Calculated Bulk Modulus of a Silicone Fluid Containing Entrained Nitrogen

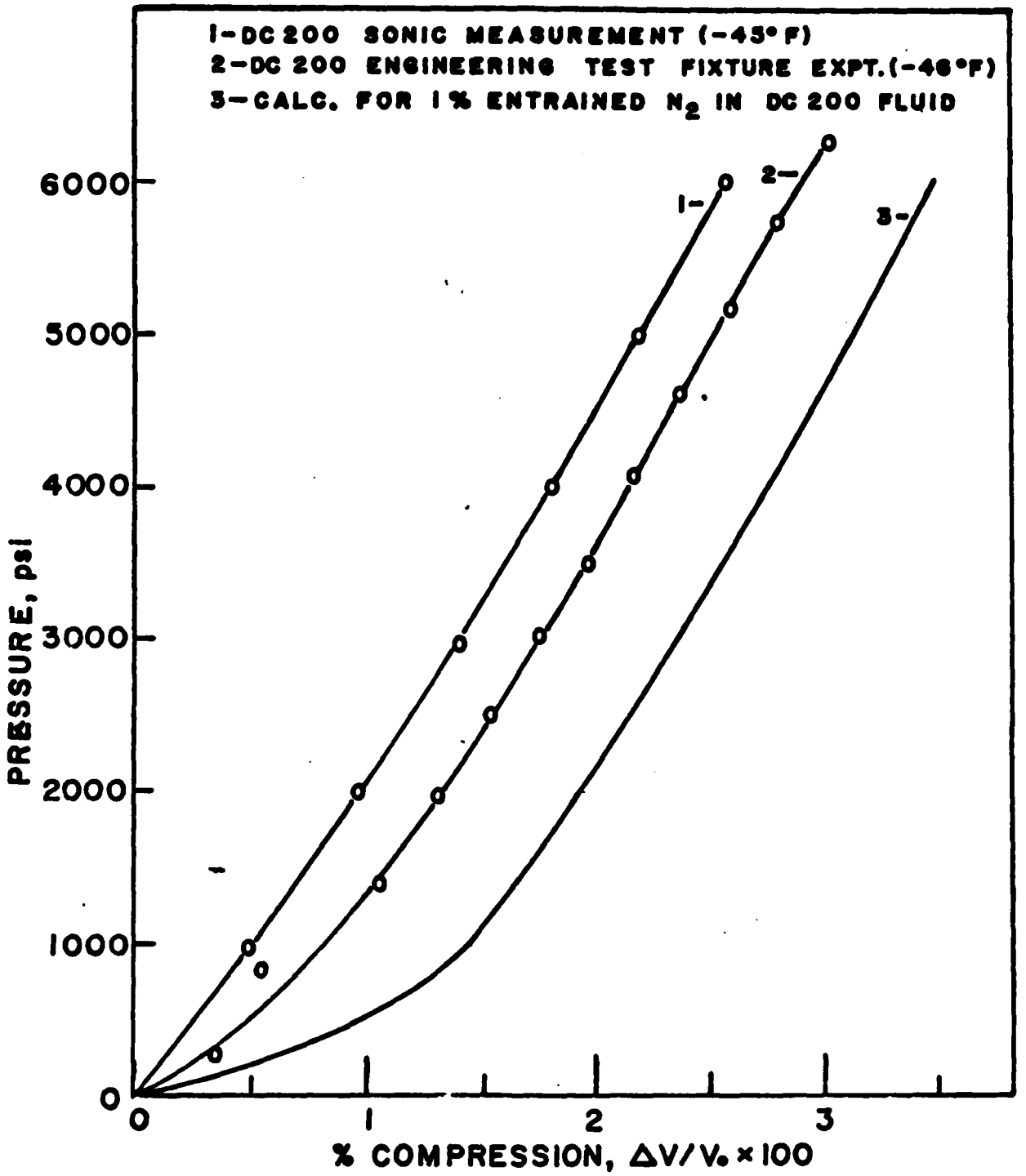


Figure 7. Comparison of Experimental Bulk Modulus With Calculated Modulus of Fluid Containing Nitrogen

SUMMARY AND CONCLUSIONS

Several fluids have been found (FC75, Freon E3 and fluorocarbon blends) which give volume compressions up to 25 percent greater than the polymethylsiloxane DC200-10cs. fluid currently under test for the CFSR mechanism. Other promising fluids are available and have not yet been tested.

Samples of the silicone fluid removed from the engineering test fixture at various times between low temperature pressurization runs contained up to three times as much air as is normally dissolved at ambient atmospheric conditions. The source of this air has not been positively identified nor is its effect on the compressible fluid completely understood.

RECOMMENDATIONS

1. The performance of the fluorocarbon and fluorinated ether fluids having higher compressibilities than the DC200-10cs. fluid should be evaluated in the CFSR engineering test fixtures.

2. The survey of fluids which may have high compressibilities has not been exhaustively completed. Additional fluids, particularly other members or mixtures of the fluorinated ethers or other fluids not previously considered "compressible" should be examined or reexamined for this property.

3. The RIA PVT apparatus should be improved and used for fluid screening purposes, particularly for materials in which the sound absorption is too high for accurate measurement by the sonic method. The Macro apparatus can be improved by the insertion of a thermocouple and pressure transducer in the bomb, and the Micro apparatus by the use of a bellows or diaphragm to separate the test fluid from the pressurizing fluid.

4. A sonic velocimeter should be obtained by the Fluids and Lubricants Laboratory for compressibility measurements.

5. The compressible fluids/materials should be tested for seal compatibility, viscosity, lubricity (friction and wear), corrosion protection and other properties related to their use in the CFSR mechanism. The ultimate goal is to discover or develop fluids or other materials which will be described by specification and be available so that CFSR mechanisms can be designed which will be more reliable, less expensive and simpler in design and construction than current recoil systems.

APPENDIX A

Tentative Specifications for

Compressible Fluid

Tentative Requirements for Compressible Fluid
for M140 Gun Mount

I. Essential Requirements:

1. Operating Pressures: 5000 psi. Max.; (4000 psi. Max. preferable); compressibility 3 to 4% at max. pressure.

2. Operating Temperature Range: -50°F to +300°F.

3. Toxicity: Should be non-toxic, non-hazardous and non-allergenic to operating personnel; specific requirements to be determined or approved by Surgeon General.

II. Desirable Properties:

1. Viscosity: Similar to MIL-H-6083; should be sufficient to lubricate bearings at 300°F.

2. Thermal Stability: Able to withstand 300°F exposure.

3. Corrosiveness and Oxidation Stability: Similar to MIL-H-6083; expected exposure to 4130 and 4140 steels, manganese and aluminum bronzes, and lead.

4. Effect on Seals: 10-15% swell in Green Tweed type seals (Nitrile Compound).

5. Flash Point and Autoignition Temperature: 550°F +

6. Surface Tension: Less than or equal to MIL-H-6083.

7. Volatility: Requirement to be established.

8. Shear Stability: Mechanical shear stability equal to or better than MIL-H-6083.

9. Corrosivity: Pass galvanic corrosivity test (See MIL-H-6083 specification).

10. Copper Strip Corrosion: Similar to MIL-H-6083.

11. Lubricity:

a) Establish best fluid-metal combination by LFW-1 (Falex Mode 1 Ring and Block Test Machine) or LFW-3 (concentric ring) friction and wear tests.

b) Using results obtained in a), establish specification test based on 4-ball method.

12. Particulate Contamination: Same as MIL-H-6083.

13. Foaming Characteristics: Same as MIL-H-6083.

14. Abrasiveness: To be established.

15. Hydrolytic Stability: To be established, depending on type of fluid.

16. Corrosion Protection: Humidity cabinet corrosion inhibition test same as MIL-H-6083.

17. Compatibility with Other Materials: Should be compatible with other hydraulic fluids, seals and seal lubricants.

18. Thermal Conductivity: To be established.

19. Specific Gravity: To be established; can be designed for various densities.

20. Storage Stability: Same as MIL-H-6083.

21. Compatibility with Water: Long periods of contact with water which may condense in the recoil system should not cause deleterious effects such as corrosion or sticking valves.

List of Establishments Contacted for Information
on Availability of Compressible Fluids

The Pennsylvania State University
Petroleum Refining Laboratory
ATTN: Dr. E. Erwin Klaus
College Park, PA 16802

Oklahoma State University
School of Mechanical and Aerospace Engineering
Fluid Power Research Center
ATTN: DR. E. C. Fitch
Stillwater, OK 74074

General Electric Company
Silicone Products Dept.
ATTN: Mr. James C. Frewin
Waterford, NY 12188

Dow Corning Corp.
Compressible Fluids Dept.
ATTN: Mr. Gene Jarubczar
Midland, MI 48640

Halocarbon Products Corp.
ATTN: Mr. William Cassanos
82 Burlews Court
Hackensack, NJ 17601

General Electric Company
ATTN: Mr. Thomas Birdwell
872 Diamond Drive
Gaithersburg, MD 20760

Monsanto Chemical Co.
Research Department
ATTN: Dr. Roger Hatton
800 N. Lindbergh Blvd.
St. Louis, MO 63166

3M Center
Chemical Division, Research Department
St. Paul, MN 55101

E.I. DuPont DeNemours & Co.
Freon Products Laboratory
ATTN: Dr. Hans J. Borchardt
Chestnut Run
Wilmington, DE 19898

E.I. DuPont DeNemours & Co.
Petroleum Chemical Division, Research Dept.
Wilmington, DE 19898

Union Carbide Croporation
Regional Product Information Center
ATTN: Mr. Marty Carbone
120 S. Riverside Pl.
Chicago, IL 60606

Commander
USA MERDC
Petroleum and Materials Dept.
ATTN: STS FB-GL, (J. Christians)
Ft. Belvoir, VA 22060

Commander
AFML/MXE, (Mr. Joe Sullivan)
Wright-Patterson Air Force Base, OH 45433

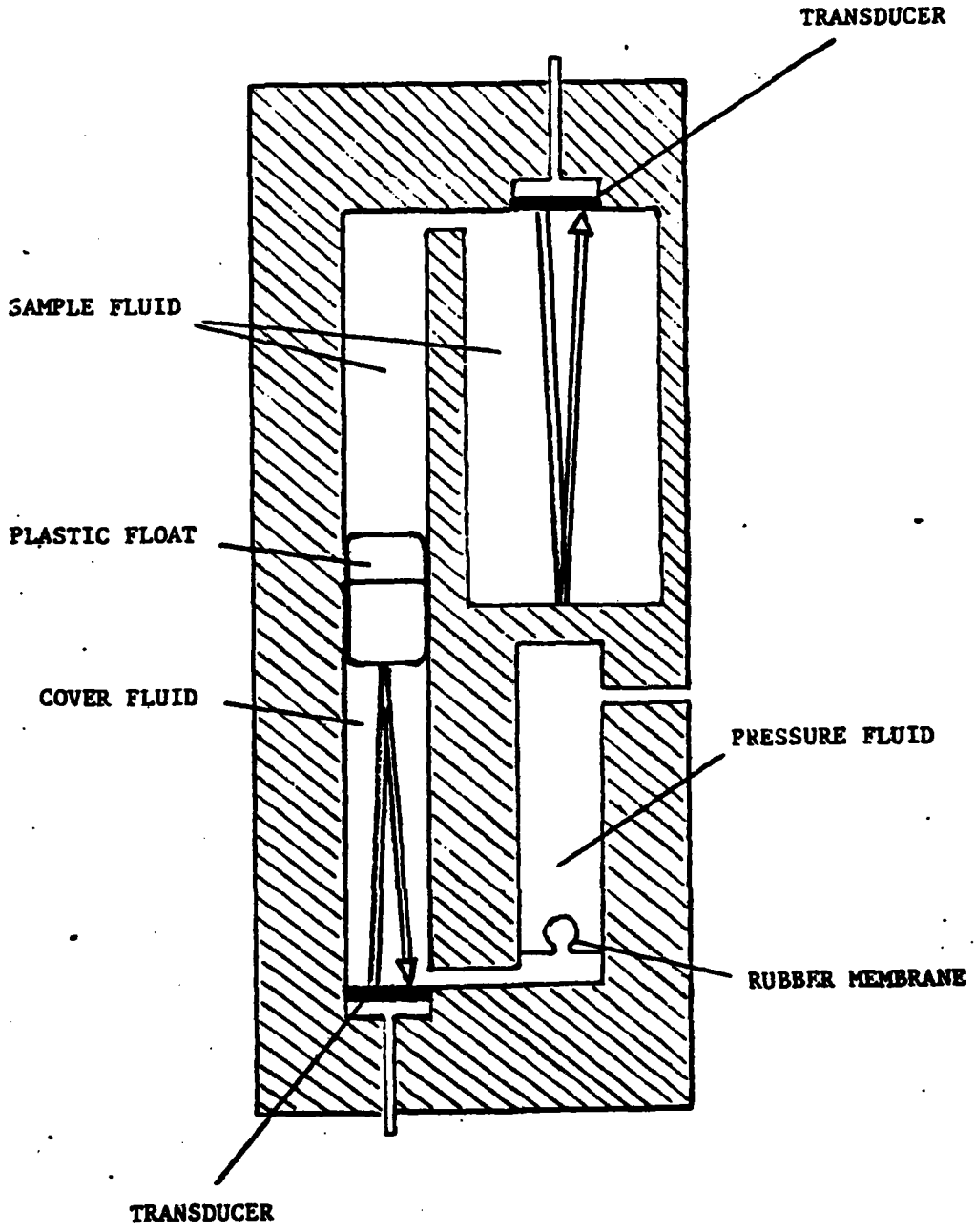
Commander
Naval Air Development Center
Aero Material Department
ATTN: Mr. A. A. Conte, Jr.
Warminster, PA 18974

APPENDIX B

1. Description of Sonic Compressibility Method.

2. Least Squares Equations for Sonic Bulk Modulus.

ULTRASONIC INSTRUMENT FOR SIMULTANEOUS MEASUREMENTS OF DENSITY AND SOUND VELOCITY IN LIQUIDS AND AMORPHOUS MATERIALS



Compressibility Tests on Selected Fluids

J. Jarzynski and C. W. Klee

The compressibility data was obtained using an ultrasonic technique, developed at NRL, for simultaneous measurements of sound velocity, c, and density, ρ, of a fluid. The adiabatic compressibility, K_s, was then calculated from the relation

$$K_s = \frac{1}{\rho c^2}$$

The ultrasonic technique is based on precise measurements of the time-of-flight of ultrasonic signals. The device used (see Fig. 1) is made of Invar. The liquid sample fills a chamber $\sim$18 ccs capacity and partly fills an adjoining vertical bore of known diameter ($\sim$1.1 cm). The chamber and the bore are connected by a small conduit. The remainder of the bore if filled with a suitable cover fluid, immiscible with the sample liquid. For sample #1 the cover fluid was a fluorocarbon liquid, FC 75, supplied by the 3M Company. For samples #8 and #10, the cover liquid was ethyl alcohol. The cover fluid is separated from the fluid used in the pressure vessel by a thin rubber membrane which transmits changes in pressure. A plastic float is freely suspended at the interface between the sample and cover liquids.

To achieve temperature control the pressure vessel is immersed in a bath filled with ethylene glycol-water mixture. Measurements were made over the temperature range -50 to 25° C, and at pressures of 14.7, 2000, 4000 and 6000 psi. The lowest temperature was attained by adding dry ice to the bath. Then, readings were taken at selected temperatures as the system slowly returned to room temperature.

Ultrasonic pulses are introduced and the return echoes detected by means of quartz transducers located at the bore and at the sample chamber. Transducers operating at frequencies of 1 and 4 MHz were used, depending on the attenuation of sound in the sample. Attenuation of sound in many liquids is proportional to frequency squared. Therefore, for samples in which the attenuation was high it was necessary to go to a lower frequency (1 MHz) to obtain a detectable ultrasonic echo through the sample. The round trip time-of-flight of a sound pulse over the fixed path length of the sample chamber is measured and used to determine the velocity of sound with an accuracy of 1 part in 10^3. Simultaneously, the time-of-flight of an ultrasonic pulse to the plastic float is measured, and combined with the known velocity of sound in the cover liquid to calculate the position of the float. Changes in float position of 0.004 cm can be detected, and used to calculate the change in volume (and hence density) of the sample liquid.

Data collected for selected liquids, supplied by the Rodman Laboratory, are tabulated on the pages which follow.

Sample #1
DC 200

Speed of Sound (meters/sec)

Temp.	Pressure (psi)			
(°C)	14.7	2000	4000	6000
-51	1227	1280	1333	1383
-46	1207	1261	1317	1367
-40	1187	1243	1300	1351
-34	1167	1225	1284	1336
-29	1148	1208	1268	1321
-23	1129	1191	1253	1306
-18	1110	1175	1237	1292
-7	1075	1143	1207	1265
+4	1043	1113	1179	1238
+16	1010	1084	1151	1213

Adiabatic compressibility ($\times 10^{12}$ cm^2/dyne)

-51	66	61	56	51
-46	69	63	57	53
-40	72	65	59	54
-34	74	67	60	55
-29	77	69	62	56
-23	80	71	64	58
-18	83	74	66	59
-7	89	79	70	63
+4	96	84	74	66
+16	103	89	78	70

Sample #8
F - 50

Speed of Sound (meters/sec)

Temp.	Pressure (psi)			
(C°)	14.7	2000	4000	6000
-40	1218	1268	1317	1365
-21	1131	1203	1257	1293
-3	1066	1136	1196	1247
+25	1002	1069	1129	1183

Adiabatic compressibility (x 10^{12} cm^2/dyne)

-40	62	57	53	49
-21	72	65	59	55
-3	84	73	65	60
+25	97	85	75	68

Sample #10
FREON E3

Speed of Sound (meters/sec)

Temp.	Pressure (psi)			
(°C)	14.7	2000	4000	6000
-48	820	878	928	980
-36	780	846	899	947
-15	718	786	842	893
+20	600	689	755	811

Adiabatic compressibility (x 10^{12} cm^2/dyne)

-48	80	69	61	55
-36	90	76	66	59
-15	109	89	77	68
+20	162	120	99	85

Table B-1

BULK MODULUS EQUATIONS ($B_S = f(P)$)
(LEAST SQUARES FIT)

PRESSURE RANGE: 0-6000 psig

Material	Temperature °C	Temperature °F	B_S, psi
DC200	+22.2	+72	$130,195 + 13.572P - 0.000256P^2$
	+15.5	+60	$140,230 + 11.940P - 0.000125P^2$
	+ 4.4	+40	$151,444 + 10.825P + 0.0000938P^2$
	- 6.7	+20	$162,308 + 11.127P + 0.0000831P^2$
	-17.8	0	$174,418 + 11.069P + 0.0000925P^2$
	-23.3	-10	$181,896 + 10.423P + 0.000179P^2$
	-23.9	-11	$175,233 + 11.197 + 0.0000630P^2$
	-28.9	-20	$187,961 + 10.978P + 0.0000918P^2$
	-34.4	-30	$195,371 + 10.663P + 0.000120P^2$
	-40	-40	$202,184 + 10.892P + 0.0000700P^2$
	-42.8	-45	$199,900 + 11.797P - 0.0000251P^2$
	-45.6	-50	$210,094 + 10.935P + 0.0000481P^2$
	-51.1	-60	$218,680 + 9.855P + 0.000135P^2$
Fluorocarbon FC75	+12.2	+54	$96,650 + 15.665P - 0.000359P^2$
	- 0.6	+31	$122,200 + 11.443P + 0.000357P^2$
	-31.1	-24	$149,300 + 19.575P - 0.000625P^2$
	-43.9	-47	$181,605 + 13.943P + 0.0000286P^2$
Halocarbon Oil 411E	+14.5	+58	$228,690 + 12.686P + 0.0000125P^2$
	- 1	+30	$253,060 + 16.090P - 0.000693P^2$
Halocarbon Oil 11-14E	+17.5	+63	$221,432 + 11.910P + 0.000112P^2$
	- 2	+28	$258,254 + 12.227P - 0.0000412P^2$
Fomblin Y04	+20	+68	$119,370 + 11.532P + 0.0000946P^2$
Freon E3	+20	+68	$89,700 + 16.15P - 0.00045P^2$
	-15	-26.1	$133,100 + 14.725P - 0.0002125P^2$
	-36	-37.8	$161,000 + 15.50P - 0.000225P^2$
	-48	-44.4	$181,227 + 14.84P - 0.0001844P^2$

APPENDIX C

Description of RIA-PVT Compressibility Apparatus

1. RIA Macro PVT Method
2. RIA Micro PVT Method

1. RIA Macro PVT Method for Secant Bulk Modulus

The apparatus for this determination is shown in Figure C-1. The procedure for its use is as follows:

1. If the coefficient of thermal expansion of the fluid is not known over the temperature range of interest, it may be obtained by the determination of the fluid density. The general procedure for the Lipkin bicapillary pycnometer, ASTM Method D1481 can be used to give sufficiently accurate densities. For lower temperatures, the pycnometer is immersed in a dry ice alcohol bath. Additional fluid may be needed in the pycnometer as the temperature is lowered to keep the fluid volume on scale. The additional fluid is weighed at the conclusion of the experiment, by collecting the excess in a small dish as it expands from the capillary. A correction should be applied for the contraction of the glass pycnometer.

An alternate method to determine the thermal expansion coefficient of the fluid can be followed. With the bomb filled and the fluid degassed as in steps 3 and 5 below, bring the fluid level to near the top of the measuring buret. With valves 4 and 6 closed and valve 5 open, cool the system to the test temperature. When the temperature has stabilized, record the volume change ΔV. The thermal expansion coefficient (α) is

$$\alpha = \frac{1}{V}\left(\frac{\Delta V}{\Delta T}\right)$$

where V = Fluid Volume in Bomb (see step 2 below).

ΔV = Change in Volume (buret measurement).

ΔT = Change in Temperature.

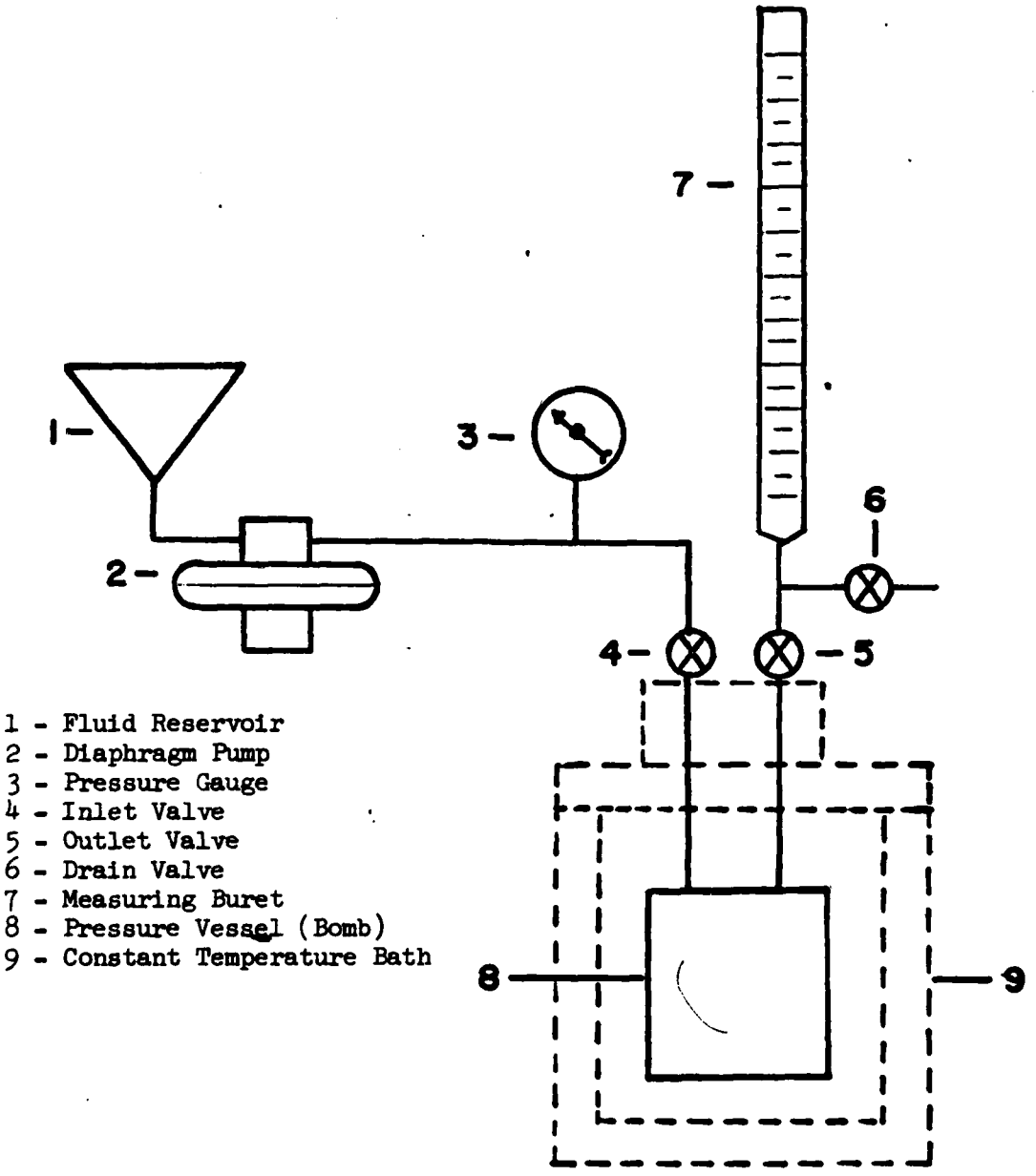
2. Measure the volume of the bomb between the inlet and outlet valves, 4 and 5, by filling it, while disassembled, with an appropriate solvent such as naphtha and draining this fluid into a graduated cylinder.

3. Evacuate a suction flask containing a sufficient quantity of the test fluid by the use of a vacuum pump to remove dissolved air. The pumping is done for 15 - 30 minutes or until foaming diminishes.

4. Fill the disassembled bomb and the diaphragm pump reservoir with the degassed fluid. Reassemble the apparatus.

5. Open valves 4 and 5 and close drain valve 3. Pump fluid through the system rapidly to remove trapped air. If necessary, to remove air bubbles, plug the buret and apply a vacuum at valve 6 until bubbles or foam are removed.

6. Bring the system to the test temperature.



1 - Fluid Reservoir
2 - Diaphragm Pump
3 - Pressure Gauge
4 - Inlet Valve
5 - Outlet Valve
6 - Drain Valve
7 - Measuring Buret
8 - Pressure Vessel (Bomb)
9 - Constant Temperature Bath

Figure C-1. RIA Macro PVT Bulk Modulus Apparatus

7. Close valves 5 and 6, open valve 4 and raise the pressure to the desired level. Read the fluid level in the buret, close valve 4 and open valve 5 slowly. When the fluid level in the buret stabilizes, record the change in volume, ΔV.

8. Calculate the secant bulk modulus from the equation:

$$\bar{B} = V_o \left(\frac{P - P_o}{V_o - V} \right)$$

or

$$\bar{B} = V_o \left(\frac{\Delta P}{\Delta V} \right)$$

where

P = Final Pressure, psig.
P_o = Initial Pressure, (0 psig.)
V = Fluid Volume at Pressure P. This is equal to the volume of the bomb.
V_o = Fluid Volume at Pressure P_o. This is equal to the volume of the bomb plus ΔV. It is the total volume of fluid compressed from P_o to P.

9. If the determination is made at other than room temperature, ΔV must be corrected for the volume expansion or contraction on passage of fluid between the bomb and outlet pipes. In addition, a correction should be made for the volume differences due to the temperature gradient in the pipes leading to valves 4 and 5. Obtain the average temperatures of these pipes by means of thermocouples and apply the corrections, using the thermal expansion coefficient of the fluid as determined in step 1.

10. If insufficient fluid is available to fill the diaphragm pump and bomb, a different procedure is used. These fluids are placed in polyethylene bottles equipped with closeable dropping caps with care to eliminate all air bubbles. The bottles are then inserted in the bomb. Another fluid such as MIL-H-5606 hydraulic fluid, for which the compressibility has been determined by the steps outlined above, is used as the compression medium to compress the fluid contained in the bottles. The portion of ΔV associated with each fluid is in the ratio of their total volumes in the bomb. Temperature corrections are made as in step 9.

Note: Possible sources of error in the use of the bomb for compressibility measurements are: a) Change in volume of the bomb due to temperature changes, b) expansion of the bomb due to pressure and, c) temperature changes in the fluid due to compression. These errors are estimated as follows:

a) Expansion and contraction of the bomb was estimated from an equation given in ASTM method D1481 for the estimation of apparent volume of a pycnometer at various temperatures. This formula is

$V_2 = V_1 (1 + c\Delta t)$, where

V_2 = apparent volume at test temperature
V_1 = apparent volume at calibration temperature
c = cubical expansion coefficient of the pycnometer material (in this case, the PVT bomb; for steel, $c = 4 \times 10^{-5}$ / °C
Δt = temperature change °C

For a temperature change from 20°C to -54°C, $V_2 = 506(0.9970)$ or $V_2 = 504.5 cm^3$. Such a small change in volume with temperature can be neglected.

b) The expansion of the bomb due to the internal pressure was estimated from stress - strain formulas given by Roark[16] for a thick cylindrical shell with ends capped. The change in internal radius (b) is given by

$$\Delta b = \frac{qb}{E}\left(\frac{a^2 + b^2}{a^2 - b^2} + \nu\right)$$

and the change in length (l) is given by

$$\Delta l = \frac{q\nu l}{E} \cdot \frac{2b^2}{a^2 - b^2}$$

where
q = pressure
b = internal radius of bomb
a = external radius of bomb
l = length of bomb cylinder
E = Young's modulus (30×10^6 for steel)
ν = Poisson's ratio (0.3 for steel)

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16. Roark, R. J. and Young, W. C., "Formulas for Stress and Strain", McGraw - Hill, NY, 1975, p. 504.

Using the approximate dimensions: b = 6cm, a = 10cm and l = 16cm, the volume change is estimated as $3 \times 10^{-5} cm^3$ for an internal pressure of 6000 psi. This magnitude of expansion is negligible in fluid bulk modulus measurements.

c) Temperature changes in the fluid due to compression were estimated from heat capacity and thermal espansion data. For an adiabatic compression,

$$\left(\frac{\partial T}{\partial P}\right)_S = \frac{T}{C_p}\left(\frac{\partial V}{\partial T}\right)_P$$

The change in volume of the DC200 fluid with temperature is $1 \times 10^{-3} cm^3$ / gm / ^oK from density data. C_p is given in manufactures' bulletins as 0.42 Cal/ gm/^oK. Using these data, and the absolute temperature T, a temperature rise of approximately 1^oC (or ^oK) for every 1000 psi. pressure can be calculated by integration of this equation. In order to minimize this error due to compression heating, the fluid should be allowed to come to thermal equilibrium at each pressure. If not, the value of bulk modulus will lie between the adiabatic and isothermal modulus. For rough measurements, or for fluid screening purposes, the method does yield reproducible data even though the fluid may not be at thermal equilibrium. An improvement in the present apparatus would be to place temperature and pressure transducers within the bomb to monitor temperatures and pressure changes.

Fluid densities versus temperature for the fluids investigated are given in Table C-1. The expansion coefficient for the polygel was determined by the alternate method of step 1 while immersed in MIL-H-5606 fluid. The volume changes of each material with temperature were taken as the ratio of the volume of each to the total volume. For the polygel, $\alpha = 9 \times 10^{-4} cm^3/cm^3/^oC$.

2. RIA Micro PVT Method for Secant Bulk Modulus

The apparatus for this method is shown in Figure C-2. The procedure for its use is as follows:

1. Select three capillary tubes with approximately 1mm. inside diameter. Calibrate the tubes by the use of a magnified scale or by measuring the length of a known quantity of mercury inserted in the capillary. For a tube of this diameter, a 140cm. length contains approximately $1 cm^3$.

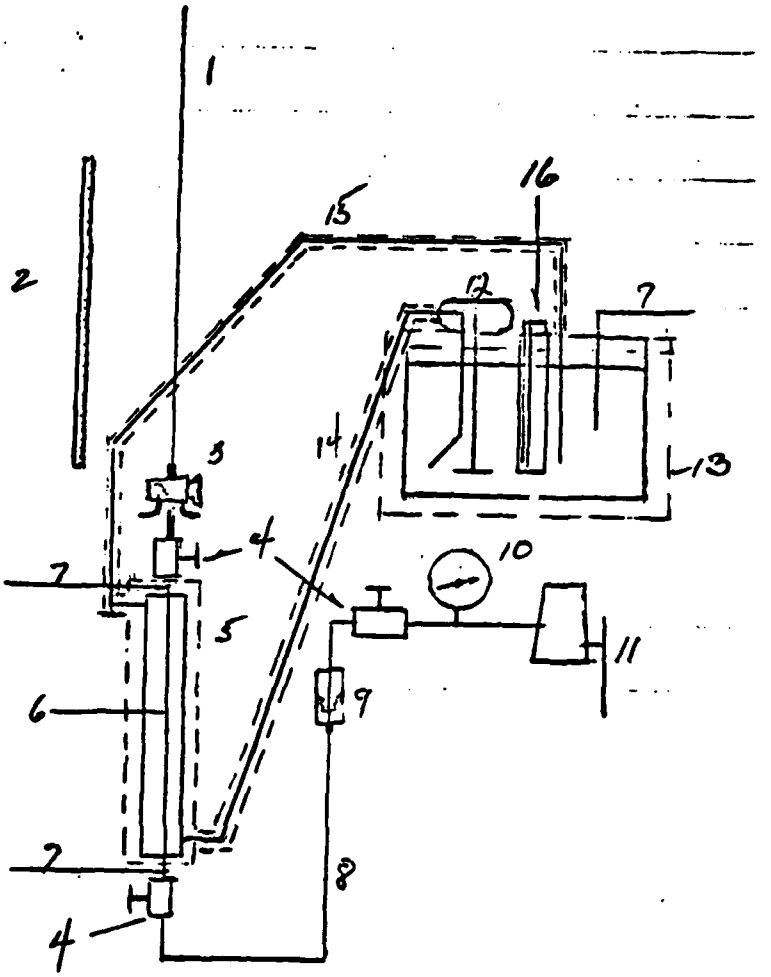
2. Determine the volume of the test chamber between the inlet and outlet valves by filling it with an appropriate fluid and measuring its volume.

3. Disconnect the flexible hydraulic pressure tube (8) and valve from the pump at the gauge (10) and fill this tube along with the test chamber up to the outlet of the stopcock (3) with the test fluid. If sufficient test

Table C-1

DENSITY - TEMPERATURE RELATIONSHIPS FOR COMPRESSIBLE FLUIDS

Fluid	Temperature, °C	Density, gm/cm^3
MIL-H-5606	23	0.864
	1	0.878
	0	0.879
	- 9	0.885
	-18	0.892
	-54	0.916
DC200	22	0.940
	10	0.948
	0	0.960
	-34	0.992
	-48	1.006
	-58	1.016
Versilube F-50	22	1.031
	20	1.032
	0	1.054
	- 8	1.060
	-41	1.092
	-54	1.106



1. Detachable calibrated capillary tube
2. Meter stick
3. Three way stopcock
4. Hydraulic valves
5. Insulated condenser
6. Stainless steel tube; test chamber. Capacity: 12.2cm^3.
7. Temperature sensors
8. Flexible hydraulic tubing
9. Brass bellows
10. Pressure gauge
11. Manual hydraulic pump
12. Pump and stirrer for coolant circulation
13. Constant temperature bath
14. Insulated inlet tube
15. Insulated outlet tube for coolant
16. Cooling and heating controls

Figure C-2. Schematic Diagram of RIA Micro PVT Apparatus for Secant Isothermal Bulk Modulus Determination

fluid is available, the hand pump (11) can also be filled with the same fluid. If only a small quantity of test fluid is available, the pump is filled with another liquid which is immiscible with the test fluid. Care must be exercised in pumping to keep the fluids from mixing in the flexible tube. A plug of mercury can also be used to separate the pumping fluid and test fluid.

4. To remove any residual air from the test fluid, the valve next to the pressure gauge is closed and a vacuum applied at the outlet of the stopcock(3).

5. The capillary tube (1) is inserted and the fluid level adjusted to a convenient height. The outlet valve of the test chamber is closed and the inlet valves opened. The temperature of the system is adjusted to the desired test temperature and then the pressure is raised to the desired level. With this system, the pressure can be controlled to ±20 psig and the temperature to ±5°F. The inlet valve to the test chamber is closed and the outlet valve is opened slowly. The excess fluid compressed in the test chamber expands into the capillary tube. The change in volume of the fluid is determined from the length of the fluid column and its diameter in the capillary tube. The change in the length of the fluid column and its temperature are recorded. The compression-expansion cycle is repeated 2 or 3 times, depending on the unused length of capillary tubing that is available. The capillary tubing is cleaned and dried before each use.

6. The secant isothermal bulk modulus given by this method is calculated from the relationship:

$$\bar{B}_T = \frac{(P - P_o) V_o'}{(V_o' - V')}$$

where $\bar{B}_T$ = secant isothermal bulk modulus, psi

P = pressure, psig

P_o = initial pressure, psig (usually 0 psig)

V_o^1 = volume at P_o (test chamber volume)

V^1 = volume at P (V_o minus effluent volume)

Note 1: These calculations are based on a method used by the Boeing Aircraft Corp. and the results are slightly different from those reported for the RIA Macro PVT Method. In the Boeing method the initial fluid volume, V_o^1, is the test chamber volume and does not include the additional fluid that is compressed into the chamber. In the RIA Macro method, the volume V_o is the total initial volume of fluid that is compressed from the initial pressure P_o to the final pressure P. This V_o is the sum of the test

chamber volume plus the effluent volume. If ΔV is the effluent volume and P_o = 0 psig, then for the

RIA Macro Method:

$$\overline{B}\ (\text{Macro}) = \frac{P(V_o' + \Delta V)}{\Delta V}$$

For the RIA Micro and Boeing methods:

$$\overline{B}\ (\text{Micro}) = \frac{P V_o'}{\Delta V}$$

The difference between the two reduces to:

$$\overline{B}\ (\text{Macro}) - \overline{B}\ (\text{Micro}) = P.$$

7. Correct the volume of the test chamber for changes due to pressure and temperature. Correct the effluent volume for the difference in temperature between the capillary tube and test chamber.

Note 2: Advantages of the RIA Micro PVT test method are as follows:

a. The apparatus is less expensive than the sonic velocimeter and can be assembled from parts readily available in the laboratory.

b. A small quantity of test fluid can be used.

c. Operation of the apparatus is simple.

d. The bulk modulus of fluids can be determined with this apparatus in cases where the sonic method does not give results. For example, for the Fomblin YO4 and the halocarbon fluids, the sound echo became too weak to detect at low temperatures.

e. The test parameters simulate the actual system in the practical application of a compressible fluid.

Disadvantages of the Micro PVT test method are as follows:

a. Measurement of the effluent volume by the use of the capillary tube is difficult.

b. Small leaks can cause considerable error in the measurement of bulk modulus.

c. When two fluids are introduced in the system, as in the cases where only a small quantity of test fluid is available, the test fluid can become contaminated with the pressurizing fluid. Insertion of a mercury divider does not always help. A suggested method to prevent this contamination is to insert a brass bellows between the pump and test chamber. Such a device will be used on future modifications of the Micro PVT apparatus.

APPENDIX D

Air Solubility Data

Table D-1

SOLUBILITY OF AIR IN FLUIDS

Fluid	Temperature °C	Bunsen Coefficient $cm^3/cm^3/atm$ @ 0°C/15.5°C/1 atm
DC200, 10cs Silicone Fluid	25	0.188, 0.182, 0.188, 0.191, 0.189, 0.176, Avg: 0.186
	0	0.201, 0.199, 0.207, 0.215, 0.208; Avg: 0.206
	-25	0.284
	-40	0.384
	-49	0.400
	-57	0.445
	-59	0.447
MIL-H-5606	25	0.113, 0.109; Avg: 0.111
	- 3	0.140
	-38	0.166