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SELF-SEALING SHIELDS FOR MICROMETEORITE PROTECTION

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ABSTRACT

Self-sealing shields for cryogenic propellant tanks are investigated. The self-sealing shields consist of a hexcel covering containing a porous media. The sealing occurs when the cryogenic propellant discharges and solidifies in the porous media which contains a vacuum. Two types of porous media are investigated, fiberglass strands and open cell polyester foam. The shields using polyester foam are shown to be a feasible method of solving the problems caused when a micrometeorite collides with a propellant tank.

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RESEARCH AND DEVELOPMENT OPERATIONS

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DEFINITION OF SYMBOLS

Symbol	Definition	Units
C	Speed of sound in the target material, Propagation of sound	km/s
d	Diameter of meteorite, diameter of a sphere with a mass equal to that of the meteorite, based on ρ_P	μ
P	Penetration depth, distance that a meteorite penetrates a target when colliding perpendicular to the target	μ
V	Velocity of the micrometeorite at impact, velocity of the meteorite relative to the tank into which it collides	km/s
ρ	Density , mass per unit volume	g/cm^3
ρ_P	Density of meteorite, mass of meteorite per unit volume based on the material of the meteorite	g/cm^3
ρ_T	Density of target material, mass per unit volume of the material used for construction of space vehicle tanks	g/cm^3

SELF-SEALING SHIELDS FOR MICROMETEORITE PROTECTION

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SUMMARY

A self-sealing shield utilizing the physical properties of a cryogenic propellant was proven feasible. The shield consists of a hexcel covering filled with a porous media applied to the outside surface of a propellant tank. The sealing occurs when the cryogenic propellant discharges through the micrometeorite puncture in the shield and tank wall. The phenomena that results is a solidification of the cryogenic propellant as it encounters the vacuum of space. The solid propellant is rigidly held in the porous media and plugs the hole. The most favorable porous material for sealing was an open cell polyester foam. Meteorite punctures as large as 0.050 inches in diameter were sealed with this type of shield.

INTRODUCTION

The meteroids traveling through space present a potential hazard to earth orbit and long range space vehicle missions. A small propellant leak caused by a meteorite puncture of a propellant tank could cause mission failure. Two approaches can be taken to eliminate this problem of leakage: prevent meteorite penetration, or allow meteorite penetration but seal the puncture.

Preventing meteorite penetration becomes quite difficult when the meteorite masses and velocities are large; furthermore, shields that are capable of absorbing large meteorite impacts become very heavy. This paper considers an attempt to seal the puncture after it is produced.

Present development of self-sealing mechanisms does not encompass cryogenic tankage. Most sealing materials become brittle at very low temperatures, thus preventing them from rebounding to their original position after penetration. To eliminate the problems of sealing materials, the properties of the propellant are considered. When cryogenic liquid propellants are exposed to pressures below their triple point, they solidify. This solidification can be utilized for sealing meteorite punctures. The sealing mechanism is obtained by filling the hexcels of a hexcel insulation with a porous media. The sealing occurs when the propellant discharges through the puncture and forms a solid in the porous media.

There are many other types of self-sealing mechanisms being studied; these include multiple metal sheets, porous materials that absorb impact, shields that produce sealing by solidification of chemicals, and small spheres or discs that maneuver themselves over the puncture. D'Anna et al.[1] have tested numerous self-sealing mechanisms at room temperatures and have had good results. They have shown that air leaks can be kept relatively small with discs, spheres and asbestos fibers. Mechanisms such as these might well seal more readily when solid formations are encountered at the small leaks that do exist.

The National Bureau of Standards conducted a program on the effects of liquid hydrogen and liquid nitrogen discharging to a vacuum. Their findings show that leaking fluids will form a solid when exposed to the vacuum. In many cases this solid builds up and plugs the discharging orifice. Brennan[2] demonstrated that partial plugging could occur when discharging LN_2 and LH_2 through 0.01 inch diameter orifices. Chelton et al.[3] showed that a tube 0.75 inches in diameter could be plugged when nozzles as large as 0.045 inches diameter discharged LN_2 and LH_2 into it. These plugs lasted as long as 45 minutes at differential pressures as high as 12.2 psi. A photograph of this type of plugging is shown in FIG 1, as taken from Ref. 2. The plugging was initiated by a build up of small particles of solid nitrogen or hydrogen.

The orifice sizes considered in this study are based on meteoroid flux near the earth taken from the "Satellite Environment Handbook." [4]

THEORY

Meteorite environments beyond the atmosphere of the earth have been confirmed by numerous satellite experiments, but the size, mass, distribution, and velocities are not well known. Johnson[4] has evaluated data on meteorite impact rates from various satellites, both American and Russian. Also included in this reference is a table by Whipple[5] for meteorite masses, radius, and flux. This table with a few additions is shown as Table I. Whipple's radius is based on spheres with a density of 0.05 g/cm³. This density assumes that the meteorites are "fluffy" particles. Dalton[6] states that meteorite densities may be classified broadly as (1) metallic, $\rho = 7.8$ g/cm³, (2) stony, $\rho = 3.5$ g/cm³, and (3) fluffy, $\rho = 0.443$ g/cm³. There appears to be some doubt about a precise value for meteorite densities. If the meteorites are stony, the radius would be smaller than that shown by Whipple. The radius based on the stony density using Whipple's data is shown in the third column of Table I. The sixth column shows the number of impacts per day on a three meter sphere derived on the assumption of 50 per cent shielding by the earth. This data may be extrapolated to show that the number of days between impacts of a meteorite of radius 0.012 inches is 61.3 days. Meteorites of diameter greater than 0.020 inches, based on $\rho = 3.5$ g/cm³, are not likely to strike a vehicle on a thirty day orbit.

Charters and Locke[7] experimentally derived an expression for the depth of penetration of spherical objects directed perpendicular to the target. The expression is:

$$\frac{P}{d} = 2.28 \left(\frac{\rho_P}{\rho_T}\right)^{0.69} \left(\frac{V}{C}\right)^{0.69} ,$$

where P is penetration depth; d is diameter of sphere; ρ_P is density of meteorite; ρ_T is density of target material; V is velocity of sphere at impact; and C is speed of sound in target material. For aluminum targets impacted by meteorites with a density and velocity range of 0.5 to 7.8 g/cm³ and 10 to 30 km/s, repectively, a P/d range of 1.13 to 16.1 is obtained. A conservative estimate of P/d between 2 and 4 for all meteorites provides a good design parameter for penetration. This conservative estimate is somewhat larger than that given by Dalton for hard aluminum.

TABLE I

PARAMETERS OF MICROMETEORITES

Mass (g)	Radius $\rho = 0.05$ (μ)	Radius $\rho = 3.5$ (μ)	Velocity (km/sec)	Kinetic Energy (ergs)	No. Striking 3-m Sphere Per Day	Days for One Impact	Flux (Particles/cm²-sec)
3.96×10^{-2}	5,740	1,395	28	1.58×10^{11}	1.63×10^{-4}	6,134	1.34×10^{-14}
1.58×10^{-2}	4,220	1,025	27	5.87×10^{10}	4.09×10^{-4}	2,445	3.36×10^{-14}
6.28×10^{-3}	3,110	756	26	2.17×10^{10}	1.03×10^{-3}	971	8.49×10^{-14}
2.50×10^{-3}	2,290	556	25	7.97×10^{9}	2.58×10^{-3}	387	2.12×10^{-13}
9.95×10^{-4}	1,680	408	24	2.93×10^{9}	6.48×10^{-3}	154	5.34×10^{-13}
3.96×10^{-4}	1,240	301	23	1.07×10^{9}	1.63×10^{-2}	61.3	1.34×10^{-12}
1.58×10^{-4}	910	221	22	3.89×10^{8}	4.09×10^{-2}	24.4	3.36×10^{-12}
6.28×10^{-5}	669	163	21	1.41×10^{8}	1.03×10^{-1}	9.7	8.49×10^{-12}
2.50×10^{-5}	492	120	20	5.10×10^{7}	2.58×10^{-1}	3.9	2.12×10^{-11}
9.95×10^{-6}	362	88	19	1.83×10^{7}	6.48×10^{-1}	1.5	5.34×10^{-11}
3.96×10^{-6}	266	65	18	6.55×10^{6}	1.63	0.6	1.34×10^{-10}

The mechanism used to seal tank punctures resulting from meteorite collisions occurs in the following manner. Immediately following the penetration, the liquid discharges into the affected hexcel that contains a vacuum. As the liquid flows into the porous media in the hexcel, the stream pressure drops. When the pressure across the porous material has dropped to the triple point, the liquid solidifies. The porous media helps initiate, maintain, and strengthen the solid obstruction. To ensure that the pressure drop will be reduced to the triple point, the faces of each hexcel are perforated to allow deeper penetration of vacuum within the hexcel. The hexcels eliminate contamination of the system by localizing the solid formation at each punctured hexcel. Since the meteorite shield is basically an insulation, it serves a dual purpose.

TEST PROCEDURE

The test apparatus is shown in FIG 2. The apparatus consisted of a liquid nitrogen supply, an accumulator tank, a 5 μ filter, a liquid nitrogen jacketed tube, and a vacuum source. The vacuum pressure was always kept at less than 1 mm of mercury.

The sequence of operation follows:

All components of the test apparatus were thoroughly cooled. The valve between the accumulator tank and specimen was opened. The specimens were visually checked for sealing, and the highest sealing pressure was determined. The LN_2 jacket and the vertical position of the approach tube assured that only liquid was exhausted into the specimen.

The hexcel used was 3/8-inch hex from point to point with a depth of 0.5 inches. The perforations on the face were 0.0625 inch holes placed at each point of the hexcel. Two types of porous media were considered: fiberglass strands with a density of 1.4 lb/ft^3, and polyester foam with a density of 1.6 lb/ft^3 and mean pore diameter of 0.030 inches. The hexcels and porous media were applied to a 0.0625 inch thick aluminum plate with Adiprene L-100 adhesive. The meteorite punctures were simulated by drilling. Liquid nitrogen was used for all tests. FIG 3 shows the types of test specimens used.

RESULTS OF TESTING

To determine the hazards of meteorite penetration, a hexcel was tested that had no filling and had a mylar sheet placed one-half inch from the hexcel face. The results of this test are shown in FIG 4. The solid buildup continued until it became so heavy that it dropped off.

Tests of the shields utilizing fiberglass strands showed that holes up to 0.020 inches in diameter could be sealed. The differential pressures obtained were as high as 45 psi. Holes 0.030 inches diameter did not seal. Inspection of the test specimens revealed that the momentum of the fluid discharging from the larger puncture pushed aside the fiberglass strands and prevented sealing.

Holes from 0.030 to 0.050 inches in diameter were sealed during tests of the shields using the polyester foam media. FIG 5 shows a typical nonsealing test when the differential pressure was too high. A fine spray of solid continually discharged from the penetration. FIG 6 shows the sealing when the differential pressure was reduced. The interior of hexcel has turned white due to the solid plug. The range of differential pressures encountered for penetration diameters from 0.030 to 0.050 inches is shown in FIG 7. Penetration sizes larger than 0.050 inches were not tested because the pressurizing system was not capable of pressures much below atmospheric. Other sealing mechanisms were not pursued because a particle accelerating device was not available. It was felt that further static testing would not give results representative of dynamic tests.

ADVANTAGES OF SELF-SEALING SHIELDS

Self-sealing shields of the type tested offer many advantages. For example, consider a ten-foot diameter spherical cryogenic tank that requires a wall thickness of only 1/16-inch aluminum. If this tank is designed for protection against meteorite penetration, a thicker wall is required. Assuming a design parameter of P/d = 3 and designing for protection against meteorites up to 0.040 inches diameter, the calculated wall thickness is 1/8-inch this additional thickness results in a weight increase of 277.3 pounds, whereas, the weight of the sealing shield is 75.5 pounds (shield density with foam = 0.24 lb/ft^2). Thus it can be easily seen that the shield affords a considerable weight savings over "beefing up" the tank wall.

If a 0.040 inch diameter meteorite penetrates the aluminum tank containing liquid hydrogen at a pressure of 15 psia, the entire tank of liquid will be lost through this penetration in 6.5 days. This penetration is less disastrous if the tank is protected by a self-sealing micrometeorite shield. Assuming that all heat radiated from the sun over the area of the affected hexcel goes to sublimation of the solid hydrogen, the loss of liquid hydrogen in 6.5 days is only 1.44 pounds. The self-sealing shield has a thermal conductivity in the range from 0.1 to 0.5 Btu-in/ft^2-hr- F.[3]

Penetrations into the ullage region of the tank could cause a loss of pressure, but cryogenic fuels such as liquid hydrogen have a contact angle near zero, thus ensuring that liquid continually covers the inside surface of the tank. Therefore, sealing will always occur.

CONCLUSIONS

The results of the testing show that the self-sealing shield is a feasible method of protection for meteorite penetration, but many problems still exist. Because the porous material could shatter on impact or be destroyed by fragmentation of the meteorite, the effects of impact on the shield must be determined. There is a good possibility that larger penetrations can be sealed by the self-sealing shields if the pressure drop length is increased. Also, the system of floating discs may be used to seal larger penetrations.

If a shield of the type studied can be proven completely reliable against impact effects, it may be applied as protection for low pressure fluid transfer lines, space vehicle fuel tanks, and tanks for storable fluids such as water.

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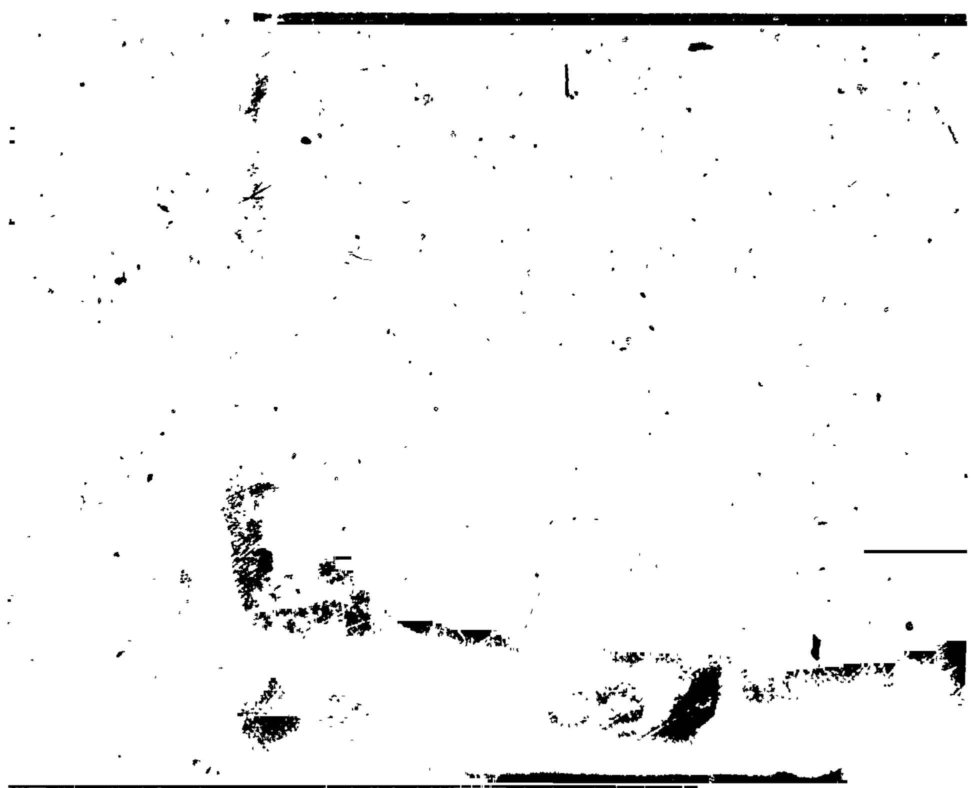


FIG 1 SOLID PLUG INITIATED BY END INTERFERENCE

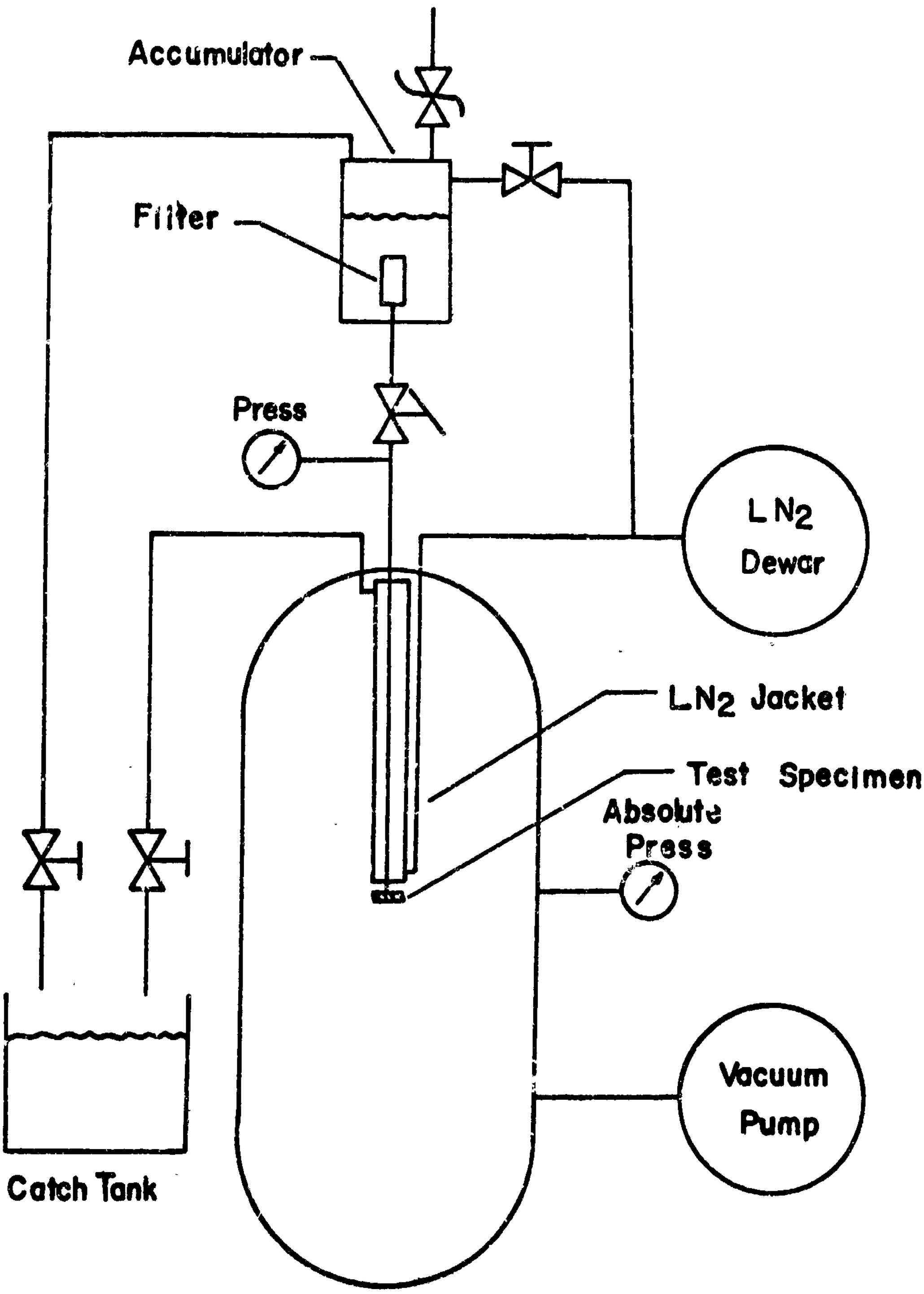
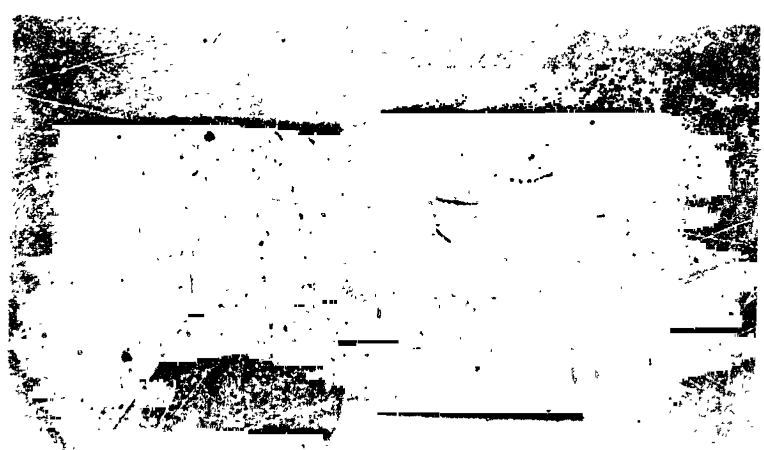


FIG 2 TEST APPARATUS

(a)



(b)

FIG 3 SELF-SEALING SHIELD SPFCIMENS

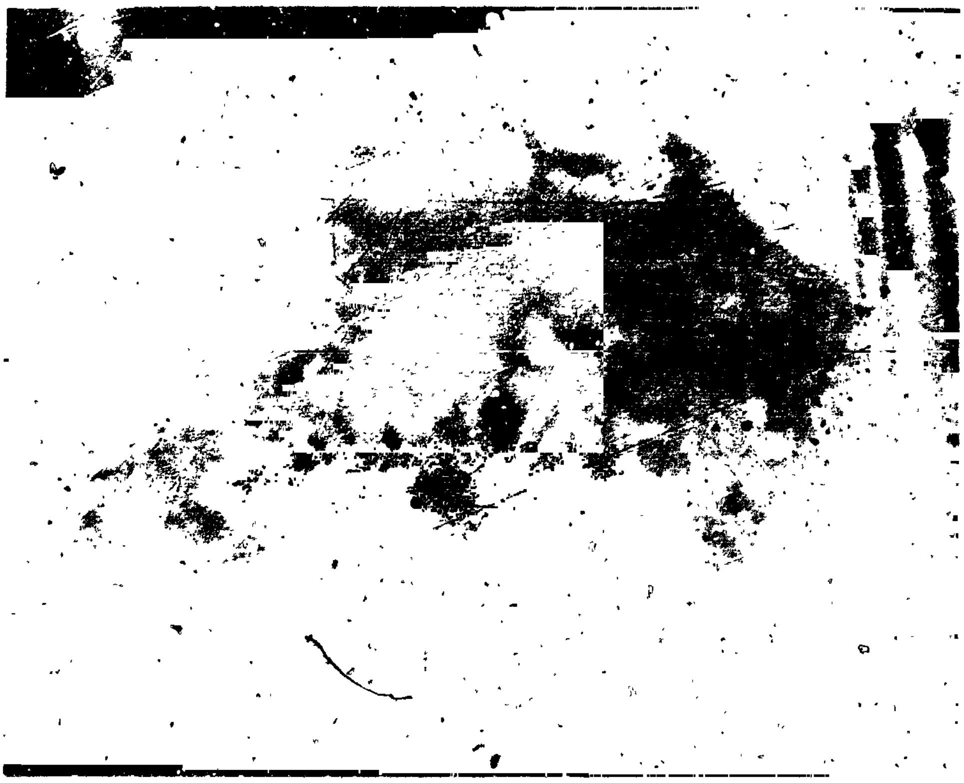


FIG 4 HAZARD OF METEORITE PUNCTURE

FIG 5 NON-SEALING TEST

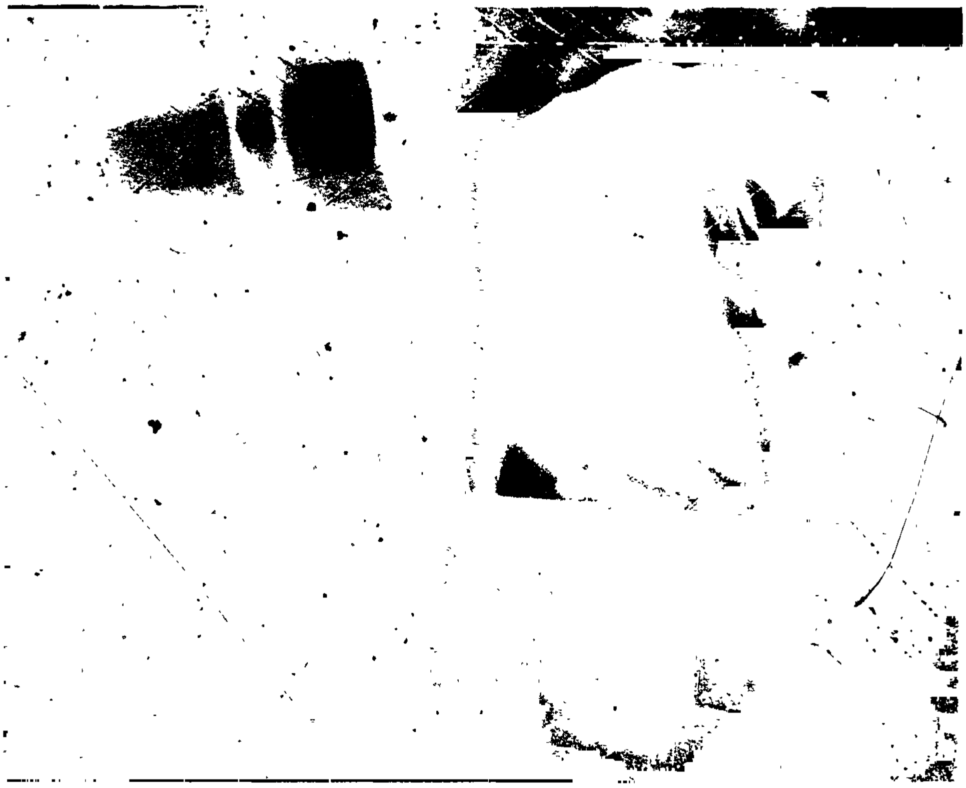


FIG 6 SEALING TEST

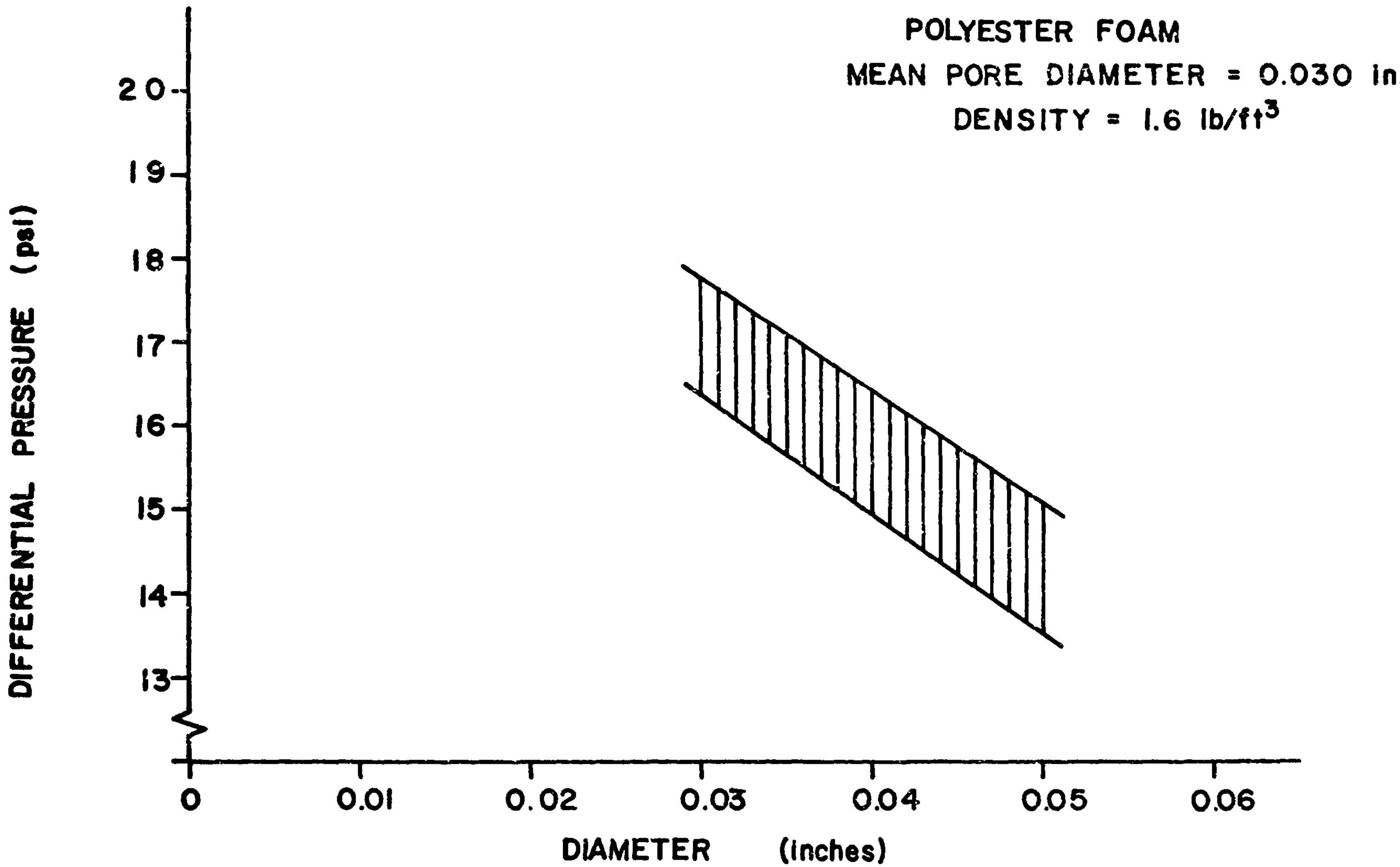


FIG 7 RANGE OF SEALING PRESSURES FOR POLYESTER FOAM

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This document has also been reviewed and approved for technical accuracy.

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