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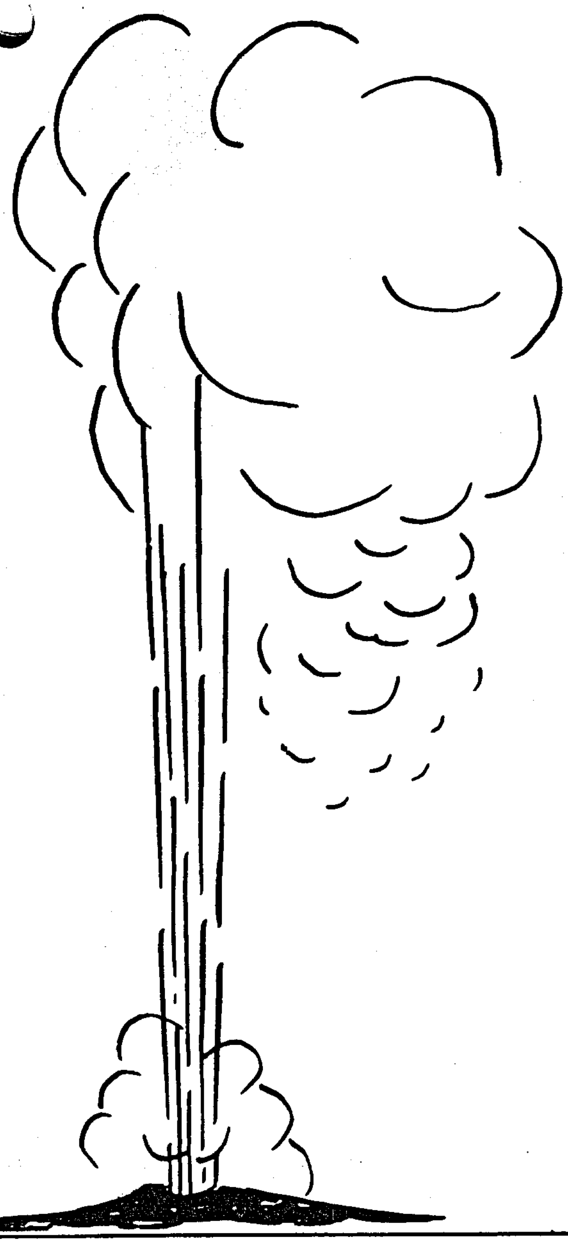

GEOTHERMAL ELASTOMERIC MATERIALS

Twelve-Months Progress Report,
October 1, 1976–September 30, 1977

By
A. R. Hirasuna
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D. L. Davis
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December 1977
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Work Performed Under Contract EG-77-C-03-1308

L'Garde, Incorporated
Newport Beach, California

MASTER

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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FOR PERIOD 1 OCTOBER 1976 - 30 SEPTEMBER 1977

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PREPARED FOR THE
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
DIVISION OF GEOTHERMAL ENERGY
UNDER CONTRACT EG-77-03-1308

FORWARD

The technical information reported herein has been developed by L'Garde, Inc., Newport Beach, California, under the Geothermal Elastomeric Materials (GEM) Program, ERDA Contract EG-77-03-1308.

The work is sponsored by the Utilization Technology Branch, Division of Geothermal Energy. Branch Chief is Mr. John Walker and the Program Manager is Dr. Robert Reeber. Technical coordination assistance is provided by Dr. Patrick Cassidy and Mr. Tom Chester.

The effort is directed for L'Garde by Mr. Alan Hirasuna. The development of this report and the technology advancement achieved under the GEM Program are also attributable to the following personnel: Mssrs. Gayle Bilyeu and Gordon Veal (Mechanical Design), Mr. Clifford Stephens (Rubber Chemistry), Mr. Douglas Hender (Heat Transfer Analysis), Drs. Mitchell Thomas and Norman Sjogren (Test Procedures), and Mssrs. Don Davis, Richard Sedwick, and James Trailer (Fabrication and Evaluation Testing).

Invaluable information was obtained through the cooperation of several Government laboratories and commercial companies in the oil and gas, and chemical products industries. Mr. Jerry Sieron, Chief of the Elastomers and Coatings Branch, Air Force Materials Laboratory; Mssrs. J. D. Foster and M. B. Jett of Dresser Industries/Guiberson Division; and Mssrs. E. H. Bigelow. W. W. Henslee, Jr., J. H. Oden, D. C. Preston, Jr., and H. K. Todee and Dr. D. M. McStravick of Baker Division/Baker Oil Tools, Inc., were especially helpful.

STATEMENT OF OBJECTIVES

The following are objectives to be accomplished under the GEM Program:

1. Define geothermal elastomeric seal application where immediate improvements will provide most benefit to the community.
2. Perform elastomer development and evaluation to meet requirements of 1) (casing packer seal element to survive 260°C (500°F) for 24 hours).
3. Design, fabricate, evaluate, and operate evaluation tests focusing on the pertinent requirements of 1).
4. Evaluate current commercially available elastomers which were developed for oil tool equipment under the geothermal conditions.
5. Perform conceptualization of improvements for a packer system for geothermal applications.

ABSTRACT

This 12-month Progress Report is a comprehensive description of work performed by L'Garde, Inc., on the GEM Program under ERDA Contract EG-77-C-03-1308. The objective of the first phase of the ERDA Elastomers Program is to develop elastomers for packer seal element applications which will survive downhole geothermal well chemistry at 260°C (500°F) for 24 hours.

To achieve this development, a three level elastomer testing and evaluation program was established. The first level Screening Tests, is a broad screening of potential candidates and with the end objective to filter out the more promising candidates for more expensive subsequent testing. The battery of tests include standard ASTM tests and a special test developed by L'Garde to test extrusion resistance using specimens all made from sheet stock. The second level or Simulation Tests provide a laboratory equivalent of downhole conditions using synthetic geothermal fluid. Full scale packer seals are tested under simulated operational conditions by a test fixture developed by L'Garde. The third level or In-Situ Tests which are currently in the planning, provide for testing the most favored materials in-situ in the geothermal well. A test module was designed by L'Garde which provides for testing of the specimen without interfacing with the well casing. A test module freely hanging on a wireline has much lower probability of causing a problem,such as becoming lodged in the well, as compared to an operational casing packer. This maximizes the number of wells (hence geothermal environments) where access can be gained and In-Situ Testing performed.

During this period commercially available polymers were investigated. Most of the work centered around formulating peroxide cured Vitons and some on EPDMs, butyls, and resin cured Vitons. Of the formulations tested to date the EPDMs appear most promising and the peroxide cured Vitons next most promising. However, data is too sparse to make any firm conclusions at this time.

Minor tasks were performed evaluating current commercially available elastomers used in oil tools and conceptualization of casing packer for the geothermal application.

CONTENTS

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION AND SUMMARY

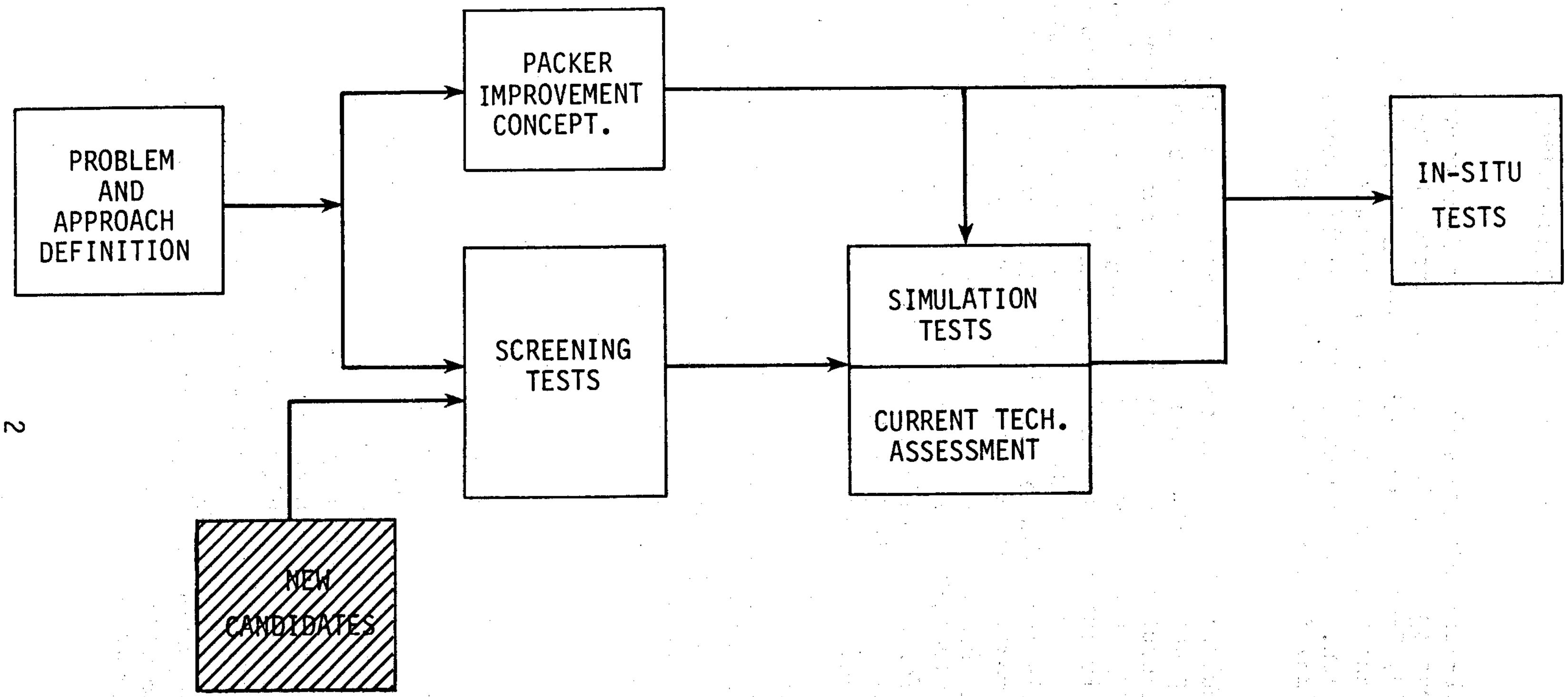
This 12-month Progress Report is a comprehensive reporting of the technology developed by L'Garde, Inc., under the Geothermal Elastomeric Materials (GEM) Program, Contract Number EG-77-03-1308. The fundamental objective of the program is to develop elastomers for the downhole geothermal seal application. Figure 1 shows the overall flowchart of the Program. The crosshatched box indicates where future candidates will enter the evaluation system.

Seal materials are most commonly made from elastomers because they are the most practical seal material. They are economical, relatively very inexpensive except for a minority made from exotic polymers and are reuseable except for very severe environments. They are very reliable and forgiving with respect to installation and manufacturing tolerances of the mating parts to be sealed. Because of the forgiving nature of elastomeric seals, they can be successfully installed by unskilled mechanics and they can be installed in field environments. On the other hand metal seals are extremely sensitive to contamination and handling. L'Garde's experience with gold plated metal K-seals on the Simulation Test, reported in Section 4.0, indelibly imprinted an appreciation for elastomeric seals. Extreme care is required for the metal seals to clean the sealing surfaces and to apply the correct and evenly distribute the preload. Furthermore, each of the three seal applications required development of special procedures for each unique set of circumstances to assure that the seal is delicately installed without abrasion or bumping. Elastomers have the added advantage of flowing and conforming to irregularities while providing elastomeric resistance to continued flow after seating. On the other hand plastic seals continue to flow after seating and do not achieve the stable equilibrium which is possible with elastomers and must be constantly recinched to maintain the sealing force.

In view of the multitude of benefits provided by elastomeric materials in seal applications, the GEM Program objective fulfills an important need. Development of elastomers to meet geothermal environments will extend their benefits into that regime.

During this contract period the formation or open-hole packer was identified as the device that is currently critical to the development of geothermal energy and where improvements will yield good return. In that the formation packer in geothermal environments represents an extremely difficult engineering problem, this first elastomer development effort has been focused on a less ambitious goal, the casing packer seal application. Rubber development for the casing packer element "kills two birds with one stone", as those materials which work successfully for the packer seal will most probably work well for O-ring seals. The O-ring application is less severe because both surfaces are machined, the clearances are small and the required deformation of the O-ring is small compared to a casing packer seal element.

FIGURE 1 -- PROGRAM FLOWCHART



The geothermal environment imposes extraordinary requirements on the casing packer seal element. The geothermal temperature and chemistry both substantially reduce the elastomeric seals ability to withstand the significant internal stresses which are generated in the rubber as the seal is compressed endwise to cause it to expand circumferentially and seat against its OD and ID. Because of the severe and complex nature of the materials and structural requirements of the seal, special tests have been designed and developed.

A three-step graduated testing and evaluation of material candidates is used. The first step, "Screening Tests", is a battery of tests performed on specimens made from sheet stock. The tests include standard ASTM tests and a special test developed by L'Garde, the Extrusion Resistometer or Punch Test. It tests the extrusion resistance of the candidate materials, a key property for geothermal packer seals. The purpose of the Screening Tests is to quickly and efficiently filter out the less qualified materials candidates to maximize coverage of potential materials and minimize the amount of more expensive subsequent testing and evaluation.

The second step, "Simulation Tests", is a laboratory equivalent of downhole operational conditions. Under the Screening Tests chemically aged flat samples are run through the battery of tests after they have been chemically aged in the autoclave. In contrast, the Simulation Test uses a full-scale, 4-inch packer seal as the test specimen and simultaneously submits it to the operational chemistry, temperature, pressure, differential pressure, and the seating forces for the required duration of the test. Based on comments from oil tool personnel regarding the post mortem specimens, the fixture is providing a good simulation of the actual packer.

The third step, as currently planned, is to test the most promising candidates from the SIM Test downhole in a geothermal well. At operational depths the specimen will be exposed to the unaltered fluid and no questions exist as to whether the specimen exposure is representative. Any possibilities of fluid modifications which may occur because of temperature or pressure changes or dilution or contamination of the fluid from other strata are eliminated. A testing module was designed which operates much as the laboratory SIM test fixture except down in the geothermal well. The design of the module is such that it is not necessary for interface with the well casing. This enables preservation of the post mortem test data and minimization of the potential for becoming lodged in the well. Minimization of the risk to the well will result in wider access to test wells and, hence, a wider variety of test chemistries. In addition, the module uses a wire-line hoist as opposed to the more complex and expensive tubing string.

The elastomer formulation effort was concentrated on the peroxide cured Viton family during this contract period as candidates to improve geothermal packer seals. Because the peroxide cured Viton results were not overwhelmingly promising some effort was also spent investigating EPDM, butyl, and resin cured Vitons. The SIM tests revealed that an important contributor to the failure of the packer seal is the substantial internal stresses which are generated within the seal as it is seated. A critical balance is required to be struck between modulus, ultimate elongation, and ultimate tensile strength of the material to allow it to be deformed while seating yet to be stiff and strong enough to bridge gaps. Striking this balance becomes increasingly difficult if not impossible as the temperature increases.

The following is prefaced with the fact that insufficient data exists to make firm conclusions and any conclusions are preliminary and tentative. At this point it appears that EPDM holds the most promise of the elastomers developed and tested thus far. Viton also holds promise, but is more extensively degraded by the synthetic geothermal fluid. Both are recommended for further development. Table I shows the typical effect of chemically ageing EPDM, Viton, and Kalrez in synthetic geothermal fluid for 24 hours at 260°C. The data reflects work reported in Section 3.2. The testing and evaluation has also resulted in a unique concept of "curing the seal in place" to preclude the stressing of the seal as it is seated. Future effort is recommended to test the feasibility and practicality of this concept.

A minor task under the GEM Program was evaluation of the current commercially available elastomers in the SIM Test to provide a reference for the ERDA developed elastomers. Five materials were received from five different companies. The elastomers included two Nitriles, one EPDM, one Epichlorohydrin, and one Viton.

Separate from the elastomer development, another minor task was performed. L'Garde developed a conceptual design of a casing packer improved to provide better potential in the geothermal environment. The design serves as a model providing guidance for development of current elastomers which may have potential, and new polymers synthesized under the sister efforts being performed by Jet Propulsion Laboratory and Hughes Aircraft Company. An adapter for the SIM Test is planned which will test O-ring specimens, rather than packer seal specimens. This will offer a practical alternative for the very expensive elastomers.

TABLE I -- EFFECT OF CHEMICAL AGEING IN SYNTHETIC GEOTHERMAL FLUID

ELASTOMER	APPEARANCE	ULTIMATE TENSILE @ RT	ULTIMATE ELONGATION @ RT	EXTRUSION RESISTANCE @ 260C	SHORE A @ 260C
EPDM (E263)	FAIR	75%*	N/A	57%	85%
Viton (201)	POOR	48%	73%	77%	80%
Kalrez (3073)**	GOOD	53%	230%	94%	84%

* Exceeds capability of tester, 840% elongation, maximum tensile stress recorded.

** No development of Kalrez for this specific application was performed; cured test sheets were obtained directly from du Pont to get "a data point".

2.0 PROBLEM AND APPROACH DEFINITION

Section 2.0 describes the process whereby the specific objectives for the GEM Program performed by L'Garde, Inc., were defined.

2.1 FORMULATION OF SPECIFIC OBJECTIVES

The initial task defined specific program objectives within the overall goal to develop improved elastomers for high temperature geothermal seals. Visits were arranged with geothermal energy producers and well owners, well tool and drilling equipment manufacturers, and Government laboratories performing related research and development. The purpose was to become familiar with problems being encountered through briefings such that L'Garde's program could be defined to best fill the needs of the geothermal community, i.e. applied R&D as opposed to pure R&D. More specifically, L'Garde's purpose was to identify that seal application which would benefit the geothermal community most if it were improved first.

The conclusion after digesting voluminous and often obscure and elusive data was that the community is in need of a formation packer. For example, formation packers are needed to evaluate specific strata in a well for identification of low quality cool zones or highly corrosive zones. This conclusion was confirmed by Mr. J. Barnea's office at the UN and Mr. J. Rowley's office at LASL. Copies of communications with them are included in Appendix A and B. However, though high temperature formation packers are needed, development of elastomers for this application was judged too ambitious a goal for the first effort. Therefore, it was recommended and approved to first develop improved elastomers for casing packer elements.

2.2 DOWNHOLE WELL CONDITIONS

High temperature downhole seals tend to fail from extrusion and hardening. The more interesting geothermal wells have temperatures of 260°C (500°F) and higher and it is not unusual to have compositons of the fluid which are unusually reactive to elastomeric compounds.

260°C causes most rubber compounds to harden by thermal breaking of double bonds and forming new crosslinks to form a three dimensional matrix with less and less ability to yield and recover when deformed. This action proceeds quite rapidly in air (oxygen). In water or steam at high temperatures the hot water acts as an active swelling and softening agent, sufficient to break crosslinkages causing most cured elastomers to devulcanize or revert and to become soft and weak. The geothermal well fluid often contains sulfur in the form of hydrogen sulfide. At high temperatures sulfur rapidly breaks double bonds and forms crosslinks until the rubber becomes hard and brittle.

The fluid also can contain considerable concentrations of metallic salts completely ionized. The effects of such salts on elastomeric compounds is not known.

2.3 EARLY CONSIDERATIONS OF ELASTOMERS

The development and evaluation of elastomers for this first period was confined to commercially available elastomers, reinforcing fillers and curing systems. The most common and lowest cost elastomers are the butadiene copolymers. These elastomers are copolymers of butadiene and styrene or butadiene and acrylonitrile (the latter is used in nearly all oil well seals because of its resistance to degradation by crude oil). These polymers have unsaturated backbone structure - C = C - C - C = C - etc., the double bond being used to get fast curing with sulfur. Unfortunately only a few of the double bonds are used to form the sulfur crosslinkages; consequently sulfur in the geothermal fluid continues to break those remaining double bonds to form more sulfur crosslinks until the seal compound becomes very hard and weak, crumbling or cracking during use.

A logical step would be to consider elastomers free of excess double bonds in the backbone. There are a considerable number of these as discussed below.

Butyl rubber is a copolymer of isobutylene and small amounts of isoprene to give an elastomer with most of the backbone as single bonds. It has a long history of use for the curing bags where it is exposed to water at 177°C (350°F); however, it softens severely at 260°C and is slowly devulcanized by the hot water.

Epichlorohydrin polymers (chlorinated epoxy propane) have the required saturated backbone. The high concentration of pendent chlorine groups makes it very resistant to solvents and fuels. There was no information about resistance to high temperature brine. A commercial formulation was selected for evaluation although softening at 260°C and extrusion failure was expected.

The polyacrylics (copolymers of ethyl acrylate and chlorovinyl ethyl ether or butyl acrylate and acrylonitrile) have the desired saturated backbone and are highly resistant to heat oxidation; however, neither are resistant to water or steam at high temperature.

The chloroprene elastomers have good oxidation resistance, but poor water resistance.

Ethylene propylene diene terpolymers are similar to the butyl rubbers in properties. They have the desired saturated backbone with a few double bonds to facilitate curing. They are widely used in tire curing bags where resistances to water at 350°F is required. It was selected for limited evaluation.

Silicone elastomers have the best high temperature oxidation resistance and maintain their physical properties better at 260°C than any of the elastomers.

The backbone is -Si-O-Si-O- which is thermally stable. No applicable information about resistance to sulfur or water or high temperatures was found. However, small amounts of oil cause severe degradation. Fluorosilicone elastomers are similar to the silicones except they have been fluorinated to give the compounds some resistance to oils. According to Dow Corning,applicability of silicone rubber to the GEM environment is uncertain, therefore, simple Screening Tests to determine the hydrolytic and sulfur resistance are recommended.

The fluoroelastomers (Vitons, Fluorels) are fluorinated hydrocarbons with completely saturated -C-C- backbone to give the best resistance to heat, oxidation and attack by sulfur. Peroxide cured Vitons were selected for compounding, evaluation of cure systems and reinforcing fillers principally because there was a considerable amount of data reported in the literature indicating good prospects in steam and fluids environments and, the Air Force Materials Laboratory has been experiencing success with them at 260°C for high performance aircraft hydraulic cylinder applications.

As a result of this task, it was determined that the elastomer development would be designed around the casing packer seal element operating at 260°C. Furthermore, it was determined that the base elastomer to be developed for this application was the then newly introduced peroxide cured family of Viton fluoroelastomers.

3.0 SCREENING TESTS

The Screening Tests are the first level evaluation of potential elastomer candidates for the geothermal seal application. A battery of simple tests using specimens cut from sheet stock are used for evaluation. The Screening Tests are designed to cover a lot of ground at the expense of preciseness of the simulation of all the operational conditions and thereby provide a bulk filter thus quickly eliminating the poorer performers prior to going into the more expensive subsequent testing.

Prior to initiation of the SIM Tests reported in Section 4.0 an abbreviated set of Screening Tests were run to generate data for refinement of the formulations as well as to investigate candidates other than peroxide cured Vitons which were previously being investigated exclusively. This work is reported in Section 3.2.

3.1 SCREENING TESTS

Thirty-five Viton formulations have been mixed and screened. The Screening Tests include the L'Garde Extrusion Resistometer or Punch, compression set, Shore A hardness, ultimate tensile strength, and ultimate elongation tests. The tests were performed on virgin material, material chem aged in synthetic geothermal fluid, and material aged in the ambient room, as a control for the chem aged material.

Based on the results of the Screening Tests, the following fillers were selected for continued development in the Simulation testing portion of the Program: 30 phr Austin Black, 30 phr HTS graphite, 5 phr Kevlar 29, and 20 phr Asbestine 3X. Other indicated improvements are use of VT-R-4590 as the base elastomer, increased level of Litharge, possible decreased amount of Diak #7, and post cure at 500°F and limit oxygen in the post cure environment.

3.1.1 Screening Test Approach

The basic development testing approach taken by L'Garde regarding programs such as GEM where high performance elastomers are involved, is to test critical performance parameters throughout the various phases of testing along with standard ASTM tests. Generally, only standard ASTM tests are used such as tensile and elongation at break, modulus at 100% Shore A hardness, tear strength, compression set, etc. For high performance applications where ultimate capability of the elastomer is required, the standard tests provide a good relative "feel" as to the progress or lack of progress being made from formulation to formulation, however, invariably the standard test results are usually not well correlated with performance in the application. Hence, to evaluate true development progress special tests are preferred.

For the 260°C (500°F) packer seal application, it was established that the most probable critical failure mode is extrusion of the seal past its back-up, i.e. for rubber which remains elastomeric. For the nitriles which harden at 260°C, and become very nonelastomeric, extrusion is not the primary problem. Hardening can provide somewhat of a temporary advantage by preventing further extrusion, however, because the rubber has lost all its resilience it can no longer withstand jarring disturbances. For materials of interest which provide the elastomeric qualities throughout the performance period a special Punch Test was designed and fabricated to test extrusion resistance at 260°C. Each of the Screening Tests is described and discussed in detail below.

The Screening Tests are designed around specimens made from sheet stock using the standard ASTM sheet mold and 1/2 inch sheet. Extrusion Resistometer, swell test, tensile/elongation dogbone specimens are cut from standard ASTM test sheets which are 6 inch x .6 inch x approximately 80 mils. The compression set and Shore A hardness specimens are cut from 3.5 inch x 3.5 inch x approximately 500 mil sheet. The specimen dimensions are shown in Table II. The use of specimens cut from sheet stock enable the tests to be relatively inexpensive, allowing screening of a maximum number of candidates. Figure 2 shows the specimens set up for an autoclave run.

All materials are tested in two states while every tenth formulation is tested in three states. The tests are run for all formulations in the virgin state within a few days of completion of post cure, and in the chemical aged state after 24 hours of ageing in a synthetic geothermal fluid at 260°C. The constituency of the geothermal fluid is as follows:

H_2S	300 ppm
CO_2	1000
NaCl	25,000
H_2O	Balance
pH (ending)	5 - 7

On every tenth formulation, tests are performed on material which has resided in the ambient room for the same amount of time after post cure as the chem aged specimens when they are tested. This is a control to separate out the positive or negative effects that have occurred because of the elapsed time as opposed to the chemical ageing.

3.1.2 Formulation Matrix

The screening is structured around a filler study based on the following nominal formulation:

Viton GH	100 phr
MT Black, N908	50-X
Filler Candidate	X
Sublimed Litharge	3
Diak #7	4
Luperco 130 XL	1.5

TABLE II -- SCREENING TEST SPECIMEN CONFIGURATIONS

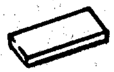
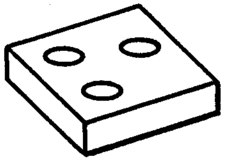
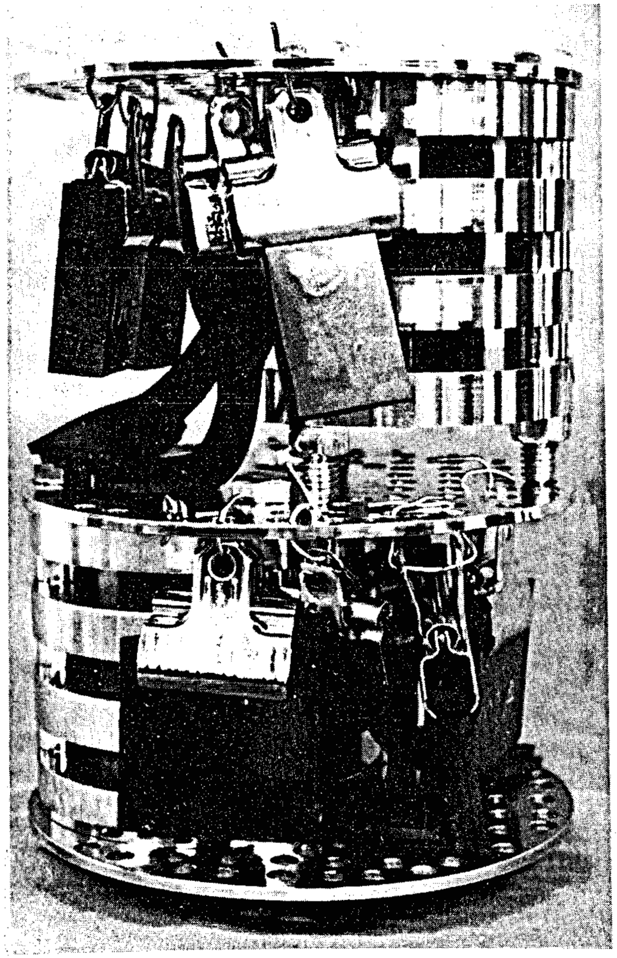
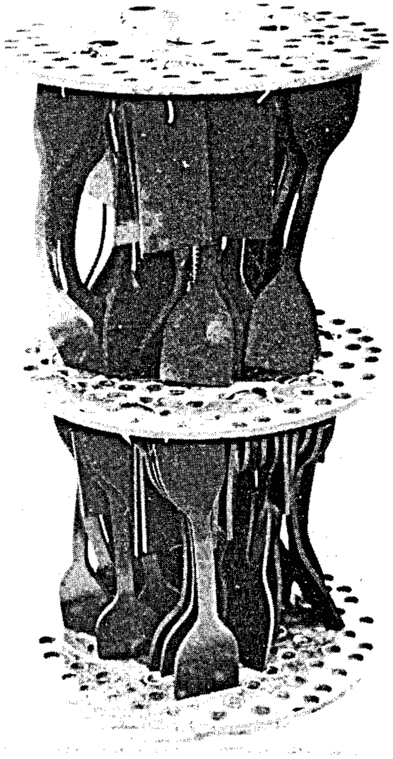
Test	Sheet Thickness Mils	Specimen Dimensions Inches
Punch	80	0.75 dia. 
Ultimate tensile	80	1.31 L x .25W x .08T test section 
Ultimate elongation	80	same as tensile
Swell	80	2L x 1W x .08T 
Compression set	500	OD x ID x .50T cut in half 
Shore A hardness	500	remains after compression set extracted 

FIGURE 2 -- SPECIMENS PREPARED FOR AUTOCLAVE CHEMICAL AGEING



75 mil Dogbone and Rectangular Specimens, and 500 mil Compression Set and Hardness Specimens



75 mil Dogbone and Rectangular Specimens

Viton GH was used for most formulations because it is stocked on the west coast. The 50 phr level of filler is based on evaluation of formulations with 30, 40, and 50 phr of MT black evaluated on the Extrusion Resistometer. The data showed a monotonic improvement with 50 phr performing the best so all the screening tests were performed at the 50 phr level. It was expected that the optimum filler level is beyond the 50 phr level and a point that was investigated during the Simulation Test period. Litharge is used as the acid acceptor because it is reported to produce better properties in the water/steam environment than the other metal oxides and hydroxides.

The filler candidates investigated are shown in Table III.

In addition to the filler options, the sensitivity to base elastomer was investigated. Both VT-R-4590 and Viton GLT were considered in addition to Viton GH. Sensitivity to the amounts of Litharge and Diak #7 were also investigated.

The nominal cure is a press cure at 177°C (350°F) for 10 minutes. Post cure was 24 hours at 233°C (450°F) in an air oven. Other post cures were a 260°C (500°F) and a 288°C (550°F) post cure for 14 hours with the rubber sealed in aluminum foil to limit oxygen exposure. Various temperature schedules were also investigated in bringing the temperature up to the post cure level.

3.1.3 Test Fixtures and Measurements

All measurements taken during the Screening Tests are discussed. Except for the L'Garde Extrusion Resistometer all measurements are standard ASTM tests and for those only points unique to the GEM measurements are discussed. A summary of the measurements taken for each formulation are shown in Table IV.

A. L'Garde Extrusion Resistometer

The Extrusion Resistometer was designed to provide a measure of the elastomers extrusion resistance. Conceptually it is similar to a paper hole punch with the punching resistance depending on the resilience, hardness, and shear strength of the test material. Figure 3 shows a cross section of the test fixture. The 3/4 inch disk specimen is pinched between the bottom cup which holds the band heater and the neck support which houses the punch. The upper piston/cylinder is thermally isolated from the lower test section and provides the punching force when gas pressure is applied to the piston.

The overall test setup is shown in Figure 4. After assembly, the entire fixture is surrounded with insulation and placed into the vacuum chamber shown. The test section is brought up to the 260°C test temperature and held at constant temperature for 14 minutes before testing. The nitrogen supply for the force cylinder is maintained at a constant supply pressure of 50 psig and supplied through a fixed orifice. This assures that consistent repeatable pressure (force) build up transient results for each run. The pressure is recorded and the maximum magnitude taken as the figure of merit for extrusion resistance.

TABLE III -- FILLER CANDIDATES

Product	Description	Producer
Austin Black	Bituminous Coal Fines	Slab Fork Coal Company
Fibrene C-400	Acicular Platy Talc	Cyprus Industrial Minerals Co.
Carbon Wool 3A, 4A	Amorphous Carbon Fibers	Barnebey Cheney
HTS Graphite, 1 mm	Intermediate Modulus Graphite Fibers, PAN precursor	Hercules, Inc.
Kevlar 29, Chopped ¼in.	Filaments coated with Resourcinal Formaldehyde Latex System	du Pont
MgO Microfibers, 6-8 microns	Material being developed for Air Force	Versar, Inc.
Cotton Flock, S/60	Natural	Microfibre, Inc.
Nylon Flock, S/16	Natural	Microfibre, Inc.
Asbestine 3X	Fibrous Acicular Magnesium Silicate	C. P. Hall

TABLE IV -- SPECIMEN MATRIX FOR EACH SCREENING TEST FORMULATION

TEST	(1) SHEET	VIRGIN	CHEM AGED (CHEM EFFECTS TEST)	AMBIENT AGED	TOTAL
Punch Test	1	1	1	,1	2,1
3/4" Disk	2	1	1	,1	2,1
	3				
Swell (D471)	1		1		1
1" x 2" x .080"	2		1		1
	3		1		1
Dog Bones	1	1	1	,1	2,1
Die C	2	1	1	,1	2,1
	3	1	1	,1	2,1
Compr. Set	½"	3	3	,3	6,3
Hardness	½"	1	1	1	2,1

(1) For each formulation made 3-80 mil sheets, 1-500 mil sheet.

FIGURE 3 -- EXTRUSION RESISTOMETER

PUNCH TEST FIXTURE

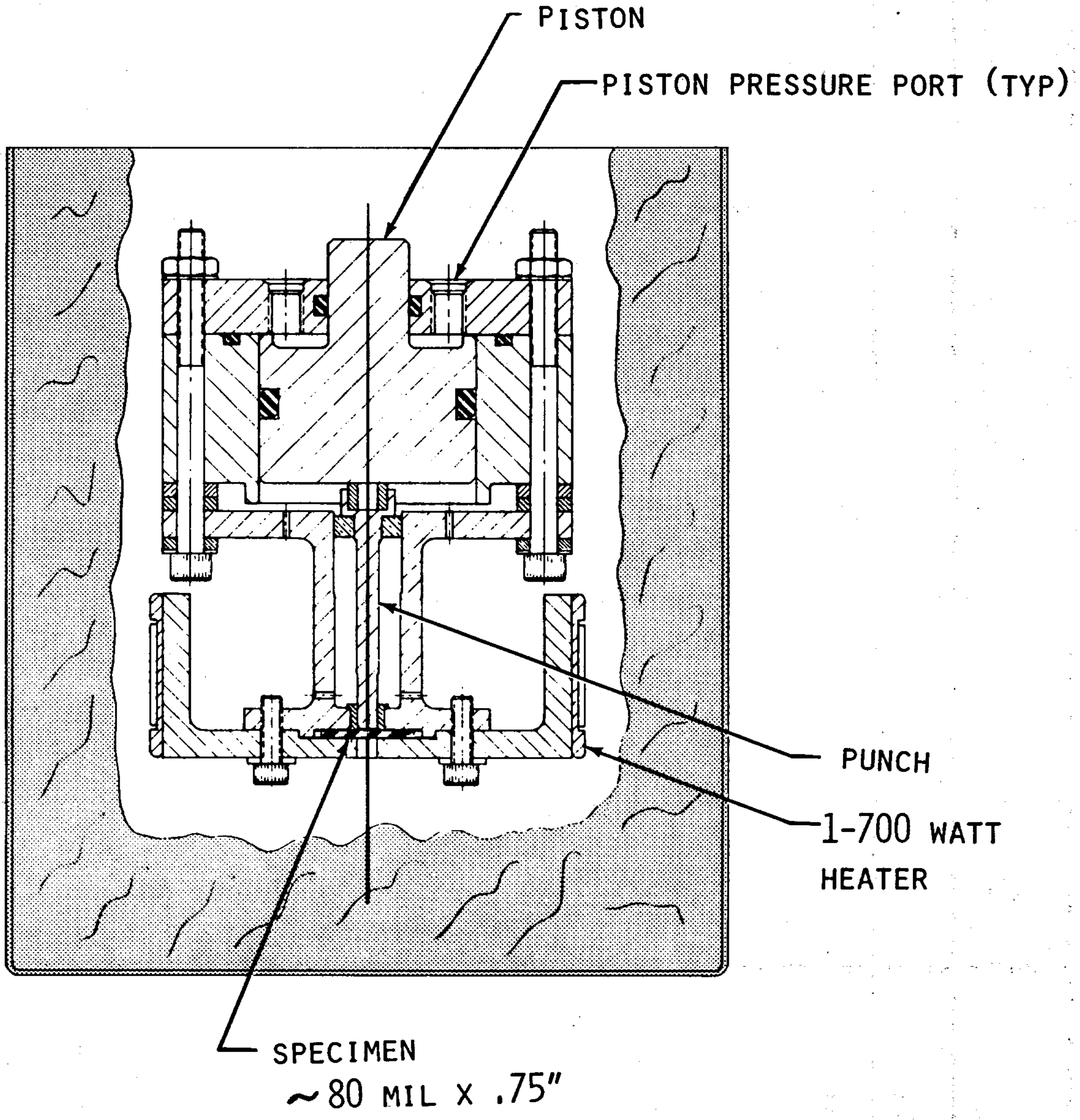
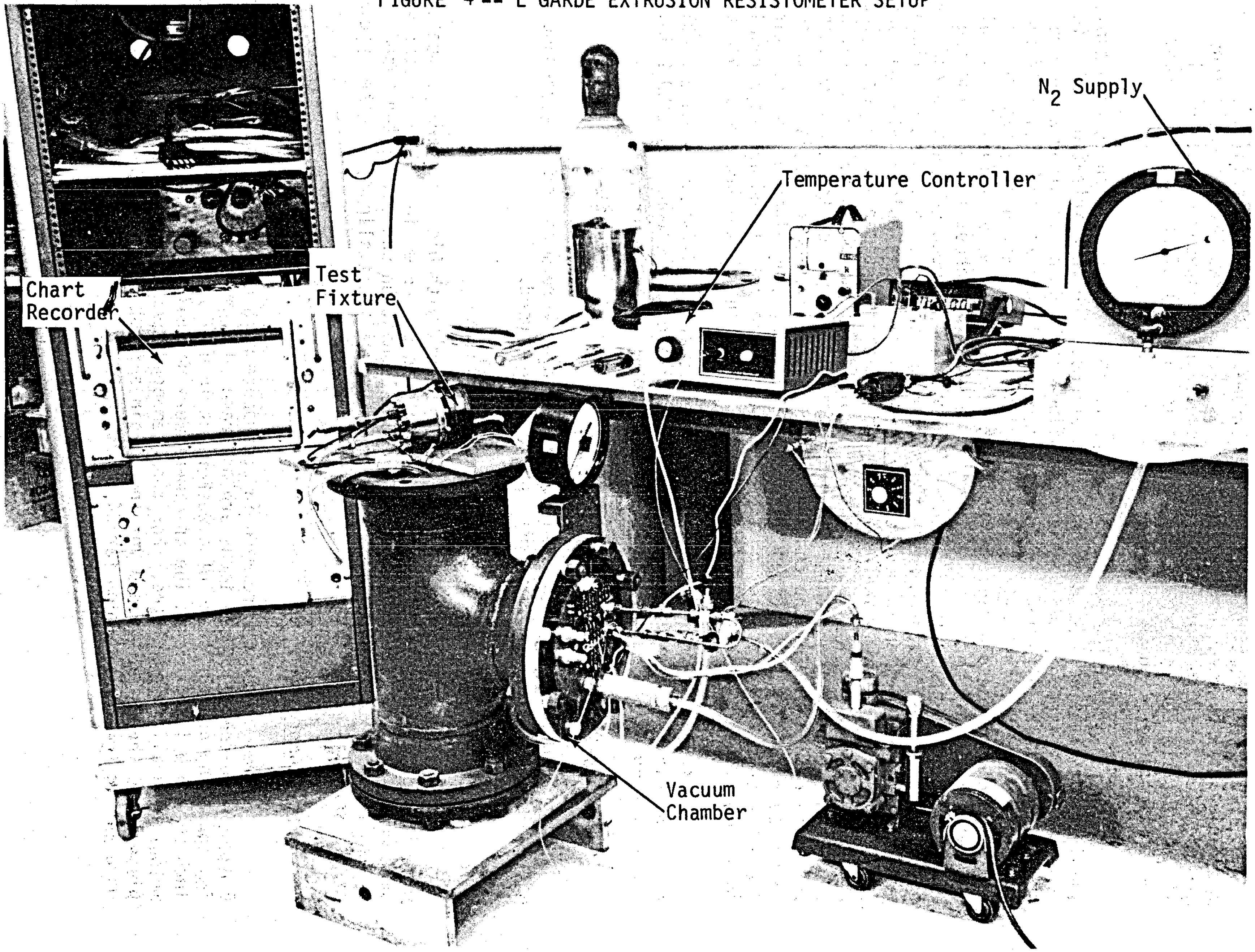


FIGURE 4 -- L'GARDE EXTRUSION RESISTOMETER SETUP



Prior to initiating the testing program for the GEM materials, an evaluation of the Extrusion Resistometer was made. Three Viton formulations with 30, 40, and 50 phr of filler were tested. Eight specimens cut from 4 different cured sheets of each formulation for a total of 24 tests were run. The specimens were run in random order.

The results of the evaluation indicate that the test is quite repeatable and differentiates well between the formulations. The coefficient of variation (standard deviation divided by the mean value) is 5.19% or in other words greater than 65% of an infinite number of measurements will fall within ± 5.19% of the mean value. A good test will have a coefficient of variation of about 10% or less. Also from these data, two redundant measurements of each formulation will provide a 95% confidence that their means falls within about ± 10% of the true mean. Regression analysis indicated no correlation between the results and the thickness of the sheets from which the specimens were cut. A two step failure occurs when the specimen is punched. First, the rubber is bulged into the punching hole and the outer laminates are popped off through a tensile failure. Then the punch shears out the remaining portion of the plug. It is not clear whether the maximum punch force occurs during the tensile failure or the shearing phase. In any event, because of the complex nature of the failure the resistive force is not correlated with specimen thickness. In fact, the values of the ultimate shear stress which normalizes out the thickness were calculated and they resulted in a worse coefficient of variation, 8.95%, than when the thickness was ignored.

The figure of merit value used is the number of divisions taken directly from the chart recorder. Twenty-five (25) divisions corresponds to a 29.2 lb. force exerted on the rubber by the 3/16" diameter punch.

B. Volume Swell

Swell on specimens which were chem aged were measured in accordance with ASTM D471. 1 x 2 x .080 inch specimens were used.

C. Ultimate Tensile Strength and Elongation

Dogbones were cut from .080 inch sheets with Die C and measurements made in accordance with ASTM D412. Measurements of rubber in all three states were made; virgin, chem aged, ambient aged. Elongation was calculated based on jaw travel. Tests were made indicating insignificant slippage of the specimen at the jaws was occurring.

D. Compression Set

Measurements were made in accordance with ASTM D1414 and D395 Method B except the chem aged specimens are not removed from the fixture for cooling. The specimens are the shape of a washer cut in half with a 1.13 inch OD x 0.39 inch ID x 0.5 inch thick. The specimens were nominally compressed 25% and measured in all three states. For the chem aged specimens, the fixture was placed into the autoclave and for the virgin and ambient aged specimens they were set in the ambient room for 24 hours.

The compression set tests of chem aged material have since been rejected as not meaningful. Because of practical constraints the autoclave and specimens must be cooled before the autoclave can be opened and the specimens removed from the fixture. Hence, the specimens cannot be cooled in an unrestricted state, i.e. removed from the fixture, as per the ASTM specification.

E. Hot Hardness

Shore A Durometer measurements were made in accordance with ASTM D2240. The specimens used were the remains of the 3.5 inch x 3.5 inch x 0.5 inch block after three 1.13 inch plugs were removed for compression set. All specimens were prepared by preheating to 260°C on a preheated 0.5 inch aluminum plate. The 260°C plate and rubber are placed in the durometer fixture on an insulated surface; two measurements are taken, the specimen is flipped, two more measurements are taken, the specimen is flipped again, and then one last measurement. Hardness measurements were also made on all three states; virgin, chem aged, and ambient aged.

F. Autoclave

A mild steel autoclave, shown in Figure 5, was made from 600 lb. pipe fittings for use in chem ageing the material. It was thought that because of the near neutral pH of the synthetic geothermal fluid that the reaction between the H_2S and iron would be acceptably slow. However, after the first run it was apparent that the H_2S was fully reacting with the iron as there was no hint of H_2S odor. Qualitative analysis confirmed this. In the interest of schedule, it was agreed with ERDA to go ahead, as is, with the Screening Tests but to make sure that this does not happen in the subsequent Simulation Tests. Thus the formulations which graduate to the Simulation Tests will see the H_2S environment during the entire test cycle.

The autoclave has eight electric band heaters supplying about 9200 watts to assist heat-up of the vessel which is placed in a 260°C oven. About 3 hours are spent bringing the vessel up to 260°C and about 1.5 hours to bring it down to about 66°C. The heating is maintained for 22 hours from the time the vessel achieves 205°C.

3.1.4 Discussion of Results

Table V is a summary of the averaged measurements taken during the Screening tests. The Extrusion Resistometer data is considered to be the most pertinent with the other measurements providing reinforcing supplementary information. Shown in the left hand column are the variables investigated. All except for the last five were filler studies at differing levels. The bottom five include sensitivity to the base elastomers, levels of the acid acceptor Litharge, level of the coagent Diak #7, and a control which is the same as the Fibrene C400 in the previous filler study. This same 30 phr Fibrene C400 formulation was the nominal one which was perturbated with the VT-R-4590, Viton GLT, 15 phr Litharge, and 2 phr Diak #7. In addition, the post cure on the bottom five was 288°C for 14 hours and rubber was tightly sealed in aluminum foil with pleats to allow for any gas expansion. The aluminum foil was used to minimize the oxygen in contact with the rubber.

FIGURE 5 -- SCREENING TEST AUTOCLAVE

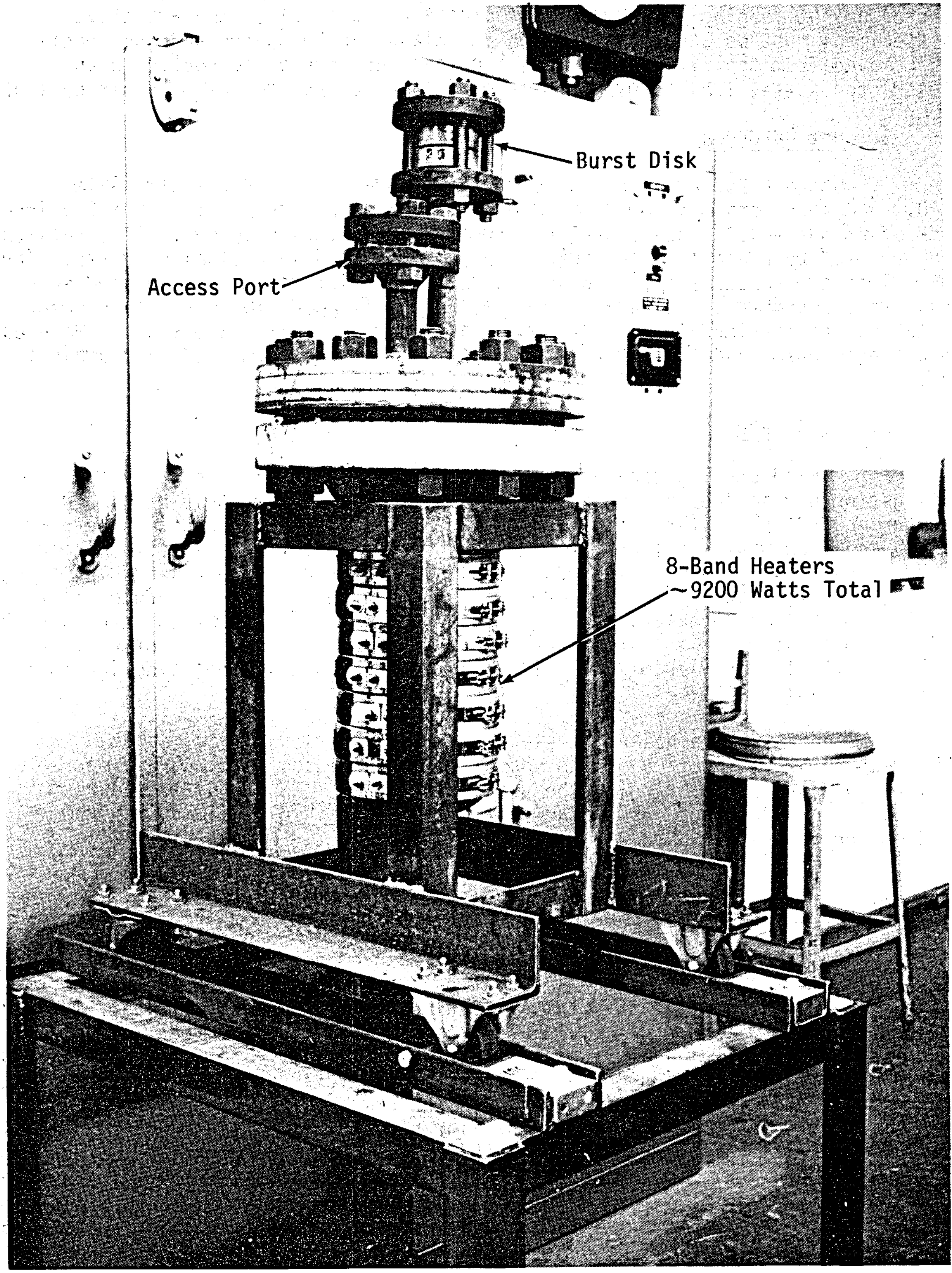


TABLE V -- AVERAGED SCREENING TEST RESULTS

Filler/Variable	phr	Clave Run	Comment	Punch, Divisions			Shore A Hardness			Elong. @ Brk, %			Tensile @ Blk, psi			Comp. Set,			VOL Swell %
				V	CA	AA	V	CA	AA	V	CA	AA	V	CA	AA	V	CA	AA	CA
Austin Black	10	1	Leak	30.8	24.7		75.4	71.2		209	173		1739	802		15	90		-.9
	20	↓	"	28.3	25.3		77.6	68.0		189	152		1570	799		16	91		3.1
	30		"	30.0	28.5		77.6	69.6		202	148		1703	854		14	93		4.7
Fibrene C400	10	↓	Leak	27.8	23.2		77.4	71.6		270	81		1866	399		15	103		7.5
	20	2	Very Brittle,CA	26.8	19.8		76.4	71.0		285	---		1829	---		14	120		-.9
	30	↓	" " "	29.3	22.5		76.8	77.8		265	---		1693	---		14	127		-.7
Carbon Wool,3A	10	↓		27.5	19.8	35.0	78.8	48.6	78.2	188	41	190	1742	201	1734	13	104	3	4.9
	20			25.5	19.3		77.6	48.2		169	25		1827	164		10	100		2.1
	30	6	Disk Rupture	27.3	15.8		77.8	56.6		151	72		1930	363		12	---		13.3
4A	10	6	" "	27.3	15.0		78.0	59.2		192	86		1542	243		16	---		10.9
HTS Graphite	10	7	Disk Rupture	30.5	14.5		80.0	57.8		162	74		1699	244		15	---		8.9
	20	7	" "	29.5	15.5		81.2	55.4		114	89		1925	391		13	---		9.0
	30	4		33.0	14.0		81.6	56.3		129	99		2377	464		15	99		2.9
Kevlar 29	3	↓		30.5	13.0		83.0	66.4		199	92		1936	409		27	119		-.3
	5			33.0	18.0		85.8	74.6		129	64		1971	493		28	127		-1.2
	7			33.5	17.0		86.8	76.6		82	41		2201	604		27	134		1.1
MgO Microfibers	10	↓		26.8	15.3	24.0	75.8	54.6	73.8	267	139	235	1581	290	1605	21	100	3.4	-.4
	20			25.3	15.5		74.0	53.4		277	126		1441	326		20	104		-1.1
	35.3	6		22.3	13.0		72.2	56.8		305	91		1354	381		22	110		1.2
Cotton Flock	10	↓	Very Brittle,CA	27.2	27.7		82.4	92.6		115	20		1370	602		27	127		-5.3
	20		" " "	27.8	37.3		83.4	---		74	13		1675	576		29	139		-12.0
Nylon Flock	10	↓		31.0	15.0		79.6	68.4		207	67		1781	413		20	107		-1.7
	20	7		28.0	17.8		80.2	69.2		167	81		1600	568		21	127		0
Asbestine 3X	10	↓		34.0	13.5		77.4	66.2		269	147		1827	478		18	100		-1.4
	20			33.0	16.1		75.8	77.6		224	104		1599	458		16	119		-1.9
	30			26.0	15.3		75.4	85.0		265	77		1855	531		26	129		.7
VT-R-4590	N/A	5	550^{0}F Post Cure	24.3	19.5	22.0	75.2	75.0	74.4	181	85	164	2013	566	1934	3	123	8	1.2
Viton GLT	N/A	↓	" " "	20.5	13.8		70.4	55.8		361	187		2032	433		10	125		-5.9
Litharge	15		" " "	24.8	26.0		79.6	84.2		185	46		1708	627		16	129		-.2
Diak #7	2		" " "	22.3	15.3		70.4	70.6		297	158		1434	452		11	115		-2.2
Fibrene C400	30		" " "	22.5	16.3		74.4	78.2		270	99		1577	413		10	135		-3.7

Anomalies occurred on two autoclave runs. We experienced a gasket leak on the Austin Black/Fibrene C400 run as noted. When the autoclave was opened at the end of the run there was only about 2 inches of liquid left in the bottom. On the Carbon Wool/HTS Graphite run, the burst disk ruptured during the heat-up cycle. The compression set specimens disintegrated so measurements could not be made. The balance of the specimens were subsequently chem aged, hence, have seen two heat-ups and one rapid depressurization.

In general, the synthetic geothermal fluid does significantly affect the rubber. The Austin Black formulations were least affected, however, its data is clouded by the fact that there was a gasket leak and the fluid level was down to about 2 inches when the vessel was opened. Looking at the virgin Extrusion Resistometer data for the Austin Black shows that the values are virtually independent of level of Austin Black, implying that its properties as a filler are equal to that of MT black. The chem aged results indicate improvements with increasing amounts of Austin Black. This result is consistent with the experience of du Pont and the Air Force.

The Fibrene C400 and the cotton flock specimens became unacceptably brittle after chem ageing. It was difficult, if possible, to straighten the dogbones sufficiently to mount them in the tester jaws without breaking them. The carbon wool and HTS Graphite specimens which survived the rapid decrease in pressure when the burst disk ruptured have a lumpy blistered surface. This also correlates with the higher values of swell for these specimens. A question has arisen regarding the manner in which the specimens are prepared for chem ageing. They are all cut from the sheet stock exposing fiber ends and then chem aged, thus promoting wicking of the fluid. The operational situation involves molded parts whereby all surfaces would tend to be sealed by the elastomer. This uncertainty will not enter into the subsequent Simulation Tests as the specimen will be a molded part.

The last five sets of measurements provided a wealth of information. As a set they were post cured differently, 14 hours at 288°C and sealed in aluminum rather than 24 hours at 233°C in air. The Fibrene C400 formulation is the same as the previous 30 phr formulation and was used for control purposes.

Comparing the control cases, it is apparent the 288°C temperature and/or the aluminum wrap was a definite benefit. A 99% elongation at break resulted as compared to a specimen that was too brittle to handle. The Punch Test results are down by about 25% which indicates a trade-off exists between sacrificing extrusion resistance for elastomeric properties.

Then comparing the other 4 cases to the control case several other important points became apparent. The VT-R-4590 is clearly a better base elastomer for the GEM application than is Viton GLT or GH. The Punch Test results, virgin and chem aged, are better while the other properties are maintained in an acceptable range. Additional Litharge, 14 phr vs 3, shows good Punch Test results especially for the chem aged state. However, the elongation at break is low indicating a trade-off to determine the optimum level. The lower level of Diak #7, 2 phr vs 4, resulted in improved elongation at break.

3.2 ABBREVIATED SCREENING TESTS

Abbreviated Screening Tests were run prior to starting into the Simulation Tests to determine optimum filler and litharge levels, optimum post cure conditions, and to evaluate Kalrez, EPDM, butyl, and resin cured Viton elastomers. The Kalrez was originally requested as a commercially available material for the evaluation described in Section 4.5.1, SIM testing. However, because of the expense of the material and the uncertainty as to whether the thick packer type seal could be made from Kalrez, it was not practical to consider evaluating it along with other currently commercially available elastomers at this time. In lieu of the above, Kalrez sheet samples were obtained from du Pont and chemically aged in these abbreviated tests to obtain "some" data. Subsequent to the Screening Tests reported in Section 3.1, the Viton development was not showing any overwhelmingly positive results, so EPDM's, butyl and the resin cured Viton compounds from the Air Force Materials Laboratory were also included in these tests to provide possible backups to the peroxide cured Vitons.

Table VI shows the test data which include Extrusion Resistometer Measurements, Shore A hardness, elongation at break, tensile strength at break, swell measurements, and weight measurements for virgin and chemically aged conditions. Three die C dogbones and two 1" x 2" specimens cut from Standard ASTM sheets were chem aged. The hardness and swell measurements were taken on the rectangular ends of the dogbones and the weight measurement on the entire dogbone. The Extrusion test specimens were cut from the rectangles. Table VII gives the formulations for the inhouse compounds.

In terms of physical appearance after the chem ageing the Kalrez, compounds 3073 and 3074 looked the best. They had smooth surfaces and by outward appearance were not significantly degraded by the chem ageing. The EPDM compounds were next best, E261 through E263. They showed some crazing which was apparent when the dogbones were stretched. The butyl B264, severely reverted and was very sticky and soft. The resin cured Viton, V265, became quite brittle and lost its properties. The L'Garde Vitons showed signs of ageing and the crazing was apparent in the relaxed position.

The EPDM's show good potential for the packer seal application. All three formulations had greater than 840% elongation before and after chem ageing. The Extrusion test, hardness, and tensile strength at maximum elongation fell off as a result of chem ageing and E262 which has Tetrone A blistered on the surface. E263 was selected for further development in the SIM test phase because it was least sensitive to chem ageing showing a relatively small reduction.

The Viton formulations 201 to 203 were tested to determine an optimum nominal level of filler. The differences were not substantial in the 50-70 phr of Austin Black, however, later work with the SIM tests showed these levels to be too high. They resulted in cracking of the SIM test seal because the rubber was not sufficiently pliable to be seated. These tests did confirm the antioxidant effect of the Austin Black. As previously experienced in the earlier screening tests but uncertain because of autoclave gasket leaks, the Austin

TABLE VI-- ABBREVIATED SCREENING TEST RESULTS

Filler/Variable	phr	Comment	Extrusion psia, 260^{o}C		Shore A, 260^{o}C		Elong A Brk%		Tensile @ Brk psi		Swell %		Weight Change
			V	CA	V	CA	V	CA	V	CA	Width	Tkness	
3073 K/Calidria			8.8	8.3	92	77	100	230	4377	2337	1.9	4.8	3.4
3074 K/Kev.			8.5	6.2	91	74	49	208	3619	1831	3.5	11.1	8.6
E261			7.2	5.5	66	43	>840	>840	>2167	>1080	-.7	0	-2.1
E262 w/Tet.A		Blistered	12.1	5.2	65	41	>840	>840	>2758	>720	-.1	0	.5
E263 w/o Tet.A			9.6	5.5	61	52	>840	>840	>1363	>1020	-.6	0	-1.1
B264		Reverted	4.3	1.1	72	5	528	153	1414	45	2	5.3	7.3
V265		Hardened	6.9	2.5	77	70	340	19	1559	189	-.1	-4.5	12.9
201 4590/Austin	50	No Fibrous Fillers	7.8	6.0	89	71	165	121	1884	901	1.0	1.0	-.2
202 4590/Austin	60	No Fibrous Fillers	8.3	6.5	91	74	122	96	2000	866	.8	1.4	-.1
203 4590/Austin	70	No Fibrous Fillers	8.8	9.1	94	72	105	79	1912	946	1.0	3.8	-.05
205 GH/C400/Lith	10		7.9	7.0	84	79	199	38	1495	500	.8	2.1	-5.7
206 GH/C400/Lith	7		7.4	7.1	84	77	237	49	1631	456	.7	-1.7	-5.1
207 4590/C400/Lith		14H, N_2, 233C(450F)	8.9	5.7	88	68	205	122	1959	563	.6	1.7	-2.5
208 4590/C400/Lith		14H, N_2, 260C(500F)	9.6	6.8	86	70	206	116	1990	595	.3	1.8	-2.2
209 4590/C400/Lith		14H, N_2, 288C(550F)	9.1	7.5	87	72	186	118	2000	681	.9	.3	-2.2
211 4590/C400/Maglite	6	14H, N_2, 260C(500F)	9.7	10.2	88	76	163	86	2240	734	.9	5.9	1.0

TABLE VII -- ABBREVIATED SCREENING TEST FORMULATIONS

Component	201	202	203	205	206	207	208	209	211
VT-R-4590	100	100	100			100	100	100	100
Viton GH				100	100				
Austin Black	50	60	70						
MT Black				20	20	20	20	20	20
Fibrene C400				30	30	30	30	30	30
Maglite D									6
Litharge	3	3	3	10	7	3	3	3	3
Diak #7	4	4	4	4	4	4	4	4	4
Luperco 130XL	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Cure ^{o}F/Min.	350/10	350/10	350/10	350/10	350/10	350/10	350/10	350/10	350/10
Postcure ^{o}F/hrs.	450/24	450/24	450/24	550/14	550/14	450/14	500/14	550/14	500/14
Atmosphere	air	air	air	Al Foil	Al Foil	N_2	N_2	N_2	N_2

Black tends to decrease the loss in tensile strength from chem ageing from a factor of 3 to 4 down to a factor of 2. This effect has been observed by both du Pont and the Air Force and du Pont is currently trying to identify the beneficial constituent in the Austin Black. The constituency is not well defined because it is a natural product made of bituminous coal fines. The level of litharge was investigated and compared to earlier results as it appeared to help maintain the Extrusion test results through chem ageing. However, the loss in elongation was severe, down to the 7 phr level so the original 3 phr level was maintained. Compounds 207 through 209 are the same formulations but post cured from 450 to 550°F for 14 hours in a nitrogen atmosphere. A trend does exist as a function of the post cure temperature, but the differences were not deemed significant. Comparing 211 containing Maglite D and 208 containing litharge shows 211 to maintain its level on the Extrusion Test, however, the associated loss of elongation is considered a significant negative and therefore not viable alternative for increasing the extrusion resistance.

The figure-of-merit for the Extrusion Resistometer or Punch Test has been changed starting with this set of data. Previously the number of divisions on the recorder were taken as the figure-of-merit as regression analysis of the fixture evaluation data revealed this to be a more repeatable technique than to calculate and use shear strength. However, a problem evolved when a new pressure transducer was used. Having different calibrations, 10 units on the recorder implied different punch forces or piston pressures depending on which transducer was used. Consequently, the implied absolute pressure is now being used as the figure-of-merit which eliminates the problem of differing calibrations and transfer functions.

In summary, based on these abbreviated tests it appears that the Kalrez is relatively unaffected by the synthetic fluid. Compound 3073 with Calidria, a pure asbestos, appears more stable of the two with about a factor of 2 increase in elongation and decrease in tensile strength after chem ageing. The EPDM compounds maintained their elastomeric properties well through the chem ageing, however, some crazing was apparent when the dogbone was stretched. Compound E263 was selected for further development as it was least sensitive to the synthetic fluid. The Austin Black was confirmed to have a definite antioxidant effect rendering the Viton to be more stable in chem ageing. The other variables examined in these tests did not produce any significant interest or promise.

4.0 SIMULATION TESTS

The Simulation (SIM) Tests are designed to provide a good simulation of the casing packer seal operational environment in the laboratory. The SIM Test fixture applies all environments simultaneously, i.e. the fluid pressure, differential pressure, temperature, mechanical forces, and the chemistry to a full scale packer type seal. The fraction of the compounds which survive the SIM Test evaluation are presently planned to be tested in-situ in an actual geothermal well.

4.1 SIMULATION TEST FIXTURE DESCRIPTION

The SIM test fixture seats and tests a full scale packer type seal as shown in Figure 6. The seal is a solid rubber cylinder with 45° chamfers on each end and typical of elements which seat against a 4.0 inch ID casing. Figure 7 shows a piping and instrument diagram of the overall test system and Figure 8 is a photograph composite. The test chamber houses the seal specimen which is mounted over a center mandrel. Rings back-up either side of the seal and a ram driven by a hydraulic cylinder pushing on the top back-up ring deforms the seal such that it seats against the ID of the vessel and the center mandrel. The chamber is electrically heated and insulated to maintain the fixture at the desired test temperature. A true power proportioning controller is used as opposed to the more common on-off controller where the period of the on-off cycle is adjusted proportionally to the error. Thus under steady state conditions a constant current of about 4 amps or about 900 watts is provided to make up the heat loss. This provides a constant temperature environment for the seal. The fluid exiting the chamber goes through an ice bath heat exchanger and into a Monel accumulator. A 316SS piston cylinder positive displacement pump stores pressurized fluid at room temperature which enters the test chamber and replaces the fluid as it leaks by the seal and into the accumulator. The pump is driven by a nitrogen cylinder which applies a constant force to the pump. A linear potentiometer senses the position of the pump and its signal is recorded, thus total leakage and leak rate can be determined within 5-10 cc. The sequence of events for the test is as follows:

1. Assemble fixture and fill pump, test chamber, and bottom of accumulator with room temperature fluid.
2. Pressurize system to 875 psig to maintain all gasses in solution.
3. Heat test chamber up to temperature, about 1 hour.
4. Seat seal.
5. Pressurize pump up to desired differential pressure across the seal.

FIGURE 6 -- SIM TEST SPECIMEN CONFIGURATION

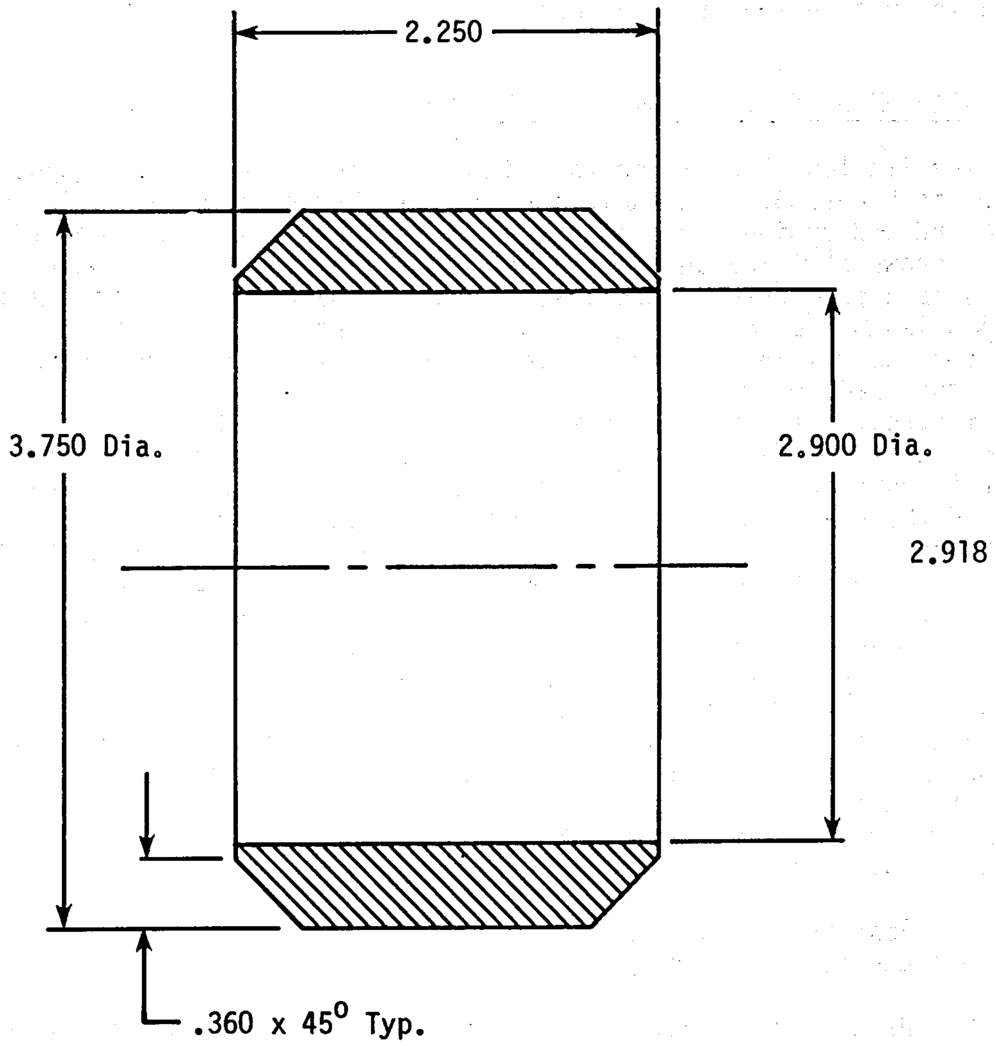


FIGURE 7 -- SIMULATION TEST APPARATUS
P & I DIAGRAM

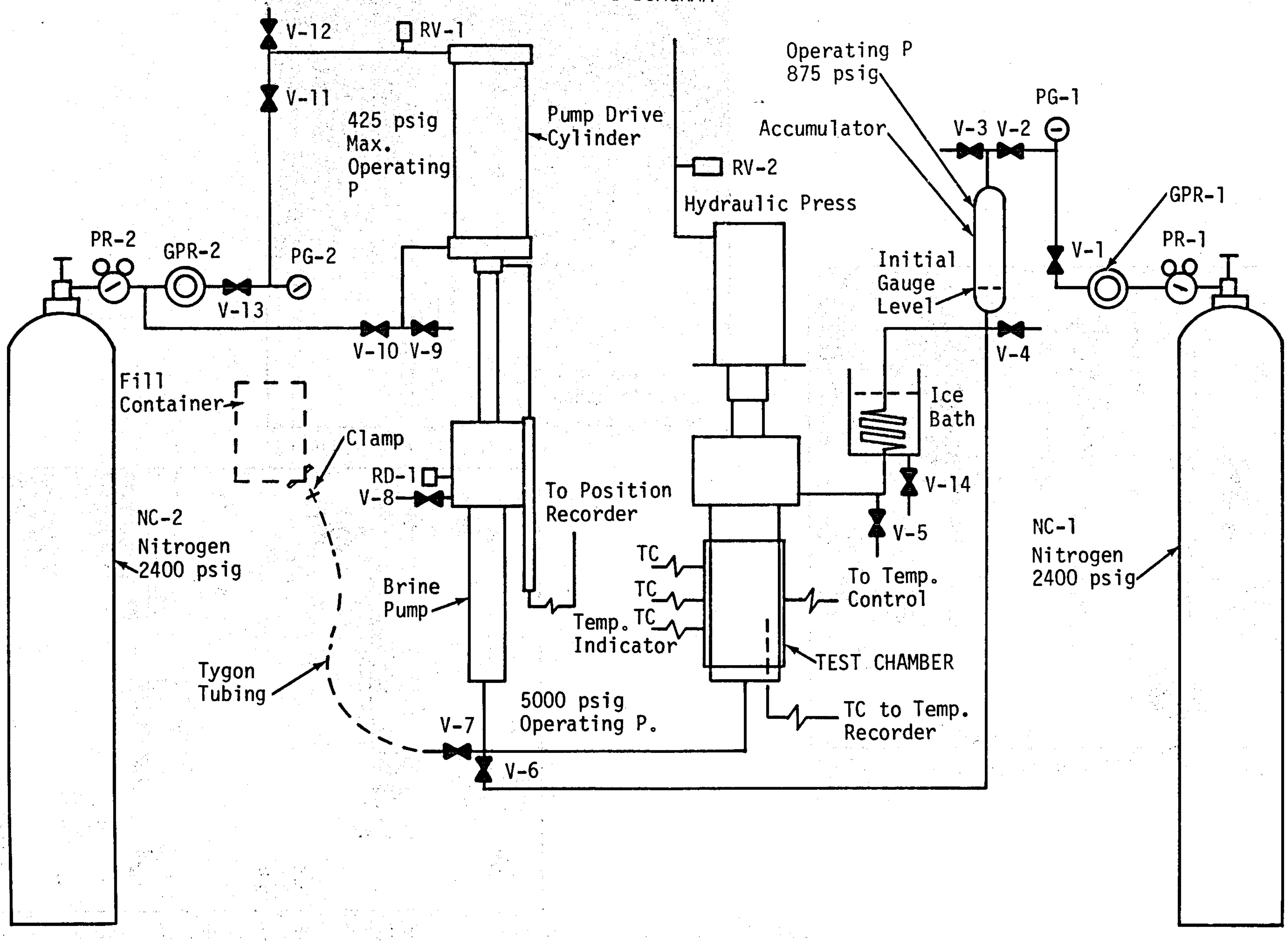
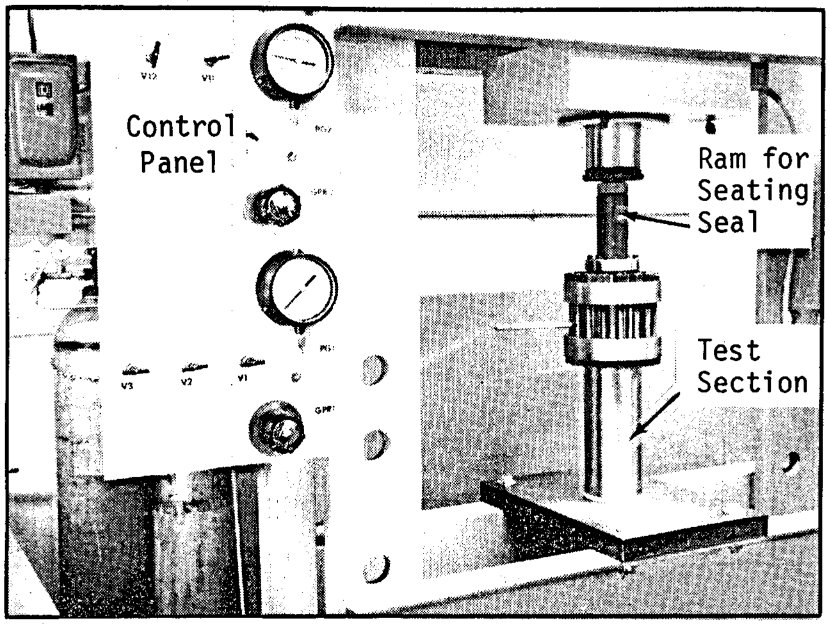
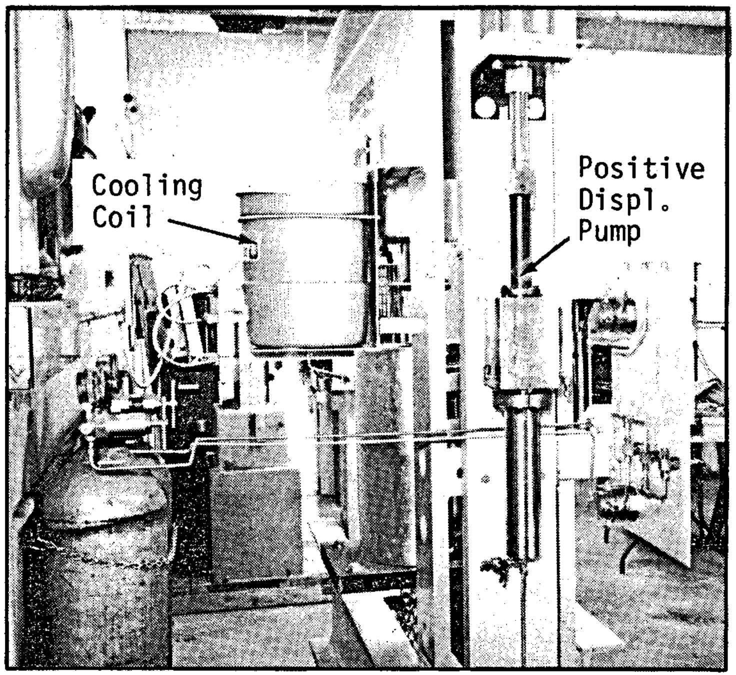
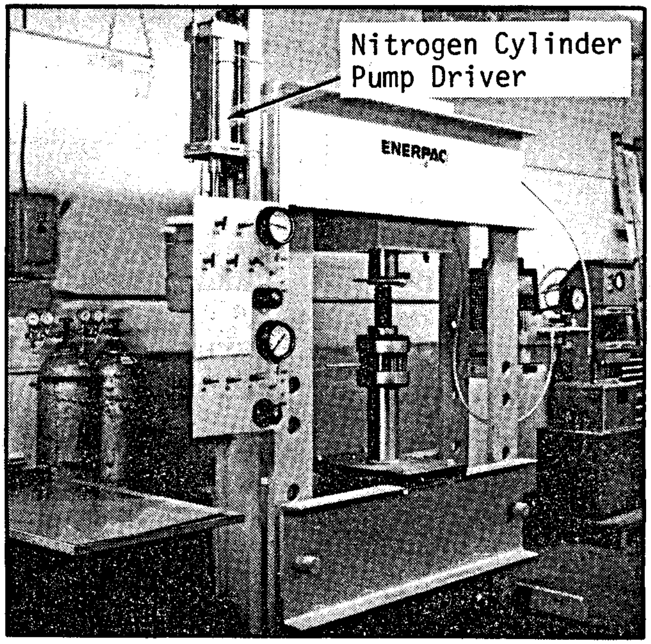


FIGURE 8 -- SIMULATION TEST


Close-up of Control Panel & Test Section


Close-up of Positive Displacement Fluid Pump


General View of SIM Test

6. Allow test to run until pump is fully displaced or 22 hours has elapsed.

7. Cool system, about 2 hours.

8. Disassemble.

4.2 SIM TEST FIXTURE DESIGN

The SIM test fixture operates at 260°C (500°F) and up to 5000 psig with a geothermal synthetic fluid which includes aqueous solutions of H_2S and NaCl. The presence of the hydrogen and chloride ions are of particular concern for the design because of the vulnerability to stress corrosion cracking and hydrogen embrittlement. Safety considerations of these possible failure modes was a very important aspect of the design effort. The safety aspect is uncompromising in that uncertainties must be almost entirely eliminated before it becomes prudent to move ahead and accept the consequences.

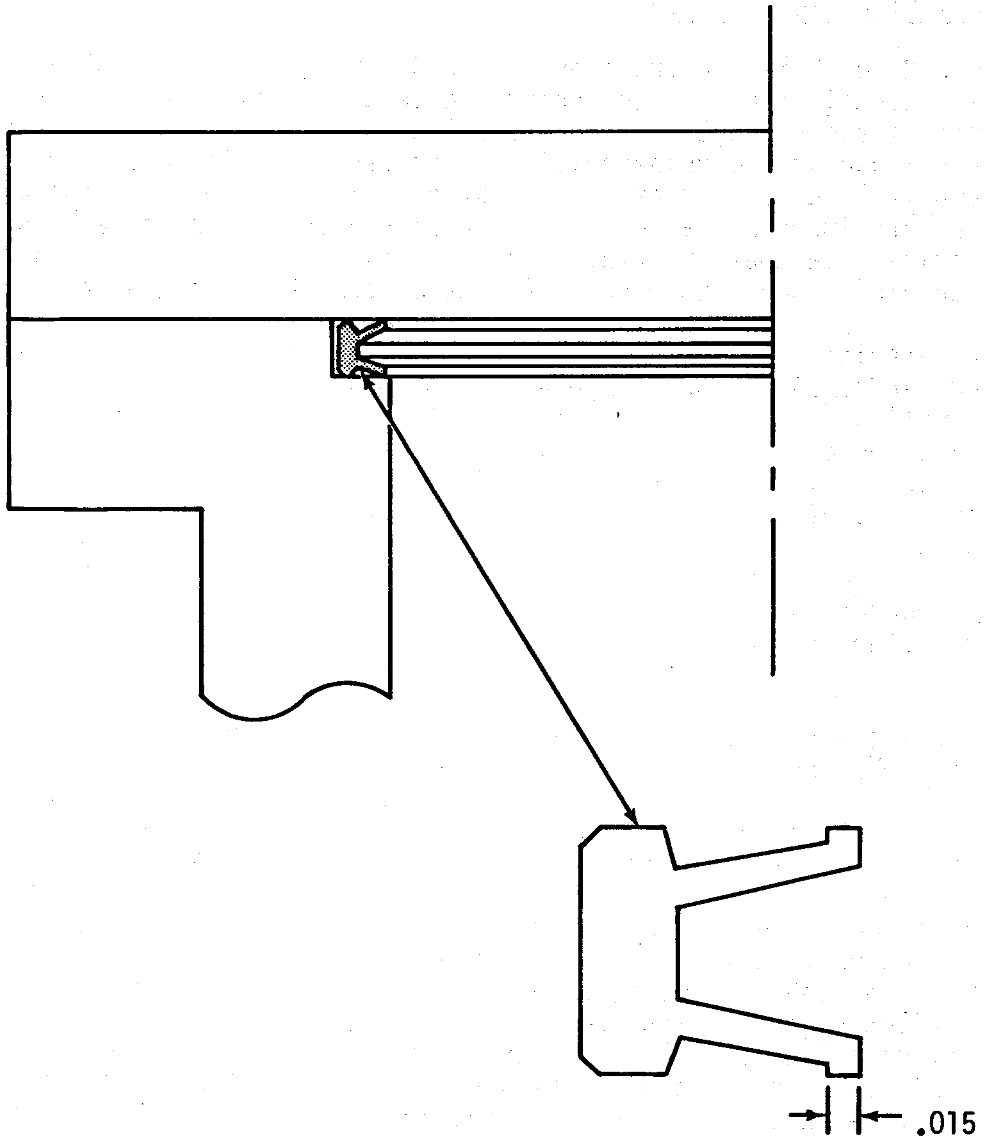
The material used was a basic concern. Inconel 600 or 624, Hastalloy C, Titanium CP, and 316SS (lower temperature components) were considered; availability as well as price were important factors along with corrosion resistance. Industry experience at Niland indicated that Carpenter 20 and 316SS at geothermal temperatures will probably crack as indicated by the pitting. Titanium would have been preferred because of slightly better machineability, however, its ASME allowable design strength per the pressure vessel code is about 25 to 40% of Inconel 600. Consequently Inconel 600 was used for all the tension carrying components which experience the test temperature while 316SS was used for all other components except external flanges which were made from firebox steel.

The seals were another design aspect which required extensive investigation. At 260°C and with the specified chemistry, there was no candidate which clearly met the requirements. For obvious reasons, in terms of general material type, metal seals were considered as opposed to elastomeric seals. C-seals, K-seals, and self-energizing O-ring seals were considered. The O-ring seals appear most economical, even though they were good for only one use, however, based on the experience of the various vendors at the time the decision was made it was very questionable that they would perform sufficiently (since then, we have located a knowledgeable and competent vendor and have successfully tried his Teflon coated O-ring seals). The C-seals were the next preference when the original decision was made, however, their delivery was unacceptable. We ultimately used the gold plated metal K-seals. The gold plate provides a malleable surface which conforms to irregularities on the sealing surface and it is inert. The K-seals are reuseable, but, begin to leak as the gold sealing surfaces become scratched.

Figure 9 is a schematic of the K-seal shown in a typical application. The sealing occurs at the surfaces on the tips of the two legs of the K which are sprung out to a height greater than the backbone of the K. When the mating

FIGURE 9 -- K-SEAL CONFIGURATION

Typical K-seal application showing the configuration and orientation of the seal and the sealing surface.



surfaces are tightened together, the legs are squeezed thus providing a sealing force. The pressure inside the vessel provides an additional self-energizing seal force. The circumferential sealing faces are 15 mils wide and the extent of contact of the 15 mils wide surface depends on the tolerance of the two mating parts and the seal itself. Microscopic inspection of one of the seals which was having leaking problems revealed that only 10-20% or 1-3 mils of the surface was contacting. It becomes obvious that the K-seals must be handled with extreme care and any minor foreign particles or irregularities on any of the sealing surfaces can result in leaks.

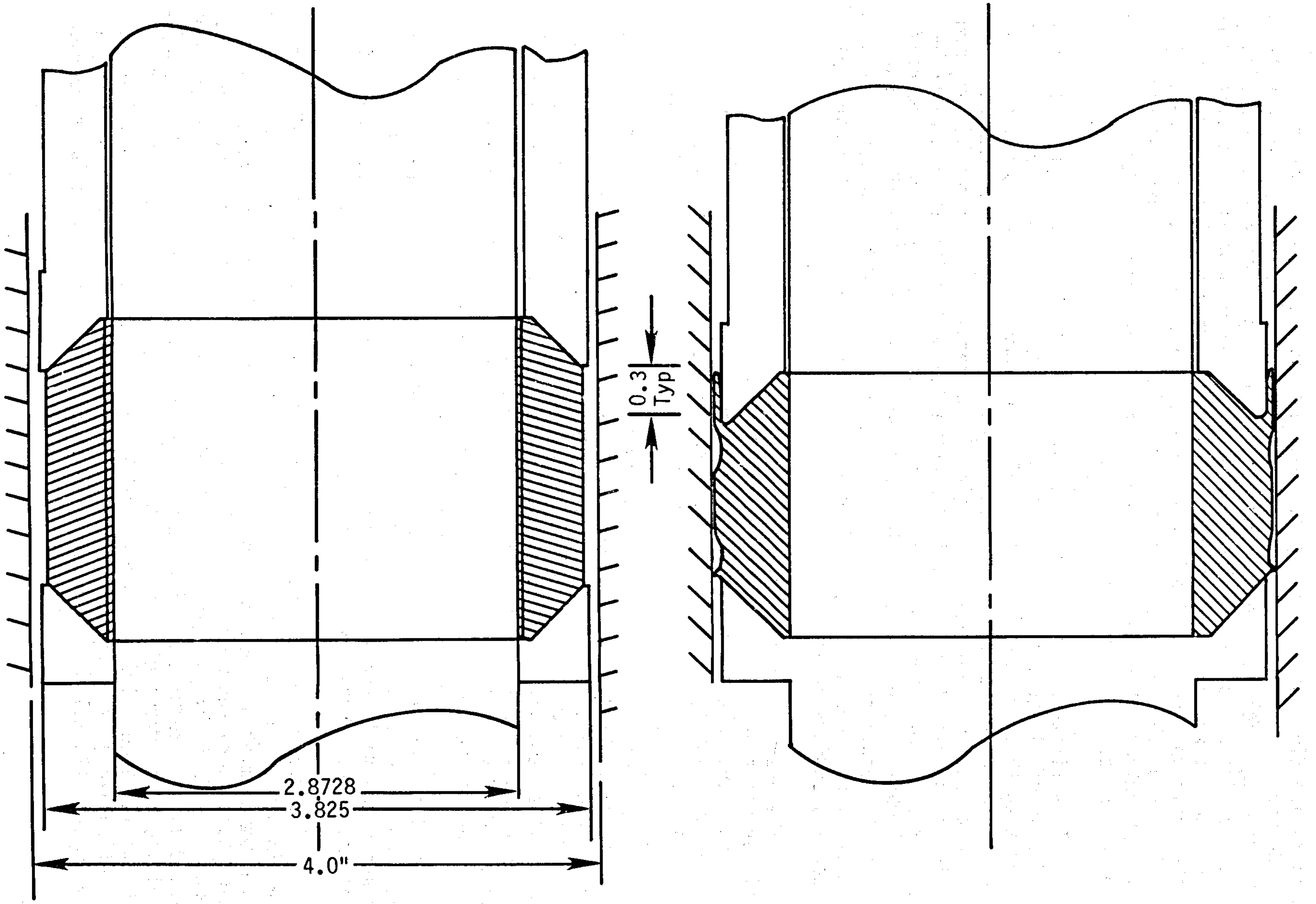
This first-hand experience with metal seals indelibly emphasizes the advantages of elastomeric seals, the fact that they are infinitely more forgiving than their metal or plastic seal counterparts. Under normal circumstances elastomeric seals can be significantly deformed without taking a permanent set. On the other hand, plastic or metal seals cannot be deformed nearly to the extent of rubber to achieve a "seated" position or configuration. Plastic will tend to flow and needs constant retightening to maintain its seal while rubber seals are in stable equilibrium. Both plastic and especially metal require very close tolerance mating parts, on the order of tens of microinches and they must be handled very delicately using special procedures and precautions.

The overall configuration of the SIM test tends to be of high aspect ratio or relatively long and skinny so sliding parts must be held to close clearances and tolerances to prevent cocking of the parts and subsequent binding and gauling. To achieve the required tolerances and finishes, all of the critical parts required grinding as the finishing machining process.

Especially critical to the SIM test are the clearances and configuration of the back-up rings surrounding the seal specimen. Figure 10 shows a schematic of the cylindrical seal with chamfered ends in the relaxed state and the seated state. The seal slides over a center mandrel and is backed up on either end with back-up rings; the ram behind the upper back-up ring slides relative to the center mandrel thereby shortening the seal and causing it to flow radially to seat against both its ID and OD. Substantial stress and elongations are generated especially on the top ram end, and this area is where failures tend to occur in the rubber. Figure 11 shows photographs of the center portion of the fixture with the seal and the ram installed over the mandrel. The overall photograph shows the assembly and the close-up shows the seal area with the ram backed off such that the seal and back-up ring chamfers and the center mandrel are visible.

The clearance and back-up ring geometry are critically correlated to the SIM test results. Testing was started with flat back-up rings, i.e. they were not chamfered to conform to the seal chamfer. With the flat configuration, tests were run with diametral clearances between the OD of the back-up rings and the ID of the vessel of 13, 25, and 175 mils. The clearances were tested using a commercial Nitrile compound run in the test at 300°F. Catalogs indicate that common diametral clearances for packers with fixed back-up systems is between 100 - 200 mils for a seal of the specimen size. This information along with no evidence of extrusion at 13 and 25 mils resulted in the jump to 175 mils. In addition the flat back-up rings were later replaced

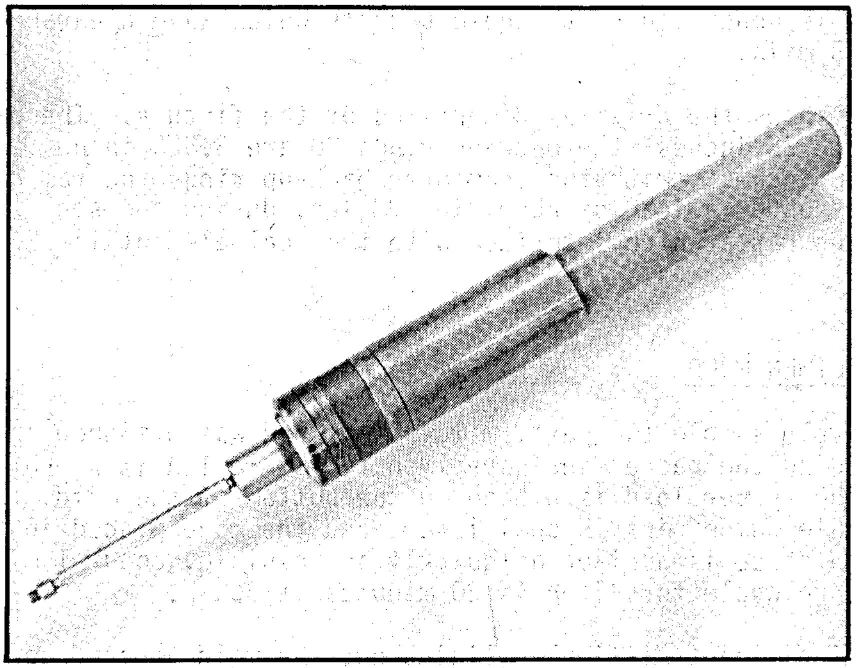
FIGURE 10 -- SEAL DEFORMATION



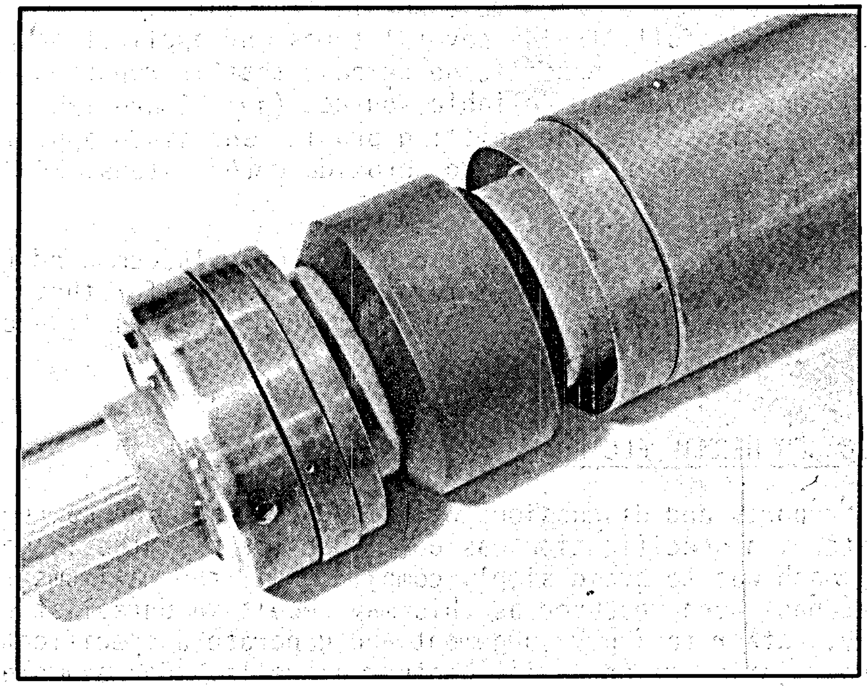
RELAXED

SEATED

FIGURE 11 -- INTERNAL FIXTURE



Internals of SIM Test with seal, back-up rings, and seating ram in place.



Close-up of seal and back-up rings with seating ram backed off.

by rings with chamfers to spread the load across more area on the ends of the seal. This is consistent with those packers which have clearances on the order of 175 mils.

Figure 9 shows the critical dimensions of the fixture. The center mandrel OD is 2.8728 inches, the back-up rings OD are 3.825 inches, and the vessel ID is 4.0 inches. With the chamfered back-up rings the ram displaces about 0.3 inches under a load of about 10,000 lbs. during the seal seating. The finish of the parts which interface with the seal element is 32 microinches.

4.3 SEAL SPECIMEN MOLD

A relatively simple two-part, mild-steel mold was designed and fabricated for molding the packer seal specimens. Figure 12A is a photograph of the mold. The rubber load is placed in the bottom of the mold, the upper half with the male guide pins is positioned, and the mold placed in the cure press. A 50 ton force is applied as quickly as possible, about 1 minute. Typical press cure cycle for Viton is 30 minutes at 350°F.

We had significant difficulty lining out the mold to produce acceptable parts. Most effective release which was being used on flat samples was a silicone release, Dow Corning Emulsion 34, as opposed to Kraxo 1711 recommended by du Pont. The same silicone release was used on the packer seal mold and knit problems occurred along a circumferential line on the inside of the seal at the base of the bottom chamfer. After much testing and inquiring, it was deduced that the problem must result from entrainment of the release. After unsuccessfully trying several types and application procedures of Frekote 33 which is a nonsilicone release that is reported to be excellent with Vitons by multiple reliable sources (see Figure 12B), the mold was Teflon coated. This solved the knitting problem and since applying Teflon we have had no problems molding resin and peroxide cured Vitons, EPDM, Nitrile, and Epichlorohydrin.

A Nitrile seal was made from a commercial company's compound (provided to L'Garde as uncured rubber) and submitted to the company for their quality control tests. They report that the resulting molded part was of excellent quality.

4.4 SYNTHETIC GEOTHERMAL FLUID

Based on reports and discussions with Dr. J. Apps at the Lawrence Berkeley Laboratory, a specification was developed for a synthetic geothermal fluid. The approach was to avoid simply compiling all the maximums for each constituent that has been measured as this may result in unrealistically severe chemistry, rather to apply judgement and generate a specification which covers the majority of potential geothermal wells. For example total dissolved solids can run as high as a few hundred thousand ppm in the Salton Sea Area, however, the great majority of known potential wells are included at levels below 25,000 ppm.

FIGURE 12A -- SIM TEST SPECIMEN MOLD

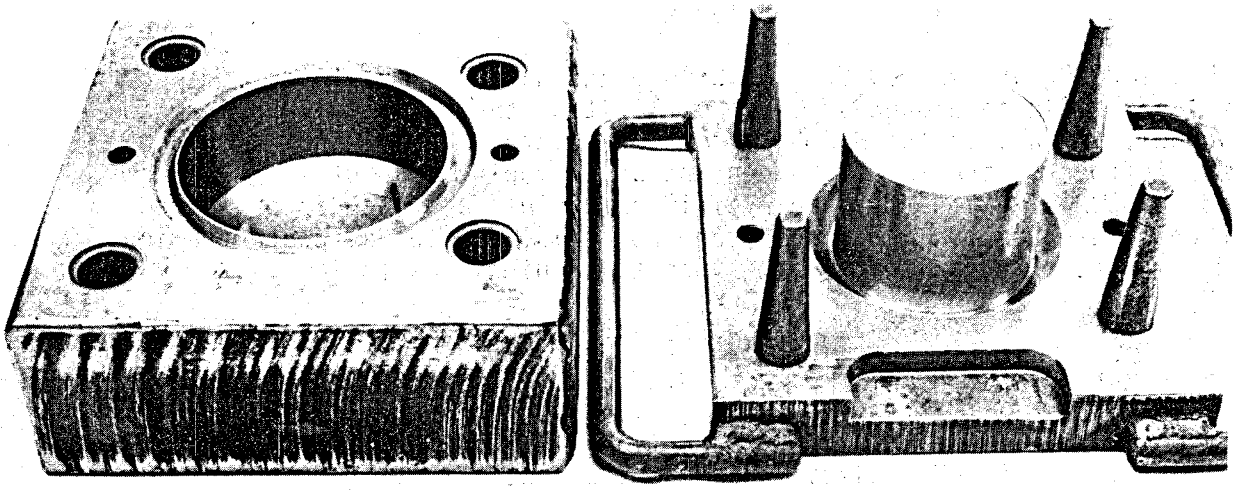
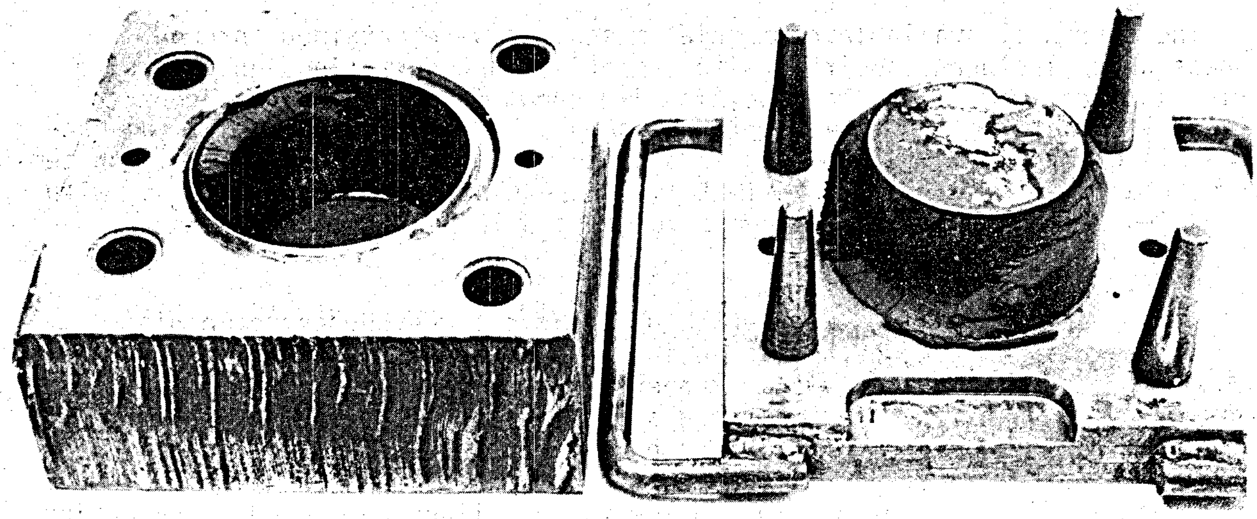


FIGURE 12B -- SPECIMEN THAT DID NOT RELEASE FROM MOLD



The constituency specification used for the current SIM tests is as follows:

H_2S	300 ppm
NaCl	25,000
CO_2	1,000
H_2O	balance

The H_2S and CO_2 are formed from $Na_2S \cdot 9H_2O$ and $NaHCO_3$ respectively. The test uses a finite amount of H_2S thus limiting the potential exposure to personnel. If all of the H_2S were to escape into the room including the excess leftovers, the resulting concentration would be about 1 ppm as compared to OSHA's maximum allowable of 10 ppm. This approach is preferred over one where bottled H_2S is used and potential for lethal concentrations of H_2S exist. The recipe for the synthetic fluid is as follows:

$Na_2S \cdot 9H_2O$	5.29 gms.
$NaHCO_3$	4.77 gms.
NaCl	56.64 gms.
H_2O distilled	1430.00 gms.
HCl(0.1N)	1.0 liter

4.5 SIM TEST RESULTS TO DATE

The SIM testing for the reported contract period is divided into two categories: evaluation of currently available commercial materials and evaluation of compounds developed under this contract.

4.5.1 Commercial Materials Evaluation

The currently available commercial materials were obtained through a process which included inquiries with companies, and selecting and obtaining material samples from five. The questionaire shown in Appendix C was sent to a mailing list obtained from the well tool composite catalog (Reference 15) containing all companies which appeared to deal in well equipment requiring high temperature elastomeric seals. Approximately 75 questionaires were mailed out with 16 companies responding of which 9 were interested in participating in the evaluation.

One of the questions asked regarded anominity, whether the companies were concerned if their names were associated with the test data. The respondees who offered to contribute rubber samples generally requested that their company names not be tied to the evaluation results so the tests were run on a coded basis. Five different compounds were requested including 2 Nitriles or Buna N's, 1 Ethylene Propylene Terpolymer (EPDM), 1 Fluoroelastomer (Viton), and 1 Epichlorohydrin. The following guidelines were used in selecting candidates:

1. The materials are elastomers as opposed to plastics to enable significant deformation of the seal for seating.

2. Representatives of all the high temperature base elastomers in use were desired.

3. Specific formulations that had been applied to larger seals such as packer elements or chevrons as opposed to "O" rings, were favored.

4. Formulations with high temperature experience were favored.

5. No more than one formulation from any one tool company or molded products supplier was requested.

The codes assigned are as follows:

Company A	Nitrile or Buna N
Company B	Ethylene Propylene Terpolymer (EPR or EPDM)
Company C	Nitrile or Buna N
Company D	Epochlorohydrin
Company E	Viton

4.5.2 In-House Materials

The in-house materials evaluated in the SIM tests were the most promising candidates graduated from the previously run Screening Tests. The compounds evaluated during the Screening test phase were all peroxide cured Vitons. Upon completion of the screening there was concern that the ultimate performance of the peroxide cured Vitons may not be sufficient so as a back-up one high temperature butyl compound, three high temperature EPDM compounds, and one resin cured Viton compound were run through abbreviated Screening Tests. These materials were chemically aged in the synthetic geothermal fluid and the butyl reverted extensively, the resin cured Viton became quite brittle while the EPDM's indicated promise. The EPDM's remained elastomeric and the formulation chosen for continued development in the SIM testing lost about 25% of its tensile strength.

4.5.3 Test Data

19 complete tests were run on the SIM test during this contract period. The first 9 of the 19 served to calibrate the fixture and to get a basic assessment of the nature of the test, i.e. how long the specimens would run before failure, failure mode, severity of the clearances and back-up ring configuration, whether the differential pressure should be cycled, etc? Table VIII is a summary of the runs. The alphanumeric specimens, e.g. A-3, correspond to the specimens made from the commercially available compounds. The A designates Company A and the 3 means that it was the third specimen made from that compound. The numeric specimens are in-house compounds and the suffix number means the same thing as with the alphanumeric specimens. Except as noted all tests were run near 260°C

TABLE VIII -- SIM TEST SUMMARY

Sequence No.	Specimen No.	Compound	Duration Hrs:Min	Inches Extrusion	Set Temp. °C	Diamet. Gap, Mils	Configuration
1	215-3	VT-R-4590,Austin 70 phr	5:52	Nil	260	13	Flat
2	215-2	VT-R-4590,Austin 70 phr	:07	Nil	260	13	Flat
3	A-3	Nitrile	24:	Nil	149	13	Flat
4	A-2	Nitrile	24:	Nil	149	25	Flat
5	A-6	Nitrile	11:	0.5	260	175	Flat
6	213-3	VT-R-4590,Asbestine 3X	:00	Nil	260	175	Flat
7	220-3	VT-R-4590,Austin 65 phr	:00	Nil	260	175	Flat
8	216-2	VT-R-4590,Kevlar	:00	Nil	260	175	Flat
9	105-II-1	Viton GH, Austin/MT	:05	Nil	260	175	Flat
10	216-1	VT-R-4590, Kevlar	:00	<0.1	260	175	Chamfered
11	A-5	Nitrile	24:	1.75	260	175	Chamfered
12	105-II-2	Viton GH, Austin/MT	:47	Nil	260	175	Chamfered
13	B-3	EPDM	24:	3.75	260	175	Chamfered
14	217-2	EPDM	24:	2.5	260	175	Chamfered
15	C-4	Nitrile	1:13	4.5	260	175	Chamfered
16	D-3	Epichlorohydrin	:00	N/A	260	175	Chamfered
17	E-3	Viton	3:44	No Meas.	260	175	Chamfered
18	222-3	VT-R-4590,Austin 40 phr	:03	0.75	260	175	Chamfered
19	221-2	VT-R-4590, Maglite K	:38	0.75	260	175	Chamfered

(500°F). Because of a calibration change the tests ran at about 245°C (470°F). To maintain consistency in the latter tests the setting was not changed, however, it will be adjusted in future testing. The formulations of all in-house compounds tested are shown on Table IX. They were cured for 30 minutes at 177°C (350°F) and post cured for 16 hours at 260°C (500°F).

Through Test No. 9 adjustments were being made on the fixture to key into the severity range appropriate for the 24 hour packer application. The No. 3 and No. 4 test specimens were made from Company A's Nitrile and tested at 149°C (300°F), its approximate upper limit, to determine the response of a commercially proven material to the SIM test fixture. The back-up ring diametral gap was enlarged to 175 mils as a result of these tests as the seals appeared nominal with the only apparent change being flattening of the chamfers. The 175 mil gap was based on commercial packer configurations without expandable back-up where seals of this size must span gaps of the order of 100 to 200 mils. Test No. 5 through No. 9 assess the effect of different compounds at 260°C. Because all the Viton seals failed upon pressurization there was concern that the flat back-up rings induced unduly high stresses on the seal so they were replaced with chamfered back-up rings.

It became apparent at this point that the only way the numerous uncertainties could be pinned down was to generate some facts in the form of data so tests No. 10 through No. 19 were run as a consistent set all under the same conditions, i.e. 260°C and chamfered back-up rings with 175 mil diametral gap.

Table X is a post mortem physical description of each of the specimens. Those that failed upon pressurization appeared to be too hard and failed in tension in a macroscopic sense, i.e. major cracks developed or chunking failures occurred. Those that survived for some period of time were more pliable but failed in tension on a more submacroscopic bases, i.e. small particles broke off at the high stress point and recombined to form an extrudent which helped to seal the gap annulus on the downstream side of the seal.

Figure 13 shows some typical post mortem specimens. The Company B EPDM is a more extreme case where the seal failed in a submacroscopic sense and the failed particles then recombined to form an extrudent. The intact portion of the seal and the extrudent were both quite pliable and resilient. The L'Garde EPDM compound looked basically the same except its extrudent was about 2.5 inches high vs the 4.0 inches shown. The Company A Nitriles were similar in appearance except the extrudent was smoother and very brittle. The L'Garde Viton maintained its integrity, however, it failed by cracking at the high stress points and at weak points created during the molding process. The Company D Epichlorohydrin lost all its structural integrity here, as well as in the Extrusion Resistometer test in vacuum, and in the hot hardness test in air. The Company E Viton survived with a slow leak for 3.75 hours. It may show improvement if it is made harder. The balance of the specimens tested during this period are shown in Figure 14.

Table XI shows the virgin properties of the materials which were SIM tested. The function of these measurements is quality control to assure that the rubber has been properly mixed and cured.

TABLE IX -- SIM TEST FORMULATIONS

Component	105	213	215	216	217	220	221	222
VT-R-4590		100	100	100		100	100	100
Viton GH	100							
Nordel 1070					100			
Austin Black	10	45	70	60		65	35	40
MT Black	40							
SAF Black					65			
Kevlar				5				
Asbestine 3X		20						
Maglite K							30	
Litharge	3	3	3	3		3		3
Antioxidant 2246					0.5			
Hypalon 20					5			
Antimony Trioxide					5			
Luperco 130XL	1.5	1.5	1.5	1.5		1.5	1.5	1.5
Diak 7	4	3	3	3		3	3	3
Dicup R					3.5			

TABLE X -- POST MORTEM OBSERVATIONS OF SIM TEST SPECIMENS

Specimen No.	Description
215-3	Chamfered ends yielded flat. Circumferential cracking on the inside of the seal approximately at the bottom edge of the chamfer. Light brown deposits at vapor escape flaws. Room temperature Shore A 80-85.
215-2	More severe chunking or breaking at the base of the chamfer along the parting line than -3. Also circumferentially cracked on the inside at the base of the chamfer. Room Temperature Shore A 95-100.
A-3	In excellent shape, no surface cracks. Some permanent deformation -- top chamfer nearly flat, bottom chamfer flattened somewhat. Circumferential dimples on the inside where we have been experiencing failure on other specimens but no break. Room Temperature Shore A 85-90.
A-2	Situation ditto as for A-3 in all respects.
A-6	Extrudent approximately 1/2 inch. Severe chunking catastrophic failure on about 30 degree section of seal. Both chamfers flattened and the failure on the 30 degree section is completely through the height of the seal. Room Temperature Shore A 85-90. Extruded pieces of rubber extremely brittle, breaks like hard plastic.
213-3	Breakage and about 1/4 inch of extrusion evident at the top chamfer on the outside. Bottom chamfer from the outside is in good shape. Some evidence of breakage at vapor escape flaws. Cracked circumferentially along the base of the chamfer along the inside of the seal. One area on the inside has a severe chunking failure. Room Temperature Shore A 90-95.
220-3	Looks to be in relatively good shape. Chamfers are intact except for one area of about 10 degrees on the top chamfer. There is a circumferential cracking on the inside along the base of the two chamfers and there is one "L" shaped crack coming vertically down the outside surface and then going circumferentially at the base of the bottom chamfer. The "L" shaped crack traverses through a vapor escape flaw that was previously marked before the test. Room Temperature Shore A about 95.
216-2	Appears very similar to 220-3 and in relatively good shape. Chunking failure at the top chamfer over a distance of about 20 degrees. Circumferential cracks on the inside at the base of the chamfers. Room Temperature Shore A hardness 95-100.
105-II-1	Rubber failed catastrophically in the high stress area along the top of the chamfer. Rubber broken into little 1/4 inch chunks. Bottom chamfer in good shape. Wide circumferential cracking around the bottom inside at the base of the chamfer. Room Temperature Shore A 85-90.

TABLE X (continued)

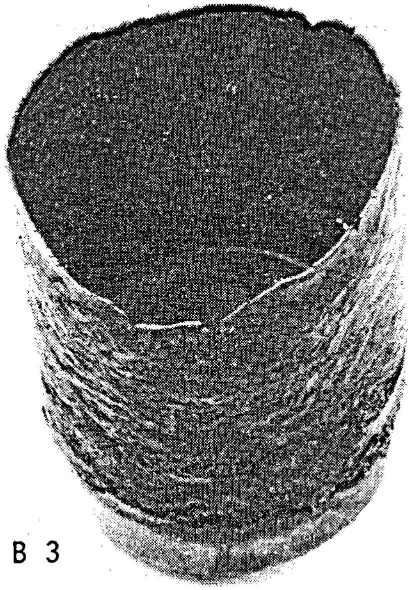
Specimen No.	Description
216-1	Extruded a minor amount, 1/8 of an inch or so. No cracking on the inside as experienced on the other specimens at the base of the chamfer. Cracking and some failure at the base of the chamfer on the outside, both ends. Three failure points on the inside of the seal around the midsection appear to be weak points. Chamfers in good shape. Room Temperature Shore A 95-100.
A-5	Extruded about 1-3/4 inches. Extrudent very hard and brittle. Breaks like hard plastic. Minor cracking on the inside of the seal right at the dimple point where the stress apparently was very high but otherwise the inside surface is in pretty good shape. Some blistering on the inside. Outside failures point at the base of the bottom chamfer. One crack in the midsection on the outside surface. Hardness approximately 90-95 but very hard to measure because there are no good flat surfaces.
105-II-2	A lot better shape than 105-II-1. No cracking on the inside. No circumferential cracking at the base of the chamfers. There is about a 70 degree circumferential crack, however, in the midsection below the base of the top chamfer. Had a great deal of extrudent, little 1/4 inch chunks, look like the other 105. Failure looks to be primarily at the flowplane of the rubber coming out of the partline. Both chamfers are in good shape and have reassumed the original chamfer angle. Room Temperature Shore A about 80-85.
B-3	Experienced most extrusion of any of the specimens at 3.75 inches. The intact part of the seal, however, is in very good shape and no evidence of cracking except for minor cracking at the very high stress points along the circumferential dimple on the inside of the seal. Extrudent is intact and sitting on the seal like a crown. Extrudent has a rough, irregular, corduroy look. Room Temperature Shore A about 80, but is very difficult to measure because of a very narrow, flat surface being available.
217-2	Very similar in appearance to B-3. Not as much extrusion, about 2½ inches. Also appears very good except very minor cracking at the high stress points along the circumferential dimple on the inside. Bottom chamfer in good shape. Top chamfer intact too, as was the top chamfer on B-3. Room Temperature Shore A, about 85 but difficult to measure because no good flat surfaces.
C-4	Almost completely gone. The bottom chamfer failed in a section about 30 degrees wide or so. Extrudent is still pliable and held together. Looks more like the EPDM extrusion as opposed to the Nitrile extrusion of earlier specimens; that is it has a rough corduroy look rather than being smoothed out through the extrusion process. Practically nothing left on this seal. Top chamfer is intact completely circumferentially but after this amount of extrusion its pretty well broken at the base. Hardness readings are difficult but are around 85 or so.

TABLE X (concluded)

Specimen No.	Description
D-3	Most catastrophic failure of all. It was evident the seal broke during seating. Post mortem it was a handful of rubber chunks. The consistency is like cheddar cheese breaking in a crumbly fashion. Visual evidence of a fibrous filler in the rubber.
E-3	The next most catastrophic failure. Top chamfer intact. Broke along the mold flowplanes. No evidence of internal circumferential cracking at the base of the bottom chamfer on the inside of the seal. Only about half an inch section of the cylindrical portion left intact; the rest of the seal has been extruded and broken into small crumbly pieces, except some minor amounts are matted together. Pieces still resilient. Room Temperature Shore A difficult to measure therefore uncertain, but about 75.
222-3	About .75 inches of extrusion. No circumferential cracking at the bases of the chamfers on the inside, however, there is a circumferential crack at the midpoint on this seal. Circumferential on the outside of the base at the bottom chamfer and also breakage at the base of the top chamfer where the rubber was extruding out. Chamfers look to be in good shape. Room Temperature Shore A 85 to 90.
221-2	No evidence of circumferential cracking on the inside of the base of the chamfers, however, there is circumferential cracking at the midpoint -- two sets; one that goes a little over 180 degrees, the other that goes about 80 degrees or so. Chamfers in good shape. Extrudent about 3/4 of an inch. Bottom chamfer on the outside shows some evidence of breakage -- not all the way around -- two sections, one about 90 degrees and the other about 45 degrees. Room Temperature Shore A about 95.

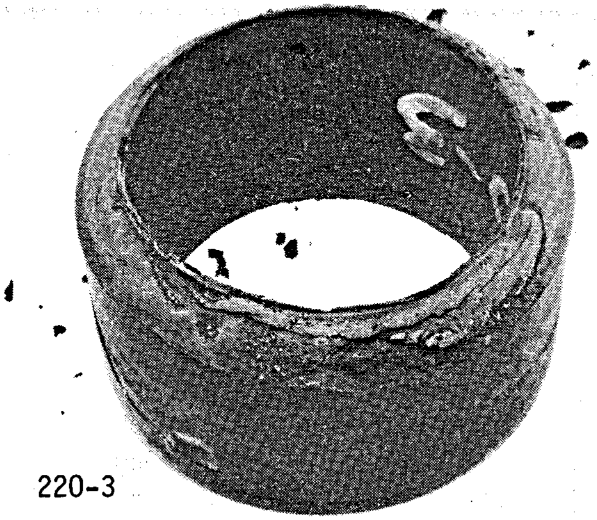
FIGURE 13 -- SIM TEST POST MORTEM SPECIMENS, TYPICAL RESULTS

Company B EPDM -- This and L'Garde EPDM remained elastomeric and survived full 24 hours. Only difference L'Garde EPDM extruded 2.5 in. vs Company B's 4.0 in.



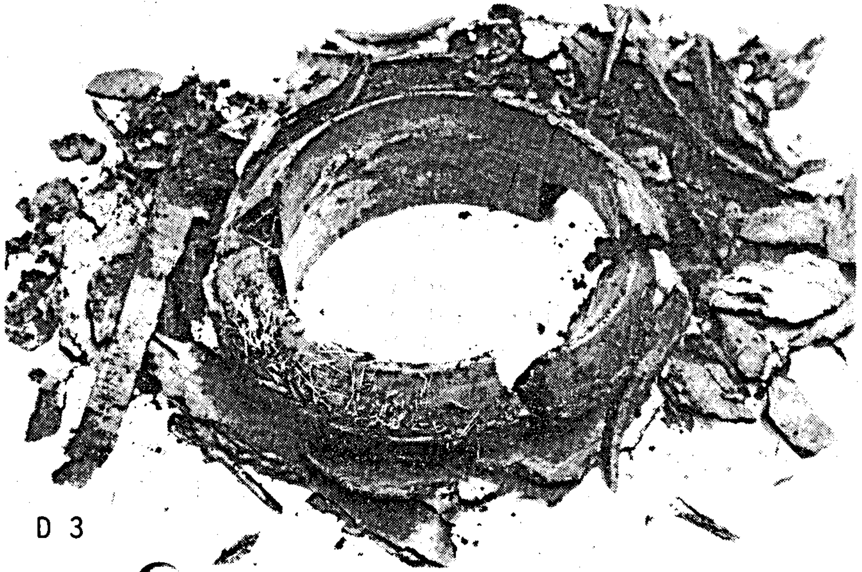
B 3

L'Garde Viton -- Failed because of inability to elongate sufficiently during seating.



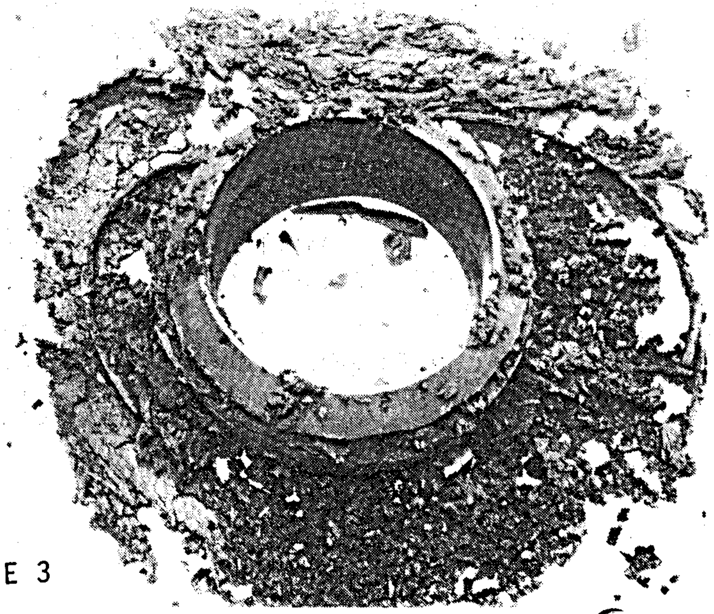
220-3

Company D Epichlorohydrin -- Lost all structural strength and became soft and crumbly before seating.



D 3

Company E Viton -- Failed by breaking in the high stress region. Survived 3.75H with slow leak, then failed.



E 3

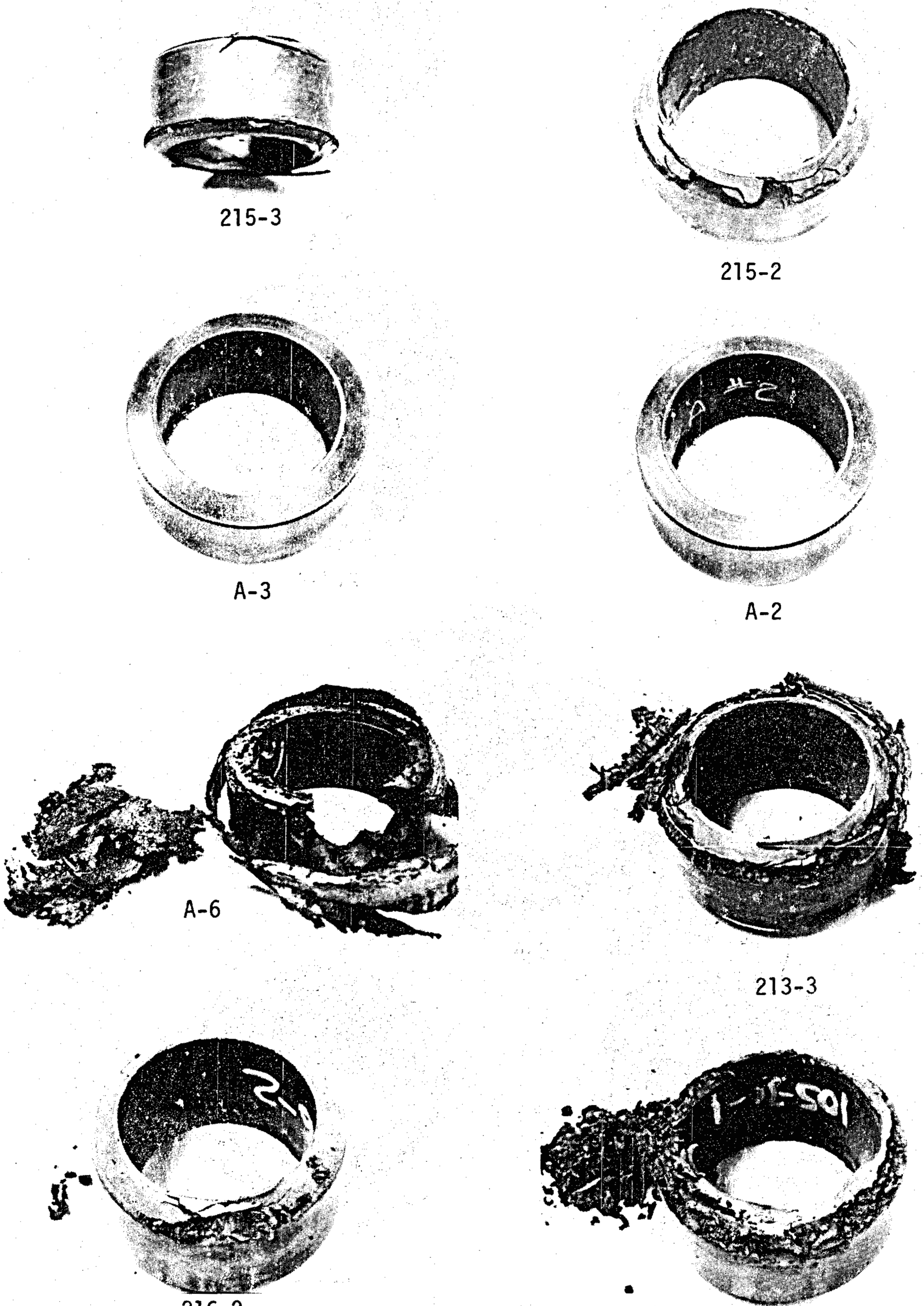


FIGURE 14 -- BALANCE OF POST MORTEM SIM TEST SPECIMENS
SHOWN IN ORDER OF TESTING

215-3

215-2

A-3

A-2

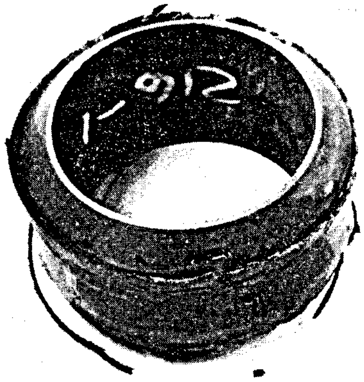
A-6

213-3

216-2

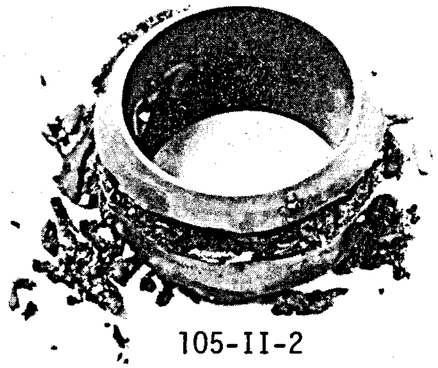
105-II-1

FIGURE 14 -- BALANCE OF POST MORTEM SIM TEST SPECIMENS SHOWN SHOWN IN ORDER OF TESTING (CONTINUED)

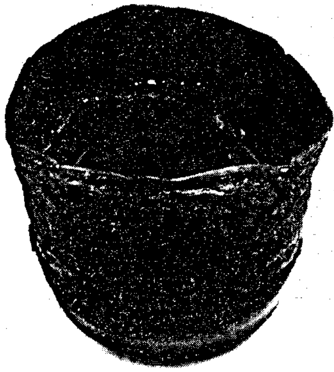


216-1

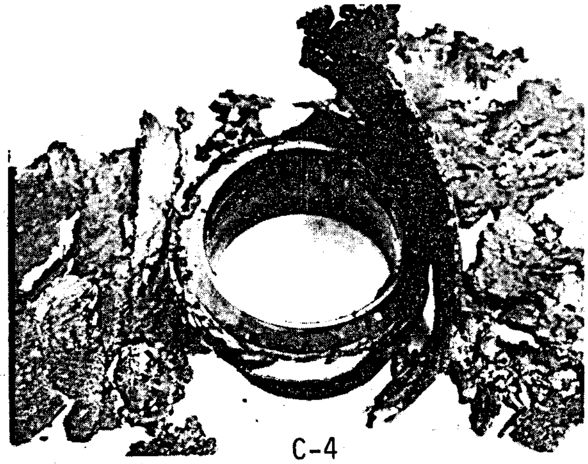
A-5



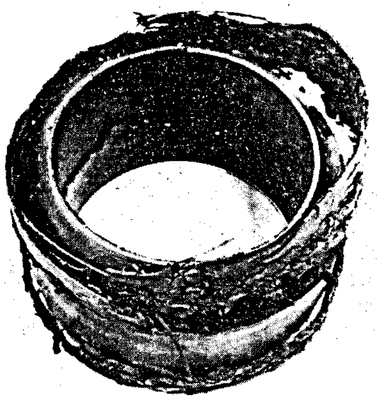
105-II-2



217-2



C-4



222-3

221-2

TABLE XI -- SUMMARY OF VIRGIN PROPERTIES
COMMERCIAL & L'GARDE CANDIDATE PROPERTIES

Specimen	Tensile @ RT psi	Elongation @ RT %	Hardness @ 500°F Shore A	Extrusion Resist psia
A	3476	302	82.2	>18
B	2424	653	65.6	13.5
C	2000	813	61.2	11.5
D	1524	812	----	3.6
E	1506	408	72.6	8.7
213	1758	127	79.2	13.3
216	2438	63	85.2	16.2
217	>1537	>840	62.8	8.9
220	1708	107	82.8	>18
221	2260	141	81.2	>18
222	1657	179	76.4	16.8

4.5.4 Conclusions

At this point it is obvious the data is much too sparse to make any firm conclusions regarding best elastomers. The casing packer type seal with solid rubber elements require extraordinary performance of the elastomer especially at higher temperatures. The process of seating the seal significantly deforms the rubber and induces high stresses at the base of the chamfers. AT 260°C the strength of the rubber was exceeded for all specimens tested resulting in macroscopic cracking and immediate failure of the seal or submacroscopic cracking and maintenance of the seal with the part that remains intact plus the extrudent in the gap annulus.

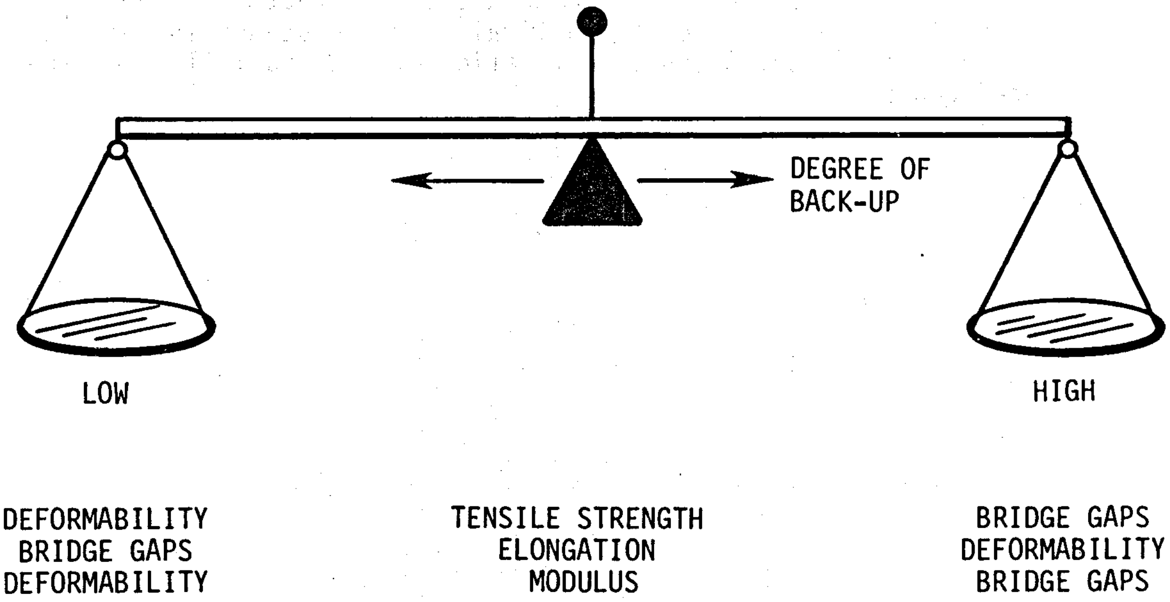
Although the Company A Nitrile and the Company B and L'Garde EPDM's held their seal for the full test cycle in spite of the breakage and extrusion of the rubber, this is not the condition one would consider satisfactory as a nominal design. However, if this is the only way the seals will work under the required conditions and the system maintains a seal for the required period of time, the bottom line objective is satisfied.

One aspect of the packer seal which is quite apparent is the complex combination of rubber characteristics required to fulfill the requirement. Figure 15 figuratively illustrates the point. The problem tends to revolve around the modulus and the ultimate tensile strength and elongation. In addition the fulcrum or balance point for these trade-offs shift depending on the degree of backup around the seal element. If minimum backup is provided a high modulus elastomer must be used to provide the stiffness to bridge the gap. At the same time, however, the rubber must be able to elongate sufficiently to allow the seal to seat without breaking. At 260°C this balance becomes more and more difficult to strike, if not impossible because of the significantly reduced ultimate tensile strength and elongation. On the other hand if maximum backup (virtually no gaps) is provided, a low modulus/high elongation compound is desirable such that it can be seated at a minimum stress level. The maximum back-up case is not so deeply wedged between conflicting requirements because it does not need the high modulus having no gaps to bridge and hence is more amenable to high temperature applications.

On the basis of the 19 SIM tests which have been run, it appears that the EPDM shows more promise than the Vitons. Future compounding to develop an EPDM which will not extrude as much and a Viton which will deform more before it cracks is planned. These indicated directions for future development are based on the results and observations of the SIM Test, a level of insight not possible on simpler tests. The SIM Test evaluates the conflicting requirements of extrusion resistance versus deformability of the elastomer.

The results of the SIM Test which demonstrate the extraordinary performance required of the casing seal elastomer has lead to identification of an idea to relieve the critical requirements. The excessive stresses which cause seal failure are induced when the seal is deformed and seated. If the material were plastically as opposed to elastomerically deformed when it is seated internal stresses would not be generated in the material. This led to the question of the possibility for increasing the potential of the

FIGURE 15 -- PACKER ELASTOMER TRADE-OFFS



elastomeric casing seals by partially seating but fully deforming them in an uncured or partially cured state, "curing them in place" and then fully seating the seals. Several practical questions arise as to timing, preventing the curing until the seal is seated, green strength of the elastomer, etc. However, one can conceive of ways to forestall curing, for example, adjusting cure temperature and rates through cure system design, cryogenic cooling systems to keep the part from heating up until after it is partially seated, etc. In addition, there are applications outside of the geothermal industry such as the oil industry steam floods which are very amenable to the "cure-in-place" concept. The steam injection packer can be partially set in the cold hole and steam then circulated down to the packer to heat up, maintain temperature, and cure the seal. Once the seal is cured the packer can be fully set and then placed into operation.

In that there is good potential to work out the practical problems if the "cure-in-place" concept proves practical from the standpoint of the elastomers, L'Garde is recommending investigation of the feasibility of the "cure-in-place" concept.

5.0 PACKER IMPROVEMENT CONCEPTUALIZATION

The Improvement Conceptualization Task reported, herein, represents a minor fraction of the overall GEM effort. Conceptualization of future systems plays an important role in applied materials development, because with the inherent lead time required for materials development the materials being developed now must be applicable to the systems in use several years hence. An additional potential benefit is derived, as this minor effort may result in some fresh ideas and concepts which will benefit the geothermal community.

The conceptualization was performed by personnel who have no oil tool experience which has its good and bad points. The bad are quite obvious they cannot be as efficient, and they are vulnerable to reinventing the wheel and repeating errors of the past. On the other hand, they do not have preconceived ideas and approaches to the design which are developed for efficiency sake, hence possess a frame of mind which allows discovery of practical ways to accomplish objectives that may have been previously rejected as impractical.

The GEM Program includes the development of a conceptual design of an oil tool device improved for geothermal service. The device selected was an inflatable, resettable casing packer. Several companies, both users and suppliers, were contacted in order to identify problems and limitations of existing designs.

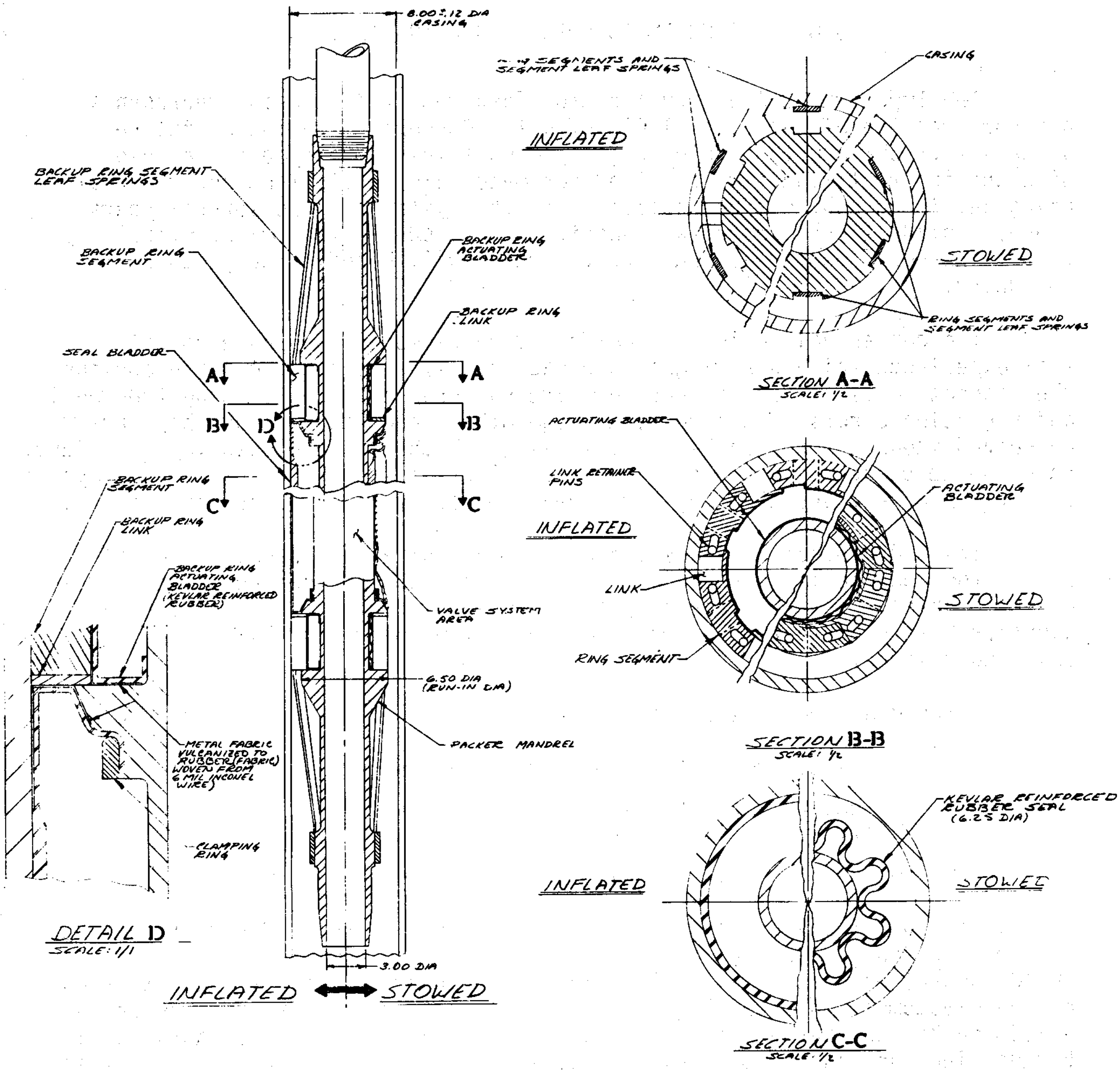
Three goals were established for the effort. These goals include:

- withstanding the geothermal environment;
- having improved retraction ratio over typical solid rubber seal element devices;
- having reset capability.

One limitation of the existing inflatable packers is the tendency of the elastomeric seal to extrude when exposed to the high temperature environments 260°C (500°F) of geothermal applications. In order to prevent the extrusion of the elastomer a design (Figure 16) was conceived that provides essentially a 100% mechanical backup of the elastomer sealing element by use of a metallic backup ring and also by providing a metallic fabric to span any gaps existing in the primary backup system. In addition a valving system concept (Figure 17) was developed to allow the packer to be repeatedly inflated and deflated so it could be reset without removal and refurbishment.

The concept shown meets all of the goals which were originally set. The design is conceptual and therefore its ultimate validity will only be proven after additional feasibility evaluation and ultimately development of the hardware. However, several aspects are worthy of attention and further interest, such as the valving subsystem, the seal backup subsystem, and the

FIGURE 16 -- INFLATABLE PACKER CONCEPT



QTY REQD	CODE IDENT	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION

PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ARE:
FRACTIONS ± DECIMALS .XX ± .XXX ± ANGLES ±
MATERIAL
FINISH
DO NOT SCALE DRAWING
NEXT ASSY USED ON
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CONTRACT NO.
APPROVALS DATE
DRAWN G Vaul 4/7/77
CHECKED

L'GARDE, INC.

INFLATABLE THERMAL CASING PACKER CONCEPT

SIZE D
CODE IDENT NO. 1F668
DRAWING NO. SK0052
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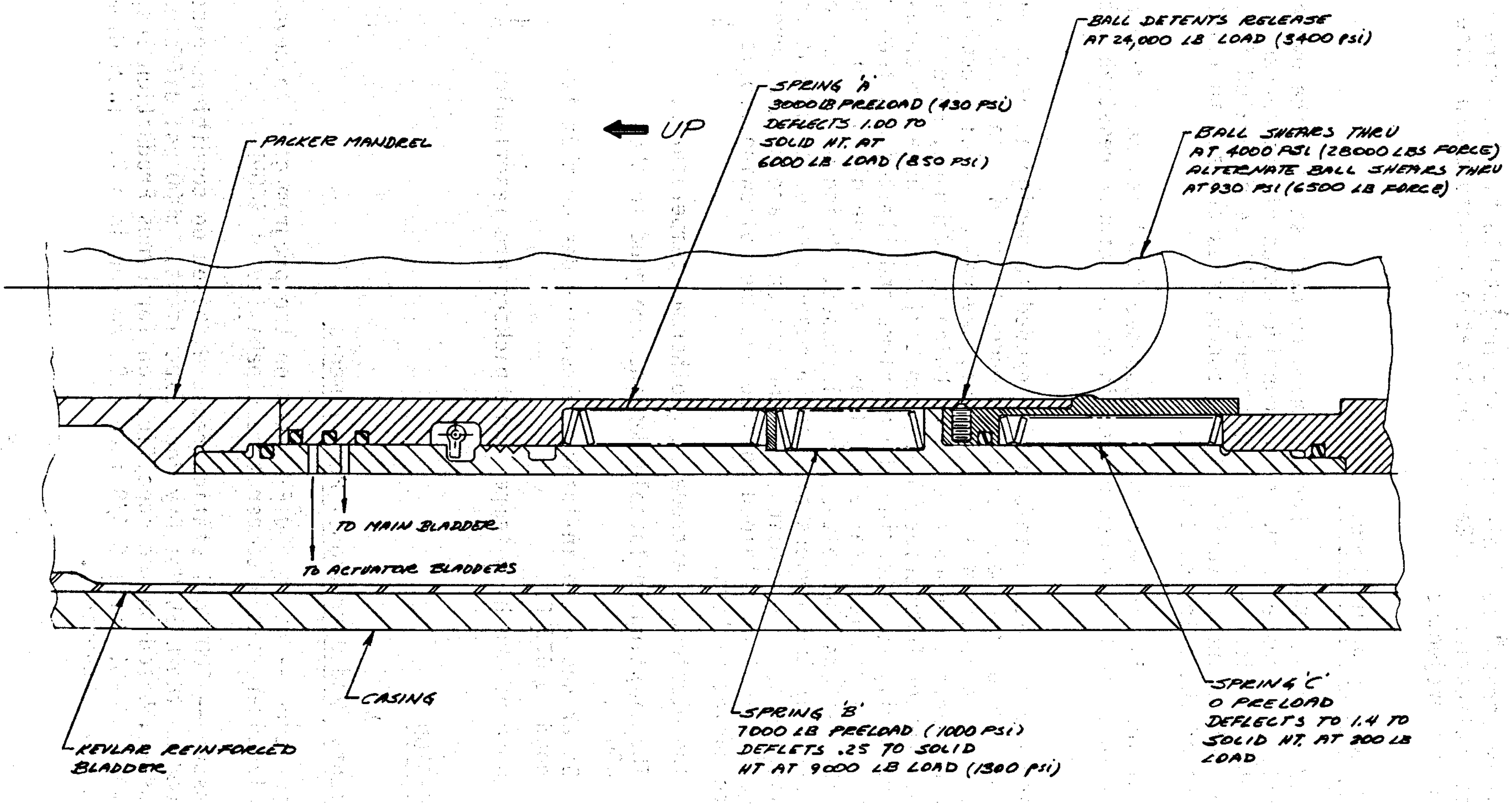
SHEET 1 OF 1

FIGURE 17 -- VALVING SYSTEM CONCEPTUAL DESIGN



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ORIG. S. Beal
CHK.
APPD.
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B'GARDE, INC.
1595 PLACENTIA AVENUE
NEWPORT BEACH
CALIFORNIA 92660

VALVE SYSTEM

SIZE C | CODE IDENT NO. 1F668 | SK-0053
SCALE: 1/1 | RELEASE | SHT. 1 OF 1

inflatable "minimum stress" seal element. The inflatable "minimum stress" seal is a direct application of L'Garde's inflatable structure expertise as applied to Air Force projects.

5.1 STATEMENT OF WORK REQUIREMENT

Task 4.2.2 entitled "Device Design Improvements" states "the overall device design will be assessed with strong consideration of its current problems and inefficiencies -- design improvements will be generated favoring those which include incorporation of new concepts as opposed to relatively minor improvement of the existing device".

The output for this task will be a cross-sectional assembly drawing. The device selected (with ERDA concurrence) is an inflatable resettable casing packer.

To provide the background information needed to design a casing packer and to understand some of the major problems encountered with these devices when they are used in a geothermal environment, several commercial companies were visited or contacted. Among those were Union Oil Company, Baker Oil Tools, Lynes, Inc., and Dresser Industries / Guiberson Division. These companies were contacted primarily to determine the problems and limitations they were experiencing with elastomeric materials but as part of the discussions the limitations of the packers themselves were discussed. Union Oil is one of the major developers in the Geysers area and a major user of equipment for geothermal applications. The remainder of the companies are manufacturers of packers. The information obtained pointed out the following problems encountered with casing packers:

- The elastomers extrude at geothermal temperatures.
- The existing inflatable designs are good to about 400°F.
- Baker has a non inflatable elastomer design that is good to 675°F.
- None of the high temperature packers are resettable.

5.2 PACKER DESIGN

5.2.1 Environmental and Operational Requirements

A. Temperature -- up to 500°F, based on the program goal to develop an elastomer with a temperature capability of 500°F

B. Pressure -- 5000 psi static pressure, based on conditions experienced on the LASL Hot Dry Rock Experiment. 5000 psi differential pressure, based on the specification for Lynes Production Inspection Packer #300-01 for a 5 5/8 inch O.D. packer in a 7.3 inch diameter hole (30% expansion).

C. Expansion Ratio -- 23% based on the specification for a Lynes Production Injection Packer with 30% to 42% expansion ratio for a 5 3/4 inch O.D. tool and the Baker expansion ratios that range from 7% to 14%. Expansion ratio is the (casing I.D. -- tool run in diameter) ÷ (tool run in diameter).

D. Tool Bore Ratio -- 38% (packer thru hole ÷ casing I.D.). The 38% was selected based on the specifications for Baker Retrievable Casing Packer which has a tool bore ratio ranging from 33% to 47%.

E. Casing I.D. Tolerance -- ± .13 inches. Allowable tolerances on the casing inside diameters ranges from ± .017 to .135 for casing sizes up to 8.84 inches inside diameter and as high as ± .284 inches for inside diameters up to 12.715 inches. This data was taken from the specification guide for the Baker Model "G" Retrievable Packer.

F. Elastomer Support -- Discussions with various members of the oil tool industry led to the conclusion that the elastomer when subjected to higher temperatures will probably extrude through gaps larger then 10 mils. Therefore, the maximum allowable gap is set at 10 mils.

5.2.2 Design Rational

An inflatable concept was selected in order to meet the requirement for a large expansion ratio. Inflatable packers are presently being produced by Lynes, Inc. A simplified cross section of the Lynes Packer is shown in Figure 18. A review of this design and pictures of failed units (note, the Lynes unit was one of the better performers for LASL at 200°C) used in the LASL Hot Dry Rock Experiment pointed out two apparent areas requiring improvement in the design when the device is used for high temperature geothermal applications.

1. The elastomeric seal material itself is required to carry all the loads imposed on it by the differential pressure across the packer; i.e., there is not metal structure to prevent the rubber from extruding.

2. The elastomeric seal material is stressed in tension by the inflation stretching and also in shear because the reinforcing convoluted metal substructure bends and stretches to provide the larger inflated diameter while the elastomer only stretches. See Figure 19.

As the operating temperature increases causing the elastomer strength to reduce, these internal stresses in the elastomer exceed its strength resulting in packer failure.

FIGURE 18 -- LYNES PACKER

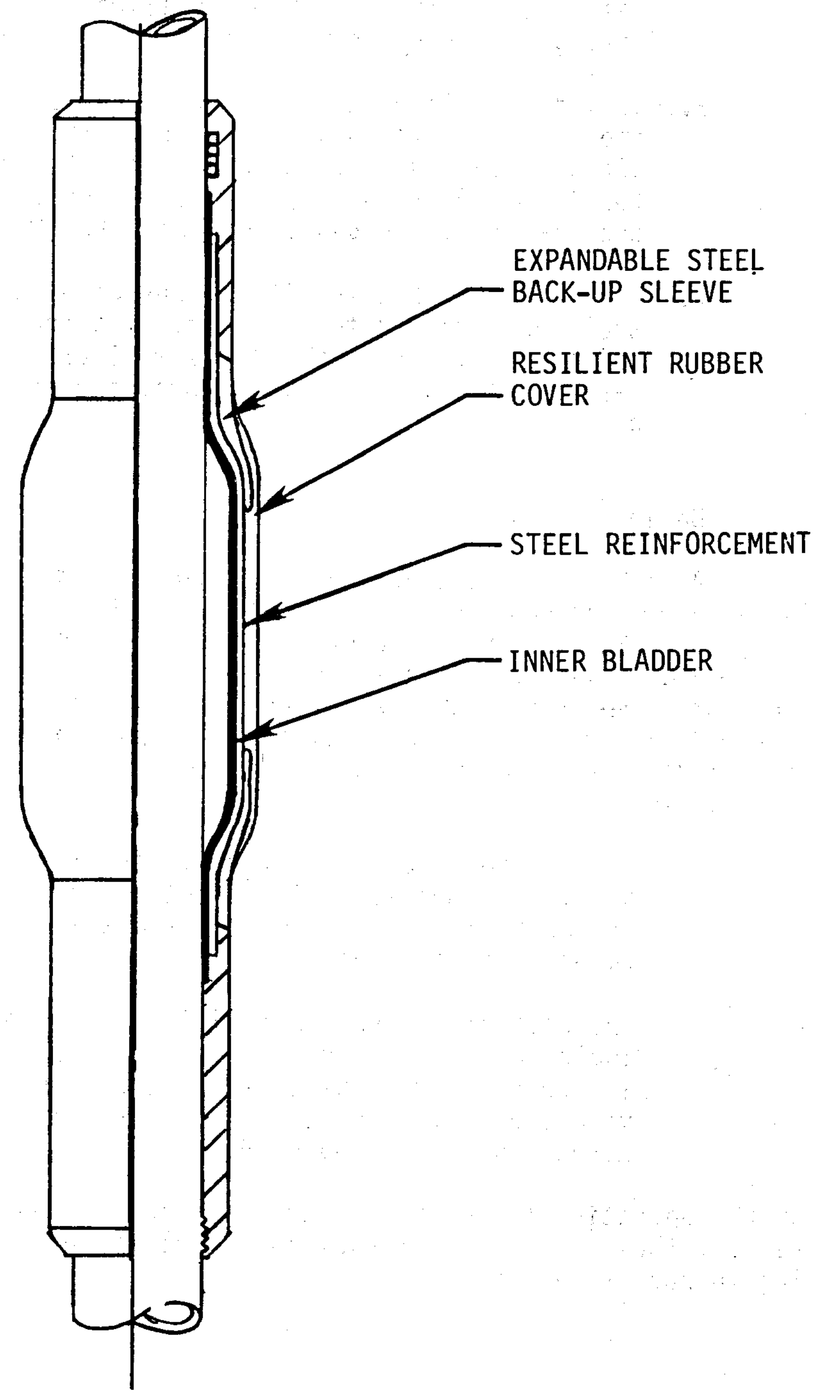
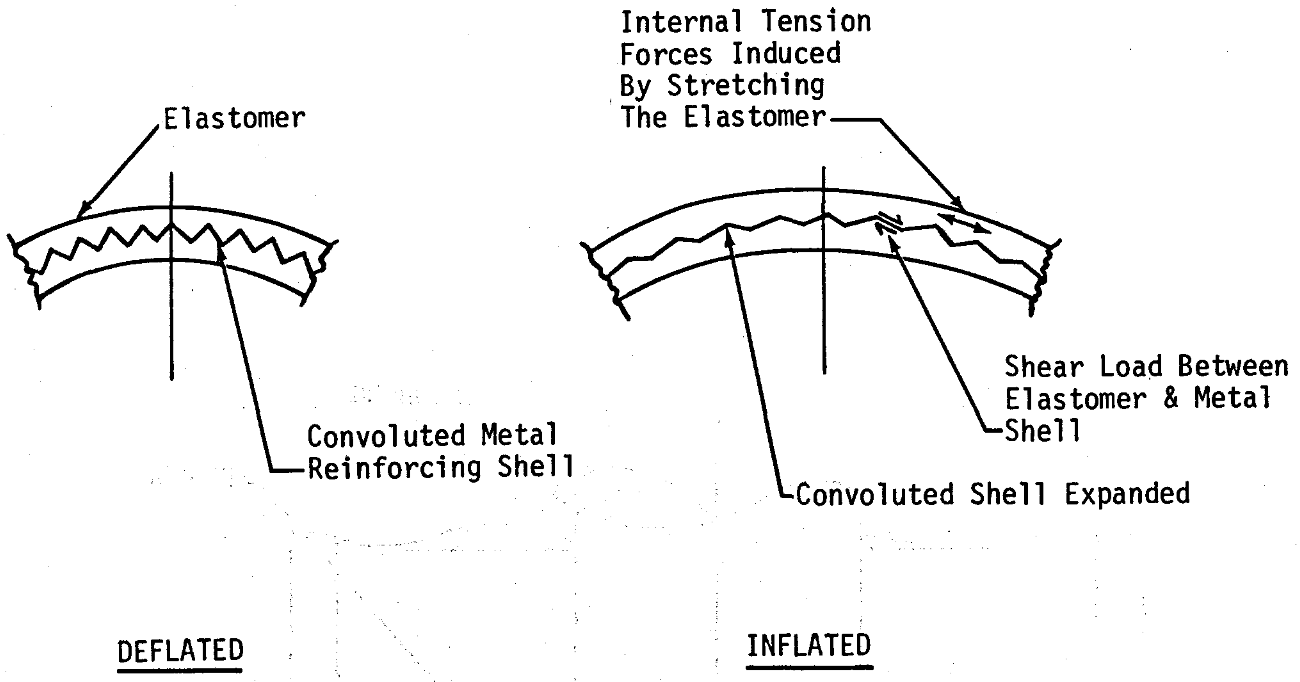


FIGURE 19-- SCHEMATIC OF LINES INFLATABLE ELEMENT



In order to maximize the temperature at which an elastomer can be used in a packer it is necessary to minimize, and preferrably eliminate, the stresses in the elastomer. This approach, regardless of the elastomer selected, provides a design that utilizes the elastomer's capabilities to their utmost. Therefore, in order to eliminate these stresses, two conditions must be incorporated in the design.

1. Complete backup of the seal with an expandable mechanical system that is capable of carrying all differential pressure loads and that eliminates all gaps or passages greater then 10 mils.

2. A bladder configuration that can be expanded by the inflatant with little or no stretching of the bladder and seal elastomer. That is, the bladder when inflated, will merely unfold to take the expanded diameter. Some stretching will be necessary to account for the normal tolerances on the casing inside diameter.

The major design problem in this task was to satisfy the first item. Several different ideas and concepts of expandable structural backup rings were evaluated, three examples are shown in Figures 20, 21, and 22. A variation of concept "C" (Figure 22) was eventually selected as the primary backup structure but with an inflatable actuator. This type of ring, although relatively gap free, still has gaps larger then 10 mils. In order to eliminate these gaps a metal fabric woven from Inconel wire was provided between the bladder elastomer and the backup ring. This was done to bridge the gaps and essentially eliminate all gaps larger then 10 mils.

FIGURE 20 -- BACK-UP RING CONCEPT 'A'

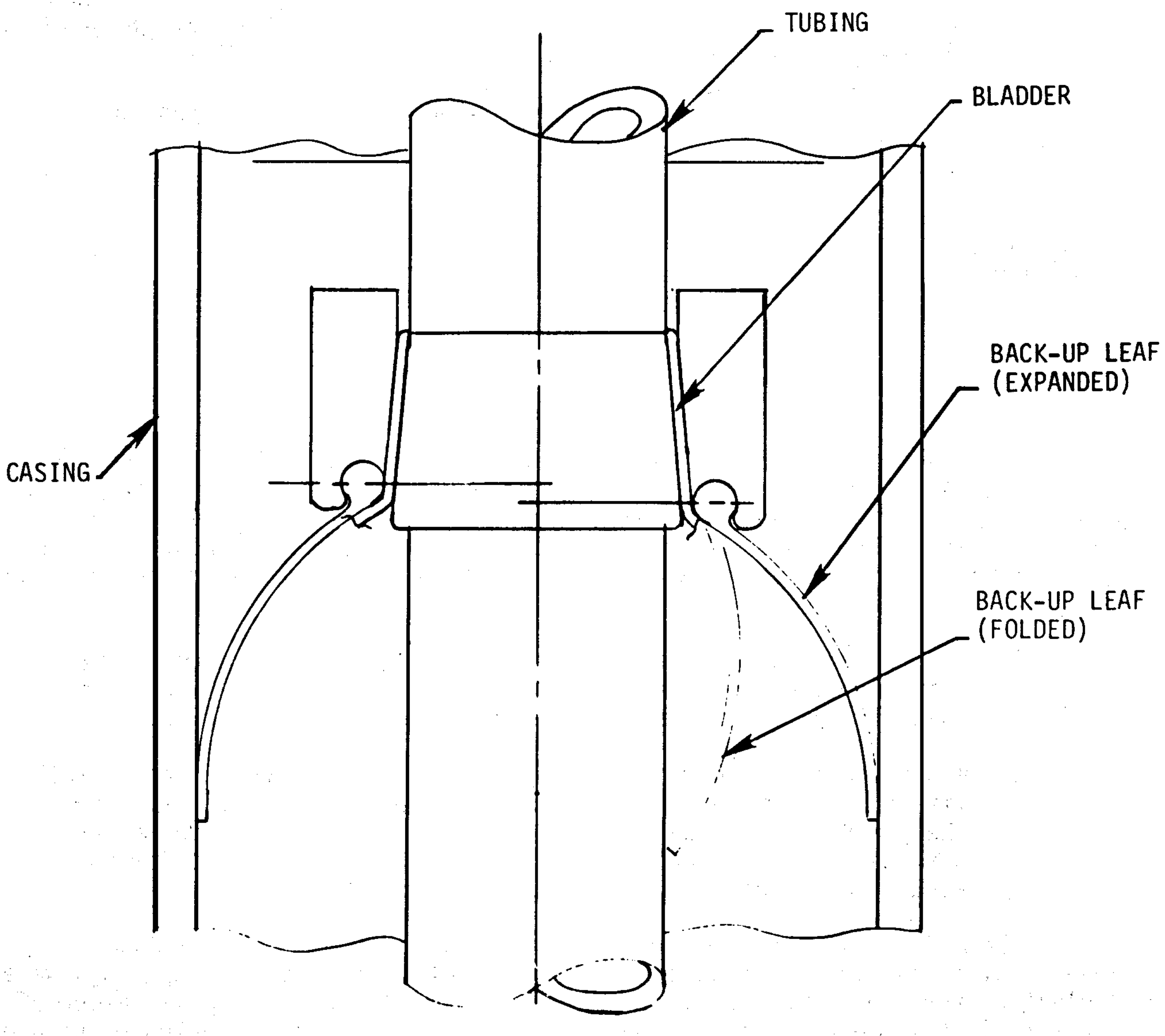


FIGURE 21 -- BACK-UP RING CONCEPT 'B'

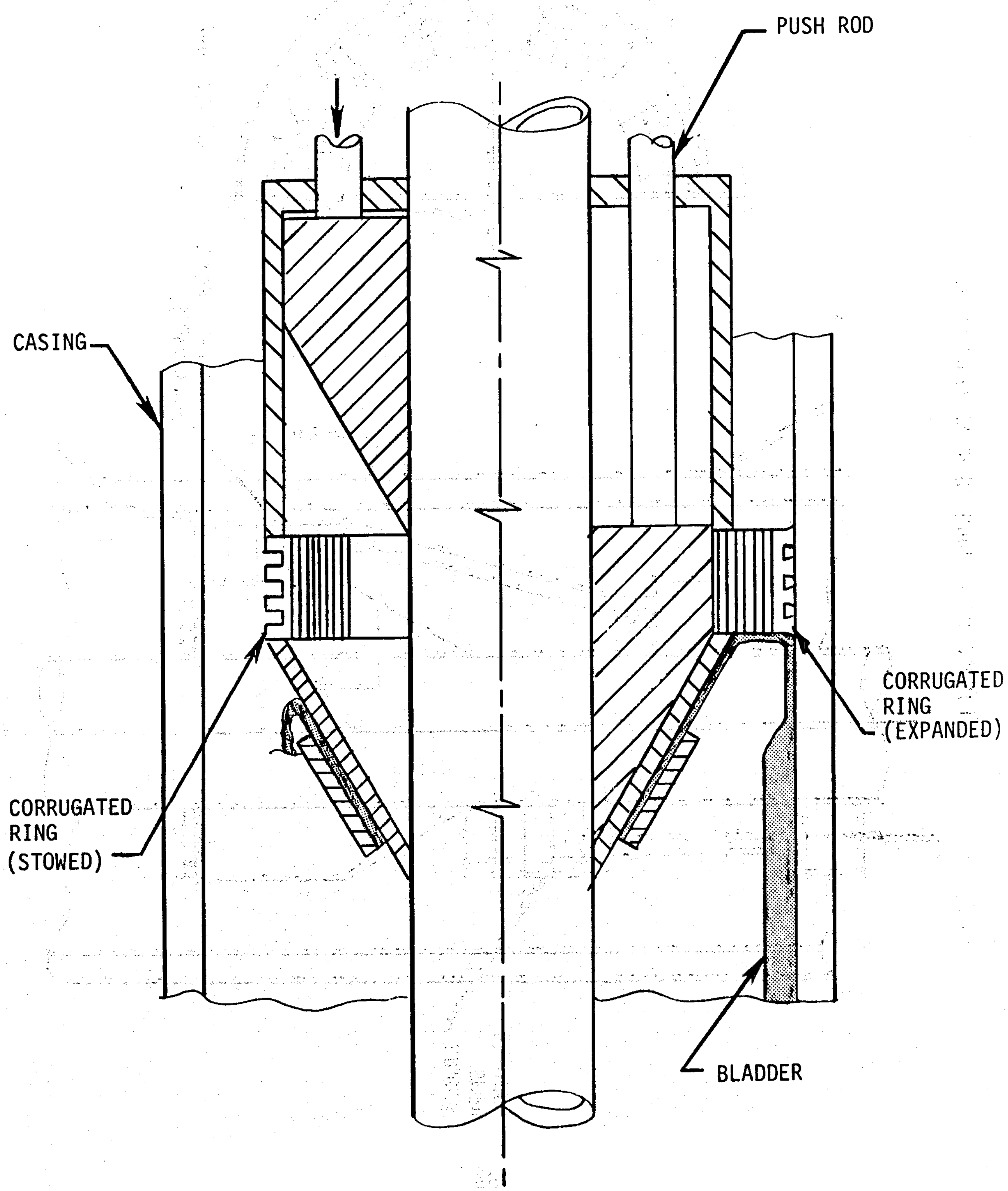
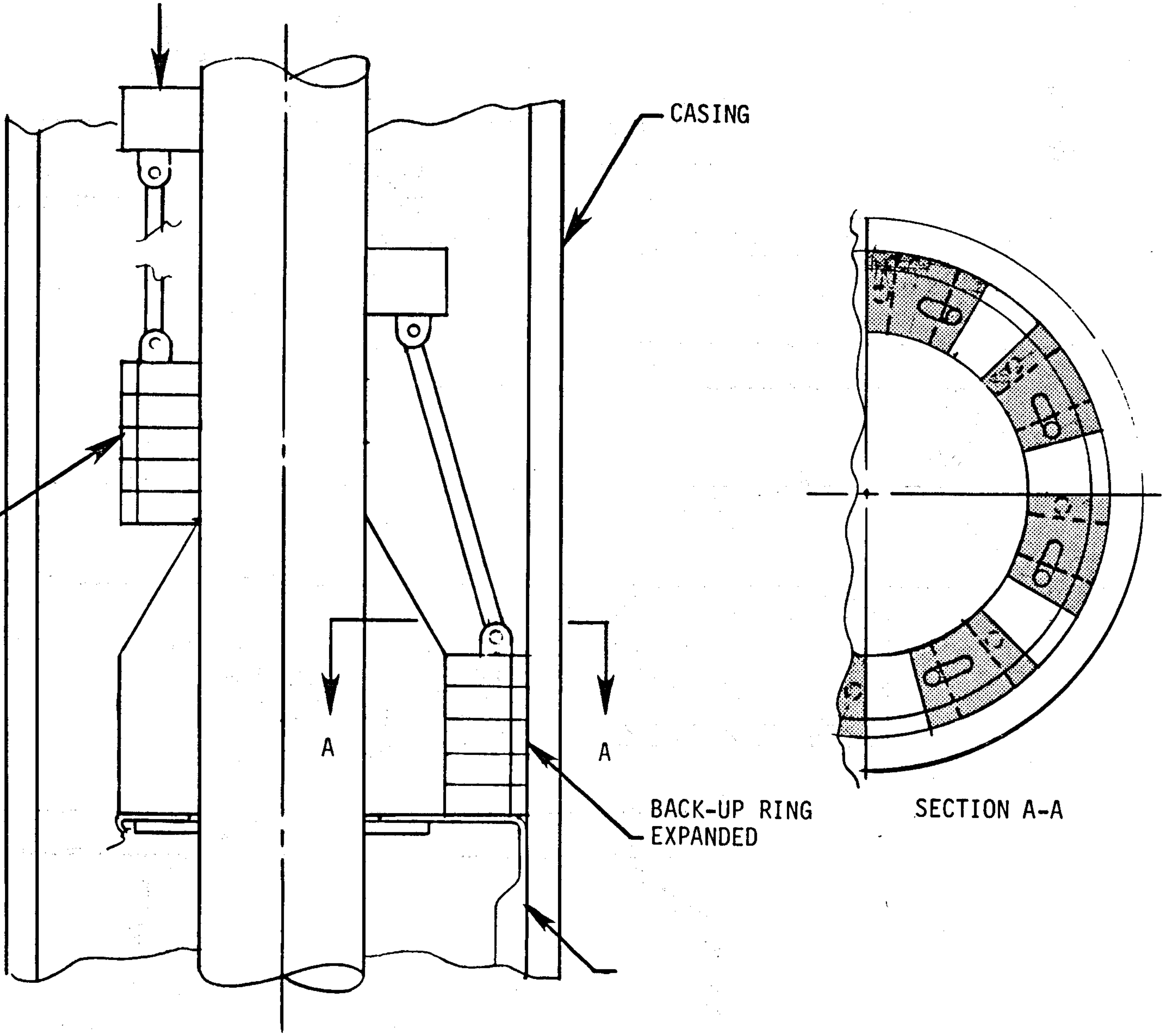


FIGURE 22 -- BACK-UP RING CONCEPT 'C'



The second item is more easily satisfied by simply fabricating the main bladder and seal in a convoluted configuration (Figure 23). The end portions of the bladder where the thick seal material is not required is made as thin as possible since this area requires the most bending and folding to retract it. These relatively tight folds will overstress the elastomer if the material is thick and required to make tight bends.

An 8 inch I.D. casing size was arbitrarily selected as the packer size for which a conceptual design would be developed that demonstrates the various ideas and concepts generated under this task. This packer conceptual design is shown in Figure 16 and the valve system design required to set, deflate, and reset the packer is shown in Figure 17.

5.2.3 Design Description

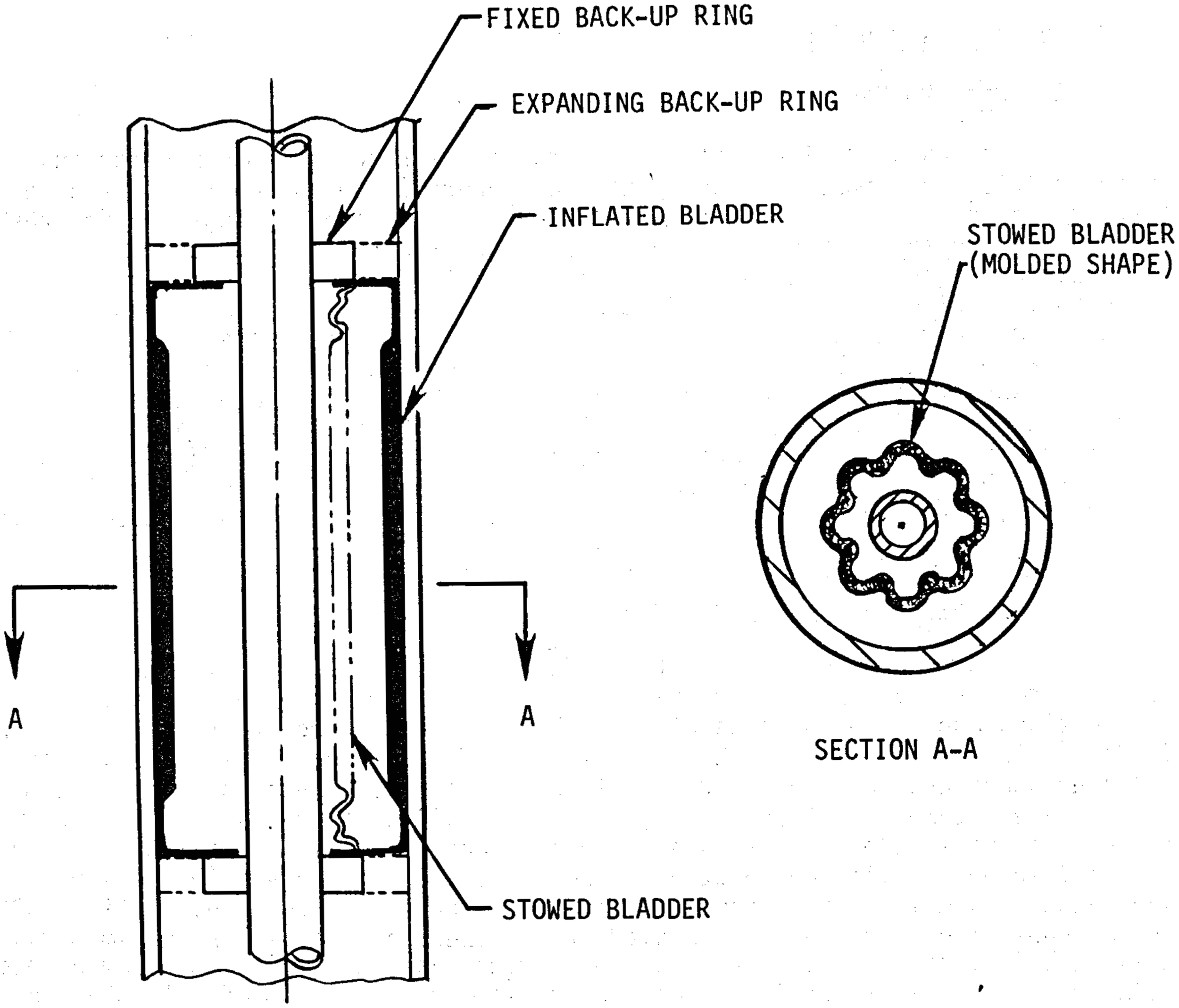
A. Back-Up Ring

The back-up ring system consists of six ring segments mounted on individual leaf springs. The segments are supported top and bottom by flanges that are an integral part of the packer mandrel. The leaf springs provide the force to return the segments to their stowed position when the packer is deflated for resetting. The segments are moved into position against the casing wall by the actuating bladder which is inflated prior to inflating the main packer seal bladder. As the ring segments are moved radially outward by the actuator bladder, gaps begin to develop between the segments. These gaps are bridged by six separate links that are attached to the segments by means of pins that slide in slots in the links (see Figure 16 - Section "BB" and Detail 'D'); all small gaps that exist (between sliding parts or between the ring segments and the casing) are bridged by the metal fabric woven of 6 mil Inconel wire (see Figure 16, Detail 'D'). The back-up ring system is the same at both the top and bottom of the packer.

B. "Minimum Stress" Bladder and Seal

The main bladder consists of Kevlar 29 (160,000 psi ultimate at 500^{0}F) reinforced elastomer that is capable of being inflated. The configuration of the end portions and method of attaching the bladder to the packer mandrel are shown in Detail 'D' of Figure 16. The end portions of the bladder are molded in the inflated shape and rely on the memory forces of the seal section to hold them in the deflated stowed position. The seal area consists of the basic Kevlar reinforced elastomer material overlayed with a thicker piece of the elastomer to provide sufficient resilience to develop the casing seal. The sealing section of the bladder is molded in a convoluted shape as shown in Figure 16, Section "CC". The expanded free diameter of the bladder is sized to just fit the minimum casing diameter, in this case 7.88 inch, if the casing was actually the maximum diameter, 8.13, then the bladder would be required to stretch a maximum of only 3%. The bladder is inflated only after the back-up rings have been deployed, therefore, there should never be any loads on the elastomer other than the pressure forces it is required to seal against.

FIGURE 23 -- PACKER CONCEPT



SECTION A-A

C. Valve System

The valve system shown in Figure 17 enables the packer to be resettable. The pressures selected to operate the system are somewhat arbitrary and depending on the applications can be adjusted to be considerably different. (NOTE: The inflation pressure of Lynes Packers is 2000 to 3000 psi). Inflating-deflating-reinflating sequence is described below:

1. Inflating Sequence -- Pump a 4000 psi ball down the drill string and pressurize to 430 psi to start the valve opening. The actuator bladder port is full open at 640 psi causing the back-up rings to set. Continued pressurizing fully opens the main bladder port at 850 psi and inflates the bladder. Pressurizing to 4000 psi shears the ball thru completing the setting procedure.

2. Deflating Sequence -- Pump a 930 psi ball down and pressurize to 850 psi. This pressure will cause both the actuator and main bladder ports to be uncovered and locked open. Continued pressurizing will shear the ball thru allowing the pressure to go to ambient.

3. Reinflating Sequence -- Pump a 4000 psi ball down and pressurize to 1300 psi. This pressure fully opens and unlocks the valve. Pressurizing to 3400 psi releases the ball detents and traps the pressure inside the bladders. Continued pressurizing shears the ball thru at 4000 psi. When reinflating both the actuator bladders and main bladder are pressurized simultaneously but since the actuator bladders have so much less volume they will be pressurized first assuring the setting of the back-up rings prior to inflation of the main bladder.

D. Detailed Calculations

Detailed calculations are shown in Appendix D.

5.3 CONCLUSIONS AND RECOMMENDATIONS

This study has resulted in a packer concept with three unique components, a) the elastomer back-up system, b) the "minimum stress" bladder configuration, and c) the valve system.

The first two items apply directly to the problem of employing an elastomer in a high temperature packer environment, the third item provides a means of mechanizing the first two. The shear ball valving system is an interesting approach and its potential warrants further detailed design/development effort. The back-up ring system concept and "minimum stress" bladder concept both provide potential solutions to the problem of elastomers failing at high temperature. The concepts developed in this study provide the potential for a packer design that develops the maximum capability of the elastomer regardless of the compound.

In view of the potential advantages of the packer concept developed during this study it is recommended that further study be instituted to further evaluate feasibility of the concept.

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APPENDICES

APPENDIX A

UNITED NATIONS NATIONS UNIES

POSTAL ADDRESS—ADRESSE POSTALE UNITED NATIONS, N.Y. 10017
CABLE ADDRESS—ADRESSE TELEGRAPHIQUE UNATIONS NEWYORK

REFERENCE: EC 333/1

2 December 1976

Dear Mr. Hirasuna,

Mr. Barnea has asked me to respond to your letter to him of 17 November 1976, requesting recommendations of devices in which the use of high temperature elastomers would advance the progress of geothermal energy development.

Certainly, we agree that down-hole formation packers would be at the top of our list. The lack of high temperature packers prevents us from making flow tests or drill-stem tests of specific productive zones below the first productive zone encountered by the drill. Consequently, we can only obtain flow test data from mixed zones, and our test data from deeper productive zones is restricted to cold water injection tests, which in many cases, do not give the data we need.

We rarely have need for casing packers as our completions are made either with slotted liners or open hole, rarely with perforated casing. If the industry ever reaches the stage of applying hydro fracturing techniques for well stimulation, casing packers would be required, but even in this case, the packers would not necessarily have to withstand high temperatures.

The development of packers for rotating drilling heads would be the second item on our list. We have found that aerated water is an ideal geothermal drilling fluid, but one of the disadvantages of the system is the need for frequent replacement of expensive drilling-head packers, which become brittle rather quickly due to the temperature of the return fluids. For the same reason, blow-out preventor rubbers also require more frequent replacement than normal, but not as frequent as the rotating packers.

Yours truly,

J. R. McNitt
Technical Adviser
Energy Section
Energy and Mineral Development Branch
Centre for Natural Resources,
Energy and Transport

Mr. Alan R. Hirasuna
GEM Program Manager
Garde, Inc.
1555 Placentia Avenue
Newport Beach, California 92660

cc: Mr. Joseph Barnea, UNITAR

APPENDIX B

UNIVERSITY OF CALIFORNIA
LOS ALAMOS SCIENTIFIC LABORATORY
(CONTRACT W-7405-ENG-36)
P.O. BOX 1663
LOS ALAMOS, NEW MEXICO 87545

IN REPLY
REFER TO: G-DOT
MAIL STOP: 570

September 28, 1977

Mr. Alan R. Hirasuna
L'Garde, Inc.
1557 Placenta Avenue
Newport Beach, CA 92660

Dear Alan:

This is another "chapter" in the high temperature formation packer story. I have enclosed a brief description of our most recent experience with the Lynes, Inc. inflatable packer system. As you will note these units operated satisfactorily at 180°C. Indeed Lynes has indicated that they will attempt to develop a system for 200° - 300°C service. I still consider that to be a difficult and risky undertaking! As a result we will very likely initiate an evaluation of high temperature compression packer systems (see enclosed copy of letters to Halliburton Services and Guiberson Dresser). I wonder if you have made any "breakthroughs" on your project in the elastomer area? Do you have a report on your initial work completed yet?

Our next drilling and fracturing needs may be as much as a year to a year and a half away, so we have some time yet to develop a source for a suitable high temperature formation packer system.

For your information I have enclosed:

(1) LASL Hot Dry Rock Geothermal Project High-Temperature Inflatable Packers, GT-2 Redrill
(2) Physics Today January 1977 Vol. 30 No. 1
(3) LASL Mini-Review 77-8
(4) LA-6906-MS
(5) LA-6889-MS
(6) ERDA-DGE Programs in Logging Technology (1976-77)

The last item lists the FY 76-77 ERDA-DGE Logging R&D efforts and I am curious if you are aware of the last entry and if anything significant has resulted from the Hughes work?

We appreciate your continued interest in our HDR geothermal project and want to continue to urge L'Garde toward a successful development of a high temperature elastomer -- there is still a great need throughout the geothermal industry as well as for many of the ERDA R&D projects.

Very truly yours,

John C. Rowley

John C. Rowley

JR:kd

Encl: a/s

cc: A. Blair/R. Brownlee w/o encl.
G. Nunz w/o encl.
J. Hill w/o encl.
R. Pettitt w/o encl.
M & R (2)
File

APPENDIX C

L'GARDE, INC.

1555 PLACENTIA AVENUE
NEWPORT BEACH, CALIFORNIA 92663
TELEPHONE (714) 546-4671 & (714) 645-4880

Gentlemen:

L'Garde, Inc. is contracted by the Energy Research and Development Administration (ERDA) Geothermal Division to develop high temperature elastomers or rubber materials for application to equipment for exploration, drilling, assessment, and production of geothermal resources. As a minor part of this effort L'Garde is tasked to evaluate five (5) currently available, commercial, high-temperature elastomers used for these applications as O-ring seals, packer seals, cable feed-through seals, etc. The purpose of this letter is to initiate the process whereby representative samples of the currently employed, commercially available elastomers can be obtained.

Evaluation of the elastomers will be accomplished using laboratory tests simulating geothermal well conditions. Temperatures may be as high as 260°C (500°F), pressures as high as 5000 psi, differential pressures across the seal as high as 5000 psi, for a duration on the order of 24 hours. A testing procedure, yet to be finalized, will be used whereby quantitative relative ranking of all samples will be accomplished. For example, all elastomers could be exposed to 260°C and the time to failure measured. The constituency of the synthetic geothermal fluid that the samples will be exposed to is as follows:

H_2O	balance
H_2S	300 ppm
NaCl	25,000 ppm
CO_2	1,000 ppm
pH	5-7

In order to accomplish this task in as efficient, comprehensive, and fair manner as possible, we are herein initiating the process by distributing the enclosed questionaire to as broad a distribution as practical. Based on these responses we will be requesting samples to be submitted for testing. We will be testing five materials judged to represent the best available, and we will choose the samples to be tested in a manner which allows consideration of as many base elastomers as practical which have high temperature potential which is at least as good as Nitrile or Buna N.

Based on the responses to question 9 on the questionaire, we will either label all or none of the data with the associated Company name. In no instance will we violate a Company's request to remain confidential. ERDA would prefer to use company names to provide maximum practical application of the data, so if a representative number of companies allow linking their Company name with the data we will chose our samples from that group. If the majority of the companies wish to remain confidential, we will publish data in a coded format and each company whose sample is tested will be informed as to their own and only their own identification code so they can identify their data. The data will include the following identification: 1) company name or code, 2) base elastomer (eg. Nitrile), and 3) application (eg. packer chevron seal). The data will be evaluation measurements taken by L'Garde.

If you are interested in pursuing the opportunity to have your material evaluated for geothermal application, please fill out the enclosed questionaire. The questionaires to be taken under consideration must be received by L'Garde by 4:30 PM, March 23, 1977.

Sincerely,

Alan R. Hirasuna
Geothermal Environmental Materials
Program Manager

ARH:pw
Enclosure

Questionaire Regarding Your Best High Temperature Elastomer for Geothermal Applications

	Yes	No
1. Do you wish to supply a sample of your highest temperature elastomer, on the order of 1 to 2 lbs. (all Kalrez to be tested will be obtained directly from du Pont)?	___	___

2. What is your base elastomer, eg. Nitrile or Buna N, Ethylene Propylene, Viton, etc.? The base elastomer will be used to identify the published test data.

____

____

____

____

3. For what applications has the elastomer been successfully used, eg. packer casing seal, packer formation seal, packer internal O-ring seal, etc.?

____

____

____

____

4. What is the time, temperature and environment that the seals in 3) operate satisfactorily?

____

____

____

____

Yes No

5. Are you willing to supply at no cost uncured stock with curing instructions should we have a specific mold to fabricate parts to fit our fixture? If NO, please explain. ___ ___

____

____

____

____

6. Are you willing to supply at no cost cured parts made to our dimensional requirements? If NO, please explain. ___ ___

____

____

____

____

7. How much lead time do you need to deliver the required material?

____

____

____

____

8. Do you have any suggestions that may improve this testing? If YES, please state. ___ ___

____

____

____

____

9. Would you object to having your company name published, identifying the test data? Please state feelings. ___ ___

____

____

____

____

[illegible]0. Person to Contact ______________________________

Company ______________________________

Address ______________________________

City/State/Zip ______________________________

Phone No. (   ) ______________________________

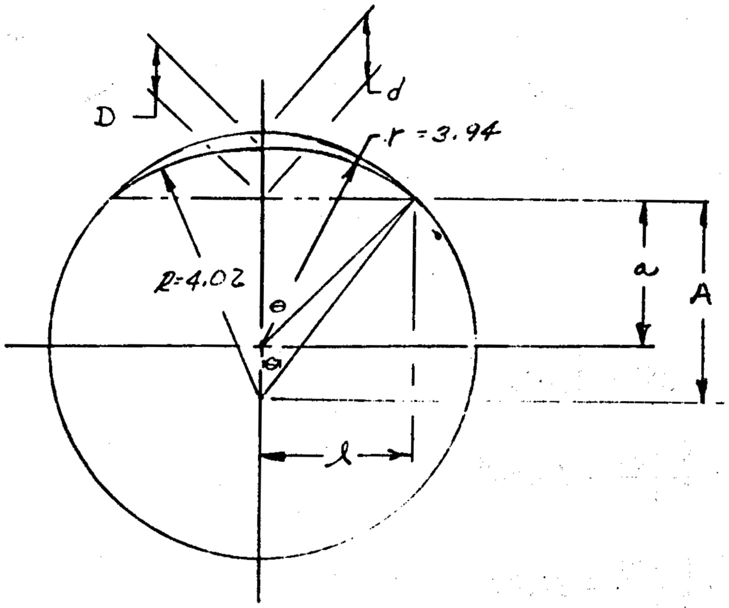
11. Please send any brochures or information describing the elastomer and its performance which may assist us in choosing representative candidates. As you might imagine, it will be very difficult to choose between the various Nitrile formulations each with its own superior proprietary ingredient.

APPENDIX D

PACKER IMPROVEMENT CONCEPTUALIZATION DESIGN CALCULATIONS

A. Maximum Gap

The maximum gap in the back-up ring will exist between the ring and the casing. Since the ring will be made to fit the nominal case diameter when expanded a gap will exist when the casing diameter is either more or less then nominal. The maximum gap is calculated as follows:



Maximum Gap = d-D

$d = r - a$ $\qquad\qquad\qquad \theta = \arc\sin \frac{\ell}{r}$

$a = r \cos \theta$

$d = r(1 - \cos \theta)$

$D = R - A$

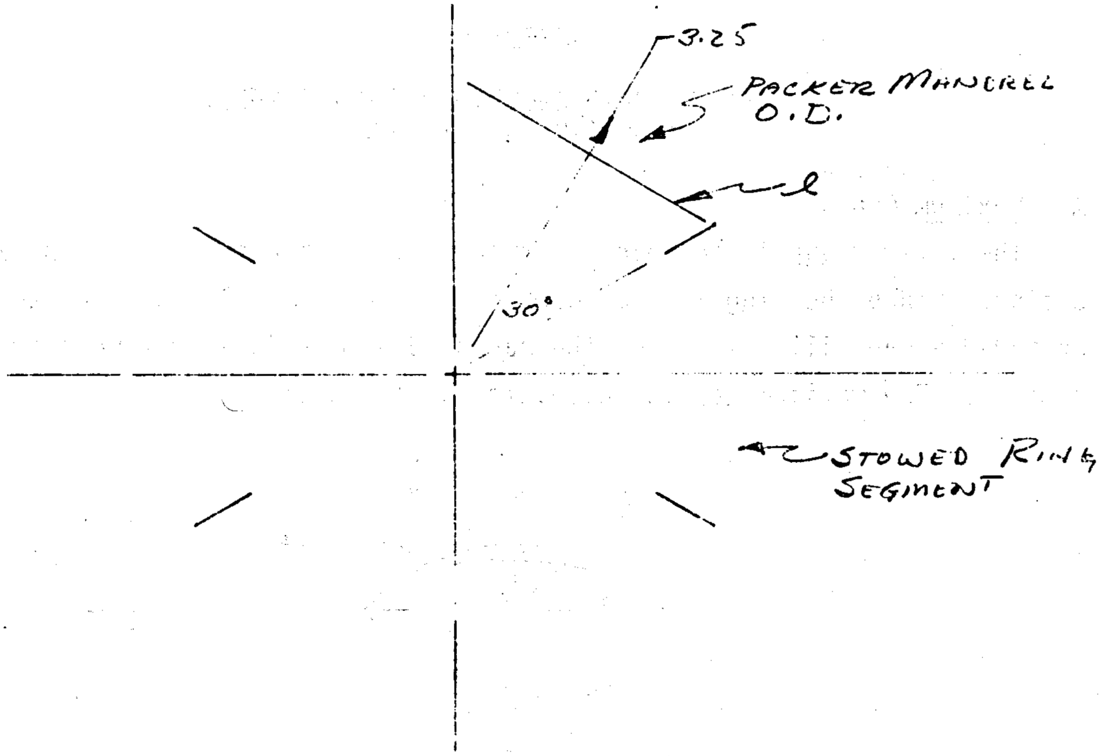
$A = R \cos \Theta$

$D = R(1 - \cos \Theta)$ $\qquad\qquad \Theta = \arc\sin \frac{\ell}{R}$

R = 4.02 high side of segment tolerance.

r = 3.94 low side of casing tolerance.

ℓ is determined from the stowed configuration of the back-up ring.



$\ell = 3.25 \tan 30^{0} = 1.876$

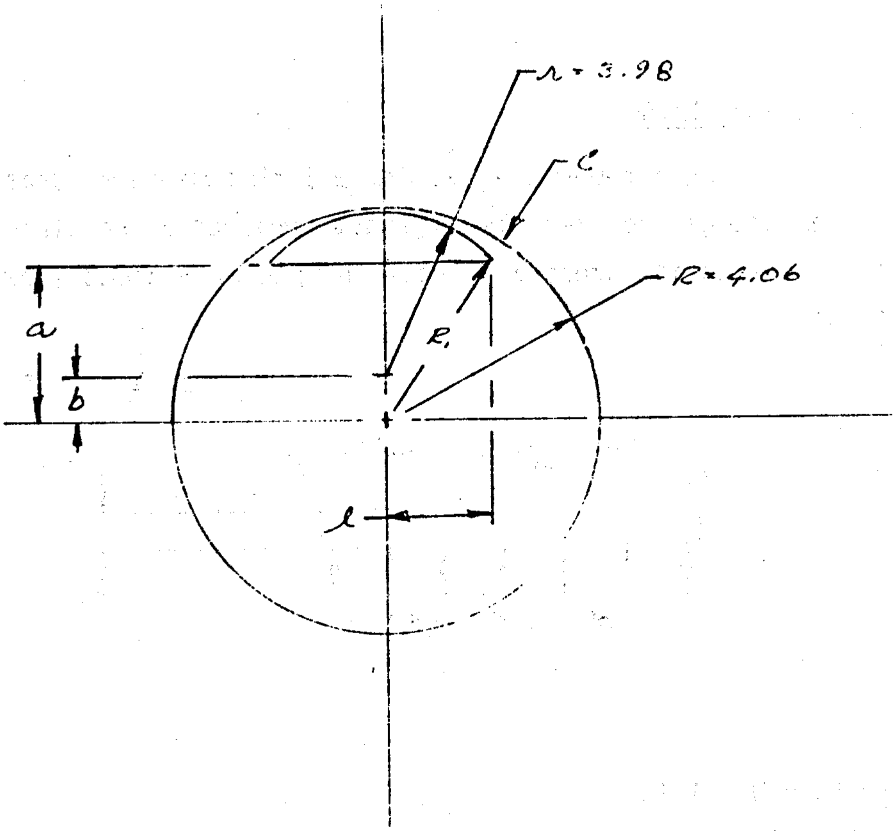
$\theta = \text{arc sin } \dfrac{1.876}{3.94} = 28.44^{0}$

$\Theta = \text{arc sin } \dfrac{1.876}{4.02} = 27.818^{0}$

$d = 3.94\ (1\text{-}\cos 28.44^{\circ}) = .4755$

$D = 4.02\ (1\text{-}\cos 27.818^{\circ}) = .4646$

Gap = .4755 - .4676 = .0109



Max Gap = C = $R-R_1$

r = 3.98 low side of segment tolerance

R = 4.06 high side of casing tolerance

$$R_1 = \sqrt{(a+b)^2 + \ell^2}$$

b = R-r = 4.06-3.98 = .08

ℓ = 1.876

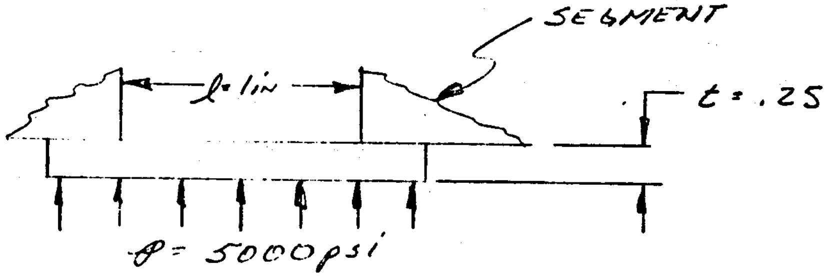
$$a = \sqrt{r^2-1^2} = \sqrt{3.98^2-1.876^2} = 3.510$$

$$R_1 = \sqrt{(3.510 + .08)^2 + 1.876^2} = 4.05$$

Gap = 4.06-4.05 = .01

B. Back-Up Ring Link

The small link between the bladder and ring segments that functions as a bridge over the gap between the expanded segments is required to resist the 5000 psi differential pressure across the packer without shearing out or undue deflection.



Link Width = W = 1 in.

Link Material is Inconel 718.

σ_{yield} = 150,000 psi

σ_{ult} = 180,000 psi (MIL-HNDBK-5, page 6-52)

Shear

$$\sigma_{shear} = \frac{p \ell w}{2 t w} = \frac{5000}{2(.25)} = 10,000 \text{ psi} -(\text{OK})$$

Bending

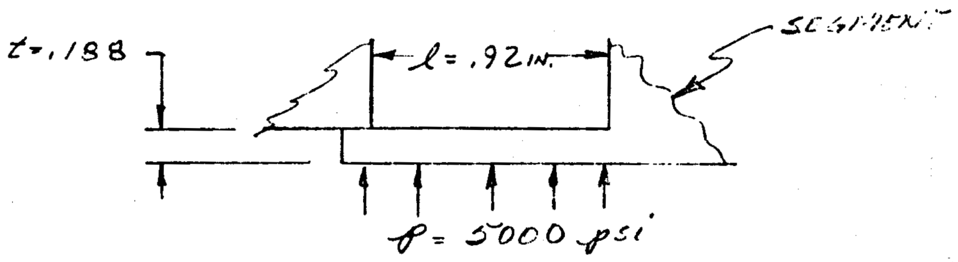
$$\sigma_{bending} = \frac{Mc}{I} \quad \frac{3 p \ell^2}{4 t^2} = 60,000 \text{ psi} -(\text{OK})$$

Deflection

$$y = \frac{15}{96} \frac{p \ell^4}{E t^3} = .0017 \text{ in} -(\text{OK})$$

C. Vertical Gap Bridge

As the back-up ring expands the vertical gap between segments must also be bridged to prevent failure of the actuator bladder. This bridge must also be capable of resisting 5000 psi.



Bridge Height = h = 4 in.

Bridge Material is Inconel 718.

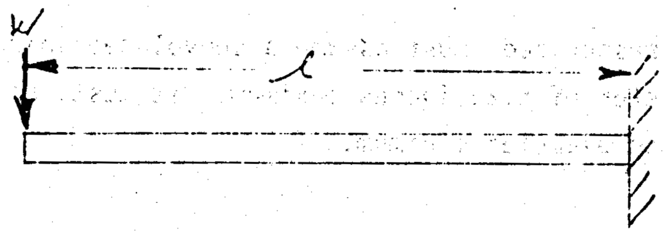
Shear

$$\sigma_{yield} = \frac{pl}{2t} = \frac{5000(.92)}{2(.188)} = 12234 \text{ psi} -(\text{OK})$$

$$\sigma_{bending} = \frac{Mc}{I} = \frac{3}{4}\frac{pl^2}{t^2} = \frac{3}{4}\ \frac{(5000)\ (.92^2)}{(.188)^2} = 89803 \text{ psi} -(\text{OK})$$

D. Leaf Spring Requirements

The leaf spring provides the force necessary to return the back-up ring segment to its stowed position when the actuator bladder is deflated. It is desirable to have this return force very high in order to overcome friction in the links at the bottom of the segment and in order to be less affected by the drilling mud. The leaf spring is required to deflect one inch without yielding.



ℓ = 12 in

y = deflection = 1 in.

W = deflection force (LBS)

t = thickness (in)

w = width = 1 in.

Material is Inconel 718

σ_{yield} = 150,000 psi

σ_{ULT} = 180,000 psi

$$\sigma = \frac{Mc}{I} = \frac{W \ell c}{I} \qquad c = t/2$$

$$y = \frac{1}{3} \frac{W \ell^3}{EI}$$

$$y = \frac{\sigma \ell^2}{3cE} \; ; \quad c = t/2 \quad \text{therefore} \quad t = \frac{2\sigma \ell^2}{3\,y\,E}$$

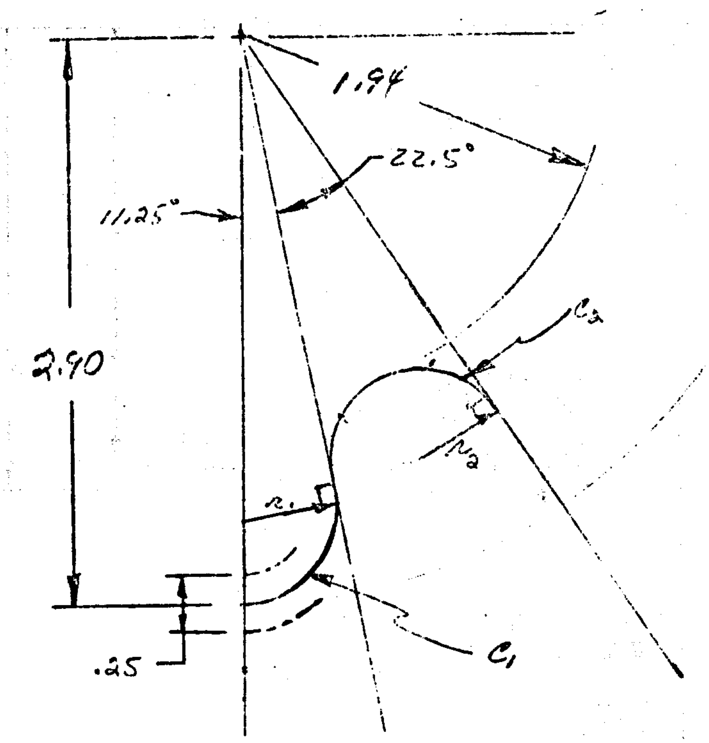
Use σ = 120,000 psi

$$t = \frac{2(120{,}000)\ (12^2)}{3(1)\ (30 \times 10^6)} = .384 \text{ in.}$$

$$W = \frac{\sigma I}{\ell c} = \frac{\sigma w t^2}{6 \ell} = \frac{(120{,}000)\ (1)\ (.384^2)}{6(12)} = 245 \text{ LBS}$$

E. Bladder Molded Shape

The bladder, when unpressurized, must assume a convoluted shape in order to reduce to an outside diameter of 6.25 inches maximum. It must, however, be able to expand to 7.88 inch diameter minimum.



$$\sin 11.25^{\circ} = \frac{r_1}{2.9 - r_1}\ ; \quad r_1 = \frac{2.9 \sin 11.25^{\circ}}{1 + \sin 11.25^{\circ}}$$

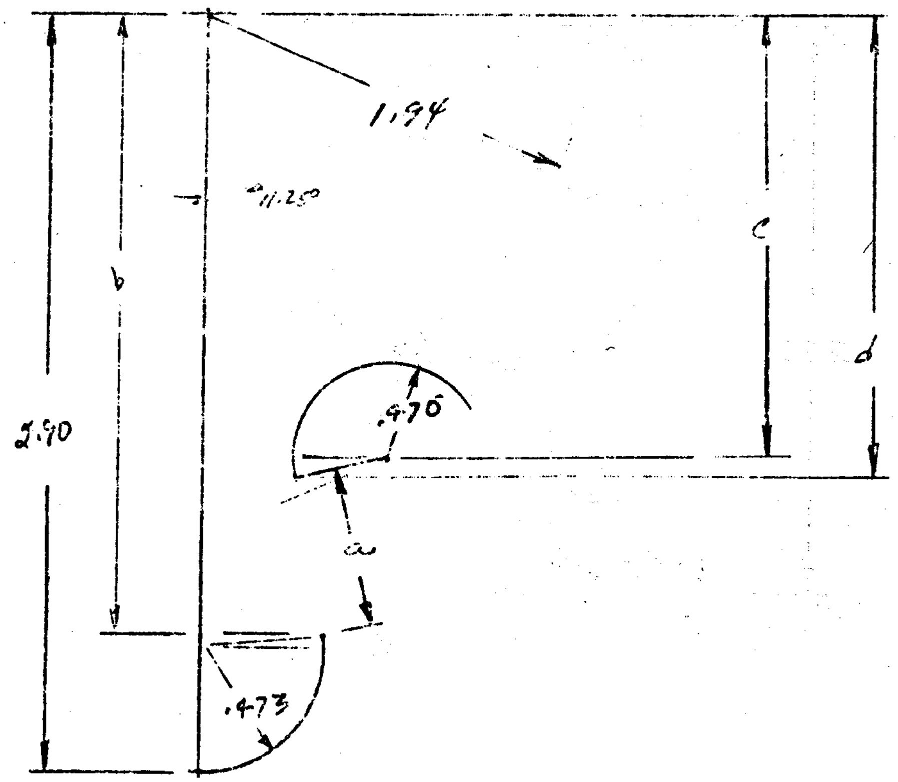
$$r_1 = .473$$

$$c_1 = \left(\frac{90 + 11.25}{360}\right)(2\pi)(.473) = .837$$

$$\sin 11.25^{\circ} = \frac{r_2}{1.94 + r_2}\ ; \quad r_2 = \frac{1.94 \sin 11.25^{\circ}}{1 - \sin 11.25^{\circ}}$$

$$r_2 = .470$$

$$c_2 = \left(\frac{180 - 2(11.25)}{360}\right)(2\pi)(.470) = 1.293$$



$$b = 2.90 - .473 - .473 \sin 11.25^0 = 2.335$$

$$c = (1.94 + .470) \cos 22.5^0 = 2.227$$

$$d = c + .470 \sin 11.25^0 = 2.319$$

$$a = \frac{b-d}{\cos 11.25^0} = .0166$$

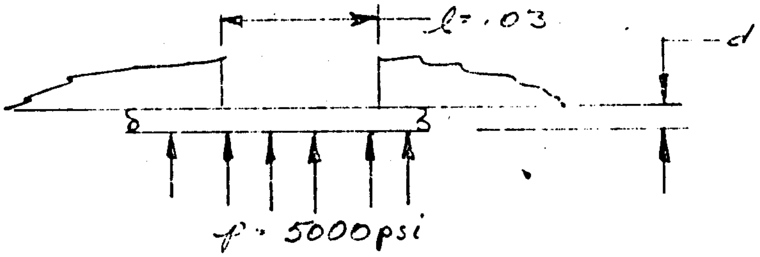
One complete cycle then is equal to $2(.837) + 1.293 + 2\,(.0166) = 3.00$ which gives for the expanded diameter of the outside of the bladder $\frac{8(3.00)}{\pi} + 2(.125) =$ 7.89 which is .01 morethen required.

F. Metal Fabric Wire Diameter

The metal fabric will be designed to span a gap of .03 under a pressure of 5000 psi. The fabric will be woven of Inconel 718 wire

$\sigma_{yield} = 150{,}000$ psi

$\sigma_{ult.} = 180{,}000$ psi



Assume 6 MIL wire

$$\sigma_{Shear} = \frac{p\,\ell\,d}{2\,\frac{\pi}{4}d^2} = \frac{2p\ell}{\pi\,d}$$

$$\sigma_{Shear} = \frac{2\,(5000)\,(.03)}{\pi\,(.006)} = 15900 \text{ psi --(OK)}$$

$$\sigma_{Bending} = \frac{Mc}{I} \qquad M_{max} = \frac{1}{24}\,pd\ell^2$$

$$I = \frac{1}{4}\,\pi\,(d/2)^4$$

$$c = d/2$$

$$\sigma_{Bending} = \frac{(\frac{1}{12}\;p\,\frac{d}{2}\,\ell^2)\,(\frac{d}{2})}{\frac{1}{4}\,\pi\,(d/2)^4} = \frac{4}{3}\,\frac{p\ell^2}{\pi\,d^2}$$

$$\text{Bending} = \frac{4\,(5000)\,(.03)^2}{3\,\pi(.006)^2} = 53{,}000 \text{ psi --(OK)}$$

This calculation was made only to determine if the wire size is approximately correct. The small diameter of the wire and small gap probably reduces the accuracy of the calculation to that of an approximation at best. The optimum diameter should be determined experimentally.

*U.S. GOVERNMENT PRINTING OFFICE: 1978-740-306/9428. Region 4.