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FINAL REPORT

OF

IMPACT REACTIVITY OF MATERIALS
AT VERY HIGH OXYGEN PRESSURE

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812
(CONTRACT NO. NAS8-35135)

May 19, 1983

PREPARED BY

SCIENTIFIC SERVICES, INC.
500 WYNN DRIVE SUITE 508 HUNTSVILLE, ALABAMA 35805 (205) 837-9731
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H. W. Connor, P.E.; J. G. Minchey; Roy Crowder, Ph.D.; Rod Davidson, Ph.D.
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500 WYNN DRIVE SUITE 508
HUNTSVILLE, ALABAMA 35805
ABSTRACT

Scientific Services, Inc., under Contract NAS8-35135, evaluated the requirements for impact testing of materials in an oxygen atmosphere at pressures from 82.7 MPa (12,000 psi) to 172 MPa (25,000 psi). The current NASA/MSFC impact tester system was evaluated for potential pressure increases from the present 69 MPa (10,000 psi) to 82.7 MPa (12,000 psi). The low pressure oxygen and nitrogen systems, the impact tower, the impact test cell, and the high pressure oxygen system were evaluated individually. Although the structural integrity of the impact test cell and the compressor were sufficient for operation at 82.7 MPa (12,000 psi), recent studies revealed possible material incompatibility at that pressure and above.

Scientific Services adopted the philosophy that if a component should be replaced for 82.7 MPa (12,000 psi) operation the replacement should meet the final objectives of 172 MPa (25,000 psi). Recommended changes in the system include: use of Monel 400 for pressures above 82.7 MPa (12,000 psi); use of bellows to replace the seal in the impact tester; use of a sapphire window attached to a fiber optic for event sensing; and use of a three diaphragm compressor. Redesign of the system will also enable incorporation of updated electronic controls and data handling, and improved remote control operation.
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I. INTRODUCTION

This study was initiated to investigate the requirements for increasing the operating pressure and temperature of the ABMA configured (1, 2, 3, 4, 5) LOX/GOX 69 MPa (10,000 psi) materials mechanical impact tester currently in use at the Marshall Space Flight Center (MSFC) (Figure 1). This investigation will consider the additional refinements necessary to increase the pressure to 172 MPa (25,000 psi) and 400°C, either incrementally or by one step.

Oxygen reactions with materials generally increase with pressure and can be self-igniting and violent under certain conditions. To qualify materials as satisfactory for use under programmed gaseous and liquid oxygen conditions, the materials must be tested at elevated pressures and temperatures. Maximum National Aeronautics and Space Administration (NASA) propulsion systems operating pressures have been in the 55.2 MPa (8,000 psi) range. With the planned utilization of liquid and gaseous oxygen at pressures in the 103 MPa (15,000 psi) range in advanced propulsion systems, materials compatibility data in the high pressure environment is critical to the risk evaluation and design decisions in propulsion technology. The reactivity of materials at increased oxygen pressures cannot adequately or safely be projected from test results at lower pressures.

Acceptance test methods for materials in an oxygen environment are essentially in what could be called the third generation. The ABMA dropweight tester, originated in the 1940's and utilized in the 1950's, was refined and standardized in the 1960's resulting in the issuance of MSFC-SPEC-106B and the similar ASTM 02512-66T.

Advanced engine technologies proposed for the 1970's required higher oxygen pressures and the resultant second generation impact testers to qualify candidate materials for oxygen service at pressures
Figure 1. Impact Tester
to 69 MPa (10,000 psi). Two different 69 MPa (10,000 psi) mechanical impact testers similar to the ABMA-MSFC design were developed by the Johnson Space Center (JSC), White Sands Test Facility (WSTF) and by MSFC/Rockwell International, Rocketdyne Division. The MSFC/Rockwell developed mechanical impact tester is being used at MSFC. Systems to evaluate the compatibility of materials in LOX and GOX in the 82.7 MPa (12,000 psi) to 172 MPa (25,000 psi) range could be considered the third generation of testers.

A mechanical impact tester at WSTF in Las Cruces, N.M., was designed for use at 138 MPa (20,000 psi), but is not routinely used at that level. It differs significantly in design and operation from the MSFC/Rocketdyne tester at MSFC. There is also a pneumatic impact tester at WSTF that is operated routinely at 82.7 MPa (12,000 psi). There are other approaches to oxygen compatibility in development such as frictional rubbing and particle impact at WSTF and laser induced combustion at The National Bureau of Standards.

Marshall Space Flight Center issued contract NAS8-35135 to Scientific Services, Inc., (SSI) to evaluate the possibility of modifying the present MSFC impact tester for operation at 82.7 MPa (12,000 psi), to conduct literature and engineering studies to determine the requirements for the design of an impact tester to operate at 82.7 MPa (12,000 psi), and to determine the extent of currently available hardware for working up to the 172 MPa (25,000 psi) range.

A comprehensive literature survey was conducted. Although published material was available on the general subject of high-pressure technology, most of it concerned research with solids, liquids, and gases other than oxygen. Only a few articles addressed pressures above 69 MPa (10,000 psi) or gave information directly related to high pressure oxygen reactions.

The primary sources containing information on oxygen and its associated materials and components are Schwinghamer and Key (1974), Bransford, Bryan, Frye, and Stohler (1980), Hust and Clark (1974),
White and Ward (1966), Baum, Goobich, and Trainer (1962), Attwood and Allen (1971), Dean (1961), Guter (1967), Kinzey (1970), Kirschfeld (1961), (1965), (1967), (1968), NASA-MSC-02681 (1972), Bond (NASA-JSC, in publication), and Johnston (NASA-JSC, in publication). These are listed in the appendix. Other articles which provide helpful information about materials, equipment, instrumentation, experimental techniques, and safety procedures are also listed.

One of the initial objectives of SSI's study was to assess the current high pressure 69 MPa (10,000 psi) oxygen impact test equipment at MSFC to determine the extent of modifications necessary to increase test pressure limits to 82.7 MPa (12,000 psi).

SSI adopted the following modification philosophy. If any of the present MSFC impact tester system requires modification or replacement, the replacement or modification should have the capability of reaching the ultimate goal of impact testing at 172 MPa (25,000 psi). Obviously, initial cost would be a consideration; however, the cost of maintaining one system at 82.7 MPa (12,000 psi), another at 103 MPa (15,000 psi), and others in increments up to 172 MPa (25,000 psi) could be substantially more.
II. The Current MSFC Impact Tester System

The philosophy of this study has been directed towards modifications essential for operation in the 82.7 MPa-172 MPa (12,000-25,000 psi) pressure range and temperatures from cryogenic to 400°C. This study concept was not intended or directed in any way towards changing or modifying the current concept for impact testing of materials.

The initial objective was to evaluate the present MSFC Impact Tester System (Figure 1) to determine which portions, if any, could be used at 82.7 MPa (12,000 psi). The system was divided into its various operational groups and each one evaluated separately.

**HIGH PRESSURE OXYGEN SOURCE**

The current impact tester high pressure oxygen source is an Aminco-Corblin (which is now Superpressure, Inc.) motor driven, two-stage diaphragm type compressor, catalog number 46-13426. It is designed to boost pressure to 138 MPa (20,000 psi) at a 14 to 1 maximum compression ratio. Compressor parts in contact with the gaseous oxygen are made of different materials. The upper head plates are A-286 alloy; the check valves are 316 stainless steel, and the two diaphragms are 302 stainless steel. The compressor is capable of furnishing 0.0906 cubic meters (3.25 SCF) per hour at a suction pressure of 3.45 MPa (500 psi).

The main disadvantages of this compressor are the compressor parts with minimum compatibility in gaseous oxygen environment at high pressure and the possible diaphragm rupture that cannot be "spotted" from the control room. A diaphragm rupture creates major problems when pulsing fluid enters the oxygen lines because of delay due to necessary tear-down, cleaning, and reassembly. White Sands Test Facility has used the same type compressor on a routine basis at pressures above MPa (10,000 psi) and indicates a diaphragm life of approximately 50 hours when pumping at high pressure.
Superpressure, Inc., the current manufacturer of this compressor, was contacted for information and philosophy on the design of these pumps for high pressure operation in the oxygen environment.

Superpressure, Incorporated (Mr. Kevin J. Lyons) responded as follows--

"I have heard of our compressors being used at 30,000 psi with oxygen. However, because of the nature of this application we make no guarantees as to safety or suitability. We sell the compressors preliminarily cleaned, and the ultimate responsibility lies with the user.

I am not sure what operating pressure is intended. I note in the file a reference that a special material would probably be needed above 15,000 psi.

This brings me to the main point of this correspondence. We have always had problems maintaining a seal above 22-25,000 with a Viton O-ring. Also with the Monel diaphragm used in this particular compressor we found the (soft) Monel would dimple (begin to extrude) into the gas and pulsing fluid ports.

In view of these facts, I advised the shop to set the limiter at 22,000 psi, i.e., set the compressor up for a maximum operating pressure of 20,000 psi. Also, to overcome the diaphragm problem we used a backup diaphragm of 302 SS (WSTF is using brass.). This is commonly done and will be a considerable benefit in terms of diaphragm life. The user should be aware of this in case he ever changes diaphragms. The diaphragms are stamped "SS" or "M" (as applicable) at the periphery.

I hope these modifications do not present the user a problem. They are definitely advisable.

If there is a problem, please get in touch."

As noted above there are solutions to problems. Both WSTF and JSC were pleased with support obtained from Superpressure, Incorporated personnel.
Discussions with two manufacturers on the advisability of modifying the current MSFC compressors evoked very little interest. Both indicated they could manufacture a new compressor to the maximum pressure requirement cheaper than they could modify those on hand.

**IMPACT TOWER AND ASSOCIATED ACCESSORIES**

The current design of the tower and the plummet are considered adequate. During the refurbishment of the system the following modifications would prove beneficial.

- Consideration should be given to welded connections at some of the stress assembly points. This would contribute to a more rigid tower structure.
- Knife edge guides for the plummet in place of the rollers would aid free fall alignment on the striker pin.
- The impact tower and its associated accessories (4, 5) should be refurbished and brought up-to-date.
- The load-cell should be sent to the manufacturer for refurbishing.

**IMPACT TEST CELL**

The structural evaluation of the current test cell was based on using K-Monel material with a safety factor of 4 and an operation pressure of 69 MPa (10,000 psi).

Since Inconel 718 was used in lieu of K-Monel, a gain in safety factor was acquired. The maximum designed pressure in the oxygen cavity was 103 MPa (15,000 psi). Proof pressure of the impact test cell was accomplished at 103 MPa (15,000 psi). Based on WSTF unpublished reactivity data Monel 400 is a more compatible material for use at 69 MPa (10,000 psi) and greater, than is Inconel 718. The current design if refabricated using Monel would meet the minimum requirements for 82.7 MPa (12,000 psi). Scientific Services recommends that the redesign be for Monel 400 for the ultimate pressure use to 172 MPa (25,000 psi). The following are items to be considered during the redesign.

- The base assembly should be redesigned to incorporate resistance heating.
Attention needs to be given to changing the seal design at the tester interface to a compression type of the Bridgman design, of proper materials, before proceeding to 12,000 psi or greater.

A redesign of the test cell sample holder volume, sensing probe locations, and event sensing should be addressed before attempting to operate at 12,000 psi or higher.

The striker assembly should be redesigned using a bellows for a seal to eliminate the "stick-break" force-pressure problems at the striker.

The redesign should incorporate an impact cell quick opening feature to speed-up testing.

The redesign should incorporate a more effective event sensing capability.

The redesign should retain the many good features of the current design and be similar in function and characteristics. These design changes are addressed in detail later under specific design considerations.

LOW PRESSURE PNEUMATIC SYSTEMS

The current design of the pneumatic support systems, i.e., actuation cylinder pressure, pneumatic valve actuation, test cell balance pressure, and the liquid nitrogen cooling system are adequate. However, they should be replaced due to age and wear as well as reconfigured to adapt to the new system.

The replacement of these systems would permit incorporation of the following component improvements.

- The liquid nitrogen test cell cooling system should incorporate a means for throttling LN\textsubscript{2} flow so that the LN\textsubscript{2} may be used as a rapid source for changing test cell temperature.

- The nitrogen test cell balance pressure should be brought up-to-date with current servo capability.

HIGH PRESSURE FEED SYSTEM

Most of the current high pressure oxygen feed system is constructed of Moqel. This includes the valves, fittings, and tubing. The exceptions are the surge tank and pressure gages. These are constructed of 316 stainless steel.
The Monel fittings in this system are from Autoclave Engineering, Incorporated and are constructed for a working pressure of 75.8 MPa (11,000 psi). As a minimum, for 82.7 MPa (12,000 psi) operation and greater, the replacement of this flow system with all oxygen wetted surfaces of 400 Monel and the elimination of the surge tank and the pressure gages from the new design will be required. There does not appear to be a sufficient cost savings to install 82.7 MPa (12,000) feed system and then replace it with higher pressure equipment later. Therefore, a system capable of 172 MPa (25,000 psi) should be used when the present 69 MPa (10,000 psi) rated system is replaced.

High pressure valves and fittings intended for oxygen service have orifice sizes for maximum flow of liquids and gases. Oxygen wetted parts are available from 400 Monel when special ordered.

The 59° included angle coned and threaded tubing seal appears to be reliable in both cryogenic and elevated temperature application. They are recommended for repetitive assembly and disassembly. However, the nature of the assembly would appear to require the replacement of the coned section when intended for high pressure due to its deterioration. Early users of these components with high pressure oxygen encountered leakage problems.

Safety weep holes are provided on both sides of all connections. This feature should be looked for when procuring these components.

Normally, valves and fittings will include the necessary tubing glands and collars unless otherwise requested.

OXYGEN SOURCE

The current MSFC mechanical impact tester source of oxygen is eleven (220 cu. ft., 2,200 psi) IA cylinders manifolded together. This makes for a simple system; however, it is a very limited supply of oxygen when flow is directly off the cylinders for pressure testing since these cylinders are rated at 15.2 MPa (2,200 psi). Volume testing at high pressure will drop the cylinder pressure quite rapidly.

MSFC has oxygen tube trailers that are routinely charged to 15.2 MPa (2,200 psi). These tube trailers would be a larger volume source for
oxygen testing and would furnish a volume in excess of ten times the current source. One of the existing 34.5 MPa (5,000 psi) tube trailers available to MSFC could be used to supply a greater volume. This same source can be used for a supply of oxygen to the suction side of a compressor intended for test pressures to 69, 82.7, 103, 138 and eventually to 172 MPa (10,000, 12,000, 15,000, 20,000, and 25,000 psi).

ITEMS TO BE REPLACED

Table I lists current installed units recommended for replacement. These items have been in use for over ten years. They are still serviceable, however, there have been instrumentation improvements that will extend testing capability.

Table II lists pneumatic enclosure hardware recommended for replacement. These enclosure systems will require rework and modification. The fittings for the oxygen system were designed for operation at 75.8 MPa (11,000 psi). The components of the system, although serviceable, have been used for over ten years. Replacement will permit staying current with progress in this very specialized area.
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<td>Peak Meter Indicator, Model 538A</td>
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<td>14.</td>
<td>Pressure Gage, Ashcroft No. 1279</td>
<td>SS</td>
<td>1/4 NPT</td>
</tr>
<tr>
<td>15.</td>
<td>Pressure Gage, Ashcroft No. 1279</td>
<td>SS</td>
<td>1/4 NPT</td>
</tr>
<tr>
<td>16.</td>
<td>Pressure Gage, Ashcroft No. 1279</td>
<td>SS</td>
<td>1/4 NPT</td>
</tr>
<tr>
<td>17.</td>
<td>Hand Valve, Control Component MV-6008</td>
<td>SS</td>
<td>1/2 NPT</td>
</tr>
<tr>
<td>18.</td>
<td>Regulator, Matheson No. 8-540</td>
<td>Brass</td>
<td>1/4 NPT</td>
</tr>
</tbody>
</table>
III. MATERIAL SELECTION

Hust and Clark (6) observed that a reaction in an oxygen system can only occur in the presence of a fuel, an oxidizer, and an ignition source. However, when a material or a component is selected or a system designed for oxygen service an awareness that the fluid can be the oxidizer, the material of the system a potential fuel, and ignition sources are ever present in many forms should always be a prime consideration.

The selection of materials and components for oxygen service should be premised on eliminating potential effects such as--

- The effects of contamination within a system.
- Eliminate ignition--select a material which is least likely to ignite under the operational conditions.
- Prevent continued reaction--select a material which tends to quench the reaction after ignition.
- Reduce the rate of reaction--select materials which react as slowly as possible after ignition to permit control of the reaction.
- Match the particular demands of an oxygen component with materials best satisfying these demands. (This assumes the existence of several types of compatibility and physical properties data for these materials.)

For example, if a component is likely to be impacted but not likely to be in a high temperature environment, materials with a low impact sensitivity should be considered with secondary considerations for their ranking according to ignition temperature.

- Equipment problems contributed by design. For example the introduction of slow opening valves and heat sinks to reduce the probability of ignition by adiabatic compression.
- Increasing oxygen wetted surface areas to aid in the dispersion of generated heat.

METALS

Although the tensile strength, hardness, and modulus of elasticity of many metallic materials increase as the temperature drops, ductility
and toughness decrease. In general, it is advisable to use a material below its "transition"\(^1\) temperature because above this temperature it has lost much of its capability to absorb energy without rupture. Nickel, copper, aluminum and some of their alloys are a few of the materials that have increasing impact strength with decreasing temperature.

Clark's (7) study of thermal expansion at low temperatures of similar alloys and alloy conditions indicates that relatively large changes in composition are required for significant changes in thermal expansions, that heat treatment or heat conditioning has little effect except when there is a basic material structure changes, and that the thermal expansion at room temperature is a good indication of the dimensional change to be expected at low temperature.

The initial materials selection for fabrication of the mechanical impact tester high pressure system and its associated equipment was based on results from limited studies of the ignition of materials in moderate pressure oxygen environment. Early materials ignition studies were conducted in gaseous oxygen at 51.7 MPa (7,500 psi) by the Battelle Memorial Institute (8). Test results indicated that metal alloys with a high percentage of nickel have the highest resistance to ignition in moderate pressure oxygen.

Additional studies by Battelle Memorial Institute (9) indicated that 316 stainless steel and monel alloys were acceptable construction materials at gaseous oxygen pressures to 51.7 MPa (7,500 psi).

Stainless steel 316 and monel (10, 11) are commonly accepted as good engineering alloys for oxygen service. Most of the standard hardware and most of the standard equipment available is fabricated from them. Monel is less strong but sufficient where weight is not a restriction. It has a low oxidation rate.

MSFC conducted ignition studies (2) and found nickel base super alloys Rene' 41, Inco 625, and Inco 718, the nickel-copper

\(^1\)In this case used to denote the arbitrarily defined temperature in a range where ductility changes rapidly with temperature.
alloys Narloy x and K-Monel, and the cobalt base super alloy HS188 all passed the impact sensitivity test at the test pressure of 69 MPa (10,000 psi) and the use temperature. Later limited ignition studies conducted in gaseous oxygen at 103 MPa (15,000 psi) by the White Sands Test Facility (WSTF) (11, 12) indicated Monel 400 was the most ignition resistant of the alloys tested. No documented test data appears to be available for higher pressures. Current technology has not ventured into the realm of extremely high pressure 172 MPa (25,000 psi) oxygen testing. This is an area for research and development. Table III lists the properties of Monel 400.

The choice of materials (6) for a high pressure oxygen mechanical impact tester system depends upon a number of interrelated factors:

- Temperature and pressure range of operation and the requirements for proof testing.
- Pressure and temperature cycling (fatigue life).
- Corrosion or erosion factors.
- The compatibility of the oxygen wetted surfaces in the environmental conditions to be encountered.

Only the best suited material should be used and stringent control requirements should prevail during procurement. There should never be any doubt about the identity and quality of the materials.

For the important parts, the parts containing high pressure oxygen wetted surfaces, a manufacturers' certificate of identity and quality should accompany the stock materials, forgings, and component parts. For cold worked billets of Monel 400 this is extremely difficult to acquire for small quantities. An alternative is to purchase two billets from the same run, one for testing and one for fabrication or verify status by non-destructive testing, proof pressure cycling, and proceed on a calculated risk basis.

Most metal manufacturers maintain a continuous watch on the quality of their materials by regular sampling and metallurgical examination. Therefore, using material on a calculated risk basis in a non-flight situation and in a research and development
### TABLE III

#### PROPERTIES OF MONEL 400

**Composition:**
- Nominal
  - Carbon: 0.12
  - Manganese: 0.90
  - Iron: 1.25
  - Sulphur: 0.005
  - Silicon: 0.15
  - Copper: 3.5
  - Nickel + Cobalt: 66.0

**Physical Constants:** (at 70°F)
- Specific gravity: 8.83
- Density, lb./cu.in.: 0.319
- Melting range, OF: 2370-2400
- Modulus of elasticity, psi, in tension x 106: 26.0
- Curie temperature, OF: 9.5
- Specific heat, Btu./lb. OF: 0.102
- Thermal conductivity, Btu./hr./in./ft./OF: 170
- Electrical resistivity, ohms/cir.mil./ft.: 307

#### Table 1 - MECHANICAL PROPERTIES - Rod & Bar:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile strength, psi</th>
<th>Yield strength, psi</th>
<th>Elongation, % in 2&quot;</th>
<th>Rockwell Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annealed</td>
<td>70000-85000</td>
<td>3000-45000</td>
<td>50-35</td>
<td>B10 max</td>
</tr>
<tr>
<td>Stress-Relaxed</td>
<td>64000-80000</td>
<td>13300-13500</td>
<td>10-15</td>
<td>B85-C2</td>
</tr>
</tbody>
</table>

#### Table 2 - IMPACT STRENGTH (Some of the specimens were completely fractured):

<table>
<thead>
<tr>
<th>Condition</th>
<th>Impact Strength, ft-lbs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Rolled</td>
<td>8000-10000</td>
</tr>
<tr>
<td>Annealed</td>
<td>5000-7000</td>
</tr>
</tbody>
</table>

#### Table 3 - MECHANICAL PROPERTIES - (Seamless) Tube & Pipe

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile strength, psi</th>
<th>Yield strength, psi</th>
<th>Elongation, % in 2&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold drawn, Annealed</td>
<td>70000-90000</td>
<td>28000-50000</td>
<td>10-15</td>
</tr>
<tr>
<td>Cold drawn, Stress Relief</td>
<td>85000-12000</td>
<td>15000-20000</td>
<td></td>
</tr>
<tr>
<td>Cold drawn, Stress Relief</td>
<td>85000-12000</td>
<td>15000-20000</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 4 - CREEP STRENGTH

<table>
<thead>
<tr>
<th>Condition</th>
<th>Stress, psi to Produce a Creep Rate of</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Rolled</td>
<td>10000-15000</td>
</tr>
<tr>
<td>Stress-relieved</td>
<td>15000-20000</td>
</tr>
</tbody>
</table>

#### Table 5 - MECHANICAL PROPERTIES - Sheet & Plate & Strip

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile strength, psi</th>
<th>Yield strength, psi</th>
<th>Elongation, % in 2&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold drawn, Annealed</td>
<td>70000-90000</td>
<td>28000-50000</td>
<td>10-15</td>
</tr>
<tr>
<td>Cold drawn, Annealed</td>
<td>70000-90000</td>
<td>28000-50000</td>
<td>10-15</td>
</tr>
<tr>
<td>Cold drawn, Annealed</td>
<td>70000-90000</td>
<td>28000-50000</td>
<td>10-15</td>
</tr>
</tbody>
</table>

#### Table 6 - LOW TEMPERATURE PROPERTIES

<table>
<thead>
<tr>
<th>Condition</th>
<th>Tensile strength, psi</th>
<th>Yield strength, psi</th>
<th>Elongation, % in 2&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold drawn</td>
<td>105000</td>
<td>95000</td>
<td>18.0</td>
</tr>
<tr>
<td>Annealed</td>
<td>110</td>
<td>109</td>
<td>17.6</td>
</tr>
</tbody>
</table>

#### Table 7 - SHORT TIME HIGH TEMPERATURE PROPERTIES OF HOT-ROLLED MONEL alloy 400

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Tensile strength, psi</th>
<th>Yield strength, psi</th>
<th>Elongation, % in 2&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Rolled</td>
<td>80000</td>
<td>70000</td>
<td>17.0</td>
</tr>
<tr>
<td>Stress-relieved</td>
<td>110000</td>
<td>100000</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 8 - Rupture STRENGTH

<table>
<thead>
<tr>
<th>Condition</th>
<th>Stress, psi to Produce Rupture in</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Drawn, Annealed</td>
<td>70000</td>
</tr>
<tr>
<td>Cold Drawn, Stress Relief</td>
<td>70000</td>
</tr>
<tr>
<td>Cold Drawn, Stress Relief</td>
<td>70000</td>
</tr>
</tbody>
</table>

**Tension Impact Strength**

<table>
<thead>
<tr>
<th>Tensile strength, psi</th>
<th>Yield strength, psi</th>
<th>Reduction of Area, %</th>
<th>Brittle hardness, Rockwell Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold drawn</td>
<td>86000</td>
<td>60000</td>
<td>45.5 in 2&quot;</td>
</tr>
<tr>
<td>Annealed</td>
<td>90000</td>
<td>70000</td>
<td>50.0 in 2&quot;</td>
</tr>
</tbody>
</table>

---

*Specimens completely broken.
environment may be acceptable since adequate steps may be taken during the design stage to compensate for anticipated material inadequacies. Complete items, such as the compressor and the test cell, should have a test certification including capacity data.

**SEALS**

Material selection for high pressure oxygen environments must be compatible and perform the basic functions required for the specified conditions. Seal materials and seal configurations are available to meet the general design requirements.

**Teflon**

Plain teflon is compatible and the material of use for those applications where extremely low friction and chemical inertness are the most important factors. Teflon has a very low coefficient of friction (0.04). It has some definite disadvantages, not the least of which is the tendency to cold flow.

**Glass Filled Teflon**

Glass filled teflon is used when an inert material is needed in applications requiring good wear compatibility under extreme conditions of pressure and temperature. Wearing of the metal mating surfaces is to be expected due to the abrasive characteristics of the glass filler; therefore, a good surface finish is essential. Good metal surface finishes reduce seal wear. Wear is nearly proportional to the metal surface finish. Good metal surface finishes permit more areas of contact at the sealing surface which improves sealing ability.

Sealing at low temperatures is substantially more difficult because plastics become harder and do not readily flow onto the metal mating surfaces; thus, better finishes must be provided. For oxygen service a surface finish of 2-4 RMS is desirable for dynamic conditions. Static applications may be adequately handled by a surface finish of 8-12 RMS. This type of compatible seal material will be required for oxygen service.
Stick-Slip of Seals

Seals made from elastomer material show a sharp increase in friction as the pressure increases. Stick-slip may be described as the jerking motion that occurs on a dynamic surface during the transition from static to dynamic movement. Surface finishes should provide a slick, hard surface (50-62 Rockwell C) which reduces adhering between sealing surfaces, reducing dynamic force requirements.

The current MSFC mechanical impact tester has stick-slip on the striker pin of 9-16% of pressure (13) and this can be expected to increase dramatically with the additional increase in pressure. This is an area that must be addressed during the modification design. The implementation of a diaphragm or bellows for a seal at the striker pin appears to have several advantages and should be considered during design.

Pressure Activated Seals

Bridgman (14, 15) has stated the one development which permitted reaching extremely high pressures without leaks was his invention of the unsupported area seal, now called Bridgman seal.

This seal works on the principle that the fluid pressure acts on the sealing material to increase the force of the seal against the part.

The seal becomes more effective as the pressure increases. It does have a limit, however, and that is the point where the deformation of sealing material is extruded.

This seal design or a modified version of this design will be required for high pressure oxygen applications.

For leak free sealing a seal material must have a minimum surface load of approximately 25 pounds per square inch.
In the event of a compressor disc rupture, pressurized oxygen comes in contact with the compressor fluids. Fomblin Y appears to offer the combined properties of being acceptable as a compressor fluid and of being non-reactive. Fomblin Y is a low molecular weight polymer with the structure of perfluorinated polyethers. Fomblin Y fluids were tested to NASA MSFC-SPEC 106B and passed the test. Fomblin Y-06 was non-reactive at pressures up to 10,000 psia as reported in a NASA WSTF report on August 27, 1980. Additional data on Fomblin Y is included in Appendix I.
IV. DESIGN CONSIDERATIONS

In the design or layout of a high pressure oxygen system each component should be considered as a high pressure vessel, whether it be a compressor, a fitting, a valve, a piece of tubing, or just a seal. In the initial layout problem areas should be considered and techniques developed to eliminate or maintain anticipated reactions to a minimum. Complicated designs tend to leave too much room for operation error. The maximum design working pressure should be premised on anticipated chemical reactions as well as the pressurizing oxygen and temperature. (8, 9, 14, 16)

This survey revealed that compressors and other high pressure equipment have been improved by use of new materials and advanced designs. High pressure equipment is available as standard catalogue items from several vendors and a few vendors offer modifications for specialized applications. Scientific Services recommends using standard catalog items to the maximum extent. Most of these pieces of equipment have been designed, fabricated, and installed to meet requirements as set forth by the American Society of Mechanical Engineers (ASME), the American Institute of Chemical Engineers (AICHE), the National Bureau of Standards (NBS), the U. S. Department of Defense, the National Aeronautics and Space Administration (NASA), and other recognized organizations.

Scientific Services contacted numerous vendors of compressed gas equipment as well as instrumentation and control manufacturers. Three high pressure vendors were ultimately selected as having sufficient experience, manufacturing capability, and design modification ability to respond to the requirements of the oxygen impact tester. Several vendors appeared qualified to supply control instrumentation off of the shelf and local Huntsville sources were found that could fabricate specialized items.
In the pressure ranges under consideration, the ASME Code (Section VIII, Division II) is of limited applicability. The basic concept of following good engineering practices and selecting the best materials is the best approach. This, plus good manufacturing and inspection procedures, can provide the basis for a good non-code design for this application. (14, 17)

D. E. Witkin (National Forge Company) (14) proposed that a safe, reasonable and good logical approach could consist of the following procedures of Section VIII, Division 2, Appendix 4 of the ASME Boiler and Pressure vessel code, modified to the following extent.

- That $S_m$ be defined as $S_y/1.5$ where $S_y$ is the yield strength.
- That Maximum Strain Energy (Maxwell/Von Mises) theory be used for combined stress calculations.
- That the following additional criteria be superimposed:
  - (a) The maximum stress intensity at the bore of the vessel at design pressure be no greater than the yield strength; (b) the burst pressure to be more than 1.25 times the hydrostatic test pressure; and (c) the full plastic flow pressure to be more than 1.10 times the hydrostatic test pressure.

The compressed oxygen for the impact tester should be viewed as three different systems, i.e., gaseous oxygen feeding the test cell cavity directly from the gaseous oxygen cylinder supply for relatively low pressure testing, the first stage of a two stage compressor system for pressures up to 34.5 MPa (5,000 psi), and the two stage compressor for extremely high pressure operation. During the design stage each of these systems should be assembled so individual operation may be selected. This concept was derived for ease in operation and to decrease the operating time on the high pressure compressor diaphragms due to problems anticipated in this area. The technology for the compressor design is available; however, delivery times can be expected to be 30 weeks or greater. These compressors are built to specific requirements and the material of construction is selected by the purchaser.
The source of the high pressure oxygen for the mechanical impact tester is the compressor with its suction and discharge. Each of these basic systems will be reviewed.

The diaphragm compressor, the most contaminant free of the pressure buildup equipment is a combination of two systems, a hydraulic system and an oxygen gas compression system. A metal diaphragm group is the isolating component between these two systems. The oxygen gas compression system consists of flat metal diaphragms clamped between two precisely contoured concave cavities, and the gaseous oxygen inlet and outlet check valves. The hydraulic system includes an electric motor driven crankshaft which reciprocates a piston in the hydraulic fluid media. This positive displacement piston pulses the hydraulic fluid against the lower side of the diaphragm group causing it to sweep the cavity displacing the oxygen gas on the other side of the diaphragm, and discharging the oxygen gas through the discharge check valve to the high pressure manifold. (See Figure 2)

The oxygen wetted surfaces within this compressor are the diaphragm, the concave head, and the inlet and outlet check valves. The material considered most ignition resistant in high pressure; high temperature LOX/GOX is Monel 400; therefore, these components should be fabricated of this material. The hydraulic fluid for oxygen service is halocarbon although Johnson Space Center in Houston (18) (JSC) uses Fomblin Y-06. This material is batch tested for JSC (Hamilton-Standard) at WSTF. They have never had a mechanical reaction when batch tested. One batch failed when tested pneumatically. This batch was replaced. (This fluid is handled by Montedison Company, NY)

It is essential that the compressor be water cooled to protect the Monel 400 diaphragm and to assure the gaseous oxygen is pumped to the test cell at ambient conditions. Water cooling will assure a high pressure oxygen supply with a Delta of 2°C.
Figure 2. Diaphragm Compressor
Three diaphragm compressor manufacturers were selected:
(a) Superpressure, Incorporated; (b) Fluitron, and (c) Pressure Products Industries. These manufacturers will produce diaphragm compressors to special requirements on special order. There are others such as Harwood Engineering who will machine to special designs when they are submitted. For additional information on capabilities of compressors consult references (19, 20).

Superpressure, Incorporated, Pressure Products Industries, and Fluitron all indicate they can furnish diaphragm compressors which offer--
- Leak free design.
- Contamination free compression.
- Pressure to 30,000 psi.
- Flow rate from 1.75-12.5 CFM
- Corrosion resistant materials (All wetted parts from Monel 400.).
- Leak detection.

The three manufacturers indicated that they could supply complete systems incorporating the following.
- Aftercooler.
- Motor starter.
- Automatic "on/off" Control system.
- Automatic unloading system.
- Suction and discharge pressure sensing instrumentation.
- Flow Control Systems.
- Temperature and pressure switches.
- Oil level switch.

One manufacturer of diaphragm compressors, Pressure Products Industries, uses their patented bootstrap closure. At pressures of 66.7 MPa (10,000 psi) and higher, sealing of the compressor head assemblies becomes difficult and high torque of the bolts is needed to accomplish a good, tight seal of the diaphragm. The bootstrap closure solves this problem (see Figure 3). A force is generated in the bootstrap cavity (between 1 and 3) by hydraulic fluid pressure, which is greater than the loads generated during the compression cycle. This assures a leak tight seal assembly.
Figure 1

8Kdnalie Mid Itcum to Base
[Figure courtesy of Pressure Products Industries, Hatboro, Pa.]

1 - Main nut, 2 - Stuffing box, 3 - Process head,
4 - Lower head with oil plate insert, 5 - Plunger
6 - Crankshaft, 7 - Bootstrap check valve and
8 - Hydraulic relief valve.

Bootstrap closure (U.S. Patent No. 3,052,188).
(Figure courtesy of Pressure Products Industries, Hatboro, Pa.)

Figure 3. Bootstrap Closure
NASA/JSC uses a Pressure Products compressor with the bootstrap closure and reported that the principle works.

Pressure surges can be expected when pumping at high pressures, especially when balancing the high pressure in the test cell cavity under cryogenic conditions. Every consideration should be given to dampening these surges during the design stage through coiled tubing or the flattened bourdon tube principal. Under no circumstances should this high pressure system be operated without dampening these impact surges. Table IV lists data showing manufacturers' capabilities.

LOW PRESSURE FLOW SYSTEMS

The low pressure flow systems should consist of four basic systems delineated by their function.

- The $\text{N}_2$ source for the plummet lifting actuation cylinder 0.55-0.69 MPa (80-100 psi).
- The $\text{N}_2$ pressure for balancing pressure regulators 1.7 MPa (2,000 psi).
- The $\text{N}_2$ pressure for pneumatic valve operation.
- The $\text{L}_2$ for cool-down of the specimen test cell.

These particular systems are basic as far as hardware is concerned. The current hardware at MSFC is functional and adequate, but should be replaced due to its age as it is reconfigured to connect with the proposed new system and to incorporate updated control instrumentation. During the replacement, consideration should be given to the increase oxygen and nitrogen volume requirements when operating at 2.07 MPa (2,000 psi) compared to a test operation at 172 MPa (25,000 psi). A tube trailer would be more acceptable than the limited volume of 2.07 MPa (2,000 psi) $\text{N}_2$ and GOX in a 1A cylinder bank.

The oxygen supply is from a bank of 1-A gas cylinders or a tube trailer feeding the suction side of the compressor. This oxygen supply should be evaluated for total hydrocarbons by an inline gas chromatograph. The moisture should be evaluated and kept to a minimum. The oxygen flow should be rough filtered to 25 microns with a final filter prior to the compressor entrance down to 1 micron. A by-pass should be provided for a cleanup of
### TABLE IV

#### ORIGINAL PAGE 18

#### OF POOR QUALITY

#### COMPRESSOR DATA:

<table>
<thead>
<tr>
<th>Process Gas</th>
<th>Oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mol. Weight</td>
<td>32</td>
</tr>
<tr>
<td>Cp/Cv Value</td>
<td>1.4</td>
</tr>
<tr>
<td>Suction Pressure</td>
<td>200-2000 PSIG</td>
</tr>
<tr>
<td>Suction Temperature</td>
<td>Ambient</td>
</tr>
<tr>
<td>Discharge Pressure</td>
<td>25,000 PSIG</td>
</tr>
<tr>
<td>Flow Required</td>
<td>Fill 1/2 in.³ chamber in 5-10 minutes</td>
</tr>
</tbody>
</table>

#### COMPRESSOR DATA:

<table>
<thead>
<tr>
<th>Type</th>
<th>Metal diaphragm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Stages</td>
<td>Two</td>
</tr>
<tr>
<td>Discharge Temperature - Approx.</td>
<td>1500°F</td>
</tr>
</tbody>
</table>

#### MATERIALS OF CONSTRUCTION:

<table>
<thead>
<tr>
<th>Process Side</th>
<th>Monel 400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Check Valves</td>
<td>Monel 400</td>
</tr>
<tr>
<td>Process Seals</td>
<td>Viton</td>
</tr>
<tr>
<td>Oil Seals</td>
<td>Buna N</td>
</tr>
<tr>
<td>Diaphragm (Process &amp; Oil Side)</td>
<td>Monel 400</td>
</tr>
<tr>
<td>Middle Diaphragm (Leak Detection)</td>
<td>Brass</td>
</tr>
<tr>
<td>Process Piping</td>
<td>Monel 400</td>
</tr>
</tbody>
</table>

#### ACCESSORIES:

- Interstage gauge, cooler and rupture assembly
- Oxygen cleaning
- Special halocarbon pulsing oil for the high pressure plungers

---

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the oxygen gas when required. A hydrocarbon cleanup can be attained by flow through silica gel and a molecular sieve.

TEST CELL

Due to the central importance of the test cell function, several areas should be considered. Some of these points are covered within other specific areas of discussion, but are again addressed with respect to the test cell assembly.

- Material Selection--This effort was required to assess any changes felt necessary for operation of the existing system at 82.7 MPa (12,000 psi) oxygen pressure. Changes are recommended. The philosophy behind this effort is to recommend whatever changes are necessary to achieve the ultimate goal of 172 MPa (25,000 psi) as long as the lesser goals stated is inclusively covered. For these philosophical reasons, as well as Monel versus Inconel preferences stated earlier, age and accumulated stress, we recommend redesign and fabrication of the test cell from 400 Monel. Additional points stated below must be considered in redesigning the test cell.

- A faster test cell closure and release is necessary to improve testing efficiency (Figure 4). An interrupted thread or "gun-bolt" design with adjustable screw stops should receive attention during the design stage. Improvement in the time for closure and release of the cell itself, would obviously increase the production rate of compatibility testing. More materials could be tested within a standard work day.

- Consideration should be given to redesigning the internal pressure balancing system so that current component improvements may be incorporated.

- The seal design and materials with regard to the striker pin is an area that must receive attention during redesign.

- Alternative methods for heat source and temperature control should be addressed. (Details discussed in Section V)

- A better means of event sensing (14, 21) should be incorporated and is specifically addressed elsewhere. In addition, the faster the response and more sensitivity that can be achieved in pressure and temperature measurement can only substantiate the validity of event occurrence and provide additional data for the reaction. (Details discussed in Section V)

- The possibility for design consideration being given to the size and shape of the test cell itself (16) should be addressed. The potential need for this lies in the unknown but potential changes in oxygen reactivity at pressures greater than 138 MPa (20,000 psi), as well as the kinetic, thermodynamic, and mechanistic nature of the ignition reactions.
Figure 4. Impact Test Cell
The structural evaluation of the current test cell was based on using K-Monel material with a safety factor of 4. Since Inconel 718 was used in lieu of K-Monel, a gain in safety factor was acquired. The maximum designed pressure in the oxygen cavity was 103 MPa (15,000 psi). Proof pressure of the impact test cell was accomplished at 103 MPa (15,000 psi).

The re-design of the impact test cell should be premised on a few salient features. There should be an awareness that rapid heating due to gas surging into confined spaces can produce a hazardous situation. It is important the test cell re-design feature the following.

- Minimum volume-maximum surface ratio.
- Consideration for the mass of the receiver.
- Heat transfer coefficient of the material.
- Number of paths available for heat dissipation.
V. INSTRUMENTATION

The current instrumentation should be replaced due to the rapid advancements in electronics since the components were installed. The redesign should incorporate some of the following approaches.

TEMPERATURE SENSING AND CONTROL

The planned temperatures ranging from that of Liquid Oxygen (LOX) to 400°C Celsius need to be measured continuously and the measured temperatures should be as near as practical to the temperature inside the test cell. The temperature sensing system should be readily compatible with the requirements for temperature control of the cell. The use of strategically placed thermocouples meets the requirements for cell temperature sensing. Four thermocouples symmetrically oriented and as near to the inner test cell wall as practical should yield satisfactory temperature sensing (see Figures 5, 6). Operational tests will be necessary to determine the amount of deviation of approach from the true temperature inside the test cell. These tests can also yield the best processing of the four sensed temperatures to yield the true test cell temperature. The averaging in pairs (1 and 3) and (2 and 4) should yield good results (see Figure 5).

(Figure 7) shows the display approach for the temperature and control system. Three of the four thermocouple probe units are connected to temperature display units, while one of the four is connected to a temperature display and control unit. Omega type "T" thermocouple probe units can be used to cover the range of -200°C to +400°C with 1.5°C accuracy from -200°C to 0°C, and a 1°C Accuracy from 0°C to 400°C. It is recommended that all four thermocouples be monitored to best estimate the test temperature while using one thermocouple output for control to simplify the control function.
Figure 5. Thermocouple Locations
Figure 6. Temperature Sensing System
Figure 7. Temperature Display and Control
Also this approach gives redundancy since the system is still operational with only one probe functioning. The output of the temperature display and control unit is fed to the power unit. The power unit provides adequate power to heat the test cell to the upper temperature of +400° C. In this section it is assured that about 1500 watts will provide adequate heating. The power unit is shown (Figure 8A) which provides adequate current handling capacity to power the heater units. (Figure 8B) shows an optional power unit which would provide lower voltage in D.C. to produce heating as an alternate approach.

When temperature control of the specimen test cell is required above ambient temperature, the temperature control system which only provides heat can adequately control the temperature. For reducing temperature it will be necessary to provide a steady cooling to the test cell in order to vary its temperature. This throttle cooling can be provided by a steady flow of liquid nitrogen into the test fixture. With this combination heating and cooling the temperature controller can provide the heating as required to achieve the desired test temperature.

All the components required to fabricate the temperature sensing and control system are readily available with the exception of custom packaging and heater elements for custom voltage operation. These items, although custom built, are not high cost or long lead time items. The packaging and integration can be performed by local Huntsville, Alabama instrumentation companies. All thermocouples digital displays, probes, reference junctions, and basic controllers are readily available from vendors such as Omega Engineering whose information was used for budgetary data.

**EVENT SENSING**

Event sensing for 82.7 MPa (12,000 psi) and greater pressures presents problems because of the pressure.

In order to define a system for event sensing it is necessary to determine some physical interaction associated with the event
Figure 8.A. Power Unit
Figure 8.B. Optional Heater Power Unit
which is measurable or which leads to such a measurable interaction. The events of interest such as rapid oxidation should liberate measurable energy. It is here assumed that such events will emit energy in the visible and/or near infrared spectrum. Although viewing ports for eye observation into the test cell might be used for event sensing, this approach has some very definite disadvantages, not the least of these being safety and high pressure sealing.

In order to overcome these problems a methodology was devised which would allow the detection of the emission of radiation in the test cell using extremely small ports and remote measurement of the occurrence. Fluitron, Inc. (22) indicates they have been successful in fabricating leak proof sapphire windows, by parallel surface grinding, to pressures of 207 MPa (30,000 psi); however, they have never been to 400°C with this assembly. Figures 9-A and 9-B show the general approach to transmitting the emitted radiation from the specimen test cell. A very small window in the upper portion of the test cell is used to transmit radiation to a coupled fiber optic. The use of two ports on opposite sides of the test cell will provide reasonable coverage for reliable event sensing. These ports can be made very small which will allow sealing at very high pressures and eliminate port breakage at such pressures. The coupled optical fiber will transmit radiation to a remote location for detection, processing and displays. Available detection systems for use with such optical fibers allow a wide variety of measurements. The following capabilities can be provided:

- Rapid sensing of the occurrence.
- Sensing of short duration events.
- Variable setting to define event occurrence.
- Measurement at different portions of spectrum by detector selection.

Figure 10 shows the operational block diagram of components required to detect emitted radiation after it is transmitted from the test cell via a fiber optic. The voltage at the output line represents the intensity of the radiation coming from the fiber.
Figure 10. Detection System Operational Block Diagram
Whenever an event occurs in the test cell that emits radiation, the voltage at the output will change.

Figure 11 shows the block diagram of the detection system and the electronic system that does the post detection processing. The threshold level sense circuitry senses whenever the output of the detection circuitry goes above a pre-set level and causes an event indicator to go on and stay on until manually reset. This gives an indication on an event occurrence independent of event duration. Simultaneously the duration sense circuitry senses the output of the detection circuitry for events above threshold that are sustained for a duration above a pre-set time period, and produces an indication of such an event. Also the output of the detection system can be monitored on an oscilloscope for visual display. A storage oscilloscope should provide long term viewing of output to determine the temporal nature of the emitted radiation due to the event.

**CALIBRATION**

The thermocouple temperature measurement system should be validated by placing a test thermocouple inside the test cell to correlate the four thermocouple readings with the actual temperature inside the test cell.

The purpose of the event sensing drive is to determine whether an event occurred or not. Calibration of such a device consists of setting threshold devices inside the electronics. Observation of signal outputs from tests with known events should be used to determine the proper setting of these threshold levels.

The pressure sensor selected has a built-in electrical signal simulator to calibrate the electronics associated with the pressure sensor system.

Pressure standards are available as complete compact and transportable units with the means of pressure generation and regulation built into one compact housing, the heaviest mass inside being 2 kilograms.
Figure 11. Event Indication System
By the extension of pressure range pressure, measurement from zero to 689 MPa (100,000 psi) is possible.

The accuracies available with this calibration are of the "N" and "S" type. The "N" class pressure standards are accurate to ±0.05% of reading over the entire range at a temperature of 20°C ± 5°C and at a standard "g" value. "S" accuracy pressure standards are accurate to ±0.01% of over the full range.

These instruments (DH Instruments, Incorporated) have traceability to the National Bureau of Standards.
A block diagram using this type of pressure transducer as a pressure measurement system is shown in Figures 12 and 13. The power supply shown provides excitation for the transducer and the signal conditioner provides the proper electronic buffering, filtering, and amplification of the transducer's output. The indicator and alarm panel provides electronic read-out of the test cell pressure and gives alarm indication if a preset pressure is exceeded. This preset pressure limit is adjustable. Also electrical outputs can be provided to control a "shut down" if a preset pressure is exceeded. This system can also be designed such that alarm and "shut down" outputs are provided if pressure transducer output is lost during testing.

The Teledyne Taber pressure transducer (Model 2107) has an excellent track record (21); however, it has similar inadequacies to other transducers as far as this oxygen system application is concerned.

The pressure sensing cavity is of stainless steel material and the high temperature limit is below the stated 400°C requirement.

To compensate for the temperature limitations, it will be necessary to offset the transducer at the specimen test cell by approximately 2 inches. This will affect the response; however, the response decay can be calculated. The offset installation should be held to a minimum and be only sufficient to limit temperature buildup in the transducers to its designed limit.

It is possible to compensate for pressure drift due to excessive temperature by placing a temperature pickup on the transducer and compensating electronically. Although the transducer cavity is of stainless steel material there is no record at current operating pressures of a dead-end connection of an offset transducer burning in an oxygen environment.

Fluitron, Incorporated will fabricate transducers of Monel-400.
The function of pressure instrumentation is to measure physical phenomena and to present this measurement in an intelligible and usable form.

A survey of available pressure transducers adequate to meet requirements led to the choice of the strain gage type transducers for the pressure sensing element. Such pressure transducers are available with the following characteristics:

<table>
<thead>
<tr>
<th>Measured Fluids</th>
<th>All fluids compatible with 316 stainless steel. Options available.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Scale Output</td>
<td>3.0 ± 0.015 MV open circuit per volt excitation. Calibrated at 10.00 VDC excitation.</td>
</tr>
<tr>
<td>Zero Balance</td>
<td>0.00 ± 0.03 MV per volt at +70°F</td>
</tr>
<tr>
<td>End Point Linearity</td>
<td>Within ± 0.15% FSO.</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>Less than 0.15% FSO.</td>
</tr>
<tr>
<td>Repeatability</td>
<td>Within 0.10% FSO.</td>
</tr>
<tr>
<td>Resolution</td>
<td>Infinite.</td>
</tr>
<tr>
<td>Natural Frequency</td>
<td></td>
</tr>
<tr>
<td>0-10,000 PSI range</td>
<td>267KHz</td>
</tr>
<tr>
<td>0-15,000 PSI range</td>
<td>317KHz</td>
</tr>
<tr>
<td>0-20,000 PSI range</td>
<td>354KHz</td>
</tr>
<tr>
<td>0-25,000 PSI range</td>
<td>392KHz</td>
</tr>
<tr>
<td>0-30,000 PSI range</td>
<td>429KHz</td>
</tr>
<tr>
<td>0-40,000 PSI range</td>
<td>496KHz</td>
</tr>
<tr>
<td>0-50,000 PSI range</td>
<td>550KHz</td>
</tr>
<tr>
<td>Proof Pressure</td>
<td></td>
</tr>
<tr>
<td>Burst Pressure Rating</td>
<td>Greater than 4.0 times rated FS pressure not to exceed 150,000 PSI.</td>
</tr>
<tr>
<td>Compensated Temperature Range</td>
<td>-30°F to +170°F. Options available.</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>-100°F to -250°F.</td>
</tr>
<tr>
<td>Thermal Sensitivity Shift</td>
<td>Less than ±0.005% FSO per °F over CTR.</td>
</tr>
<tr>
<td>Thermal Zero Shift</td>
<td>Less than ±0.010% FSO per °F over CTR.</td>
</tr>
<tr>
<td>Triaxial Mechanical Shock</td>
<td>30 G's applied for 11 milliseconds will not cause change in transducer performance characteristics.</td>
</tr>
<tr>
<td>Acceleration Error</td>
<td>Less than ±0.0015% FSO per G.</td>
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<tr>
<td>Excitation</td>
<td>10 volts DC or AC RMS recommended. 15 volts maximum.</td>
</tr>
<tr>
<td>Input Resistance</td>
<td>350 ± 3.5 ohms at -70°F. Input circuitry symmetrical.</td>
</tr>
<tr>
<td>Output Resistance</td>
<td>350 ± 5.0 ohms.</td>
</tr>
<tr>
<td>Insulation Resistance</td>
<td>Greater than 10K megohms at 50 VDC between all terminals in parallel and transducer case at -70°F.</td>
</tr>
<tr>
<td>Pressure Connection</td>
<td>AE F250-C with bleed hole for 1/4&quot; high pressure tubing.</td>
</tr>
<tr>
<td>Pressure Cavity Volume</td>
<td>0.012 cubic inches.</td>
</tr>
<tr>
<td>Enclosure</td>
<td>Entire housing and pressure cavity of stainless steel. All electrical components sealed against adverse environmental conditions.</td>
</tr>
<tr>
<td>Weight</td>
<td>Approximately 30 ounces.</td>
</tr>
</tbody>
</table>

Options Available

- Pressure cavity materials of 304 and 347 stainless steel.
- Double, single internal, or external shunt. Tracking throughout compensated temperature range.
- Compensated temperature ranges available for any range within 100°F to +250°F.
- Electrical receptacles MS series 5 or 6 pin and pigmy series.
Figure 12. Pressure Sensing Block Diagram
Figure 13. Pressure Sensing Signal Conditioner
VI. Component Selection

The design and fabrication of high pressure oxygen systems should be by competent, experienced people. Therefore the use of as much standard high pressure equipment as possible should be selected from established manufacturers. Although only a limited number of manufacturers are involved, SSI established that sufficient capability exists in the high pressure component area.

High pressure valves, tubing, fittings, and rupture discs are available as standard catalogue items. A long delivery time may be required for the exact sizes and quantities required. High pressure compressors are generally manufactured to customer requirements and are not "off the shelf" items. Three compressor vendors have been identified that have the capability to manufacture a compressor to the requirements of the impact tester system. Each of the compressor manufacturers offers a compressor with different design concepts and options and as would be expected, different prices.

Obviously each and every component cannot be selected prior to the final design. The items listed in the component selection list (Table III) gives the part number (or catalogue number) style, type, size and other pertinent information that would meet the requirements discussed in other sections of this report. A recommended source for the items is also included.

Although only a limited number of manufacturers are involved in high pressure equipment and related instrumentation, the capability is sufficient to meet the needs of the impact tester system. Many of the manufacturers serve a market that is relatively small and does not justify a large "agency" type of marketing service since much of their work is to customer requirements. Therefore, a list of high pressure equipment manufacturers and suppliers is given in Table IV.
<table>
<thead>
<tr>
<th>Item</th>
<th>Quan.</th>
<th>P/N</th>
<th>Description</th>
<th>Material</th>
<th>Size</th>
<th>Supplier</th>
<th>Maximum Operating Pressure</th>
<th>Fluid</th>
<th>Remarks</th>
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<tr>
<td>1</td>
<td>1</td>
<td>CL6600</td>
<td>Elbow</td>
<td>Monel</td>
<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
<td>414 MPa (60,000 psi)</td>
<td>Oxygen</td>
<td>Cost-$71.00/F375C Connection</td>
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<td>2</td>
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<td>CT6660</td>
<td>Tee</td>
<td>Monel</td>
<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
<td>414 MPa (60,000 psi)</td>
<td>Oxygen</td>
<td>Cost-$76.00/F375C Connection</td>
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<td>3</td>
<td>1</td>
<td>CX6666</td>
<td>Cross</td>
<td>Monel</td>
<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
<td>414 MPa (60,000 psi)</td>
<td>Oxygen</td>
<td>Cost-$91.00/F375C Connection</td>
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<td>4</td>
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<td>60F6633</td>
<td>Straight Coupling</td>
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<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
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<td>3/8&quot;</td>
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<td>60B6633</td>
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<td>F375C Connections</td>
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<td>7</td>
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<td>10V6071</td>
<td>AE Non-Rotating Stem Valve (2-Way)</td>
<td>Monel</td>
<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
<td>79.3 MPa (15,000 psi)</td>
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<td>60V6071-OHP</td>
<td>AE Non-Rotating Stem Valve-Air to Open Heavy Duty (2-Way)</td>
<td>Monel</td>
<td>3/8&quot;</td>
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<td>414 MPa (60,000 psi)</td>
<td>Oxygen</td>
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<td>10V6071-OHD</td>
<td>AE Non-Rotating Stem Valve-Air to Open Heavy Duty (2-Way)</td>
<td>Monel</td>
<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
<td>(11,500 psi)</td>
<td>Oxygen</td>
<td>Cost-$1,000.00/</td>
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<td>CB6601</td>
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<td>13</td>
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<td>Tubing 3/8&quot; X 1/8&quot;-</td>
<td>Monel</td>
<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
<td>30,000</td>
<td>Oxygen</td>
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<td>$17.00/Feat. Pressure</td>
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<td>30,000 psi @ 100°F &amp;</td>
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<td>400°F C (750°F F)</td>
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<td>(.75) X 30,000 = 22,500 psi</td>
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<td>14</td>
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<td>Elbows, Tees &amp; Crosses</td>
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<td>Oxygen</td>
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<td>138 MPa (20,000 psi)</td>
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<td>Teflon O-Ring Material-SS Std.</td>
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<td>Maximum Operating Pressure</td>
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<td>Nitrogen</td>
<td>Teflon O-Ring Materials-55 Std.</td>
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<td>SWF 6-5</td>
<td>AE Cup Type Line Filter (5 Micron)</td>
<td>Stainless Steel</td>
<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
<td>51.7 MPa (7,500 psi)</td>
<td>Nitrogen</td>
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<tr>
<td>21</td>
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<td>SWF 6-35</td>
<td>AE Cup Type Line Filter (35 Micron)</td>
<td>Stainless Steel</td>
<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
<td>51.7 MPa (7,500 psi)</td>
<td>Nitrogen</td>
<td></td>
</tr>
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</table>

Monel Items-Special Order
## COMPONENT SELECTION LIST continued

<table>
<thead>
<tr>
<th>Item</th>
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<th>P/N</th>
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<th>Material</th>
<th>Size</th>
<th>Supplier</th>
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<tr>
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<td>SLF6600</td>
<td>AE Dual Disc Line Filter (35/65 Micron)</td>
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<td>51.7 MPa (7,500 psi)</td>
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<tr>
<td>23</td>
<td>1</td>
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<td>6</td>
<td>CSX9600-1/4&quot;</td>
<td>AE Universal Safety Head</td>
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<td>3/8&quot;</td>
<td>Autoclave Engineers</td>
<td>(60,000 psi)</td>
<td>Oxygen</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>101A-0438</td>
<td>Body</td>
<td>-</td>
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<tr>
<td></td>
<td>6</td>
<td>2010-0438</td>
<td>Plug</td>
<td>-</td>
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</tr>
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<td></td>
<td>6</td>
<td>1010-7434</td>
<td>Hold Down Nut</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>25</td>
<td>6</td>
<td>1/4 Angle</td>
<td>AE Prebulged Rupture Disc</td>
<td>Monel</td>
<td>1/4&quot;</td>
<td>Autoclave Engineers</td>
<td>276 MPa (40,000 psi)</td>
<td>Oxygen</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>6</td>
<td>1/4 Angle</td>
<td>AE Prebulged Rupture Disc</td>
<td>Monel</td>
<td>1/4&quot;</td>
<td>-</td>
<td>52.7 MPa (7,500 psi)</td>
<td>Nitrogen</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>1</td>
<td>Model 2107</td>
<td>Pressure Transducer (Built-316SS In Press. Sim.)</td>
<td>-</td>
<td>3/8&quot;</td>
<td>Teledyne Taber</td>
<td>(0-10,000 psi)</td>
<td>Nitrogen</td>
<td>Cost-$1,200.00</td>
</tr>
<tr>
<td>28</td>
<td>1</td>
<td>Model 2107</td>
<td>Pressure Transducer (Built-316SS In Press. Simulation)</td>
<td>-</td>
<td>3/8&quot;</td>
<td>Teledyne Taber</td>
<td>(0-50,000 psi)</td>
<td>Oxygen</td>
<td>Cost-$1,200.00</td>
</tr>
<tr>
<td>29</td>
<td>1</td>
<td>-</td>
<td>Pressure Transducer</td>
<td>Monel</td>
<td>3/8&quot;</td>
<td>Fluitron, Inc.</td>
<td>(0-50,000 psi)</td>
<td>Oxygen</td>
<td>Special Order</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>1/2&quot;-385A-U2</td>
<td>General Purpose Thermocouple Well-3/8&quot; Diameter Element</td>
<td>Monel</td>
<td>3/8&quot;</td>
<td>Omega Engineering, Inc.</td>
<td>-</td>
<td>-</td>
<td>Special Order</td>
</tr>
<tr>
<td>Item</td>
<td>Quan.</td>
<td>P/N</td>
<td>Description</td>
<td>Material</td>
<td>Size</td>
<td>Supplier</td>
<td>Maximum Operating Pressure</td>
<td>Fluid</td>
<td>Remarks</td>
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<tr>
<td>31</td>
<td>1</td>
<td>MB2-2</td>
<td>Thermocouple Head</td>
<td>Aluminum</td>
<td>1/2&quot; NPT</td>
<td>Omega Engineering, Inc.</td>
<td>-</td>
<td>-</td>
<td>Cost-$28.00</td>
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<tr>
<td>32</td>
<td>1</td>
<td>MB2-CPSS-14G-12</td>
<td>Thermocouple Assembly</td>
<td>304SS</td>
<td>1/4&quot; NPT</td>
<td>Omega Engineering, Inc.</td>
<td>-</td>
<td>-</td>
<td>Cost-$47.00</td>
</tr>
<tr>
<td>33</td>
<td>1</td>
<td>MB2-CPSS-14G-12</td>
<td>Thermocouple Assembly</td>
<td>Monel</td>
<td>1/4&quot; NPT</td>
<td>Omega Engineering, Inc.</td>
<td>-</td>
<td>-</td>
<td>Special Order</td>
</tr>
<tr>
<td>34</td>
<td>1</td>
<td>-</td>
<td>Pressure Transducer Signal Conditioner</td>
<td>-</td>
<td>-</td>
<td>Technology Development, Inc.</td>
<td>-</td>
<td>-</td>
<td>Cost-$5,000.00</td>
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<tr>
<td>35</td>
<td>1</td>
<td>-</td>
<td>Power Supplies and Indicator/Alarm Panel</td>
<td>-</td>
<td>-</td>
<td>Technology Development, Inc.</td>
<td>-</td>
<td>-</td>
<td>Cost-$5,000.00</td>
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<tr>
<td>36</td>
<td>1</td>
<td>-</td>
<td>Event Sensing Detection System</td>
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<td>-</td>
<td>Technology Development, Inc.</td>
<td>-</td>
<td>-</td>
<td>Cost-$10,000.00</td>
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<tr>
<td>37</td>
<td>1</td>
<td>-</td>
<td>Event Sensing Level &amp; Duration</td>
<td>-</td>
<td>-</td>
<td>Technology Development, Inc.</td>
<td>-</td>
<td>-</td>
<td>Cost-$5,000.00</td>
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<tr>
<td>38</td>
<td>1</td>
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<td>Indicator Panel</td>
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<td>Technology Development, Inc.</td>
<td>-</td>
<td>-</td>
<td>Cost-$1,000.00</td>
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<tr>
<td>39</td>
<td>3</td>
<td>-</td>
<td>Digital Thermometers</td>
<td>-</td>
<td>-</td>
<td>Technology Development, Inc.</td>
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<td>-</td>
<td>Cost-$420.00 Ea.</td>
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<tr>
<td>40</td>
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<td>-</td>
<td>Digital Indicating Temperature Display &amp; Control</td>
<td>-</td>
<td>-</td>
<td>Technology Development, Inc.</td>
<td>-</td>
<td>-</td>
<td>Cost-$650.00 Ea.</td>
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<td>Item</td>
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<td>P/N</td>
<td>Description</td>
<td>Material</td>
<td>Size</td>
<td>Supplier</td>
<td>Maximum Operating Pressure</td>
<td>Fluid</td>
<td>Remarks</td>
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<td>40</td>
<td>4</td>
<td></td>
<td>Temperature Probes</td>
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<td>Technology Development, Inc.</td>
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<td>Cost-450.00 Ea.</td>
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<tr>
<td>41</td>
<td>4</td>
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<td>Reference Junction</td>
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<td>Technology Development, Inc.</td>
<td>-</td>
<td></td>
<td>Cost-$100.00 Ea.</td>
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<tr>
<td>42</td>
<td></td>
<td></td>
<td>System Mounting &amp; Wiring</td>
<td></td>
<td></td>
<td>Technology Development, Inc.</td>
<td>-</td>
<td></td>
<td>Cost-$2,500.00</td>
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<tr>
<td>43</td>
<td></td>
<td></td>
<td>Power Unit-A.C. Heating</td>
<td></td>
<td></td>
<td>Technology Development, Inc.</td>
<td>-</td>
<td></td>
<td>Cost-$2,000.00</td>
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<tr>
<td>44</td>
<td></td>
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<td>Power Unit-D.C Heating</td>
<td></td>
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<td>Technology Development, Inc.</td>
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<td>Cost-$2,000.00</td>
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<tr>
<td>45</td>
<td></td>
<td></td>
<td>1.5 KW Heater System</td>
<td></td>
<td></td>
<td>Technology Development, Inc.</td>
<td>-</td>
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<td>Cost-$1,500.00</td>
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<tr>
<td>46</td>
<td>1</td>
<td>HDD-600/2,000</td>
<td>Metal Diaphragm Two Stage Compressor System</td>
<td>Monel 0.004 CFM</td>
<td>Fluitron, Inc. 25,000 psi</td>
<td>-</td>
<td>Cost-$45,740.00</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Suction-200/2,000 psig</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Discharge-25,000 psig</td>
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<td>47</td>
<td>1</td>
<td>3,078/3,033</td>
<td>Metal Diaphragm Two Stage Compressor System</td>
<td>Monel 1.80 SCFM</td>
<td>Pressure Products Industries 30,000 psi</td>
<td>-</td>
<td>Cost-$125,000.00</td>
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<td>Suction-350 psig</td>
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<td></td>
<td>Discharge-30,000 psig</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>Displacement-3.34/.105 In.³/ Stroke</td>
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</tr>
<tr>
<td>Item</td>
<td>P/N</td>
<td>Description</td>
<td>Material</td>
<td>Size</td>
<td>Supplier</td>
<td>Maximum Operating Pressure</td>
<td>Fluid</td>
<td>Remarks</td>
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<tr>
<td>48</td>
<td>#767 (4 1/2&quot;)</td>
<td>Gauge</td>
<td>S. Stl. Soc.</td>
<td>1/2 MPT Robert Shaw (Black Conn.)</td>
<td>(0-5,000 psig)</td>
<td>Fluid</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>49</td>
<td>#767 (4 1/2&quot;)</td>
<td>Gauge</td>
<td>S. Stl. Soc.</td>
<td>1/2 MPT Robert Shaw (Black Conn.)</td>
<td>(0-7,500 psig)</td>
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<tr>
<td>50</td>
<td>W-15-1-HLR-Exp.</td>
<td>Astratact Type II</td>
<td>1/4 HPF Pressure Products (Exp. Proof)</td>
<td>(0-15,000 psig)</td>
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<tr>
<td>51</td>
<td>CX-4604-108</td>
<td>Aftercooler (See B/M-L)</td>
<td>3/8 HP Pressure Products Industries</td>
<td>(0-15,000 psig)</td>
<td></td>
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<tr>
<td>52</td>
<td>#8320A199</td>
<td>Solenoid Valve (Class 1 Group D)</td>
<td>1/4 FPT ASCO</td>
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<tr>
<td>53</td>
<td>#709 AEB</td>
<td>AC Motor Starter NEMA NEMA Type 7 Class 1 Group D Exp: Proof with Control Transformer 460 V/120V, with Hand Off Auto Switch in Cover and (3) Type N-21 Overload Relays</td>
<td>0 Allen Bradley</td>
<td></td>
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</tr>
<tr>
<td>54</td>
<td>#800H-2HA7</td>
<td>Push Button Station Start-Stop NEMA Type 7 Class 1, Group D.</td>
<td>Allen Bradley</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Item #</td>
<td>P/N</td>
<td>Description</td>
<td>Material</td>
<td>Size</td>
<td>Supplier</td>
<td>Maximum Operating Pressure</td>
<td>Fluid</td>
<td>Remarks</td>
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<tr>
<td>55</td>
<td>CAT # EMP 9030</td>
<td>Push Button Station Enclosure with (1) Push Button On-Off and (2) Pilot Lights (1) Red and (1) Amber</td>
<td></td>
<td></td>
<td>Crouse Hinds</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>56</td>
<td>#EJB 121206-6-9B</td>
<td>Junction Box Class 1, Group D Exp: Proof with (2) 1&quot; NPT, Tap Openings on Each Side and (2) 1&quot; NPT Tap Openings on Top and Bottom</td>
<td></td>
<td></td>
<td>Crouse Hinds</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>57</td>
<td>#Z-163</td>
<td>Press: Switch Exp: Proof Class 1, Group D.</td>
<td></td>
<td></td>
<td>Custom Components</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>58</td>
<td>ATC Type 319</td>
<td>Time Delay Relay AC Range 1 to 60 Sec.</td>
<td></td>
<td></td>
<td>Pressure Products Industries</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>59</td>
<td>#TM 21 K 095</td>
<td>Elapsed Time Indicator OTO 99,999 Hrs. 120V. 60 cy. 2.5 Watts</td>
<td></td>
<td></td>
<td>Herbach &amp; Rademan, Inc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>60</td>
<td>611G9163</td>
<td>Pressure Switch SSTL</td>
<td></td>
<td></td>
<td></td>
<td>Set at Dual Snap 50 psig Decreasing Pressure</td>
<td></td>
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</tr>
</tbody>
</table>
# TABLE VI

## HIGH PRESSURE MANUFACTURERS AND SUPPLIERS

1. **Almac Cryogenics, Inc.**  
   1108 26 Street  
   Oakland, CA  94607  
   Phone: (415) 832-1505  
   (Temperature Level and Flow Controls, Sensor Units, Indicators,  
   Transfer Lines, etc.)

2. **Autoclave Engineers, Inc.**  
   The Fred Gasche Building  
   2930 West 22 Street  
   Erie, PA 16512  
   Phone: (814) 838-2071  
   (Atlanta Representative:  
   Kent L. Fredrick  
   2030 Tucker Industrial Road  
   Tucker, GA 30084  
   Phone: (404) 493-1158  
   (Non-Rotating Stem Valves—High Temperature and Cryogenic Valves,  
   Air Operated Valves, Relief Valves, Line Filters, Check Valves,  
   Safety Heads, Rupture Discs, Valves and Fittings, Gages, Indicators,  
   Transducers, Thermocouples, Electrodes, Tubing and Fittings.)

3. **BLH Electronics**  
   42 Fourth Avenue  
   Waltham, MA 02254  
   Phone: 617/890-6700  
   Locally: Currie, Peak & Frazier  
   205/536-1506  
   Instrumentation  
   Pressure Transducers  
   Temperature Sensors  
   Strain Gage Accessories)

4. **Chromalox**  
   (Industrial Heating Products)  
   4 Allegheny Center  
   Pittsburgh, PA 15212  
   (Chromalox Cartridge Heaters)
5. Circle Seal Controls
Technetics Division
Brunswick Corporation
Post Office Box 3666/1111 North Brookhurst Street
Anaheim, CA 92803
Phone: (714) 774-6110
(Valves, Fittings, Relief Valves, Solenoid Valves, Check Valves, Manifold and Instrumentation Valves, Pressure Regulators and Back Pressure Regulators, Dynaflow Relief Valves)

6. Control & Power, Inc.
1920 27 Avenue, South
P. O. Box 617
Birmingham, AL 35259
Phone: 205/870-0274
(Valves, Fittings & Instrumentation)

7. Cryogenic Energy Company
6533 N. Washington Street
Denver, CO 80229
Phone: (303) 287-3371
(Vacuum Jacketed Pipes and Tubes, Liquid Oxygen-Liquid Nitrogen Trailer Style Dewars)

8. CVI, Incorporated
P. O. Box 2138
Columbus, OH 43216
Phone: (614) 876-7381
(Cryogenic Valves, Cryogenic Pumps.)

9. Flexonics Division
300 East Devon Avenue
Bartlett, IL 60103
Phone: (312) 625-1210
(Flexible Metal Hose and Fittings, Expansion Joints, Ducting, Flexible Connectors, Bellows, Expansion Compensators)
10. Fluitron, Inc.
30 Industrial Drive
Ivyland, PA 18974
Phone: (215) 355-9970
(Manufacturing-Total Capability Valves, Diaphragm Compressors, Fittings, Reaction Vessels, Containment Vessels)

South Street
Walpole, MA 02081
Phone: (617) 668-3600
(Tubing and Fittings, Valves-Manual, Check, Automatic and Remotely Controlled, Pumps and Compressors, Pressure Gages, Load Cells, High Pressure Systems for High Velocity Jet Cutting, etc.)

12. High Pressure Equipment Company
1224 Linden Avenue
Erie, PA 16505
Phone: (814) 838-2128
(Gauges, Pumps, Pressure Vessels, Tubing and Fittings, Couplings, Valves, Intensifiers)

13. Metal Bellows Corporation
1075 Providence Highway
Sharon, MA 02067
(Vacuum Pumps and Compressors, Pressure and Temperature Sensors, Flexible Couplings, Expansion Joints, Metal Hose Assemblies, Ducting, Fabricated Assemblies)

808 Wilson Street, N.E.
Decatur, AL 35601
Phone: (205) 355-6121
(ASCO Solenoid Valves, Pressure Switches Relays, Transformers, Wiring Accessories)
15. Parke Hannifin Corporation
   Instrumentation Connectors
   Division
   P. O. Box 4288
   Huntsville, AL  35802
   Phone:  (205) 881-2040
   (Process Control and Instrumentation Valves and Fittings)

16. Pressure Products Industries Division
   The Duriron Company, Inc.
   900 Louis Drive
   Warminster, PA  18974
   Phone:  (215) 675-1600
   (Diaphragm Compressors, Valves and Fittings, Reactors and
    Pressure Vessels, Pumps, Gages, Instrumentation)

17. Omega Engineering, Inc.
   One Omega Drive
   Box 4047
   Stamford, CT  06907
   Phone:  (203) 322-1666
   (Temperature Measurement and Control Components)

18. Orange Research, Inc.
   140 Cascade Boulevard
   Milford, CT  06460
   Phone:  (203) 877-5657
   (Differential Pressure Gages, Compound Range Gages, Switche,
    Indicating Switches.)

19. Oriel Corporation
   15 Market Street
   Stamford, CT  06902
   Phone:  (203) 357-1600
   (Precision Optical Components)
20. Rosemont, Inc.  
One Riverchase Office Plaza  
Suite 118  
Birmingham, AL 35244  
Phone: 205/988-5759  
(Instruments, Pressure Transducers, Temperature Sensors)

21. Ruska Instrument Corporation  
P. O. Box 36010  
Houston, TX 77236  
Phone: (713) 774-2533  
(Digital Direct Reading Pressure Gages, Controllers, Test Sets, Air Data Calibrators, Computer Interfaces, Positive Displacement Pumps, Precision Pressure Standards)

22. Setra Systems, Inc.  
45 Magog Park  
Acton, MA 01720  
Phone: (617) 263-1400  
(Digital Pressure Measurement Systems and Readout Devices)

23. Superpressure, Inc.  
8030 Georgia Avenue  
Silver Spring, MD 20910  
Phone: (301) 589-1727  
(Diaphragm Compressors, Pneumatic Test Stands, Valves and Fittings, Pumps and Intensifiers, Shaking Assemblies, Reaction Vessels, Optical Absorption Cells, Union Connectors, Non-Rotating Stem Valves, Check Valves, Pneumatically Operated Valves, Proportioning Valves, High Temperature Valves, Line Filters, Relief Valves, Tubing and Fittings, Swivel Joints, Adapters, Electrical Connectors, Thermocouple Assemblies, Rupture Disc Assemblies)

24. Technology Development, Inc.  
500 Wynn Drive (Suite 114)  
Huntsville, AL 35805  
Phone: (205) 837-7762  
(Design and Fabrication of Instrumentation Systems)
25. Teledyne Taber
455 Bryant Street
N. Tonawanda, NY
Phone: (716) 694-4000
(Pressure Transducers-Low Level, High Level, Differential,
Pressure Transmitters, Oceanographic)

26. Wahl Instruments, Inc.
5750 Hannum Avenue
Culver City, CA 90230
Phone: (800) 421-2853
(213) 641-6931
(Thermocouples, Calibration Standard, Probes, etc.)
VII. MECHANICAL IMPACT TESTING OF MATERIALS IN AN OXYGEN ENVIRONMENT TO 172 MPA (25,000 PSI)

The hardware and the high pressure technology is available for venturing into 103, 138, and 172 MPa pressure ranges (15,000, 20,000, 25,000 psi).

This investigation revealed that there is a requirement for additional information about oxygen and materials at these pressures and temperatures.

The impact testing pressure and heating systems lend themselves to additional applications for investigations of oxygen and these additional possibilities should be addressed during the redesign.

SEALS

Seal compatibility for these pressures and temperatures are recommended for maximum operation to 280°C. This is an area where judicious care must be applied in selecting the seal design that will permit leak free testing to 400°C.

The Bal-Seal has some good features for static applications.

The seal problem at the specimen test cell is an area that needs addressing during redesign.

Bal-Seal Engineering Company (Mr. Peter Bartheld) proposed a seal for the striker pin for 172 MPa (25,000 psi) and cryogenic temperatures. Bal-Seal proposes their teflon-glass material with a back-up ring made from Kel-F and a loading spring made from 302 stainless steel. (This loading ring should be from Monel 400 Series). They propose their flange type seal which has the unique advantage that, as the temperature decreases, a greater load is applied to the striker pin shaft.

During any high pressure application, the force that is required to move the striker pin is determined by the area of seal contact with the striker pin shaft. Bal-Seal recommends a seal with a design that combines flexibility with minimum area of contact, which is their part number 2FEHUR304-113G.
SSI does not concur with their recommendation for this seal at the striker pin due to the excessive "break" force for the striker pin during operation with a seal of this type.

Essentially, SSI recommends the use of the bellows for a seal at the striker pin because the "break" force will always be predictable.

**CLEANLINESS**

Cleanliness cannot be over emphasized when operating at these pressures and temperatures.

The equipment layout should be such as to permit easy scrubbing and maintenance of the testing area.

**FITTINGS, VALVES AND TUBING**

The fittings and valves for 82.7 MPa (12,000 psi) or 172 MPa (25,000 psi) are made from the same-size piece of material. The only difference is the flow system inside diameter and the valve seats. As the pressure increases the flow path size decreases, with a corresponding slight increase in cost due to the design and machining problems encountered.

All of the components are special order and the delivery time can be up to six (6) months. If a volume production is scheduled at the time an order is placed a cost benefit can be anticipated. Even tubing is a special order at these pressures.

**MATERIAL, SPECIMEN TEST CELL AND COMPRESSOR**

Certified billets of Monel-400 are available and are needed for the compressor heads and the specimen test cells. These billets are not plentiful but they can be found. However, they are expensive.

The machining operations on the specimen test cell are complex and of course costly.
The two most expensive sections of the system are the specimen test cells and the compressor section.

The two stage compressor can be made the most flexible because it may be controlled so that one or two compressors are the source of high pressure oxygen depending on the pressure required for testing. This is the most flexible pressurization technique; but again, it is the most expensive. It presents twice the maintenance problems.

The two stage, individual stage controlled, compressor is the type recommended due to its flexibility in operation.

Since a relief value is very undesirable at these pressures, automatic unloading by automatically lowering the suction pressure to the compressor should be considered when the system is designed.

Premised on WSTF and JSC experiences, the Fluিরোন, Incorporated, compressor is recommended.

This compressor has Monel-400 material for all oxygen wetted surfaces with a hydraulic drive diaphragm rated at 172 MPa (25,000 psi).
VIII. Cost Analysis

Individual components, recommended materials, measurement and control instrumentation, and design considerations for the high pressure oxygen impact tester have been discussed in previous sections. In some cases more than one manufacturer or vendor had acceptable items or could readily manufacture items to the clients required specifications. Some concepts or recommended items are not essential to the safe or minimal operation of the impact tester but should be seriously considered to obtain the best data while advancing the science and understanding of high pressure oxygen impact testing.

Costs of individual item are discussed in Section VI. as well as estimated costs of research and development items/systems to be developed. The following cost analysis is divided into the various operational sections of the impact tester.

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Pressure Nitrogen and Oxygen Systems</td>
<td>$15,000</td>
</tr>
<tr>
<td>Compressor and Associated Control Systems</td>
<td>60,000</td>
</tr>
<tr>
<td>High Pressure Oxygen System Excluding Dead Weight Tester</td>
<td>37,000</td>
</tr>
<tr>
<td>Test Cell - Minimum of Three Required, One Each for Metals Testing, Oil and Grease Testing, and Plastics Testing</td>
<td>3 @ $18,000 each</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>45,000</td>
</tr>
<tr>
<td>Tower Refurbishment</td>
<td>6,000</td>
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<tr>
<td>Installation</td>
<td>75,000</td>
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<tr>
<td>Design</td>
<td>36,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$328,000</td>
</tr>
</tbody>
</table>
IX. Conclusions and Recommendations

This document attempts to assimilate the pertinent information needed to understand liquid and gaseous oxygen characteristics in combination with the engineering materials necessary to develop the flow systems for a materials compatibility impact tester for operation in an oxygen environment at pressures up to 172 MPa (25,000 psi) and temperatures from -181° to 400° C.

Current high pressure technology is capable of operation at the required levels, however, no documented information was found indicating previous operations with oxygen at these extremes of temperature and pressures. Therefore, operation in an oxygen environment above 103 MPa (15,000 psi) and to 400° C should be considered in the area of research and development. As a result all of the current MSFC material impact tester systems, with the exception of the tower, should be redesigned to reflect current technological developments, and increased operating pressure to 172 MPa (25,000 psi). Items to be considered are:

**Impact Tower and Associated Accessories**

The current tower and associated accessories are meeting requirements, however, it should be reworked to conform with projected requirements.

- The load-cell should be sent to the manufacturer for refurbishing.
- The impact tower accessories should be replaced to bring them in line with current technology.
- Welding of the tower at strategic stress points would produce a more rigid structure.
- Knife edge guides for the plummet in place of rollers would simplify adjustment and aid free fall alignment on the striker pin.
**IMPACT TEST CELL**

The impact test cell redesign should be similar to the current ones in operation but incorporate features for the improvement of testing.

- The test cell should be redesigned of Monel 400 for temperatures from (-)180° to (+)400° C with design stresses sufficient to operate at 172 MPa (25,000 psi) plus the maximum pressure anticipated due to chemical reaction.
- The base assembly should be redesigned to incorporate resistance heating of the cartridge type or its equivalent.
- The seal design should be changed at the test cell interface to a compression type of the Bridgman design with the proper materials.
- The test cell sample holder volume, sensing probe locations, and event sensing should be addressed in the redesign.
- The striker pin assembly should be redesigned using a bellows or diaphragm for a seal to eliminate the "stick-break" force-pressure problems at the striker. Using this approach the striker "break" force would be a known quantity.
- The redesign should incorporate an impact cell quick opening feature to speed-up testing.
- The redesign should incorporate a more effective event sensing capability.
- The redesign should incorporate a chromatograph-mass spectrometer analysis feature for analysis of the test residual gases.
- The delivery of high pressure oxygen to the test cell should be at ambient conditions and then the temperature should be increased to the test limits desired. This approach will extend the life of the hardware during the initial exploratory testing at extremes of temperature and pressure.
- The location of the temperature, pressure and event sensing sensors in the test cell is a real designing challenge but it can be accomplished so the cell may be readily opened for specimen replacement.

**LOW PRESSURE PNEUMATIC SYSTEMS**

The pneumatic support systems, i.e., actuation cylinder pressure, pneumatic valve actuation, test cell balance pressure, and the liquid nitrogen cooling systems should be replaced due to age and wear as well permitting reconfiguration to incorporate component improvements.
The liquid nitrogen test cell cooling system should incorporate a means for throttling LN2 flow so that the LN2 may be used as a rapid temperature changing source for the impact test cell.

The nitrogen test cell balance pressure should be brought up-to-date with current servo capability.

The nitrogen test cell balance pressure volume should be increased.

**HIGH PRESSURE OXYGEN FEED SYSTEM**

This system needs to be redesigned to meet currently programmed requirements.

- All oxygen wetted surfaces within this system should be constructed of Monel 400.
- All valves, fittings and tubing intended for this system should be special ordered of Monel 400.
- Relief valves or orifices should not be used in this system. Rupture disc holders should be barricaded.
- Where tubing of this system is exposed to temperature the operating pressure should be reduced to 75% of that normally recommended.

**OXYGEN SOURCE**

The current gaseous oxygen source, i.e., eleven 1A cylinders manifolded together should be replaced.

- An MSFC oxygen tube trailer charged to 15.2 MPa (2,200 psi) would give in excess ten times the volume currently available. If volume testing is planned an additional larger source of oxygen will be necessary.
- One of the existing 34.5 MPa (5,000 psi) tube trailers available at MSFC could be used to supply a greater volume.
- This oxygen source should be designed and installed so this system could be connected to the test cell as a source for low pressure testing.
- This system should also be designed and controlled so it may be used for a supply of oxygen to the suction side of the compressor.
- This oxygen supply should be evaluated for total hydrocarbons by an inline chromatograph.
The moisture should be evaluated and kept to a minimum below (-)55°C.

This oxygen source should be rough filtered to 25 microns with a final filter prior to compressor entrance down to one micron.

A by-pass should be provided for a cleanup of the oxygen when required. A hydrocarbon cleanup can be attained by a flow through silica gel and a molecular sieve.

**HIGH PRESSURE OXYGEN COMPRESSOR**

The current impact tester system compressor, an Aminco-Corblin (which is now Superpressure, Inc.) motor driven, two stage diaphragm type, catalog number 46-13426 should be replaced. It needs the upper head plates, the check valves and the diaphragms replaced with Monel 400 material to comply with current technology for operation at the projected extremes of temperature and pressure.

Two manufacturers contacted for modification of this compressor indicated they could build another to specific requirements more economically than modifying the current one.

This compressor should incorporate the following.

- Leak free design capable of delivering 207 MPa (30,000 psi) oxygen pressure.
- Contamination free compression.
- Flow rate of 1.75 CFM or greater.
- Corrosion resistant materials (All oxygen wetted parts from Monel 400).
- Leak detection.
- Aftercooler
  
  The compressor head plate should incorporate water cooling. This will extend the Monel 400 diaphragm life and permit delivery of oxygen to the test cell at ambient conditions, an essential requirement for operation at planned extremes of temperature and pressure.
- Motor starter.
- Automatic "ON/OFF" Control system.
- Automatic unloading system. Since a relief valve is very undesirable at these pressures, automatic unloading by automatically lowering the suction pressure to the compressor should be considered when the system is designed.
Suction and discharge pressure instrumentation.
Flow control systems.
Temperature and pressure switches.
Oil level switch.

MATERIAL

Studies of materials available for use with temperature and pressure extremes in an oxygen environment indicate that Monel 400 is the most acceptable for this application. Monel 400 is less strong than many of the other metals but sufficient where weight is not a restriction.

Certified billets of Monel 400 are needed for the compressor heads, the specimen test cell and the various valves and components used to control the high pressure oxygen.

INSTRUMENTATION

There have been rapid advances in electronics since the installed units were selected, therefore, these units should be replaced with components incorporating some of the following functions with improved capability.

- Instantaneous indication of existing variables in a system.
- Recording of variables.
- Programming of variables with time.
- Actuation of control circuits and recording of events by time.
- Visual and audio indications of malfunctions.

These functions are applicable to temperature, pressure, and event sensing.

TEMPERATURE SENSING AND CONTROL

The test cell temperature sensing system should be readily compatible with the requirement for controlling and recording the temperature of the specimen test cell from (-)181°C to (+)400°C. Four symmetrically placed thermocouples will do this. The Omega Engineering "T" thermocouples will perform this function satisfactorily.
The throttling of liquid nitrogen to the test cell will provide an adjunct to the heating and permit the temperature controller to provide the heating as required to achieve the desired test temperature.

**CALIBRATION**

The thermocouple temperature measurement system is validated by placing a test thermocouple inside the test cell to correlate the test thermocouple readings with the actual temperature within the test cell.

**EVENT SENSING**

The extremes of pressure and temperature programmed for the material impact tester present problems of high pressure sealing. The current system is inadequate and is not being used.

In order to overcome these problems and allow the detection of the emission of radiation in the test cell a very small window located in the upper segment of the test cell and coupled to a fiber optic will transmit radiation. The use of two such event sensing parts on opposite sides of the test cell will provide reasonable coverage for event sensing.

The coupled optic fiber will transmit radiation to a remote location for detection processing and display. Available detection systems for use with such optical fibers allow a wide variety of measurements such as--

- Rapid sensing of the occurrence.
- Sensing of short duration events.
- Variable setting to define event occurrence.
- Measurement of different portions of spectrum by detector selection.
CALIBRATION

The purpose of the event sensing drive is to determine whether an event occurred. Calibration consists of setting threshold devices inside the electronics. Observation of signal outputs from tests with known events should be used to determine the correct setting of threshold levels. Two sensing element ports will permit laser calibration for accurate use in the visible or near IR range with NBS traceability.

PRESSURE SENSING

The pressure instrumentation measures physical phenomena and presents this measurement in an intelligible and usable form for recording and controlling events.

- This system should provide a power supply for transducer excitation and signal conditioning.
- An indicator for electronic recording and readout of test cell pressure.
- An alarm if preset pressure is exceeded.
- This system should also incorporate an alarm and "shut down" if the pressure transducer is lost during testing.

The Teledyne-Taber pressure transducer (Model 2107) has an excellent track record; however, the pressure sensing cavity is of stainless steel and the operating temperature limit is below the 400°C requirement.

To compensate for the temperature limitations, it will be necessary to offset the transducer at the test cell by approximately two inches. This will affect the response, however, the response decay can be calculated.

There is no record of a stainless steel "dead-end" connection of this type encountering problems from an oxygen environment.
CALIBRATION

The pressure sensor selected has a built-in electrical signal simulator to calibrate the electronics associated with the pressure sensor system. Pressure standards are available with accuracies of the "N" and "S" type as complete, compact, and transportable units with the means of pressure generation and regulation built into one compact housing, with the heaviest weight inside being 2 kilograms.

AREAS OF CONCERN

There are areas of uncertainty to be considered when undertaking any task for the first time, especially, at these planned extremes of temperature and pressure in an oxygen environment.

Some areas of concern considered pertinent enough to warrant additional study are:

- Reactive nature of oxygen at pressures greater than 138 MPa (20,000 psi).
- Oxygen reaction kinetics and thermodynamics.
- The internal shape and dimensions of the material impact test cell itself with respect to the propagation or support of oxidation. (20)

This work would determine the ignition limits and their dependence on temperature and the oxidizing media as well as the analysis of the residuals.

To extend a specific, limited study to a variety of problems to be encountered in the use of various materials under widely differing conditions, there is a need to develop theoretical postulations based on thermodynamics, kinetics and physical properties.

Once a sufficient number of experimental data are accumulated the practical applicability of such a theoretical system can then be tested.

The accumulation of ignition-decomposition characteristics of a sufficient number of related substances would permit the tailoring of a materials properties for a specific application.
Evaluation of material reactions has shown certain data are basic when assessing these reactions, i.e., (1) thermodynamic data, (2) kinetic parameters and (3) physical properties.

These specific parameters are:

- **Thermodynamic.**
  - Reaction energy.
  - Adiabatic temperature increase.
  - Specific quantity of gas generated.
  - Maximum pressure in the test cell.

- **Kinetic.**
  - Reaction rate.
  - Rate of heat production.
  - Rate of pressure increase in the test cell.
  - Adiabatic time to maximum rate.
  - Apparent activation energy.
  - Initial temperature of detectable exothermic reaction.

- **Physical.**
  - Heat capacity.
  - Thermal conductivity.

There is a close relationship between the exothermic reaction energy and the adiabatic temperature rise which can be measured by appropriate instrumentation. The specific volume of the gas generated by the reaction, together with the adiabatic temperature rise determines the maximum pressure developed in the test cell.

The basic thermochemical variable that requires consideration is the temperature-dependent, concentration-dependent rate of the exothermic reaction. Both the total energy of reaction and rates of heat generation and heat accumulation must be determined.

Pressure changes in the test cell will also be dependent upon the reaction rate. From the adiabatic temperature rise and the adiabatic self heat production, the derived variables, i.e., such as activation energy, adiabatic time to maximum rate, and maximum time to pressure rise can be calculated.
The heat generation rates of specific samples depend on temperature, degree of conversion, and often, previous thermal history. The start of a particular heat release rate will be detected at widely different temperatures, depending on sensitivity of the instrumentation.

The primary objective of these thermo-kinetic studies is to aid the selection criteria and establish the use parameters for a material in a GOX, LOX environment through the application of limited data.
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The extreme aggressiveness of oxygen in the pure state, or diluted with small quantities of other gases, involves serious problems each time lubricants come into contact with atmospheres of that type.

The difficulty of finding materials suitable for this use has induced equipment designers to exclude lubrication, or else to separate the zone where oxygen is present from the one in which the lubricant acts, using diaphragms or the like.

The latter solution, which would appear the most logical wherever it is feasible, entails the serious risk of causing oxygen to come into contact with the lubricant in the event of accidental rupture of the separator elements, so the lubricant must be capable of withstanding such contact.

These difficulties have in some cases aroused the attention of legislative authorities; for instance, in the German Federal Republic law forbids the use of lubricants which have not been approved by a special Federal Institute (1).

A valid contribution to these problems is offered by Fomblin* Fluorinated fluids, which are perfectly compatible with oxygen and possess thermal stability, chemical inertness and lubricating properties capable of meeting every type of requirement.

Properties of Fomblin Y
Fluorinated fluids

Fomblin Y fluids are linear perfluoropolyethers, available in several grades with differing average molecular weight and viscosities. Table 1 gives some properties of the Fomblin Y grades suggested for oxygen application. For fuller details reference should be made to the specific technical bulletin "Fomblin Y Fluorinated fluids" edited by Ausimont.

Different grades of Fomblin Y are miscible one with the other, yielding types having properties intermediate between those illustrated.

Viscosity-temperature properties

These properties are illustrated in the graph in Figure 1. As compared with the fluorinated compounds oxygen compatible on the market, Fomblin Y fluorinated fluids have viscoelastic properties that are among the best.

Lubricating properties

Fomblin Y fluids are good lubricants in boundary lubrication conditions.

Under such conditions they behave as a good additive-free, typical mineral oil.

Fomblin Y also exhibit good EP properties.

Compatibility with oxygen

At atmospheric pressure, no reaction is observed between pure oxygen or air and Fomblin Y Fluorinated fluids up to temperatures around 400°C and not excessively prolonged contact times. For this reason no reference is made here to flash points, combustion or self-igniting temperatures for Fomblin Y fluids, which are to be considered as non-flammable.

At high pressures the maximum service temperature of Fomblin Y in the presence of oxygen decreases. Its value is also affected by the manner in which the gases and the fluids reach contact; in particular by pressure application speed.

This phenomenon is not confined to the Fomblin fluids, but is general.

Test methods capable of reproducing as faithfully as possible actual service conditions, when a lubricant is in contact with oxygen, have therefore been developed. In addition to those adopted by the BAM of Berlin, methods and test results on the compatibility of oxygen placed in contact with the Fomblin fluids are described hereafter.

Static oxygen resistance

Tests carried out in Montedison’s laboratories, heating Fomblin Y Fluorinated fluids at 200°C in a stainless steel autoclave with oxygen at 200 kg/cm² and analyzing the fluid after 160 hours have shown that the sample thus treated remains completely unaltered.

Liquid oxygen impact test

This test allows determination of the compatibility of lubricants with liquid oxygen.

It reproduces the service conditions of a lubricant for valves or compressor used in air separation plants, in rocket motors and the like.

Fomblin Y fluids, tested in accordance with the U.S. standard MSFC-SPEC. 106 B «Testing Compatibility of Materials for Liquid Oxygen Systems», passed the test. They have thus been approved for use in liquid oxygen systems by the National Aeronautics and Space Ad-
ministration - NASA (G.C. Marshall Space Flight Center, Alabama) and by the Naval Ship Engineering Center of the U.S. Navy.

Copies of three letters of approval are shown in Enclosures 1, 2 and 3 (1).

Fomblin Y 06 passed the tests as appeared in the NASA - White Sands Test Facility Report of August 27, 1960. At pressures up to 10,000 psia, has been found to be non-reactive under the conditions of the tests.

The first test, the Heated Mechanical Impact Test, was performed according to the requirements of Part 2 of Test No. 13 of NHB 8060.1A. Using gaseous oxygen, with the Impact Energy of 72 foot-pounds a pressure of 10,000 psia, a temperature of 150 °F, no reaction occurred after 20 tests.

The second test, the Heated GOX Pneumatic Impact Test, was performed according to the requirements of Test No. 14 of NHB 8060.1A.

At a pressure of 10,000 psia and a temperature of 150 °F, no reaction occurred after 20 tests.

Injection in oxygen

This test reproduces what occurs when in a membrane compressor for oxygen, operating with the fluid under examination, the membrane breaks with a consequent injection of the fluid into the gas. A 50/50 mixture of Fomblin Y 04 heated at 50°C, was injected into a stainless steel autoclave containing oxygen at 150°C and 260 atm. The sample, analyzed after about 30 minutes of dwell in the oxygen, was absolutely unaltered, demonstrating the resistance of the fluid to oxygen under the conditions described.

Ignition temperature in oxygen

This has been determined by the Bundesanstalt für Materialprüfung, Berlin for each Fomblin Fluid type heating in a cylinder 500-700 mg of product in an oxygen atmosphere at 100 kglas cm² and 20°C, up to reaction temperature (Enclosure 4).

The results are reported in Table 2, which also gives the oxygen pressure corresponding to ignition temperature.

Maximum service temperature

For all Fomblin Y Fluorinated fluids, this temperature must not exceed 250°C (2). In fact, if for some of them a higher temperature is feasible, for technical reasons it was not possible to determine at the impact test the corresponding pressure.

Oxygen impact resistance under pressure

This test reproduces what occurs when there is an instantaneous pressure increase of the oxygen in an environment having a relatively low pressure, and in which the lubricant is present at a certain initial temperature.

During this instantaneous pressure, which in an early approximation may be considered as adiabatic, the temperature of the system increases to a value which is a function of the initial conditions (initial temperature and pressure) and of the final pressure reached. If the final conditions exceed the stability limits of the products, these ignite.

The results of these determinations, conducted by the BAM of Berlin, are shown in Figures 2 and 3.

Fomblin Fluorinated greases, T series

By appropriately thickening Fomblin fluids, greases for advanced lubrication can be prepared. Some of these greases are presented by Ausimont as Fomblin Fluorinated greases, T series. Some of the properties of these greases are given in Table 3, but here again reference should be made to the specific literature for fuller details.

The Fomblin Fluorinated greases, T series, have also been examined and approved by the BAM, Berlin for use in contact with oxygen.

The results are given in Table 4 and Figures 5, 6 and 7.

(1) These letters indicate Fomblin Y Fluorinated fluids as Brayco 810, 811, 812 and 813 oils, respectively. This is the name with which they are sold in the U.S.A.

(2) The maximum service temperature for each grade must be 100 °C lower than the ignition temperature as per Table 2.
Table 1 — General properties of Fomblin Y Fluorinated fluids

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<th>Property</th>
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<td>250</td>
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<td>Pour point, °C</td>
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<td>—35</td>
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<td>Volatility (% weight loss for 24 hours at 149°C)</td>
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<td>—</td>
<td>7</td>
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<td>Volatility (% weight loss for 100 hours at 80°C)</td>
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<td>5.0</td>
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</table>

Table 2 — Ignition temperature of Fomblin Y Fluorinated fluids in an oxygen atmosphere

<table>
<thead>
<tr>
<th>Fomblin Fluorinated fluids</th>
<th>Ignition temperature</th>
<th>Corresponding oxygen pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y 04</td>
<td>360 ± 5</td>
<td>215</td>
</tr>
<tr>
<td>LOX</td>
<td>385 ± 5</td>
<td>220</td>
</tr>
<tr>
<td>Y 25</td>
<td>395 ± 5</td>
<td>230</td>
</tr>
</tbody>
</table>

Table 3 — Some of the properties of Fomblin Fluorinated greases, T series

<table>
<thead>
<tr>
<th></th>
<th>OT 20</th>
<th>UT 18</th>
<th>RT 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penetration ASTM D217, mm/10 at 25°C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>— without mechanical work</td>
<td>285</td>
<td>280</td>
<td>275</td>
</tr>
<tr>
<td>— after 10,000 cycles</td>
<td>345</td>
<td>310</td>
<td>290</td>
</tr>
<tr>
<td>Pour point, °C</td>
<td>&gt;200</td>
<td>&gt;200</td>
<td>&gt;200</td>
</tr>
<tr>
<td>Service temperature range, °C</td>
<td>—70 +100</td>
<td>—30 +150</td>
<td>—20 +200</td>
</tr>
</tbody>
</table>

Table 4 — Compatibility of Fomblin Fluorinated greases, T series, with oxygen

<table>
<thead>
<tr>
<th></th>
<th>OT 20</th>
<th>UT 18</th>
<th>RT 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ignition temperature, °C</td>
<td>225 ± 5</td>
<td>310 ± 5</td>
<td>320 ± 5</td>
</tr>
<tr>
<td>Corresponding pressure, kg/cm²</td>
<td>180</td>
<td>200</td>
<td>200</td>
</tr>
</tbody>
</table>
Figure 1 — Kinematic Viscosity of Fomblin Y Fluorinated fluids vs temperature (Chart ASI MD 341- E)

Figure 2 — Pressure vs temperature plot for Fomblin Y Fluorinated fluid Y 04

Figure 3 — Pressure vs temperature plot for Fomblin Y Fluorinated fluid Y 25
Figure 5 — Pressure vs temperature plot for Fomblin Fluorinated grease UT 18

Figure 6 — Pressure vs temperature plot for Fomblin Fluorinated grease RT 15
Dear Dr. Fainman:

The samples of Brayco 631A grease and Brayco 810, 811, 812, and 813 oils you submitted have been evaluated for compatibility with liquid oxygen by the procedures outlined in MSFC-SPEC-106B, "Testing Compatibility of Materials for Liquid Oxygen Systems."

Brayco 631A grease and Brayco 810, 811, 812, and 813 oils met the required criteria and are approved for use in liquid oxygen systems.

Sincerely yours,

R. J. Schwinghamer

Enclosure 2

Mr. Richard A. Steenrod, Jr.
Post Office Drawer L
Bridgeton, Missouri 63044

Dear Mr. Steenrod:

The samples of Fomblin Y-25 S-1, Y-25 S-2, Y-25 S-3, and Y-25 S-4 have been evaluated for compatibility with liquid and gaseous oxygen at 10,000 psia by the procedures outlined in NHB 8060.1A. The above samples met the acceptance criteria of NHB 8060.1A for Type D materials contingent on each manufacturer's batch being evaluated to ensure LOX/GOX compatibility.

Sincerely,

R. J. Schwinghamer

Enclosure 1
NAVAL SHIP ENGINEERING CENTER
CENTER BUILDING
PRINCE GEORGE'S CENTER
NAVAL SHIP ENGINEERING CENTER
CENTER BUILDING
PRINCE GEORGE'S CENTER

Dr. M. Z. Feinman,
Bray Oil Company,
1925 North Miramonte Avenue,
Los Angeles, California 90032

Dear Dr. Feinman:

In response to your letter of 26 June 1969 forwarding results of tests conducted by the George C. Marshall Space Flight Center, Bray Oil Company’s “Bravco 81” and “Brayco 631A” fluids and “Brayco 631A” grease will be placed on the list of acceptable materials in the revised SURFHPS INSTRUCTION 9230.18.

Sincerely yours,

H. F. King

Enclosure 4

BUNDESANSTALT FÜR MATERIALPRÜFUNG
(BAM)

Firma:
Montan-Chemie GmbH
6 Frankfurt/Main
Gobellasse 9

Datum: 4.4.69
Nummer des Begehens: 9251/69
Nummer der Proben: 709 8445
Datum der Übersendung: 5. Febr. 1970

Beitrag: Prüfung von "Fonblin"-Gleitmitteln auf Reaktionsfähigkeit
mit verdichtetem Sauerstoff

Wir übersenden Ihnen den Bericht über die Prüfung von 16 "Fonblin"-Gleitmitteln auf Ausbreitungsneigung gegen Sauerstoff-Druckstöße.


Durch die Prüfung sind Gehänge nach heiligenden Gehäusebescheid entstanden.

(Mr.-Ing. R. H. Müller)
Oberregierungsrat
The data, information and suggestions are provided for guidance purposes only. No responsibility is accepted for the results obtained therefrom, nor for their utilization in infringement of possible patent rights.
APPENDIX II
FUNDAMENTAL DATA FOR OXYGEN & NITROGEN

Liquid oxygen is pale blue in color, will flow like water, and weights 1.0688 grams per cubic centimeter (23).

One cubic meter of liquid represents 800 standard cubic meters of gas and could build up to a pressure of more than 82.7 MPa (12,000 psi) if confined at ambient conditions.

Oxygen can exist as a gas, liquid or solid. However, it will be liquified when cooled below -181°C at atmospheric pressure. With an increase in pressure, oxygen may exist as a liquid at temperatures above -181°C, but pressure will not keep it in a liquid state above -119°C.

SOME OF THE PROPERTIES OF LIQUID OXYGEN

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiling point at 1 atm</td>
<td>-183°C or -297°F</td>
</tr>
<tr>
<td>Critical temperature</td>
<td>-118.8°C or 181.8°F</td>
</tr>
<tr>
<td>Critical pressure</td>
<td>715.6 psig</td>
</tr>
<tr>
<td>Density (liquid 1 atm)</td>
<td>71.27/ft³</td>
</tr>
<tr>
<td>Density (gas 1 atm)</td>
<td>0.082716/ft³</td>
</tr>
<tr>
<td>Cu ft of gas/cu ft of liquid (1 atm)</td>
<td>862</td>
</tr>
<tr>
<td>Cu ft of gas/gallon of liquid (1 atm)</td>
<td>115.2</td>
</tr>
<tr>
<td>Wt of gallon of liquid</td>
<td>9.5316</td>
</tr>
<tr>
<td>Specific volume at n.t.p.</td>
<td>12.1 ft³/16</td>
</tr>
<tr>
<td>Heat content of saturated vapor</td>
<td>94 Btu/16</td>
</tr>
<tr>
<td>Heat of vaporization at 1 atm</td>
<td>32</td>
</tr>
<tr>
<td>Mol wt</td>
<td>1.14</td>
</tr>
<tr>
<td>Specific gravity at -297°F</td>
<td>1.14</td>
</tr>
</tbody>
</table>

NITROGEN PROPERTIES

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting point</td>
<td>-209.9°C</td>
</tr>
<tr>
<td>Boiling point</td>
<td>-195.8°C</td>
</tr>
<tr>
<td>Density</td>
<td>1.25 kg/liter</td>
</tr>
<tr>
<td>Specific gravity at 320°F</td>
<td>50.4 lb/ft³</td>
</tr>
<tr>
<td>Specific gravity at 320°F</td>
<td>0.808</td>
</tr>
<tr>
<td>Cu ft gas/cu ft liquid 1 atm</td>
<td>696</td>
</tr>
<tr>
<td>Cu ft gas/gallon liquid 1 atm</td>
<td>93</td>
</tr>
<tr>
<td>Lb/gallon of liquid</td>
<td>6.74</td>
</tr>
<tr>
<td>Heat of vaporization 1 atm</td>
<td>86 Btu/lb</td>
</tr>
</tbody>
</table>
APPENDIX III

BIBLIOGRAPHY PREFACE

This bibliographical listing of articles and books pertaining to or associated with activities involving gaseous or liquid oxygen enriched environments was compiled to aid those persons involved in this rapidly advancing area of technology.

It is a listing of authors, whether senior, sole or one or multiple authors whose articles are listed.

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APPENDIX IV
MATERIALS, COMPONENTS AND METHODS

This listing of articles and books pertains to sources and techniques applicable to high pressure.

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