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DEVELOPMENT OF A HIGH TEMPERATURE NUCLEAR-RADIATION-RESISTANT PNEUMATIC POWER SYSTEM FOR FLIGHT VEHICLES

QUARTERLY REPORT

AF33(616)-7582

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DEVELOPMENT OF A HIGH-TEMPERATURE, NUCLEAR-RADIATION-RESISTANT PNEUMATIC POWER SYSTEM FOR FLIGHT VEHICLES

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NOTICE

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FOREWORD

This report was prepared by General Dynamics/Convair, a Division of General Dynamics Corporation, and covers research and development work accomplished under Air Force Contract AF 33(616)-7582 during the period of 25 December 1961 to 24 March 1962.

USAF Contract AF 33(616)-7582 was initiated under Project Task No. 61085 by the Flight Accessories Laboratory, Aeronautical Systems Division, Wright Patterson Air Force Base, Ohio. The work is administered under the direction of Mr. B. Brooks, ASRMFP-3, Transmission Technology Section, Flight Vehicle Power Branch of the Flight Accessories Laboratory, and is conducted by Convair under the direction of Mr. R. W. Casebolt.

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I. INTRODUCTION

The development of a high-temperature, nuclear-radiation-resistant pneumatic power system for flight vehicles was initiated by the Flight Accessories Laboratory of ASD to advance the state of the art of pneumatic power systems.

Future flight vehicles will be subjected to extreme thermal environments because of heat generated by high speeds or by the propulsion systems. Materials in propulsion systems are now in advanced state of development, which results in new requirements for components and auxiliary systems capable of operating under wide temperature excursions in the presence of nuclear radiation.

Pneumatics offer a number of advantages over competitive systems for both power actuation and control. Air is thermally stable: no change in state occurs over an extremely wide temperature range. It does not deteriorate when exposed to nuclear radiation, and there are no handling, maintenance or disposal problems.

The design of pneumatic power systems for the operational support of future flight vehicles depends on numerous factors. No particular system can be considered optimum, or even acceptable, for every conceivable application. The ultimate goal of this program, therefore, is to provide sufficient data for the design of pneumatic power systems applicable to a wide variety of advanced flight vehicles.

The first portion of the program was completed prior to this reporting period. After evaluating the work accomplished in this phase of the program, it has been established that subsequent work should be directed toward the development and testing of a closed high-pressure pneumatic system for powering aerodynamic controls. This type of system has been selected for development in the hardware phases of the program because -

1. Greater advances can be made in the state of the art through mechanization of this type of system.

2. System components will be subjected to the severe thermal and nuclear environment in which a typical, advanced flight vehicle will operate.

3. Solutions for system hardware development problems will be applicable to other components operating in less severe environments.

A ram air turbine-driven compressor has been selected as the most feasible means of supplying the pneumatic power source (the program was revised to include compressor development).

II. SUMMARY

The major emphasis during this reporting period was directed towards close liaison with component manufacturers to ensure that all problem areas were resolved as quickly as possible.

The development of components for the high-temperature and nuclear-radiation-resistant pneumatic system has, in general, been satisfactory. Some setbacks were encountered in connection with servo control valve stability, welding of the accumulator and sintering of the filter element. None of these problems, however, appears insoluble at this time.

Although some initial difficulty was encountered during development of the check valve spring, these were later resolved. Two pneumatic check valves were received by General Dynamics/Convair during this reporting period.

The first phase of the tube fitting and boss seal evaluation was completed. Based on this limited testing program, one tube fitting and one boss seal showed promise for use in the high-temperature pneumatic system.

The modifications to the environmental chamber were evaluated in preparation for component testing. Since this test equipment was found inadequate for sustained operation at 1500° F, an alternative approach was initiated.

III. WORK ACCOMPLISHED

COMPRESSOR AND DRIVE UNIT

Progress of Phase I — feasibility study and preliminary development testing of the turbine-driven air compressor — is broken down into four specific study areas:

1. By-pass valve
2. Compressor development
3. Air bearing development
4. Labyrinth air seals

By-Pass Valve

Final sizing of the compressor impellers and combined analysis of compressor characteristics indicated the advantage of decreasing the by-pass valve main actuator spring from 1040 pounds per inch to 250 pounds per inch to reduce valve droop and increase valve sensitivity. It is anticipated that valve droop will be approximately 10% in terms of compressor air flow. This is considered adequate for the selected impeller sizes. The detail design of the by-pass valve is now considered complete.

Compressor Development

The previous report described the results of testing with impeller configurations which simulated the fourth stage and the second stage of the final machine. During this reporting period, a third impeller configuration was tested. In this configuration the inlet eye was again cut back to allow greater air flows. Figures 1 and 2 show compressor performance for three different inducer lengths, and the basic physical dimensions of the three test configurations. Testing has been completed and the final configuration of the impellers for each stage has been determined. The four stages will vary only in the length of the inducer section.

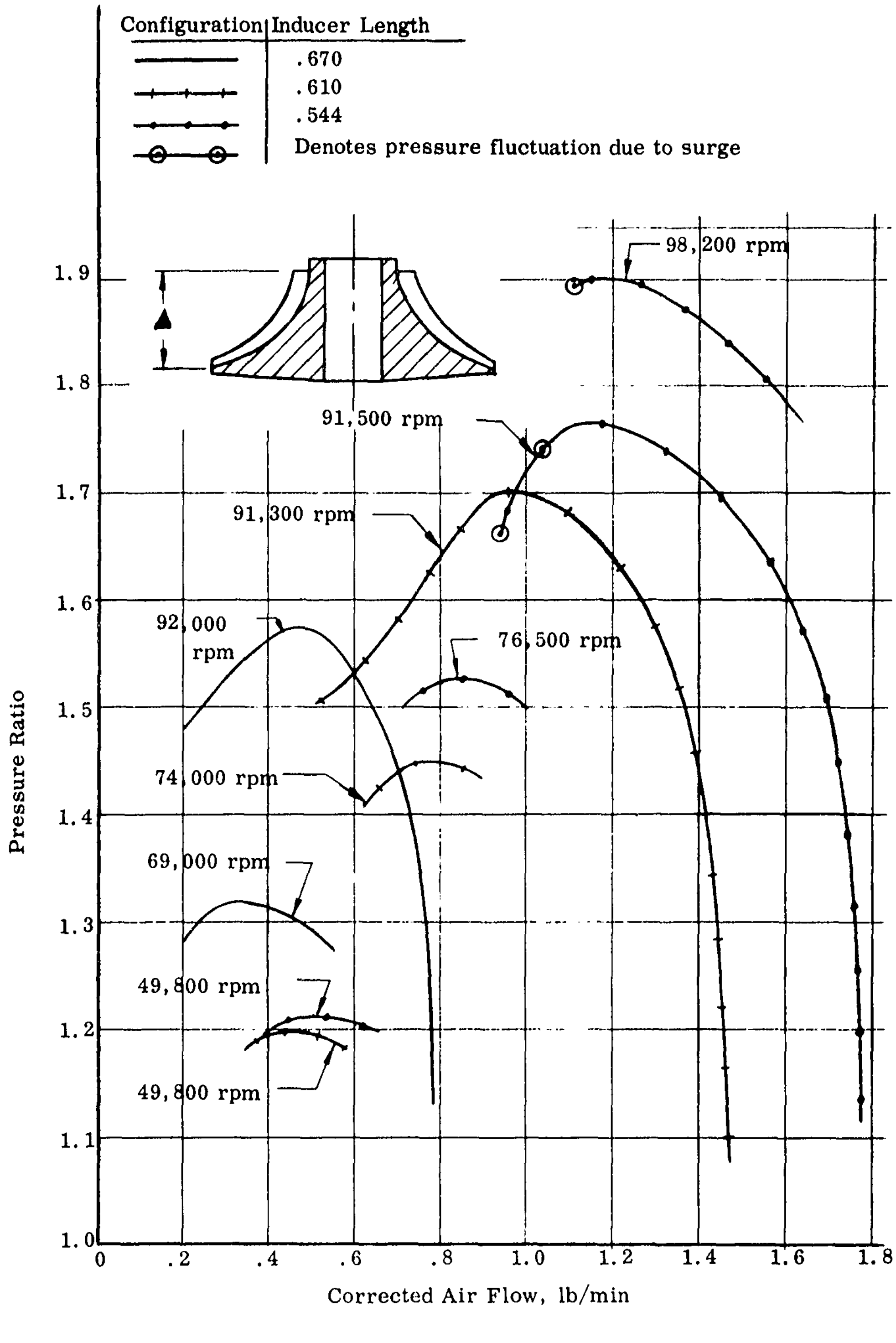

Figure 1. COMPRESSOR IMPELLER AIR FLOWS VERSUS PRESSURE RATIOS

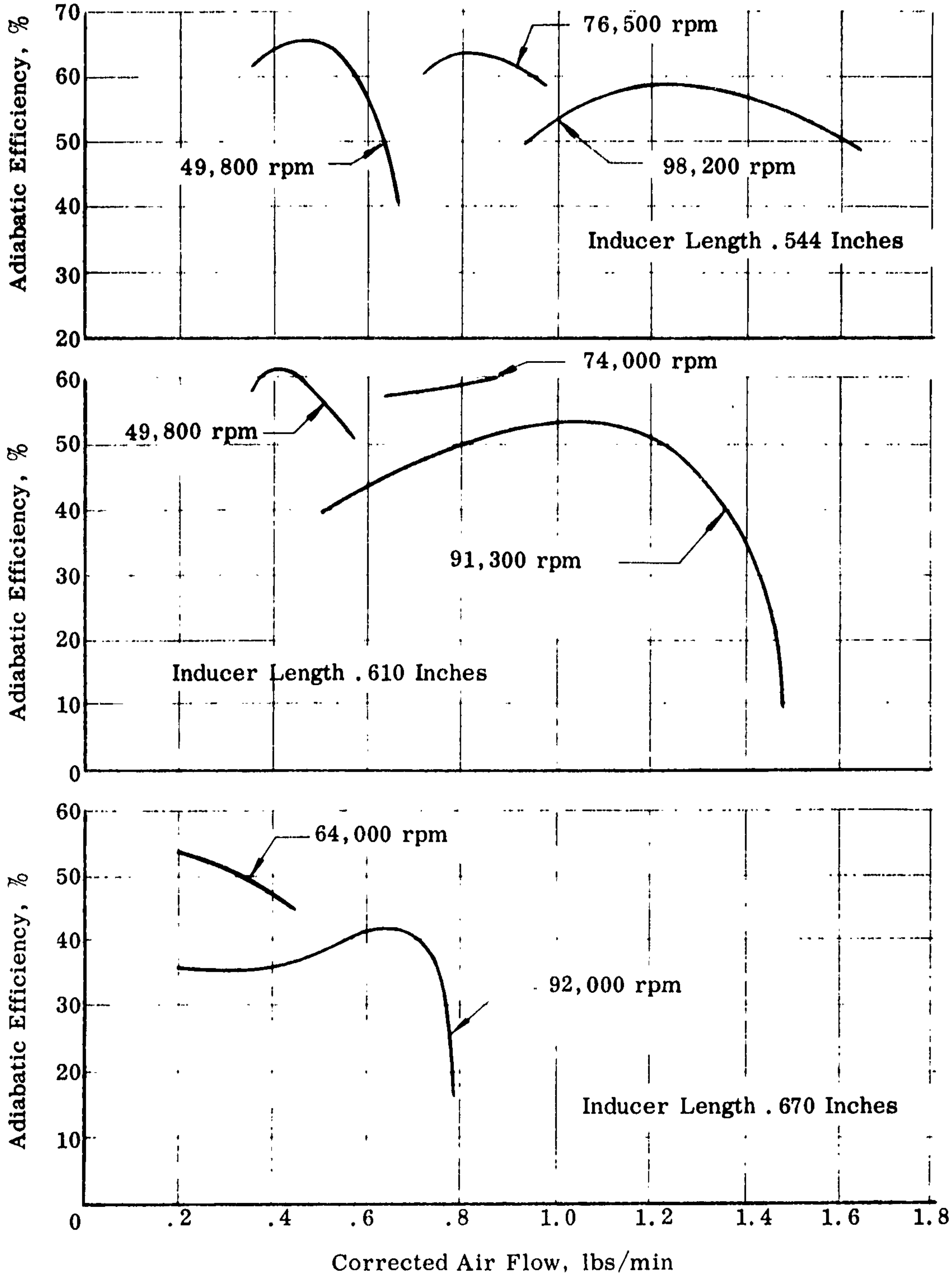

Figure 2. COMPRESSOR IMPELLER AIR FLOWS VERSUS ADIABATIC EFFICIENCIES

The speed of rotation at the operating inlet temperature of 700° F will be 119,000 rpm.

The turbine wheel size has also been fixed. An axial type wheel has been chosen, primarily because of the overall thrust advantage that can be gained from the turbine wheel hub diameter. The hub diameter will be made to match the air bearing diameter as a means of balancing out axial thrust.

Air Bearing Development

Fabrication of the air bearing test rig is in progress, and is nearing completion. In addition, back-up spares (one each) of the shaft, bushing, thrust plate and dummy impeller set are being made available. Provision has been made to operate the test bearing assembly using either hot or cold air. Initial testing will be accomplished using unheated air supplied to the test bearing. As development testing progresses, the bearing supply air temperature will be increased to the design values. Figure 3 is a schematic diagram of the proposed test bearing set-up.

Labyrinth Air Seals

As previously reported, the development of a successful seal design will be accomplished during operation of the air bearing test rig.

ROTARY ACTUATOR AND SERVO CONTROL VALVE

Actuator

Many of the minor sub-assemblies of the power actuator are now complete and a number of the major sub-assemblies are in the final stages of manufacture. To date, the following parts have been completed:

1. Flange seals
2. Tab washers
3. Spacers

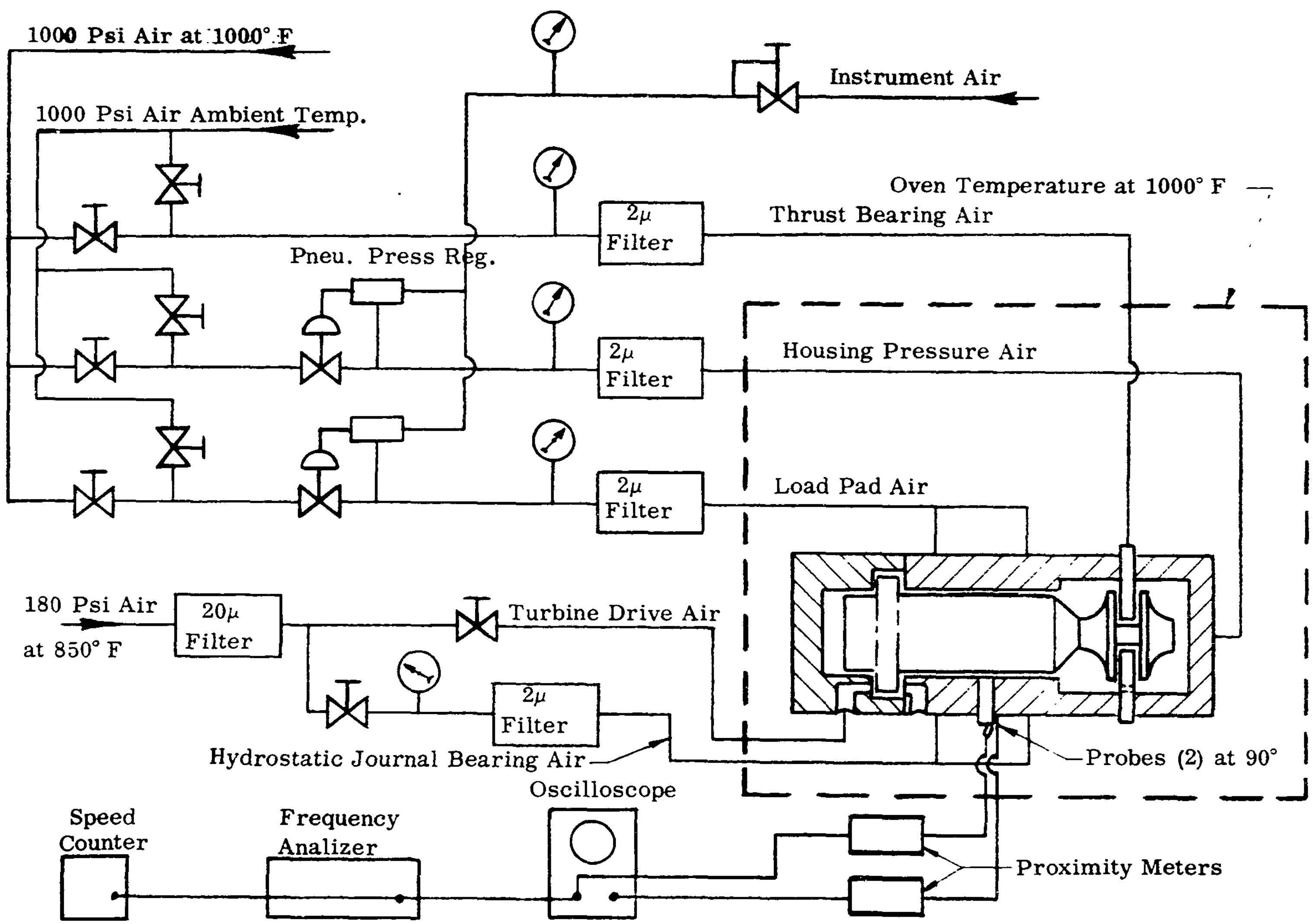

Figure 3. SCHEMATIC LAYOUT OF TURBO-COMPRESSOR TEST RIG

4. End cap tubes
5. Thrust washers
6. Cap nuts
7. Split-ring seals
8. Bellows and shaft seal
9. K-seals
10. Piston rings

No significant problems were encountered in the fabrication of these parts. Some complications were expected in the manufacture of the bellows and shaft seal which are welded assemblies of René 41 material; however, none have developed. These assemblies were made by the Bell-Metrics Co., of Los Angeles, and appear to be excellent products. Geometry and surface finish are well within specification and all welds are sound both visually and by x-ray inspection. The structural integrity and performance of the bellows and seal will be evaluated during the actuator bore coating tests to be performed on the test actuator assembly.

Bearings

First article inspection of the actuator bearings has been made. These units are being developed by Industrial Tectonics, Inc. of Compton, California, and are described as spherical roller bearings. Both races and rolling elements are being fabricated from René 41 material. The contact surfaces of both races are coated with ceramic-bonded calcium fluoride according to a process described by NASA Report TN-1190. In the coating process, the base material is blued at 1700° F, spray coated with the fluoride material, then given a one-minute bake at 2000° F. Slight dimensional changes are noted to occur during the baking process and will require regrinding or redimensioning of the base material. The coatings thus far produced look reasonably good but have not yet been subjected to any qualifying performance tests.

Static Contact Adhesion Tests

Some gross data has been accumulated which relates to assembly or disassembly of the unit after it has been operated in a high-temperature environment. Several sets of the René 41 pins which will be used to lock the actuator shaft and the collar were prepared. Some of the pins were given a light oxide coating by heating in air for several minutes; the remaining pins were left "as ground." The pins were assembled into the collar with a light press fit, after which the assembly was subjected to 1500° F temperatures for seven hours. Upon disassembly, the oxidized pins were removed fairly easily while the bare pins were found to be firmly stuck. Some difficulty was also experienced in removing the collar itself and it was decided to open the clearance here to 0.0002 inch minimum. Some adhesion tests were also run on silver-plated samples under compression during heating, and welding to the contacting material occurred frequently. As a result, an evaluation will be made between the performance of silver-plated bolts and bolts with only an oxide finish. Rhodium coatings will also be evaluated for application to the "K" seals employed throughout the unit.

Actuator Housing Castings

The first housing casings have been received from Precision Cast Parts, Inc., and are sound and of good quality. Unfortunately, some dimensional errors were made which will require a re-run on this part. The nature of the error produced a thicker wall cross-section than required and resulted in interferences with the mechanism to be enclosed by the housing. Contour machining to remove this excess is being considered to salvage this part. If the repair is successful, this housing assembly will be utilized in the surface coating test actuator and little program delay will result.

Actuator Shaft

The cast billets for the shafts have been received and one unit has been finish machined. These pieces, which were produced as sand mold castings using an argon blanket, were found to contain numerous surface gas pockets and discontinuities. For the part that was finish machined, stock removal was sufficient to remove these aberrations and a usable assembly resulted. Some difficulty was experienced in locating x-ray equipment of sufficient capacity to handle the large cross section and high-density material of the shaft castings. At present, a 2×10^6 volt machine at the Los Angeles cancer research center is being utilized to establish the soundness of these parts. As a result of x-ray inspection, only one casting was rejected as being marginal and is being replaced by the casting vendor.

Servo Valve

The basic concept of the two-stage pressure control and feedback compensation network as outlined in the December Quarterly Report (ZR-1001-11) has been adhered to and has been probed by continued analytical studies. Fabrication schedule for the valve is being paced by the power actuator development program so as to allow the maximum amount of time for the valve analysis. The early results of the analog computer simulation performed at the EAI Computation Center in Los Angeles have been verified by a simplified version of the simulation which was set up in the Convair computer laboratory. These studies indicated that the method of generating the position and velocity feedback signal (Figure 4) was incompatible with the compensating network provided for the pressure control second stage. To achieve a stable system with this valve configuration, the pressure gain of the first valve stage must be reduced to a value of 3.0 to 3.5 psi/psi which reduces the static stiffness of the system to an undesirable degree. Inasmuch as the static stiffness parameter is not clearly defined in the original valve specification, a minimum acceptable value of one degree deflection for 10% load increment has been established. This static stiffness goal has been achieved in several of the revised configurations studied, the most promising of which consists of producing and summing the position and velocity signals separately rather than with the differentiating network. Only small lags are allowed in the feedback loop with this configuration, and the restriction between the second-stage valve body and the pressure control bellows chamber must be eliminated. For all valve and actuator configurations, the effect of coulomb friction is influential in stabilizing the system. For values of friction in the vicinity of 4.0% of maximum actuator capacity, the study indicates that only position feedback would be necessary if the forward loop were lagged sufficiently. This solution, however, is considered undesirable due to the decrease in system response and the need to incorporate some type of friction damper. In all practical cases, a maximum value of friction equivalent to only 0.5% of actuator torque capacity was introduced into the system.

The effects of major non-linearities associated with this type of valve have been taken into consideration in all of the configurations studied and indicate that no problem will exist within the normal operating regime. Some problems may develop due to mechanical limiting of the second stage valve if the unit is driven with large amplitude inputs at frequencies above that of the system natural frequency, however, inputs of this type may reasonably be excluded from our application.

In support of the analog computer simulation, a linear analysis of the general value configuration is being performed. This approach is being used to predict general trends regarding changes suggested for incorporation in the computer study and to establish initial values and ranges to investigate in the program. The linear analysis is being done in sufficient depth to include the pumping terms due to velocity effects in the bellows networks and other elements where variable volumes are introduced. These terms are usually disregarded in initial simplifcations and were responsible for the lack of success encountered with the initial valve configuration. At present, the computer simulation is being modified to include a pneumatic dash pot to provide some damping to the second-stage pressure control valve, bellows, and operating linkage. In this

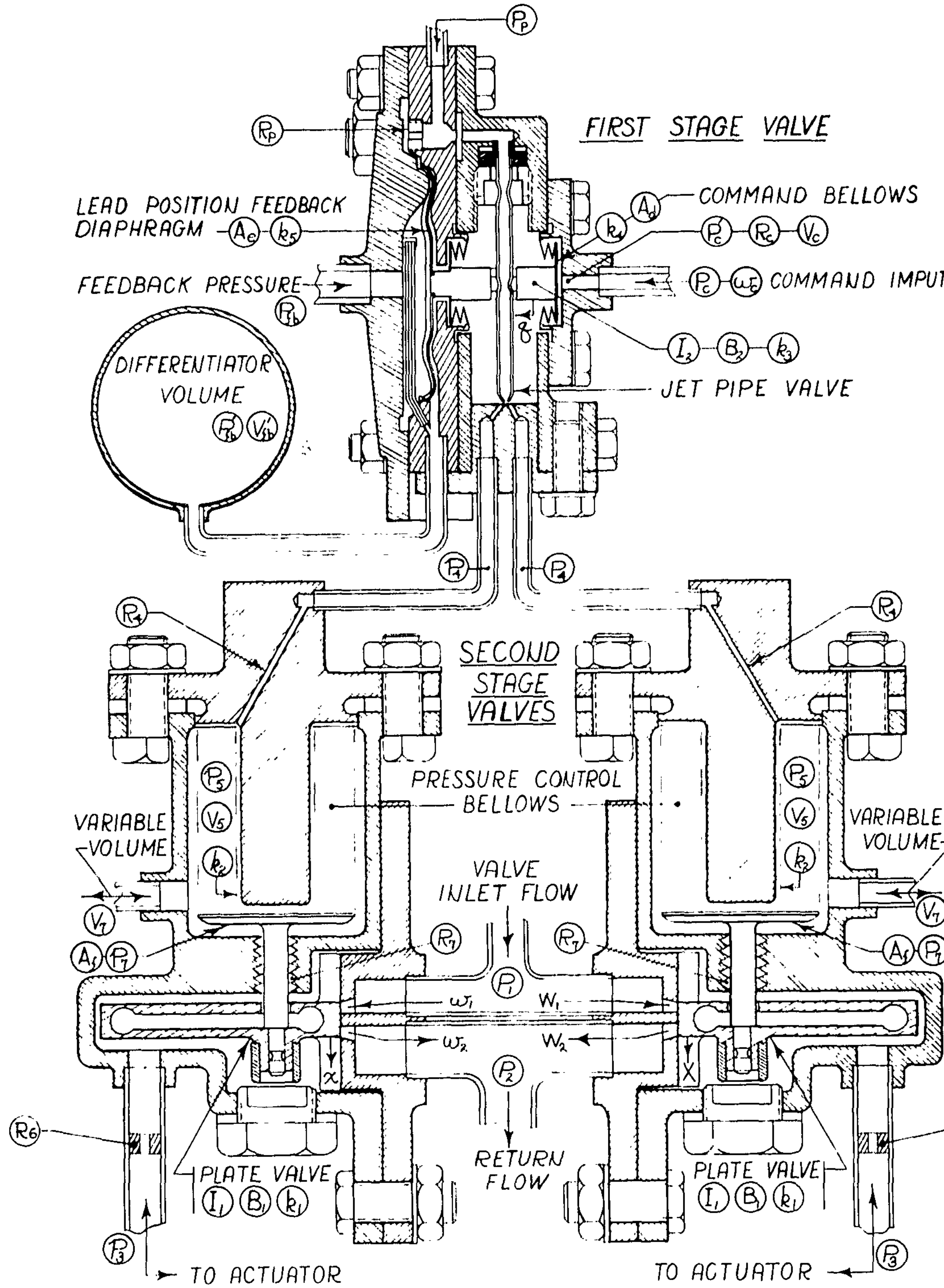

Figure 4. CONTROL VALVE AND COMPENSATING MECHANISM SCHEMATIC

configuration, a sliding seal will be introduced between the pressure control bellows chamber and the second-stage valve. Balancing pressure for the control bellows will then be fed from a point down stream from the actuator restriction R6, as shown in Figure 4, with a small lag introduced between the actuator pressure and the pressure control bellows chamber pressure.

PRESSURE REGULATOR AND RELIEF VALVE

Fabrication of all detail parts, for both the pressure regulator and relief valve, with the exception of the pressure regulator bellows, was completed during the period covered by this report. Room temperature testing of the relief valve was initiated.

High-temperature oxidation tests (in air at 1500° F) were completed on specimens of René 41. The main objective of this test was to have a protective process available should the René 41 alloy exhibit excessive oxidation under the anticipated operating conditions. The chromallizing process resulted in a dimensional build-up of approximately 0.001 inch and a change in the original surface roughness from 8 microinches to 80 microinches (RMS). The surface of the chromallized test specimen was refinished to 8 microinches prior to conducting the oxidation tests.

Both test samples were then exposed to an ambient temperature of 1500° F in air for a period of three hours. When cooled, the plain René 41 sample was covered with a green film (assumed to be chromium oxide) and the surface roughness was comparable to the original 8 microinch finish. The chromallized test piece had turned blueish in color. When the surface finish was compared to the initial measurement it was found that, as for the plain René 41 sample, no change in surface finish had occurred.

The plain René test piece was then liquid-honed to remove the film of oxide from its outer surface. It can easily be removed. After this cleaning operation, the test piece was again subjected to 1500° F in an air atmosphere for three hours.

After removal from the oven it was found that no further build-up of oxide took place.

Visual and mechanical comparison of the two test pieces indicates that the chromallized process does prevent the formation of a loose oxide film on the René 41 alloy. The dimensional changes due to this process, however, have to be compensated for in the detail design of components. Critical surfaces will have to be refinished after the process. The plain René 41 alloy, when subjected to the operating temperature of 1500° F, forms a loose oxide film which could cause contamination of system components. As determined by the above tests, after one thermal cycle to 1500° F the components can be cleaned after which the formation of the oxide ceases. This procedure will be adopted for the prototype regulator and relief valves.

As anticipated, fabrication of the relief valve reference spring was a tedious and time consuming process. For the first attempt, the spring was heat treated (aged) at 1350° F for 16 hours, then subjected to a heat-set operation at 1600° F for seven hours. The relaxation subsequent to this operation was excessive. A number of other combinations of heat treatment and heat setting were performed before an acceptable approach was evolved. The following procedure resulted in a spring which exhibited the desired free length within 1% and the desired load within 5%:

1. The spring was wound to a free length 25% higher than the desired free length.
2. The spring was then heat treated at 2150 (+0, -50)° F for one hour, furnace cooled and held at 1600° F for four hours.
3. The spring was then subjected to a heat set operation at 1500° F for seven hours under load.

Initial tests at room temperature were conducted on the completed relief valve with the following results:

	TEST RESULTS	GD/CV SPEC
	PSI ΔP	PSI ΔP
Cracking Pressure	1730	> 1300
Full Flow Pressure	1890	< 1900
Reseat Pressure	1700	> 1150

As indicated by this data, the relief valve met the specified crack, full flow, and reseat pressure points at room temperature.

ACCUMULATOR

To meet the conflicting requirements of extreme environment and minimum weight, Udimet 500 nickel-base alloy was selected for the accumulator. This material is a recent addition to the family of superalloys developed for use at temperatures up to 1800° F. Two problems were encountered in the design of the accumulator:

1. Availability of satisfactory material for forgings and for weld evaluation.

2. Obtaining a satisfactory weld.

A bar of Udimet 500 (6-inch diameter) was received, but inspection revealed a number of cracks throughout the material. These cracks rendered the material unsatisfactory for use in the weld development work required. The material required for production forgings was also initially rejected by the forging manufacturer, Steel Improvement Co. However, since that time satisfactory production forgings were received.

To select the optimum heat treatment, for the Udimet 500 material, a number of specimens were subjected to three different heat treatments followed by tensile testing at room temperature. The results are tabulated in Table 1.

Table 1

TENSILE TEST RESULTS ON UDIMET 500 AT ROOM TEMPERATURE

HEAT TREATMENT	SPECIMEN NO.	ULTIMATE TENSILE STRENGTH KSI	YIELD STRENGTH (0.2%) KSI	ELONGATION % IN 1 INCH	REDUCTION IN AREA %
	1	179.5	126.2	11	11.4
A	2	159.2	125.2	6	8.9
	3	170.7	132.3	8	10.0
	4	153.5	113.3	8	11.5
B	5	168.8	115.4	11	15.2
	6	189.2	133.3	17	19.6
C	7	176.9	125.2	13	17.5
	8	181.4	122.8	17	17.8

Heat Treatment A

1975° F/1 hour, air cooled

1550° F/24 hours, air cooled

1400° F/16 hours, air cooled

Heat Treatment B

1975° F/1 hour, air cooled

1400° F/24 hours, air cooled

1550° F/16 hours, air cooled

Heat Treatment C

1975° F/1 hour, air cooled

1400° F/16 hours, air cooled

Figure 5 summarizes this data in graphical form. Although heat treatment "C" appears to produce the most satisfactory results at room temperature, heat treatment "A" will be used because of superior creep strength at 1500° F. This is in agreement with the recommendation of the material producer.

Menasco has successfully welded other nickel-base alloys (i.e., Inconel alloy X-750 and Haynes 25) using the pressure welding technique but has experienced some difficulty in obtaining a satisfactory weld with Udimet 500.

One basic difference between Udimet 500 and these other alloys is in the aluminum content. Haynes No. 25 contains no aluminum, Inconel Alloy X-750 contains 0.6%, while Udimet 500 contains 2.5 to 3.25%. During weld qualification it was discovered that a thin oxide layer forms at the weld interface which does not break up during the upset to allow the grains to migrate across the weld plane. Purging the inside diameter with an inert gas was not effective in preventing oxide formation.

Uniform heating of the weldment was not obtainable using the oxygen-acetylene torch. The forging temperature range for Udimet 500 is between 1900° F and 2175° F. During the weld cycle, the temperature of the outer diameter surface material would exceed 2175° F and start to melt before the inner diameter was in the forging range. The strength of Udimet 500 at elevated temperatures is exceptionally high. The material is subject to embrittlement at high temperature and parent material cracking occurred before the inner diameter was heated sufficiently to complete the upset. These difficulties required a re-evaluation of the welding technique.

In order to obtain more uniform heating of the joint it was decided to use an induction heater in place of the oxygen-acetylene torch. Six pressure welds using an induction heater and inner diameter purging were completed. Considerable improvement in the weld bond was experienced. One variable tested involved weld face geometry before welding. Although a successful weld had not been made to date using this technique, the results have been sufficiently

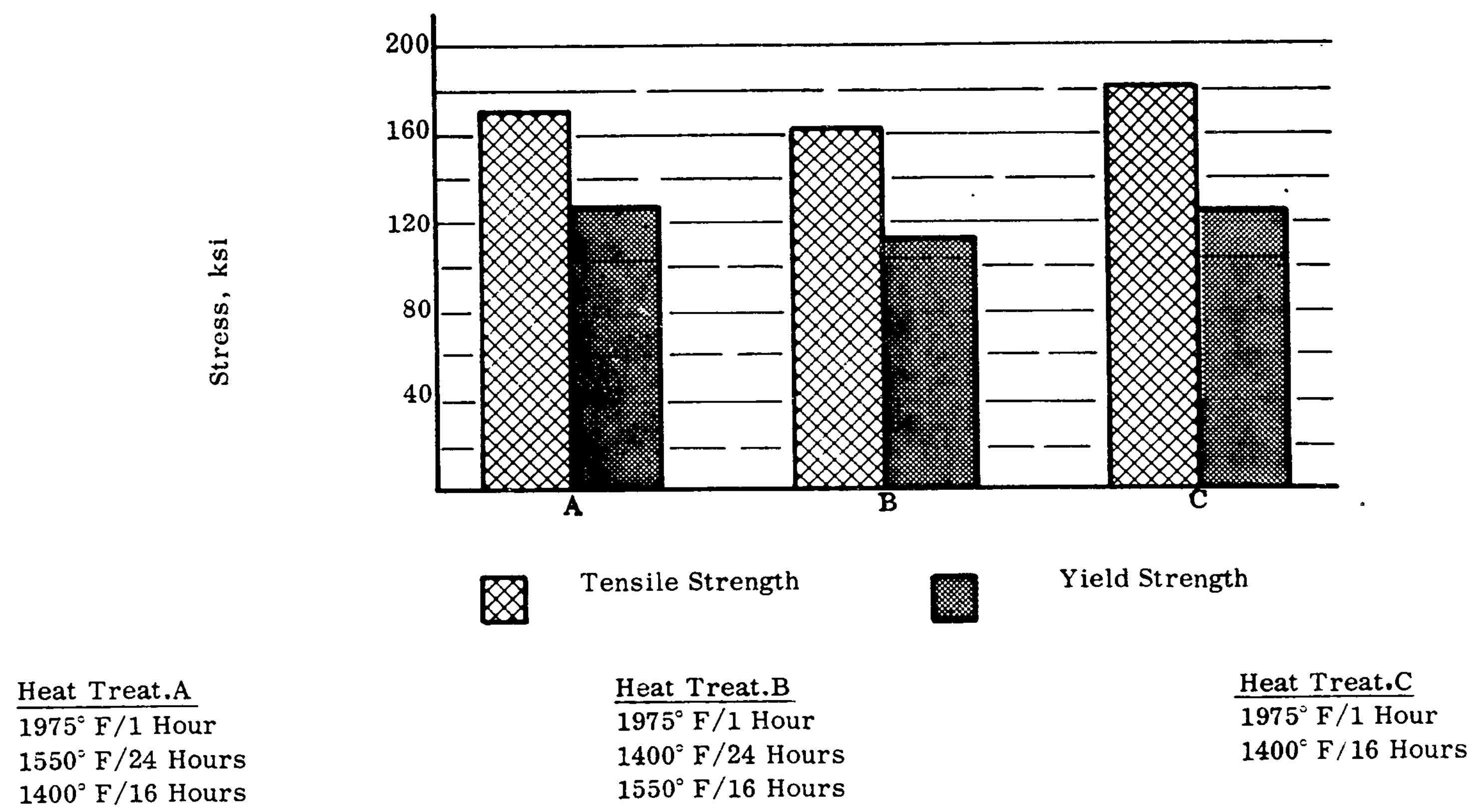

Figure 5. TENSILE TEST RESULTS ON UDIMET 500 AT ROOM TEMPERATURE

encouraging to warrant further investigation. A chamber is under construction to permit pressure welding in an inert atmosphere using the induction heater.

A second method of welding Udimet 500 was also investigated. This is the electron beam welding process. Several electron beam welding sources were contacted; none had welded Udimet 500. Samples were presented to Hamilton Standard Division, United Aircraft Corporation, Windsor Locks, Connecticut, to determine the feasibility of welding this material with electron beam equipment. The electron beam process requires a vacuum chamber and a device to hold and rotate the pressure vessel while it is being welded. Since it has not been demonstrated that Udimet 500 can be successfully welded by the electron beam process and since this is a relatively recent welding process it appears that a long term development effort will be required to obtain a satisfactory weld using this process.

The third welding process investigated was the TIG (inert-gas-shielded tungsten-arc) process. This method has been successfully employed for welding of Inconel alloy X-750 and the Nimonic alloys. A number of flat strips were welded using the TIG process with considerable success. Additional welds will be made for metallurgical evaluation. It is presently planned to use the TIG process for welding the Udimet 500 accumulator with induction heater pressure welding as a back-up method. In order to qualify the weld, two Udimet 500 cylinders, each 4 inches long, will be welded. Ten strip-type tensile specimens will be machined from the cylinder, heat treated, then subjected to tensile tests at both room temperature and 1500° F and stress-rupture tests at 1500° F.

FILTER

All detail parts, except the filter element, were completed during this reporting period. Major emphasis is now being placed on development of a satisfactory filter element.

The René 41 wire used for fabricating the filter element failed during the first winding attempt. The wire, which had been nickel plated, broke during winding due to embrittlement.

A second problem was encountered during the sintering of the first two filter elements. The sintering process is being conducted in a vacuum upon the recommendation of General Electric Corporation. Both the first and second sintering attempts failed due to malfunction of the sintering equipment. An air leak in the furnace wall resulted in rapid deterioration of the René 41 filter element. A third attempt at vacuum sintering is now in progress.

CHECK VALVE

Two check valves were completed and delivered to General Dynamics/Convair during this reporting period. The following summarizes the major problem area encountered during the development of this component.

As anticipated the most troublesome item in this unit was the spring. A number of materials were considered for evaluation as spring materials. These included two refractory alloys and René 41.

The initial effort was expended in attempting to achieve a goal of around 50,000 psi shear stress using 1/2% titanium balance molybdenum wire. Wire of this material, produced by Fansteel Metallurgical Corporation, was exhaustively tested with considerable disappointment. There was a lack of consistency of results from one strip of wire to another after being formed into identical springs by the same method. This problem was attributed to work hardening and galling of the wire during the coiling operation. A second problem was difficulty in obtaining a satisfactory oxidation-resistant coating that could be applied to the coiled spring. A coating designated as Durag "B" was applied by the Chromizing Corporation, Los Angeles, California. Unfortunately, this coating is susceptible to pin holes, which allows any oxidizing atmosphere to attack the wire and with time will allow complete sublimation of the wire. Detection of these pin holes is somewhat unreliable, and consequently the assurance of a perfect coating is uncertain.

A test was also conducted on 0.062-inch diameter wire of a composition consisting of 33% tantalum, 0.8% zirconium, balance columbium. Although the oxidation rate was less than the molybdenum alloys, it was unsatisfactory.

As a result of these difficulties, it was decided to evaluate René 41 as a spring material. Early attempts were made to determine the upper shear stress limit for the spring. A shear stress of 30,000 psi was found to be unacceptable in combination with prolonged exposure to 1500° F.

Oxidation of the 0.022-inch diameter wire tended to aggravate the situation. At this point it was decided to reduce the shear stress level in the wire by increasing both the wire diameter and the length of the spring. The result of using a larger wire diameter not only reduces the stress level but also minimizes the effects of oxidation during the required 70 hours at 1500° F. Since the oxide formed is virtually independent of wire diameter, oxidation of larger diameter René 41 wire will be less percentagewise than that for small diameter wire. A 70-hour test at 1500° F confirmed this phenomenon.

By the process of continually derating the springs, by reducing stresses, it was possible to achieve acceptable results at a corrected maximum shear stress of 18,200 psi. This meant increasing the length of the valve to 3 inches and using 0.032-inch diameter René 41 wire. The final spring is stable and not susceptible to buckling in spite of the large number of convolutions.

The heat treatment of the René 41 spring also required some investigation before a satisfactory design evolved. The initial heat treatment consisted of heating the coiled spring to 1400° F for 16 hours followed by heat setting at 1500° F to varying stress levels and for different lengths of time. This method did not produce acceptable springs. The relaxation levels, for even short periods of time, were excessive as shown in Table 2.

The heat treatment process was then changed to that used on the final springs. This consisted of a solution treatment of 2150° F for 1/2 hour, plus aging at 1650° F for 4 hours, followed by heat setting at maximum load and 1500° F for 20 hours. Table 2 shows that this process gave more acceptable results; in fact, the relaxation was zero after 21 hours exposure to 1500° F at a stress level of 20,000 psi. For lesser time there is a gain in strength, while for 70 hours, relaxation amounted to 22.6%.

Table 2

RELAXATION OF RENÉ 41 SPRINGS

Stress Level: 20,000 psi   Temperature: 1500° F

TEST TIME HOURS	HEAT TREAT."A" 1400° F/16 HOURS	HEAT TREAT."B" 2150° F/0.5 HOUR 1650° F/4 HOURS
7	62.6	-8.0
14	67.2	-3.8
21	75.1	0.0
35	80.5	5.4
70	87.5	22.6

A duplicate spring to those used in check valve serial numbers 1 and 2 was tested to verify performance over a 70-hour period at 1500° F. The relaxation was 25%. This testing, which was conducted in an air ambient, demonstrated that after the 70-hour high-temperature test the spring was capable of exerting a force equivalent to a cracking pressure of one psid. This value includes the shift of shear modulus (25-1/2%) which occurs only at 1500° F.

TUBING, TUBE FITTINGS, AND BOSS SEALS

A preliminary evaluation of the tubing for use in the high-temperature pneumatic system was completed during this reporting period. In addition, a total of three tube fittings and three boss seals was subjected to a removal and reinstallation test in combination with thermal cycling from room temperature to 1000° F and room temperature to 1500° F with operating pressure applied. The results of this initial tube fitting and boss seal evaluation, are summarized in Figures 6 and 7. The Gamah tube coupling was the only fitting that completed the 1500° F portion of the test without failure. Preliminary results indicate that the Natorq boss seal provides a more satisfactory seal at 1500° F than the ASD X59 boss seal. The following section gives the test procedure and results to date.

Tubing

Three 1500° F stress-rupture tests were conducted on the tubing (Inconel alloy X-750) at a stress level of 22,000 psi. This was done to determine the optimum heat treatment for the tubing and to compare the results with published data for bar stock.

The results obtained are outlined below and shown in Figure 8. The stress rupture properties of the tubing is considerably less than that predicted for bar at 1500° F.

1. Precipitation heat treatment (1300° F/20 hours): stress-rupture life was 20.5 hours.

2. Double age heat treatment (1550° F/24 hours, 1300° F/20 hours): stress-rupture life was 14.25 hours.

3. Triple heat treatment (2100° F/2 hours, 1550° F/24 hours, 1300° F/20 hours): stress rupture life was 22.4 hours.

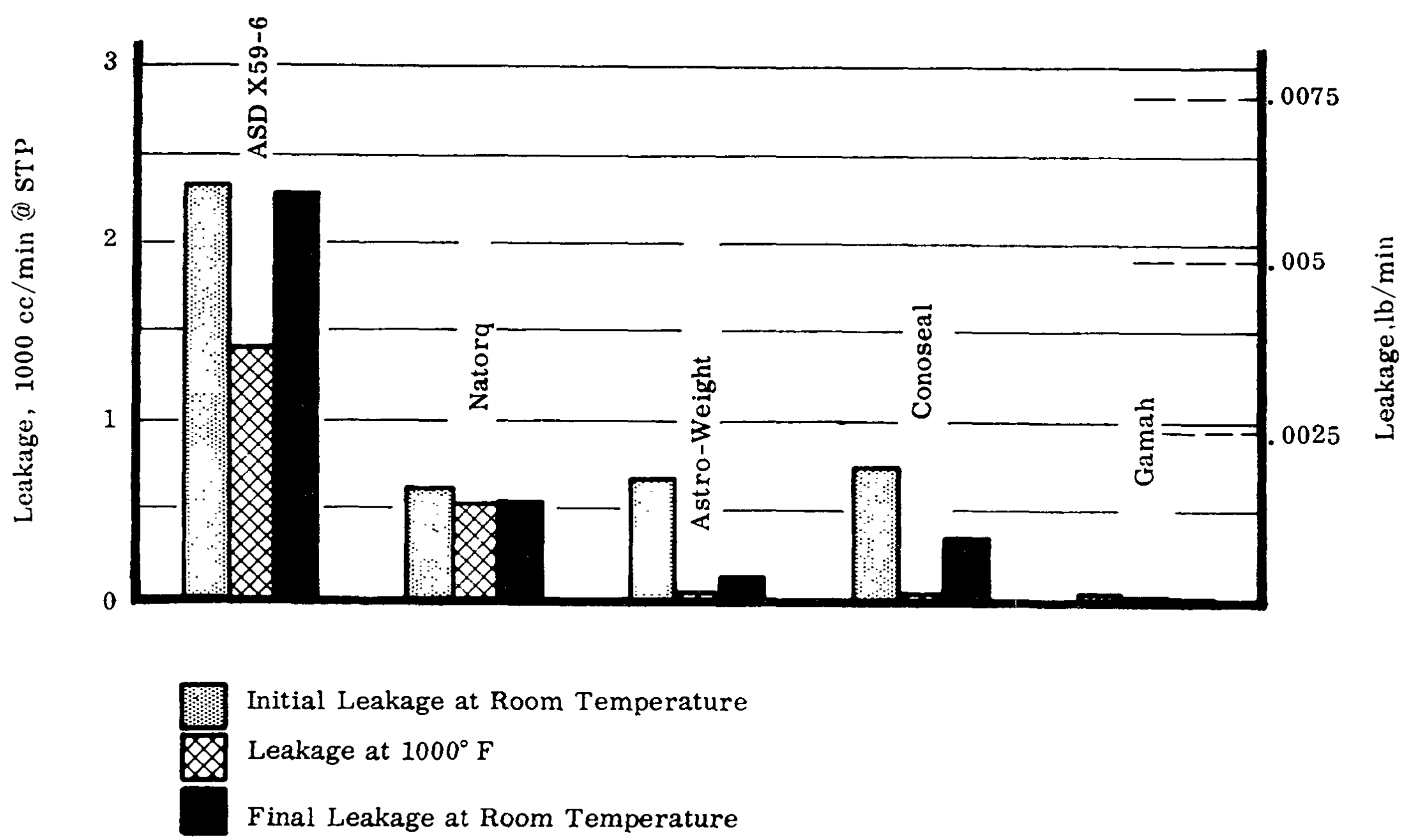

Figure 6. EVALUATION OF TUBE FITTINGS AND BOSS SEALS AT 1000° F

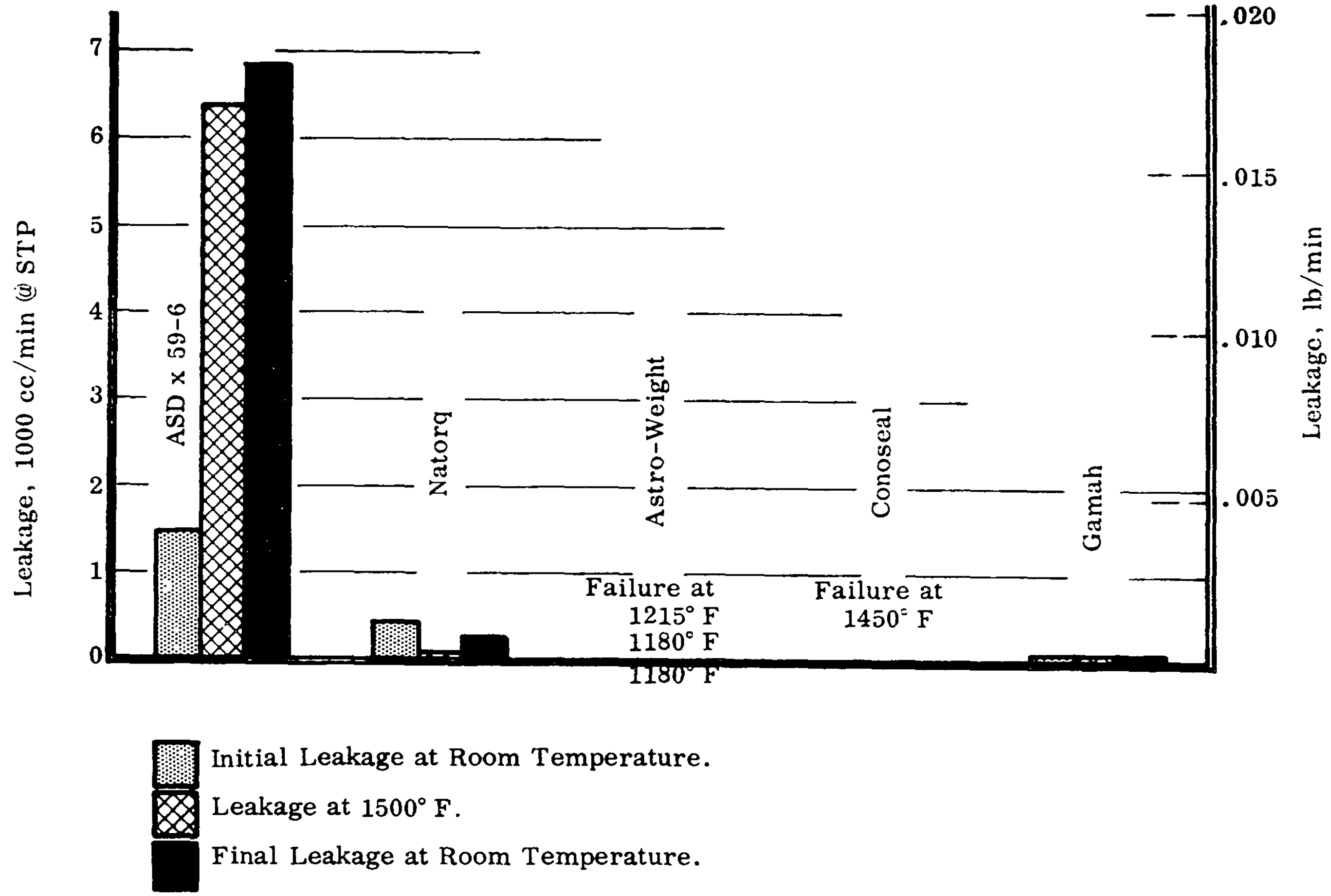

Figure 7. EVALUATION OF TUBE FITTINGS AND BOSS SEALS AT 1500° F

There is some disagreement as to the proper heat treatment for Inconel alloy X-750 (formerly Inconel "X" alloy) tubing for use at temperatures in excess of 1100° F.

International Nickel Company Technical Bulletin T-38 (August 1959), recommends a solution heat treatment and double age, per AMS (Aeronautical Material Specification) 5668 dated 1 December 1953, for maximum creep, relaxation, and rupture strength above 1100° F, consisting of the following:

1. 2100° F for 2 to 4 hours, air cool
2. 1550° F for 24 hours, air cool
3. 1300° F for 20 hours, air cool

The 100 hour rupture strength for bar stock at 1500° is given as 25,000 psi.

Superior Tube Company (Norristown, Pa.) recommended a single precipitation heat treatment at 1300° F for 20 hours, followed by air cooling. This is in agreement with AMS 5582 (6/15/59). AMS 5582 is recommended for fluid lines requiring high strength up to 1500° F and oxidation resistance up to 1800° F. Superior estimated that 100-hour rupture strength for Inconel alloy X-750 tubing at 1500° F is 22,000 psi.

Based on the three stress rupture tests conducted on the tubing there was no significant improvement in time to rupture between the single (point 1, Figure 8) and triple (point 3, Figure 8) heat treatments. Although the double heat treatment (point 2, Figure 8) resulted in the lowest time to rupture the difference in rupture time between points 2 and 3 is not statistically significant.

The preceding discussion emphasizes one of the problems associated with the development of a high-temperature pneumatic system: existing data on the mechanical properties of high-temperature alloys is limited in scope. Caution must be used by the designer in selecting allowable stresses based on limited testing of superalloys at high temperature. Minimum values for the mechanical

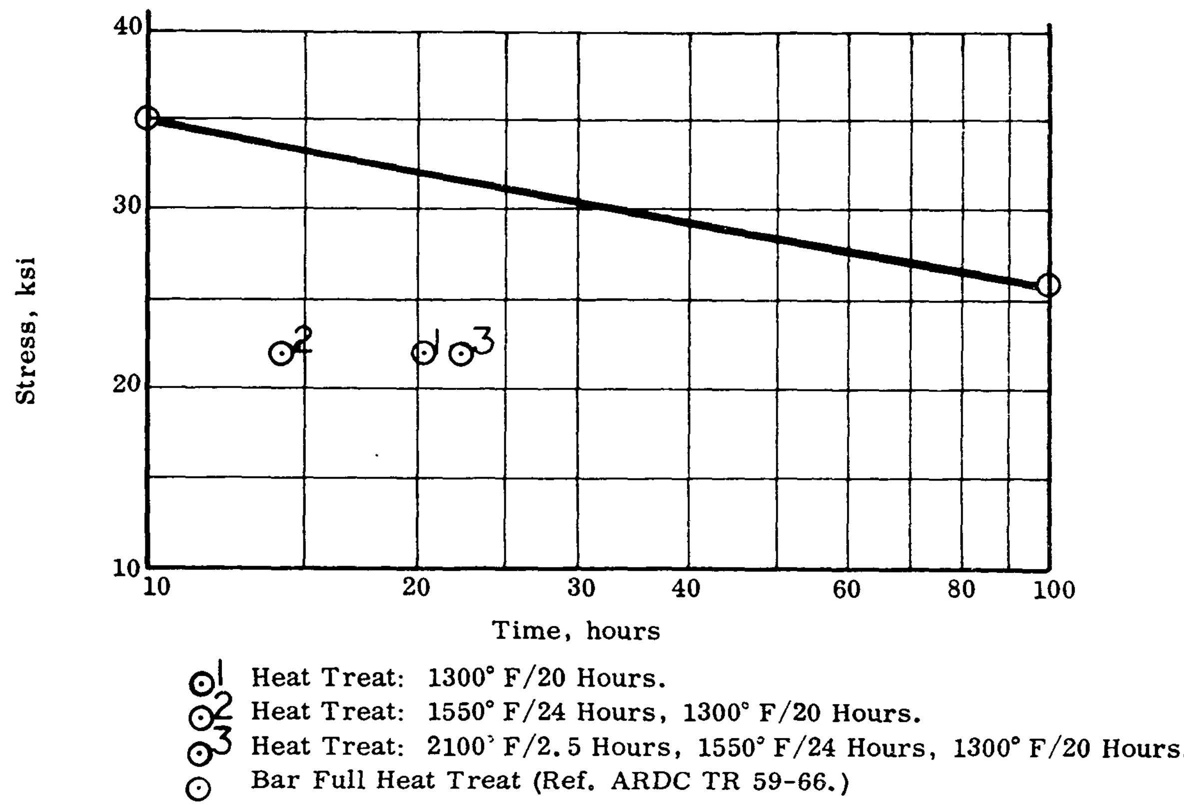

Figure 8. TUBING STRESS RUPTURE DATA AT 1500° F (INCONEL ALLOY X-750)

properties and the optimum heat treatment for each mechanical property, product type, or operating temperature range have not generally been established.

The stress rupture results obtained on the tubing, although disappointing, are considered satisfactory since the design of the tubing was based on an operating stress level of less than 7,000 pounds per square inch.

Tube Fittings

Three different tube fittings were evaluated for use in the high-temperature pneumatic system. The purpose of this evaluation was to obtain a satisfactory coupling for long-term operation at 1500° F and at a pressure of 2000 psi. All couplings tested were 3/8-inch (-6) size.

The testing included an examination for conformance with applicable vendor drawing, proof pressure at 4,000 psi, and a leakage check at room temperature and a pressure of 2,000 psi. This was followed by a removal and reinstallation test in conjunction with thermal cycling.

The following procedure was followed during the removal and reinstallation test. An anti-seize compound (silver goop) was applied to the fitting threads and the fitting was assembled with the torque recommended by the manufacturer. The fitting was installed in the induction heater test set up shown in Figure 9, and operating pressure (2,000 psig) applied. The room temperature leakage was then determined by recording the air bottle pressure drop over a five-minute interval.

The specimen temperature was then increased to 1000° F in approximately five minutes followed by a second leakage check. After reducing the specimen temperature to room temperature in approximately 10 minutes, a third leakage check was made. The torque required to disassemble the tube coupling was then recorded. This procedure was repeated for a total of five thermal cycles from room temperature to 1000° F and five thermal cycles from room temperature to 1500° F. Unless otherwise noted, the original seal was replaced after each

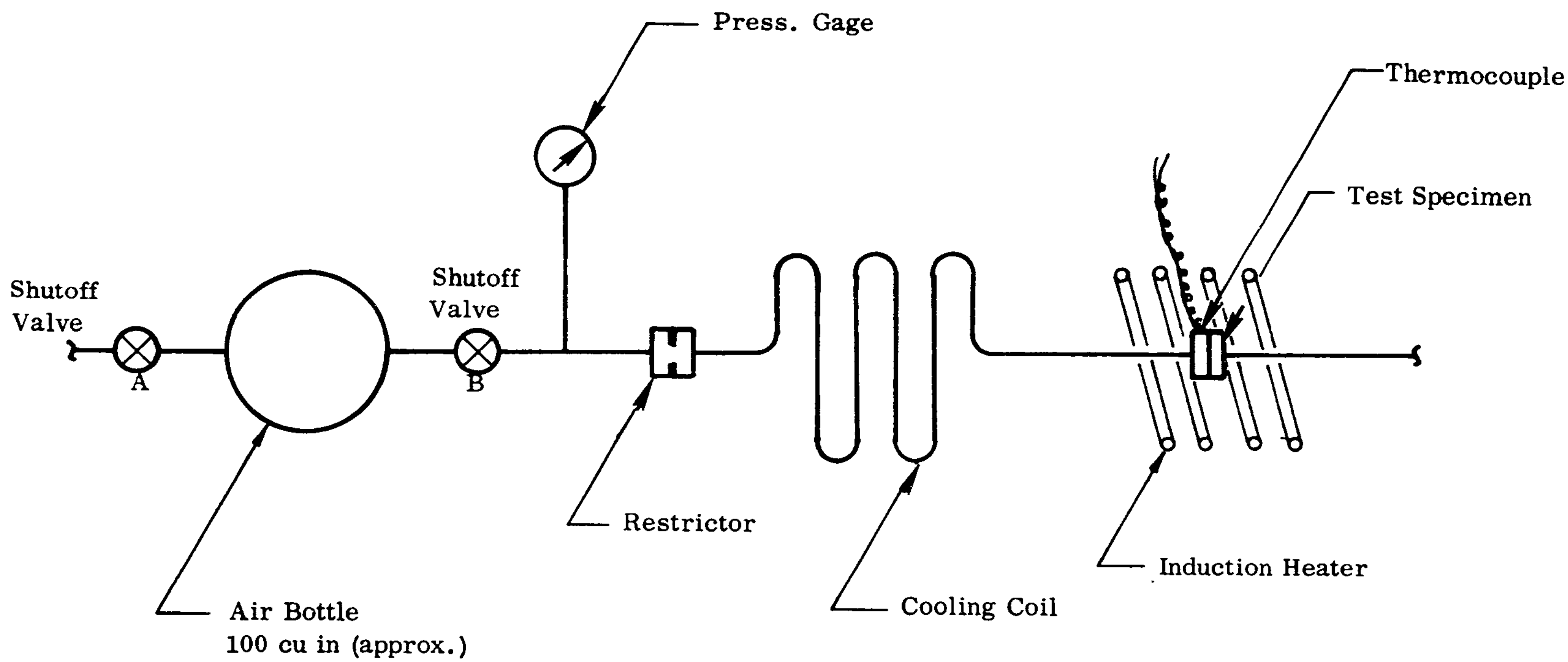

Figure 9. REMOVAL AND REINSTALLATION TEST SCHEMATIC

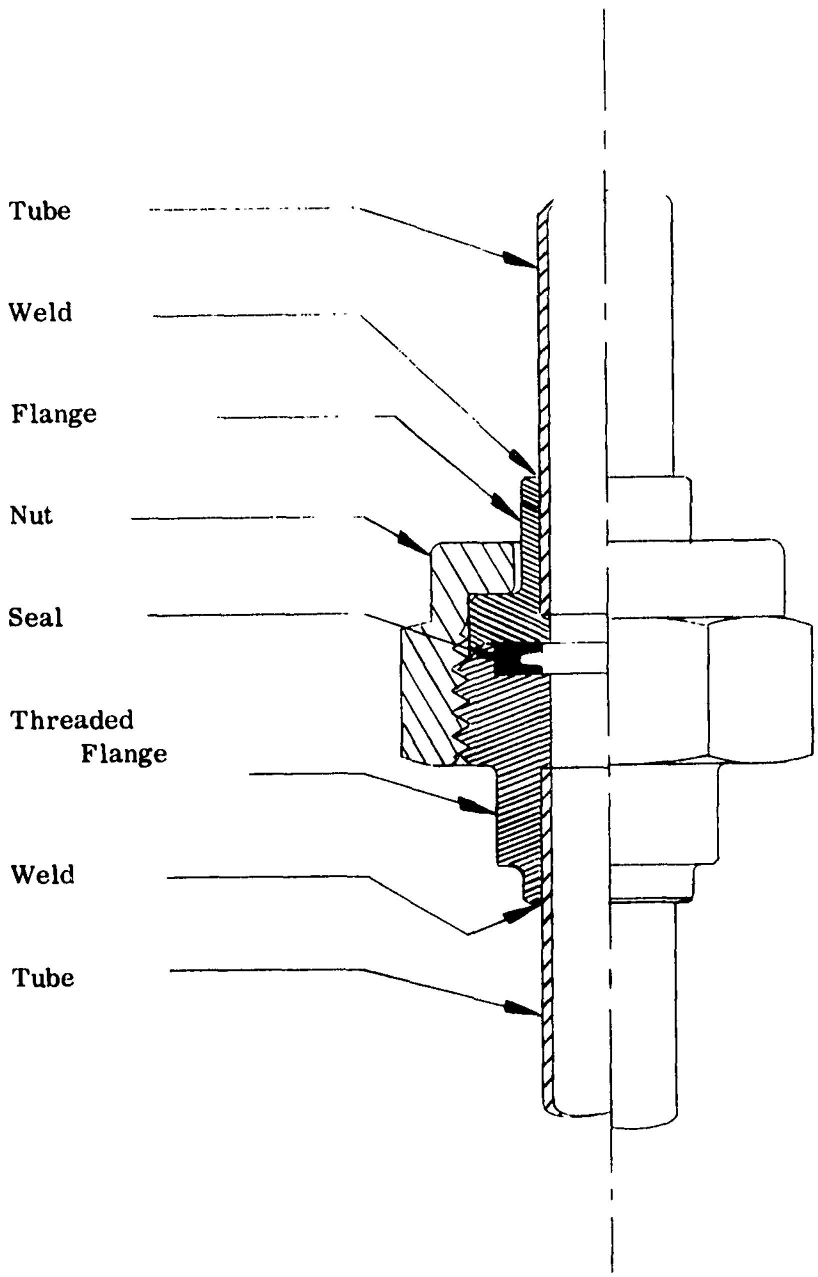

Figure 10. ASTRO-WEIGHT TUBE FITTING, ASSEMBLY DRAWING (Harrison P/N 400019)

thermal cycle. The results of the removal and reinstallation test are tabulated in Tables 3 through 5.

Astro-Weight (Harrison Manufacturing Company, Burbank, California)

The Astro-Weight tube fitting is shown in Figure 10. This fitting was manufactured from Inconel Alloy X-750 while the "K" seal was made of A-286 nickel-chromium steel. As shown in Table 3, this tube coupling met the removal and reinstallation test at 1000° F provided that a new "K" seal was used after each disassembly. Three attempts were made to reach 1500° F with unsuccessful results.

Table 3

ASTRO-WEIGHT TUBE FITTING — REMOVAL AND REINSTALLATION TEST RESULTS

		Initial Leakage (P = 2000 psig) CC/minute at STP					
Cycle	Assembly Torque lb-ft.	Initial Room Temp.		High Temp.	Final Room Temp.	Removal Torque lb-ft.	Remarks
1	35	71		0	338	42	Seal No. 1
2	35	2700		--	--	--	Seal No. 1
3	35	15		15	25	100	Seal No. 2
4	a) 35	19,000	1000° F	--	--	--	Seal No. 2
	b) 25	1,950		15	97	--	*Seal No. 3
5	--	--		15	15	130	*Seal No. 3
6	25	1600		***	65,500	130	** Failure at 1215° F. Seal No. 4
7	12	135	1500° F	***	5,500	22	** Failure at 1180° F. Seal No. 5
8	15	550		***	8,200	--	** Failure at 1180° F. Seal No. 6

* No disassembly between cycles 4b and 5
** Failure due to radial crack in seal
*** Leakage excessive (unable to maintain temperature).

All three seals failed at approximately 1200° F. Examination of the seals revealed that a radial crack had developed in each case. Seals one through four were coated with copper, gold, plus a flash of tin. Seals No. 5 and 6 were coated with rhodium, bold plus a flash of tin. The vendor revealed that there was some evidence to indicate that the tin was alloying with the base metal (A-286) thus causing embrittlement. Figure 11 is a photograph of the fitting after thermal cycling. Evaluation of "K" seals made from Inconel alloy X-750 and René 41 will be conducted as time permits.

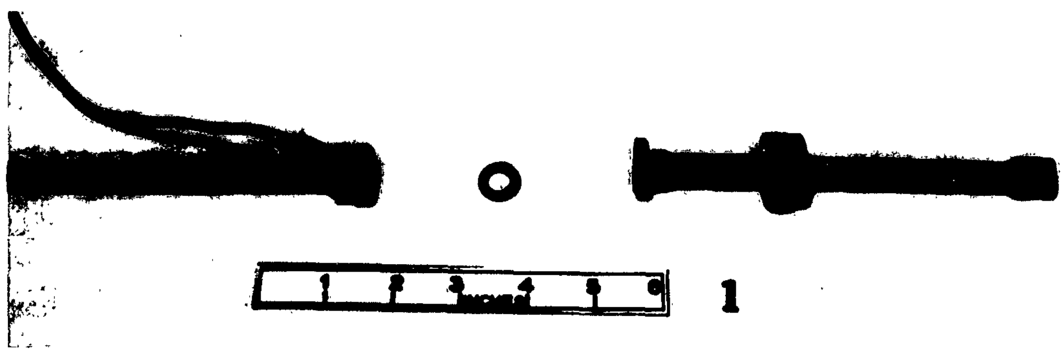

Figure 11. ASTRO-WEIGHT TUBE FITTING

Conoseal (Marmon Division, Aeroquip Corp., Los Angeles, Calif.)

The Conoseal tube fitting shown in Figure 12 was manufactured from Inconel alloy X-750 (AMS 5668) and the seal was manufactured from Inconel alloy 600 (formerly Inconel alloy). Table 4 summarizes the results of the removal and reinstallation test. The Conoseal tube fitting successfully completed all five thermal cycles from room temperature to 1000° F. The seal was replaced after each disassembly on the recommendation of the manufacturer. During the sixth cycle a failure occurred at 1450° F. Visual examination revealed that the nut had distorted, resulting in high leakage flow. This fitting is shown subsequent to failure in Figure 13. The face of the nut was originally perpendicular to the centerline of the nut. A review of the nut design revealed that a high bending stress would be induced at the maximum recommended torque of 405

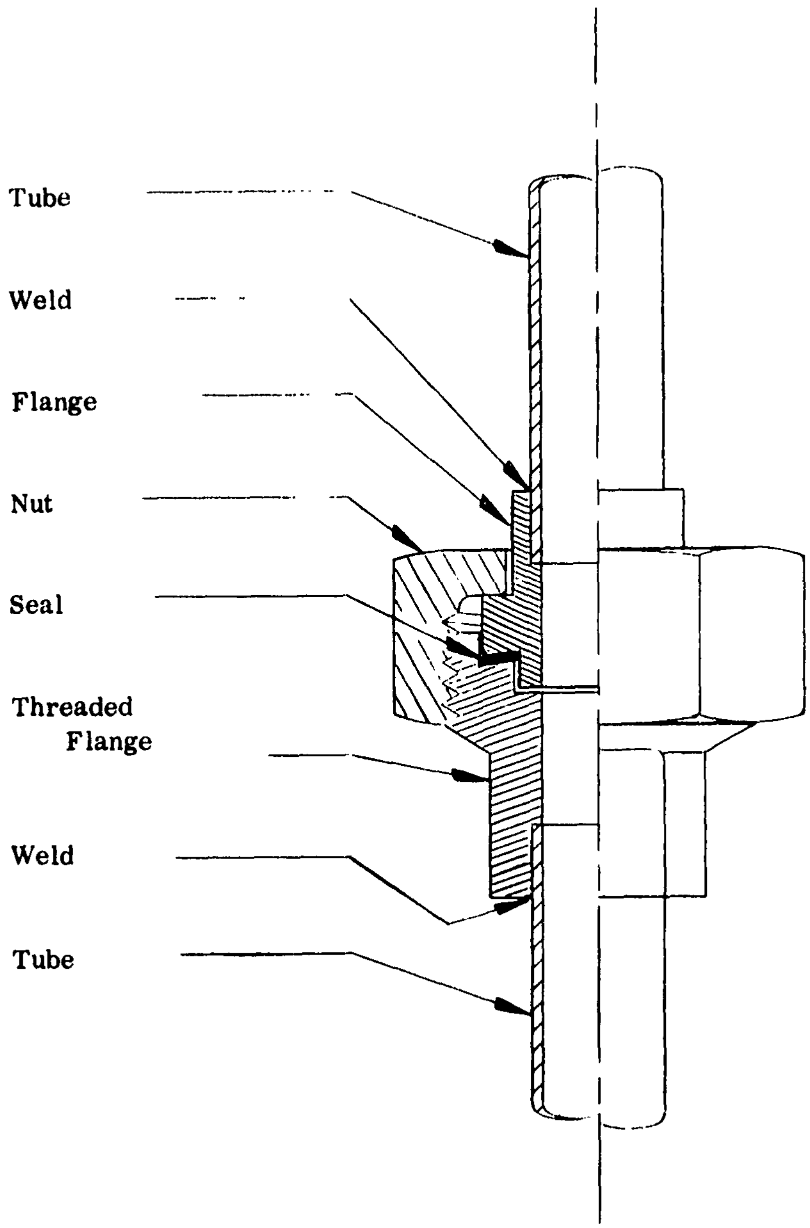

Figure 12. CONOSEAL TUBE FITTING, ASSEMBLY DRAWING
(Marman P/N 55979)

pound-inches; this maximum torque was required to effect a satisfactory seal during the test. A redesigned nut was received to permit continued evaluation of the Conoseal tube fitting within the test program schedule limitations.

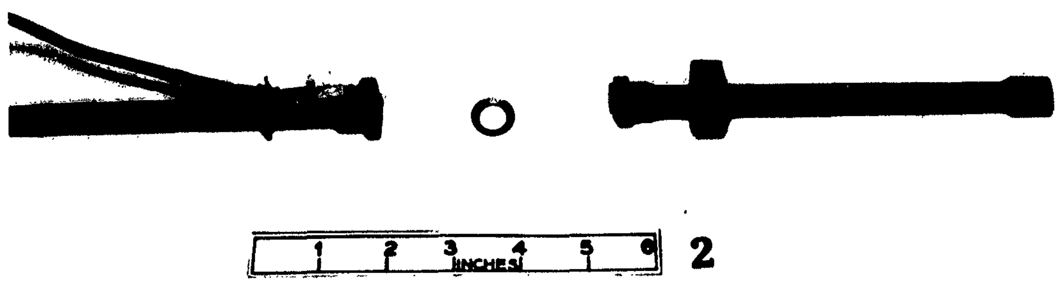

Figure 13. CONOSEAL TUBE FITTING

Table 4

CONOSEAL TUBE FITTING — REMOVAL AND REINSTALLATION TEST RESULTS

Cycle	Assembly Torque lb-ft.	Initial Leakage (P = 2000 psig) CC/minute at STP: Initial Room Temp		High Temp.	Final Room Temp.	Removal Torque lb-ft.	Remarks
1	25	97	1000° F	50	97	20	Seal No. 1
2	a) 25**	2200		--	--	--	Seal No. 2
	b) 34**	50		0	15	35	
3	34	900		145	272	25	Seal No. 3
4	35	2700		--	1300	35	Seal No. 4
5	35	0		0	50	40	Seal No. 5
6	34	15	1500° F	*	--	--	Seal No. 6 *Failure at 1450° F, nut deformed

** retorqued to higher value

Gamah (Gamah Corp., Santa Monica, Calif.)

Two tube couplings, manufactured from Inconel alloy X-750, were received from the Gamah Corporation. This fitting is shown in Figure 14. Although some initial difficulty was encountered, the tubing was mechanically attached to the tube fitting by swaging. However, the tubing had been subjected to a double age heat treatment (1550° F/24 hours, 1300° F/20 hours) only, and was not in the full age-hardened condition. The tubing hardness was recorded as 23 on the Rockwell "C" scale. A second tubing sample triple heat treated per AMS 5668D (2100° F/2 hours, 1550° F/24 hours, 1300° F/20 hours) was forwarded to Gamah to determine whether this specimen can be swaged into the tubing.

The Gamah coupling successfully completed five thermal cycles from room temperature to 1000° F and four thermal cycles from room temperature to 1500° F. The results of the removal and reinstallation test are given in Table 5. The same seal was used for cycles 1 through 9. During the ninth cycle, excessive leakage was recorded at 1450° F. Reversing the seal did not improve the situation. When a new seal was installed, for cycle number ten, the leakage was reduced to an acceptable level. A photograph of this tube coupling, subsequent to the assembly and disassembly test, is shown in Figure 15.

Based on the preceding test results, the "Gamah" tube coupling appears to be the most satisfactory fitting for use in the high-temperature pneumatic system. This fitting will be subjected to a combined thermal cycling and pressure cycling test.

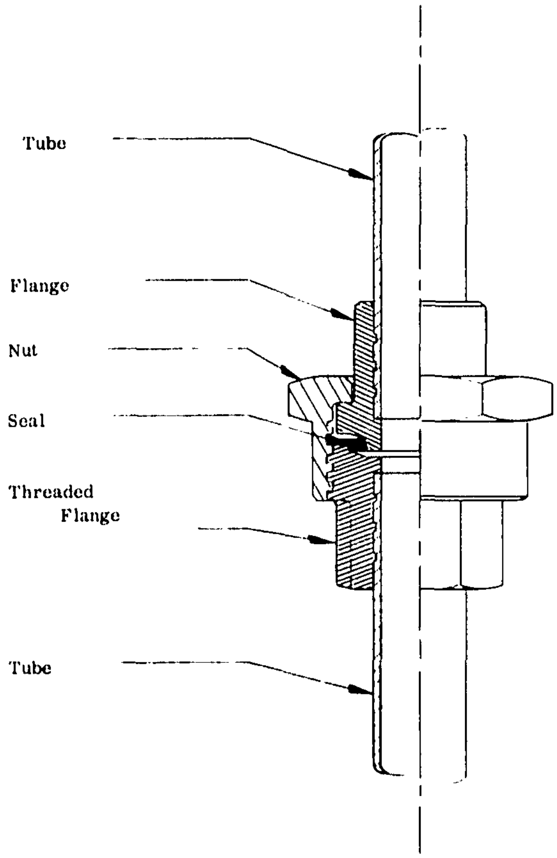

Figure 14. GAMAH TUBE FITTING ASSEMBLY DRAWING (Gamah P/N JT 29)

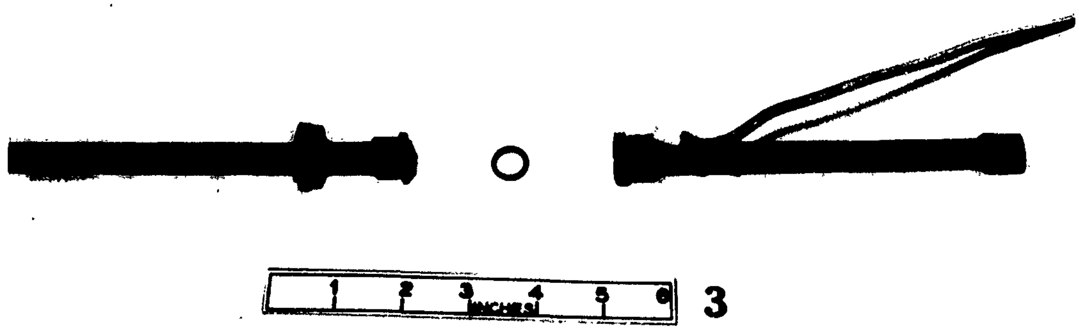

Figure 15. GAMAH TUBE FITTING

Table 5

GAMAH TUBE FITTING –
REMOVAL AND REINSTALLATION TEST RESULTS

Cycle	Assembly Torque lb-ft.	Initial Leakage (P = 2000 psig) CC/minute at STP: Initial Room Temp.		High Temp.	Final Room Temp.	Removal Torque lb-ft.	Remarks
1	7	15		15	0	15	Seal No. 1
2	7	59		0	0	12	Seal No. 1
3	7	15	1000° F	15	15	10	Seal No. 1
4	7	15		0	0	9.6	Seal No. 1
5.	7.	0		0	0	9.6	Seal No. 1
6	7.	0		0	49	25	Seal No. 1
7	7.	0		--	0	35	Seal No. 1
8	7.	15		--	29,500	5	Seal No. 1
9	--	--	1500° F	*	--	--	Seal No. 1
10	7.	200		200	200	--	Seal No. 2

* Excessive leakage at 1450° F and 1420° F (seal reversed). Unable to attain 1500° F.

Boss Seals

A total of three boss seals were subjected to the removal and reinstallation test. These included the Natorq boss seal in the 3/8 inch (-6) size and modified ASD X59 seals (General Dynamics/Convair P/N SD 61-2014) in the 3/8 inch (-6) and 1/2 inch (-8) sizes. These seals are shown in Figures 16 and 17. The Natorq seal was made from Inconel alloy X-750 and heat treated per AMS 5667 while the ASD X-59 seals were manufactured from Inconel alloy X-750 and heat treated per AMS 5668. A standard boss per AND 10050 was machined into a René 41 block and subsequently heat treated per AMS 5713. The plug consisting

ASD X59 Natorq

Figure 16. BOSS SEAL CROSS SECTIONS

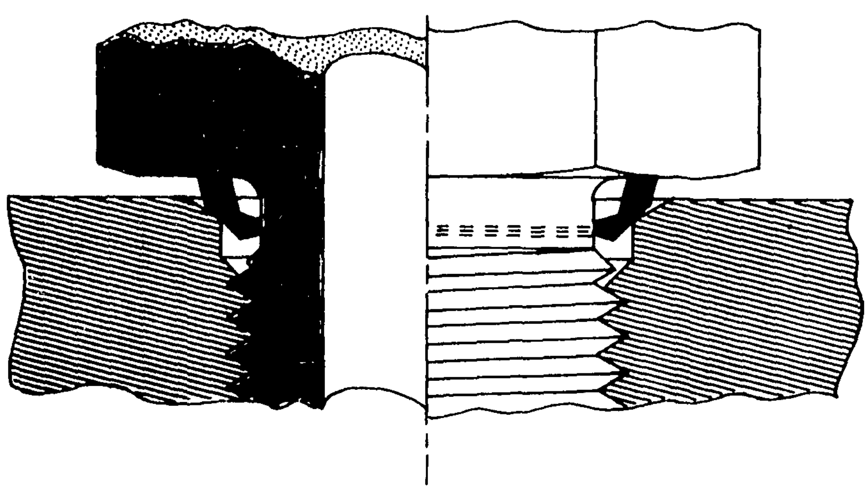

Figure 17. BOSS SEAL INSTALLATION DRAWING

of a hexagonal head and fitting end per MS 33656 was machined from Inconel alloy X-750 and subsequently heat treated per AMS 5668. The test procedure used was the same as that for the tube fittings. Figure 18 is a photograph of the boss, ASD X59 seal and plug used during this test phase.

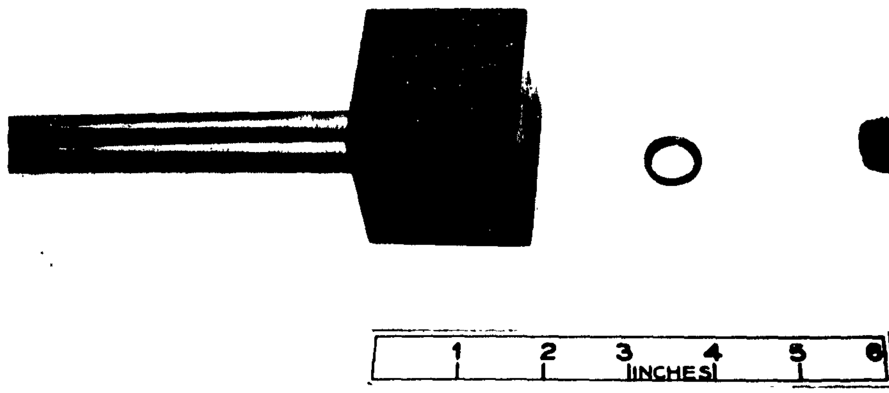

Figure 18. BOSS SEAL TEST FIXTURE

ASD X59 Boss Seal

Tables 6 and 7 summarize the results of the removal and reinstallation test for the -6 and -8, X59 boss seals. The original -6 seal completed five thermal cycles from room temperature to 1000° F followed by two thermal cycles from room temperature to 1500° F. Since the leakage had increased considerably during the seventh cycle, the seal was replaced. The plug was not removed following the eighth, ninth and tenth thermal cycles in order to determine the effects of thermal cycling on seal efficiency.

Because of the limited scope of this test program it was not possible to investigate the effectiveness of ASD X59 seal at higher installation torques. The recommended torque range for the ASD X59 seal in the stainless steel configuration is: 30 to 35 lb-ft. for the -6 size, and 45 to 55 lb-ft. for the -8 size. During this test program the torque used was the minimum consistent with a satisfactory seal. This was done to obtain maximum reusability of the seal and to assist in maintaining a lower removal torque.

Table 7 summarizes the testing on the ASD X59-8 seal at an operating pressure of 500 psig. One seal successfully completed all ten thermal cycles including eight disassemblies.

Based on the preceding data, it is apparent that the ASD X59 boss seal, (in Inconel alloy X-750 configuration) does not provide an absolute pressure seal from room temperature at 1500° F. The results to date however, are sufficiently encouraging to warrant further investigation of this boss seal.

Natorq Boss Seal

The Natorq boss seal successfully completed five thermal cycles from room temperature to 1000° F. During the sixth cycle excessive leakage was recorded at 1500° F. The installation torque was increased from 30 to 35 lb-ft prior to the seventh, eighth, and ninth cycles thereby resulting in improved sealing. The results of this testing are given in Table 8. This seal will be evaluated under pressure cycling conditions at 1500° F in combination with thermal cycling from room temperature to 1500° F.

HIGH TEMPERATURE TEST LABORATORY

The major high-temperature test laboratory activity was directed towards preparation of the environmental chamber and the air heater which are required for component evaluation.

All material required for modification of the environmental chamber was received and installed during this reporting period. This included installation of additional heating elements and replacing the high-temperature insulation. A number of runs were attempted to check out the environmental chamber. During the initial run a temperature of 1330° F was attained before a heating element failure resulted in stopping the test. The heating element was replaced and two

Table 6

ASD X59-6 BOSS SEAL
REMOVAL AND REINSTALLATION TEST RESULTS

Cycle	Assembly Torque lb-ft.	Initial Leakage (P = 2000 psig) CC/Minute at STP				Removal Torque lb-ft.	Remarks
		Initial Room Temp.		High Temp.	Final Room Temp.		
1	30	3,900		3,650	4,200	95	Seal No. 1
2	35	4,000		--	4,000	35	Seal No. 1
3	35	1,050		500	880	40	Seal No. 1
4	35	1,280	1000° F	700	1,150	35	Seal No. 1
5	a) 35 *						
	b) 30	1,350		800	1,300	35	Seal No. 1
6	30	1,300		--	10,000	40	Seal No. 1
7	30	2,950		18,400	13,000	50	Seal No. 1
8	a) 45 *	720		600	1,150	--	**Seal No. 2
	b) 30		1500° F				
9	--	--		2,720	5,320	--	**Seal No. 2
10	--	--		4,050	5,320	--	**Seal No. 2
11	45	900		--	--	45	Room Temp. test only.

* Initially torqued to maximum value followed by disassembly and retorquing to second value.

** No disassembly between cycles 8, 9, and 10.

Table 7

ASD X59-8 BOSS SEAL —
REMOVAL AND REINSTALLATION TEST RESULTS

Cycle	Assembly Torque lb-ft.	Initial Leakage (P = 500 psig) CC/minute at STP: Initial Room Temp.		High Temp.	Final Room Temp.	Removal Torque lb-ft.	Remarks
1	50	37	1000° F	37	0	135	
2	50	56	1000° F	13	0	115	
3	50	37	1000° F	0	0	90	
4	45	461	1000° F	154	282	107	
5	45	525	1000° F	192	384	90	
6	50	410	1500° F	25	37	110	
7	50	512	1500° F	37	37	125	
8	55	870	1500° F	18	31	150	
9	50	1200	1500° F	120	154	---	*
10	--	----	1500° F	74	109	---	*

* No disassembly between cycles 9 and 10

Table 8

NATORQ BOSS SEAL —
REMOVAL AND REINSTALLATION TEST RESULTS

Cycle	Assembly Torque lb-ft.	Initial Leakage (P = 2000 psig) CC/minute at STP: Initial Room Temp.		High Temp.	Final Room Temp.	Removal Torque lb-ft.	Remarks
1	30	215		215	184	40	
2	30	184		112	53	70	
3	30	2400	1000° F	2300	2210	65	
4	30	92		53	77	70	
5	30	305		155	217	55	
6	30	1400		*	1100	100	No seal damage.
7	35	53		37	77	90	New silver GOOP Ran tap into thread. Brushed surface of boss.
8	35	217	1500° F	194	183	90	
9	35	62		10	10	--	No disassembly between cycles 9 and 10
10	--	--		43	10	--	

* Leakage excessive (unable to maintain temperature).

additional runs were completed with maximum recorded temperatures of 1320° and 1400° F, respectively. During the third run failure of the fan wheels resulted in the loss of all heating elements.

An investigation was conducted to determine the advisability of rebuilding the environmental chamber for sustained operation at 1500° F as well as to evaluate other alternatives of attaining the test temperature. A survey of the environmental chamber revealed that the top of the chamber had warped, thereby permitting heat leakage around the explosion door (which covers the roof of the chamber). The chromolox heating elements, although rated for 1500° F, appear to be marginal for this application; air must be circulated across the elements to prevent their surface temperature exceeding 1800° F. The fans, which were manufactured from stainless steel, are also unacceptable for operation at 1500° F. It was therefore concluded that the existing environmental chamber was unacceptable for sustained operation at 1500° F.

Since it is desirable to keep the test system reasonably compact, a number of schemes involving the use of a 1500° F inner chamber within the larger environmental chamber were evaluated. These included a gas underfired furnace. an external air heater, and a radiant heat furnace. The radiant heat type furnace was selected as the most promising approach due to its relatively rapid heat-up time, light weight, and cleanliness.

All components required for modification of the air heater were received and this unit is in the final stages of assembly.

Work was completed on the air flow bench in preparation for component tests at room temperature.

IV. MAJOR PROBLEM AREAS

As indicated in the previous quarterly progress report (ZR-1001-11, Development of a High-Temperature, Nuclear-Radiation-Resistant Pneumatic Power System For Flight Vehicles), the potential problem areas include springs and bellows, bearings, seals (dynamic and static), and material combinations. During this reporting period, it was discovered that the welding of Udimet 500 also presented some difficulties.

The design of springs and bellows for use at high temperature must be governed by both stress relaxation effects and change of the elastic modulus of the material as a function of temperature. Although springs are still considered a potential problem area some success was achieved in obtaining a satisfactory check valve spring. This was accomplished by operating at a reduced stress level and using a heat setting process. The maximum anticipated relaxation of this spring is 25% after a 70-hour exposure to 1500° F.

The development of suitable bearings for extended operation at 1500° F continues as a major problem area. Although no performance testing has been accomplished, the spherical roller bearings for the rotary actuator were received. A gas film lubricated bearing was selected for the compressor on which, it is anticipated, testing will be initiated during the next reporting period.

Seal design is the controlling factor in determining overall system efficiency. Although little work was accomplished on dynamic seals, a satisfactory metal boss seal was evaluated during this reporting period. This testing is covered in detail under "Tubing, Tube Fittings and Boss Seals."

Material wear properties continue to present a major problem area. As indicated under the "Rotary Actuator and Servo Control Valve" section, ceramic bonded calcium fluoride will be evaluated as part of the actuator bearing.

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The difficulties encountered in welding of Udimet 500 are discussed in greater detail under accumulator development. Three different approaches are in progress including induction pressure welding, electron beam welding, and TIG welding.

V. FUTURE WORK

Work to be performed during the next reporting period will be concerned with the testing and evaluation of components for subsequent inclusion in the high-temperature pneumatic system.

Fixture and instrumentation buildup will also continue in preparation for system testing.

Completion of this phase of the program will lay the groundwork for testing the entire pneumatic system in both high-temperature and nuclear-radiation environments.