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Report L-910900-14

Development of a Model and Test
Equipment for Cold-Flow Tests at
500 Atm of Small Nuclear Light
Bulb Configurations

NASA Contract No. SNPC-70



United Aircraft Research Laboratories

EAST HARTFORD, CONNECTICUT

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FOREWORD

An exploratory experimental and theoretical investigation of gaseous nuclear rocket technology was conducted by the United Aircraft Research Laboratories under Contract SNPC-70 with the joint AEC-NASA Space Nuclear Systems Office. The Technical Supervisors of the Contract for NASA were Captain C. E. Franklin (USAF) of SNSO for the initial portion of the Contract performance period, and Dr. Karlheinz Thom of SNSO and Mr. Herbert J. Heppler of the NASA Lewis Research Center for the final portions. The following nine reports (including the present report) comprise the required Final Technical Report under the Contract:

1. Roman, W. C. and J. F. Jaminet: Development of RF Plasma Simulations of In-Reactor Tests of Small Models of the Nuclear Light Bulb Fuel Region. United Aircraft Research Laboratories Report L-910900-12, September 1972.
2. Klein, J. F.: Nuclear Light Bulb Propellant Heating Simulation Using a Tungsten-Particle/Argon Aerosol and Radiation from a DC Arc Surrounded by a Segmented Mirror Cavity. United Aircraft Research Laboratories Report L-910900-13, September 1972.
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Development of a Model and Test Equipment
for Cold-Flow Tests at 500 Atm of Small
Nuclear Light Bulb Configurations

SUMMARY

A model and test equipment were developed and cold-flow-tested at greater than 500 atm in preparation for future high-pressure rf plasma experiments and in-reactor tests with small nuclear light bulb configurations. With minor exceptions, the model chamber is similar in design and dimensions to a proposed in-reactor geometry for tests with fissioning uranium plasmas in the Nuclear Furnace. The model and the equipment were designed for use with the UARL 1.2-MW rf induction heater in tests with rf plasmas at pressures up to 500 atm.

The model consists of (1) a 6.6-cm-diam, 17.8-cm-long vortex chamber formed by a fused silica tube with water-cooled copper and stainless-steel end walls, (2) a fiberglass filament-wound pressure vessel around the fused silica tube, and (3) a pair of stainless-steel split retainer flanges which transmit the axial pressure load from the end walls to the pressure vessel. Each 7.75-cm-o.d. end wall has seven 0.84-mm-i.d. injectors at its periphery through which argon is injected to drive the vortex and a 0.8-cm-i.d. thru-flow exhaust port at its center. Also, each end wall has a single 1.7-mm-i.d. off-axis fuel injector at a radius of approximately 1.0 cm and ten equally spaced 1.6-mm-i.d. ports at radii from 1.43 to 2.87 cm. The latter could be used as view ports for instrumentation for measuring the radial distribution of fuel in the chamber, or as static pressure taps. All components of the model were designed to withstand the heat loads expected in rf plasma tests with greater than 200 kW of power in the plasma.

The fiberglass filament-wound pressure vessel, which was designed for an operating pressure of 500 atm, has an inside diameter of 7.76 cm, a length of 28.1 cm, and a maximum wall thickness of approximately 5 mm. Alternate axial and hoop layers (a total of 28 layers) are used to provide the required strength. Immediately inside the filament-wound pressure vessel is a silicone rubber sealing liner. Cooling water flows in the annulus between the liner and the fused silica tube. This cooling water will contain dye in tests with plasmas to protect the liner and pressure vessel from the intense thermal radiation.

Equipment was assembled in a test facility adjacent to the UARL 1.2-MW rf induction heater for use with the model in cold-flow tests and in future high-pressure rf plasma tests. The gas flow system provides a metered flow of argon

at pressures up to 680 atm. At a chamber pressure of 500 atm, the maximum argon flow rate available is approximately 7.55 liter/sec (STP). A submerged pump in a pressure vessel provides up to 29 gal/min of cooling water at approximately the chamber pressure.

Initially, tests were conducted to verify the strength and reliability of the filament-wound pressure vessel design. One vessel was hydrostatically tested to 680 atm before it failed. Another was cycled more than 60 times between 0 and at least 545 atm before it developed a crack in the outer fiber layers.

A series of cold-flow tests of the model was then conducted at pressures up to about 510 atm. At 504 atm, the flow rates of argon and cooling water were 3.35 liter/sec (STP) and 26 gal/min, respectively. It was demonstrated that the model is capable of being operated for extended periods at the 500-atm pressure level and is, therefore, ready for use in initial high-pressure rf plasma experiments.

INTRODUCTION

An experimental and theoretical investigation of different phases of gaseous nuclear rocket technology has been conducted by the United Aircraft Research Laboratories under Contract SNPC-70 administered by the joint AEC-NASA Space Nuclear Systems Office. This investigation has been primarily directed toward evaluating the feasibility of the nuclear light bulb engine concept.

Details of this engine concept are discussed in Refs. 1 through 5. The full-scale reference engine design consists of a cluster of seven cavities. In each cavity, energy is transferred by thermal radiation from fissioning gaseous nuclear fuel (uranium) contained in a vortex, through an internally-cooled transparent wall, to seeded hydrogen propellant flowing in an annulus surrounding the transparent wall. The hydrogen propellant is seeded with submicron-sized tungsten particles to increase its opacity. A transparent buffer gas (neon) is injected near the inner surface of the transparent wall to form the vortex which contains and isolates the fuel from the wall. To obtain the fuel density required to maintain nuclear criticality, the pressure in the fuel and propellant regions must be 500 atm for the reference engine. High purity, internally gas-cooled, fused silica tubes (tube wall thicknesses in the range from 0.125 to 0.25 mm) appear suitable for the transparent wall.

The neon and the entrained gaseous nuclear fuel and fission products exit through ports located at the centers of one or both end walls of the cavity. Cold neon bypass gas is used to rapidly cool the hot exhaust gas mixture, thereby condensing the fuel. The condensed fuel is centrifugally separated from the neon and pumped back into the fuel containment region of the vortex. The neon is further cooled and pumped back into the cavity to drive the vortex. This closed-cycle fuel system concept is unique because the physical interface between the nuclear fuel and the seeded hydrogen propellant (the internally-cooled transparent wall) offers the possibility of providing perfect containment of the gaseous nuclear fuel and fission products.

Because of the high temperatures in the fuel region, engines of this type offer the ultimate potential of providing values of specific impulse greater than 3000 sec and engine thrust-to-weight ratios greater than unity. A summary of the estimated performance characteristics is presented in Ref. 6.

Increased emphasis has been placed on research necessary to prepare for tests of small models of a nuclear light bulb unit cavity in a driver reactor with high thermal neutron flux levels, such as the Los Alamos Scientific Laboratory's Nuclear Furnace. Several analytical studies have been conducted (see Ref. 7 for most recent results) to define the characteristics of in-reactor test configurations having several levels of complexity. Figure 1 is a preliminary layout illustrating an initial in-reactor test

configuration which could be used to study the characteristics of fissioning uranium plasmas, i.e., of the fuel region. The vortex chamber consists of an approximately 6.6-cm-i.d. by 17.8-cm-long cylindrical cavity. As in the reference engine unit cavity, the buffer gas is injected tangentially from the periphery of the cavity, through the wall of the reflective aluminum liner. The uranium fuel is injected at the centers of the symmetrical end walls. This in-reactor configuration for the Nuclear Furnace is also designed to operate at a cavity pressure of 500 atm.

The research program discussed in the present report is concerned with the development and cold-flow testing of a small model capable of withstanding the pressure environment of the in-reactor test. The eventual goal of simulating the pressure and thermal environments simultaneously was also taken into consideration in the design of the model.

Previous investigations were directed at developing the technology required to fabricate reliable fiberglass filament-wound pressure vessels suitable for use at 500 atm in an rf environment. Initially, hydrostatic tests were conducted (Ref. 8) in which a fiberglass filament-wound tube was pressurized to 550 atm. The configuration was such that the axial loads on the end walls as well as the hoop loads on the pressure vessel were sustained by the filament-wound tube. In addition, rf-heated plasma tests utilizing fiberglass filament-wound pressure vessels at relatively low pressures have been accomplished (Refs. 8 and 9).

The objectives in the present program were (1) to develop and demonstrate the reliability of fiberglass filament-wound pressure vessels for use at 500 atm, (2) to design and construct equipment suitable for gas and water cold-flow tests at 500 atm, and (3) to conduct 500-atm cold-flow tests of an in-reactor configuration which could be used in future high pressure rf-heated plasma tests.

DESCRIPTION OF EQUIPMENT AND PROCEDURES

Test Equipment

High-Pressure ModelGeneral Description of Model

A 500-atm model was designed and fabricated. The model was designed to be as similar as possible to the proposed in-reactor geometry (IRG) and to be capable of being used in future high-pressure rf-heated plasma tests in the 1.2-MW rf induction heater.

A sketch of the 500-atm model test configuration used in cold-flow tests is shown in Fig. 2, and a photograph of the assembled model is shown in Fig. 3. Argon is injected tangentially through seven vortex injectors located at the periphery of each end wall and is exhausted through a 0.8-cm-i.d. thru-flow port at the center of each end wall. Each injector has an i.d. of 0.84 mm (total injection area of 0.077 cm^2). A 1.7-mm-i.d. simulated-fuel injection port is located in each end-wall surface near the test chamber centerline at a radius of approximately 1.0 cm. These ports were designed for use in an rf-heated test with simulated-fuel injection and were not used during this program. The front faces of the end walls are copper for effective heat transfer while the remainder is stainless steel. This design allows the end walls to withstand a heat flux of at least 1.2 kW/cm^2 . Ten ports (1.6-mm i.d.), equally spaced between radii of 1.43 cm and 2.87 cm, are oppositely located in each end wall. With modification, these ports could be used with instrumentation now being developed (Ref. 9) to measure the distribution of simulated fuel contained in the vortex or to observe the location of the "edge-of-plasma" during rf plasma tests (see Ref. 9). During cold-flow tests, the view ports can be used for static pressure measurements.

The high-pressure components consist of a fiberglass filament-wound pressure vessel; a silicone rubber sealing liner; and two two-piece, split retainer flanges which transmit the axial force on the end walls to the filament-wound pressure vessel. The o.d. of the retainer flanges is grooved (see Fig. 2) to allow installation and brazing of coolant tubing (not required for cold-flow tests). This assembly must then be silver plated to prevent rf heating of the retainer flanges during future rf plasma tests. A photograph of the filament-wound tube, silicone rubber sealing liner, and a pyrex tube (2-mm wall) used in some tests (in place of the fused silica tube) is shown in Fig. 4. The overall pressure vessel design is similar to that successfully tested hydrostatically to 550 atm during the FY 1971 program (see Ref. 8).

One main water-coolant path is employed in this configuration. The coolant flows, in sequence, to the right thru-flow duct, the right end wall, the annulus surrounding the fused silica tube, the left end wall, and the left thru-flow duct. For rf plasma tests, dye would be added to the water to absorb most of the radiant energy transmitted through the fused silica inner peripheral wall before this energy can reach the silicone rubber sealing liner.

Pressure Vessel Fabrication Method

Filament-wound pressure vessels employed in this program were made in the Materials Laboratory at United Aircraft Research Laboratories. The method used for fabricating the tube to the precise size and shape required by the geometry shown in Fig. 2 is shown in Fig. 5. Not shown in Fig. 5 is the preliminary step of winding several layers of fiberglass and uncured liquid resin on a large cylinder. These layers are partially cured to facilitate handling and then cut into long strips, each of which is sufficiently wide to cover half of the periphery of the mandril. Five of these axial layers are shown installed in staggered fashion on the mandril in Fig. 5(a). The mandril, shown installed on the winding motors, can be simultaneously rotated and axially traversed during the winding of the hoop layers.

One of the major improvements in the winding technique used in this program is the capability to alternate the axial and hoop layers of fiberglass as shown in Fig. 5(a). Previously, all the axial layers were installed, followed by all the hoop layers. This change results in increased pressure vessel strength and an improved modulus of elasticity (see Table I and later discussion). Another improvement in winding technique is the considerable increase in fiber tension used during winding of the hoop layers. This resulted in an as-cured fiber density of approximately 60 percent (i.e., with 40 percent resin) by weight which is in the range of the optimum fiber density for good strength properties.

After installation of the winding rings on the holding pins (see Fig. 5(b)), the five axial fiber layers are doubled over the winding rings with the ends of the fibers overlapped. These layers are also alternated with hoop layers as shown in Fig. 5(b). Additional hoop layers are then wound such that there are a total of 28 layers, including the 10 axial layers, in the central section, decreasing as shown in Fig. 5(c) to 21 layers at the end of the pressure vessel.

At this point in the winding procedure, the holding pins are retracted and the end caps and forming sleeves installed as shown in Fig. 5(c). The forming sleeves are split into three segments to facilitate installation. The whole assembly is inserted into an oven and the pressure vessel is cured at the temperatures and for the times required by the particular epoxy resin, as recommended by the manufacturer.

The epoxy resin used in fabricating the four pressure vessels tested during this program (see Table I) was a mixture of 60 percent acetone (by weight) solvent, 31.5 percent Union Carbide ERL-2256 resin with 8.5 percent ZZL-0820 curing agent. This resin was chosen for its relatively high strength, good rf properties, and ease of handling.

RF Tests of Filament-Wound Tube

A series of tests was conducted in the 1.2-MW rf induction heater to verify that a filament-wound pressure vessel fabricated using this epoxy resin could be used in the rf environment expected in rf in-reactor simulation tests. These tests employed a 5.7-cm-diam, low-pressure salt-water load with electrical characteristics which approximate those of a plasma load typical of that expected in future rf in-reactor simulation tests. A 6.5-cm-i.d., cylindrical filament-wound tube was fabricated using ERL-2256 epoxy resin. Coolant water for the filament-wound tube flowed in the annulus between the filament-wound tube and the fused silica tube which contained the salt water. No rubber sealing liner was used due to the low pressures involved. Tests were conducted with up to 315 kW deposited into the salt-water load by the rf heater, and with resonator voltages up to 17 kV. No significant heating of the filament-wound tube was measured. The results of these tests indicate that a filament-wound pressure vessel fabricated with Union Carbide ERL-2256 resin could be used in the rf fields expected in rf in-reactor simulation tests.

High-Pressure Test Facility

The high-pressure test facility allows cold-flow testing at 500 atm of models designed for future heated tests in the 1.2-MW rf induction heater. With some additional plumbing and heat exchangers in the water-coolant loop and in the thru-flow exhaust ducting, this facility can be employed in initial 500-atm rf-heated tests.

A schematic of the 500-atm flow system, configured for cold-flow tests, is presented in Fig. 6. The gas flow system provides a metered flow of argon at pressures up to 680 atm and flow rates up to 7.55 liter/sec (STP) by means of a diaphragm compressor. The discharge pressure of the compressor and the argon flow rate are controlled by the bypass valve and the flow control valve shown in Fig. 6. The back-pressure valve, in the exhaust duct just upstream of the flowmeter, is used to control the model chamber pressure. All plumbing and system components, except the submersible pump, are designed for an operating pressure of at least 680 atm. The plumbing was interconnected using Imperial-Eastman Braze-Seal fittings which resulted in very few leaks, even during initial hydrostatic tests. The submersible pump in the pressure vessel, which is at the system pressure, provides the water-coolant flow for the system. The flow is controlled by means of the bypass valve and the flow control valve shown in Fig. 6.

The pressure in the water flow system must be maintained approximately equal to the pressure in the vortex chamber to reduce the force on the walls of low-pressure components of the test model --- such as the fused silica tube, the end walls, and the thru-flow ducts. Each of these components was designed to withstand a minimum differential pressure of 20 atm. Maintaining this low differential pressure is accomplished automatically by pressurizing the complete water system using an accumulator, the gas side of which senses model chamber pressure (see Fig. 6). A sketch of the accumulator is shown in Fig. 7.

Several safety devices have been incorporated in the test facility. An interlock is provided on the door from the personnel area to the area containing the high-pressure components. This interlock shuts down the compressor and shuts off the argon flow to the model, should the door be opened with the system under pressure. Another safety device is provided to protect the components in the model from a reduction in the cooling water pressure. In the event of leakage from the water system, the accumulator will maintain constant pressure until the piston (see Fig. 7) bottoms out in the accumulator. A position sensor is located on the accumulator to detect the piston location as it approaches the end of its travel (within the last 1.3 cm of piston travel). The sensor operates a switch which shuts down the compressor, shuts off the argon flow and also opens a valve in the thru-flow exhaust line to vent the chamber pressure. Another interlock prevents the water pump from being run longer than about 15 sec with no water in the system. With no water in the system, the water pump current is considerably decreased (9 A, no load vs 21 A, full load), causing a cut-out relay in the pump ammeter to shut it down.

The high-pressure components and equipment are shown installed in the test area in Fig. 8. The test area is located near the 1.2-MW rf induction heater. The three cinder block walls of the test area are covered with steel plate (approximately 0.32-cm thick) as a safety precaution. The wall separating the test area and the personnel area is approximately 0.64-cm-thick steel boiler plate (see Figs. 8(a) and 8(b)). Figure 8(a) shows the front of the control panel including the cabinet housing the electrical controls for all components, including the interlock control circuits and ammeters for the compressor and water pump. The left side of the panel contains the gas (argon) system controls. Figure 8(b) shows the rear of the control panel and cabinet in relation to the model test table. A boiler plate shield for the rear of the control panel was removed prior to the photograph being taken. Two viewing stations consisting of a 2.5-cm-thick lucite shield bolted over slots cut in the boiler-plate wall are visible. The model has steel plate located above, below and on three sides as a safety precaution in the event of an accident.

The diaphragm compressor is shown installed near the model in Fig. 8(c); the accumulator and pressure vessel containing the submersible pump are shown in Fig. 8(d). The compressor is a standard Pressure Products, Inc. Model 3047 with

a calibrated maximum output of 6.85 liter/sec (STP) at 680-atm discharge pressure, or 7.55 liter/sec (STP) at 510-atm discharge pressure (performance in both cases with 170-atm suction pressure). The calibration curves supplied by the compressor manufacturer are shown in Fig. 9(a). The argon flow rate is plotted vs suction pressure for three discharge pressures.

The submersible pump is a standard 10-cm-diam, 5-hp, 24-stage submersible pump and motor --- Tait Model B50C424. It provided a maximum water flow rate of approximately 29 gal/min at a head of 13 atm when installed in the system described above but with a straight tube in place of the model. The manufacturer's performance curve is shown in Fig. 9(b); the pump output is plotted vs discharge pressure. The pressure vessel is identical to the accumulator (Fig. 7) except that it is longer and has no piston. A standard Conax Corp. high-pressure thermocouple feed-through was used as a high-pressure water seal for the three power leads to the submersible pump.

The design of this test facility is suitable for future growth. Its proximity to the 1.2-MW rf induction heater assures its usefulness in 500-atm rf-heated plasma tests. Also, space has been provided for incorporation of an additional compressor and water pump should these be required in future rf tests.

Test Procedures

Hydrostatic Tests

Hydrostatic tests of the fiberglass filament-wound pressure vessel were conducted to verify that the burst pressure of the pressure vessel was greater than the operating pressure by an adequate factor of safety. It was also especially necessary to verify that the pressure vessel had an adequate fatigue strength since normal testing procedure usually involves many pressurization cycles.

Each of the four filament-wound pressure vessels fabricated was hydrostatically tested. Details of the geometry and test results for each pressure vessel can be found in Table I. An approximate measurement of the axial strain on two of the filament-wound pressure vessels was obtained during the hydrostatic tests by visual readings at 500 atm using a steel tape measure. The configuration tested was similar to that shown in Fig. 2 in that the retainer flanges and sealing liner used in the subsequent cold-flow tests were employed. However, for the hydrostatic tests, the end walls consisted of solid plugs, and the fused silica tube was not installed. The first filament-wound tube fabricated failed at 270-atm pressure. It was subsequently determined that this was due to weakened areas of the pressure vessel wall caused by fiber dislocation which occurred when the forming sleeves were installed. Modifications to the forming sleeves (see Fig. 5) and retainer flanges

(see Fig. 2), in which the i.d. was increased, resulted in less compression and dislocation of the wet fibers during forming. A second filament-wound pressure vessel was then fabricated. This pressure vessel was hydrostatically tested and failed at 680-atm pressure. Although a burst pressure of 680 atm is adequate for these tests, it was considered desirable to determine the specific cause of the failure. In this case the failure was traced to a stress concentration which is present at the interface of the retainer flanges and the filament-wound pressure vessel when the pressure vessel is expanded due to the internal pressure. To correct this problem the taper at the ends of the retainer flanges (see Fig. 2) was increased slightly. As insurance, the third filament-wound pressure vessel fabricated was hydrostatically tested to only 640 atm in the proof test.

In order to determine the fatigue limits of these filament-wound pressure vessels, the third pressure vessel was continuously cycled from 0 to a pressure of 540 atm, following the proof test. On the 62nd cycle, a crack in the wall developed. However, this failure was not catastrophic in that no pressure was lost. Although the number of cycles was low by ordinary standards, it was decided that the pressure vessels demonstrated adequate reliability necessary to proceed with the gas tests. A fourth filament-wound pressure vessel, identical to the third pressure vessel, was then fabricated. This pressure vessel was also proof tested to 620 atm hydrostatically to verify its integrity. It was then used in the cold-flow tests described below. The end walls shown in Fig. 2 were used for this hydrostatic test, thus providing a proof test of these end walls.

Prior to its use in any cold-flow gas test, the facility itself was hydrostatically tested to 800-atm pressure. This was accomplished prior to the installation of the submersible pump in the pressure vessel shown in Fig. 8(d), as a precaution to prevent any possible damage to the pump. During this test, several leaks and inferior connections in the plumbing were discovered and repaired. During preliminary testing, a straight pipe was substituted for the model and a flowmeter temporarily installed in the water flow system. The water pump was then flow tested resulting in a measured flow rate of 29 gal/min with a discharge pressure of 13 atm. Also at this time, the diaphragm compressor hydraulic system relief valve was set at 780 atm per the manufacturer's instructions.

Cold-Flow Tests

After all hydrostatic tests had been completed, cold-flow tests with argon were initiated. When the cold-flow model was first installed in the system it was found that there was no water flow through the system. This problem was found to be caused by the silicone rubber sealing liner which blocked the water flow annulus in the model. This was caused by air trapped between the sealing liner and the filament-wound pressure vessel during installation. It was found that it was impossible to assemble the model without trapping air using the planned

3-mm wall thickness fused silica tube (see Fig. 2). This problem was corrected by employing a 2-mm-wall pyrex tube which was readily available. The use of a tube with only a 2-mm wall thickness resulted in much less trapped air and an increased gap in the water-coolant annular passage which was not blocked by the sealing liner. With the pyrex tube installed in the model a measured water flow rate of 22 gal/min at a pump discharge pressure of 19 atm was obtained with the chamber pressure at 1 atm. The flowmeter installed in the water system for this measurement was then removed for higher pressure tests. These water-coolant flow data points are shown compared to the manufacturer's calibration curve in Fig. 9(b). Before the model was installed the complete water system was evacuated to 710 mm Hg vacuum, and the system filled with water, assuring that there was virtually no air in the system. The model water passages were then filled with water and final connections made with a small amount of water flowing.

The cold-flow tests of the model at 500 atm were conducted as follows. With the compressor bypass valve open, the compressor was started. The argon inlet valve was then opened, equalizing the compressor discharge pressure and the suction pressure (see Fig. 6). A constant flow rate of argon injected into the model vortex chamber was set by opening the back-pressure valve and adjusting the flow control valve. The compressor discharge pressure was set by partially closing the compressor bypass valve. The model chamber pressure and argon flow rate were then adjusted using the flow control valve and the back-pressure valve.

When the model chamber pressure was at a steady-state condition of 500 atm, the water pump was started. After the water pump was started, the water system bypass valve was fully closed, resulting in all of the water flow passing through the model annular passage. It was necessary to delay starting the water pump until 500-atm chamber pressure was reached since the water temperature rose rapidly during pump operation. The manufacturer's recommended water temperature limit for the water pump is approximately 60°C which allowed a run time in this system of approximately 10 min. This will not be a problem in future tests since a heat exchanger will be installed in the water system. At the end of the test the water pump and compressor were shut off and the chamber pressure vented using the back-pressure valve. Minor problems were encountered during these preliminary tests, such as water leaks past the pyrex tube O-ring seals into the vortex chamber and the ejecting of the submersible pump electrical wires out through the Conax fitting. The difficulty with the pump wires was solved by the addition of a hose clamp on the wires inside the submersible pump pressure vessel.

DISCUSSION OF TEST RESULTS

Hydrostatic Tests

The hydrostatic tests verified the design and fabrication of the model and test equipment. They also proved the integrity of the filament-wound pressure vessel during reliability tests and proof tests. The results of the hydrostatic tests of the pressure vessels are detailed in Table I. The strain measurements accomplished during hydrostatic testing resulted in an approximate modulus of elasticity in the axial direction of 2.0 to 2.2×10^{10} N/m² which is numerically about the same as that shown in the results of strain measurements during FY 1971 (see Ref. 8). These data demonstrate the advantage of alternating the axial and hoop fiber layers, since the same strain was measured using a pressure vessel which had fewer axial fiber layers and approximately the same axial stress as the FY 1971 pressure vessels (see Table I).

Cold-Flow Tests

Steady-state cold-flow tests at 500 atm, simulating the configuration and pressure environment of the Nuclear Furnace in-reactor geometry, were accomplished. Details of the data from these tests are presented in Table II and Fig. 9. An argon vortex flow rate of 3.35 liter/sec (STP) and a cooling-water flow rate of 26 gal/min were established while the model chamber pressure was maintained at 504 atm. Although the model was designed for eventual heated tests in the 1.2-MW rf induction heater, there was no heat input to the model in any of the present tests.

During the first cold-flow test shown in Table II, a chamber pressure of 450 atm was attained with the water pump not running. At this point in the test water leakage was noted from a bleed valve at the accumulator and from an O-ring seal at a pressure tap disconnect point. This resulted in fracture of the pyrex tube. During the second test, leakage of water past the pyrex tube O-ring seals caused icing of the back-pressure valve resulting in substantial fluctuations in the chamber pressure and argon flow rate. However, the pyrex tube was replaced and the third test resulted in the steady-state conditions shown in Table II. Although the test could have been continued indefinitely, the 500-atm chamber pressure was held for approximately 15 min. During the second and third tests shown in Table II the submersible pump was operated for approximately 10 min. The maximum chamber pressure allowed in any of the cold-flow tests was 510 atm. During venting of the system following these tests, a maximum chamber pressure drop rate of approximately 7 atm/sec was used resulting in no discernible damage to the pyrex tube or low-pressure components. This indicates that the frequency response between the water system and the argon gas system is reasonably well damped.

The results of the cold-flow tests at 500 atm indicate that, with the addition of heat exchangers and piping to the 1.2-MW rf induction heater, it is possible to attempt rf-heated plasma tests at pressures up to 500 atm in a future program. However, it is recommended that, prior to rf tests, additional cold-flow testing be accomplished. These tests should include venting tests to determine the maximum allowable chamber pressure drop rate without damaging the low-pressure components of the model. From these pressure rate data, a damping coefficient for this system would then be calculated. End-wall vortex pressure measurements should also be obtained using the pressure taps provided in the end walls. From these data, an indication of the properties of the isothermal vortex at 500 atm would be obtained. All of this information would be of value during subsequent rf-heated plasma tests up to 500 atm.

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LIST OF SYMBOLS

E_a	Fiberglass filament-wound pressure vessel axial modulus of elasticity, N/m^2
P_d	Water pump or diaphragm compressor discharge pressure, atm
P_s	Compressor suction pressure, atm
W_a	Compressor output, liter/sec (STP)
W_w	Water pump output, gal/min

TABLE I
SUMMARY OF FIBERGLASS FILAMENT-WOUND
PRESSURE VESSEL CONFIGURATIONS TESTED

Tube	Number of Fiber Layers		Wall Thickness, (c) cm		Hydrostatically Proof-Tested to (atm)	No. of Cycles to 400 atm or Greater	Calculated Modulus of Elasticity, E_d -N/m ²	Result of Tests
	Axial	Hoop	At Ends	At Center				
1	10 ^(a)	16	0.32	0.32	270	0	Data Not Taken	Failed: wall split.
2	10 ^(a)	21-28 ^(b)	0.40	0.50	680	6	2.2 x 10 ¹⁰	Failed: wall split.
3	10 ^(a)	21-28 ^(b)	0.40	0.50	640	62 ^(d)	2.02 x 10 ¹⁰	Outer fiber layers cracked at 545 atm; no leakage.
4	10 ^(a)	21-28 ^(b)	0.40	0.50	620	7	Data Not Taken	Satisfactory operation in cold-flow tests at 500 atm with argon and water.

(a) Layers alternated with first 10 hoop layers; see Figs. 5(a) and 5(b).

(b) See Fig. 5(c) for hoop layer arrangement.

(c) All pressure vessels were same length (28.14 cm), same i.d. (7.76 cm), and same maximum o.d. (at ends --- 9.68 cm).

(d) All cycles to 545 atm or greater.

TABLE II

SUMMARY OF TEST CONDITIONS FOR
COLD-FLOW TESTS AT 500 ATM

Test No.	Preliminary Tests	1	2	3
<u>Model Flow Conditions</u>				
Maximum Chamber Pressure, atm	1	450	510	504
Argon Flow Rate, liter/sec (STP)	0	0.5	2.6	3.35
Water Flow Rate, gal/min	21.6(a)	0	27.5(b)	26(b)
Water Temperature, °C	--	--	38	27
<u>Compressor Operating Conditions</u>				
Discharge Pressure, atm	780(c)	610	690	630
Suction Pressure, atm	100(c)	143	97	121
Argon Flow Rate, liter/sec (STP)	0(c)	5.9(b)	3.7(b)	4.8(b)
Discharge Temperature, °C	--	--	80	128
Current, A (d)	18(c)	20-22	22	22
<u>Water Pump Operating Conditions</u>				
Discharge Pressure, atm	19.4(a) 13(e)	450	524	519
Suction Pressure, atm	1(a,e)	450	510	504
Differential Pressure, atm	18.4(a) 12(e)	0	13.6	15
Water Flow Rate, gal/min	21.6(a) 29(e)	0	27.5(b)	26(b)
Current, A(d)	19.8(a) 19.6(e) 9.3(f)	0	21.0	21.0

(a) Model and flowmeter in water system.

(b) Assumed from calibration curves.

(c) During compressor hydraulic relief valve set-up.

(d) Compressor (7.5 hp) and water pump (5 hp) used 230 V ac, 3 phase motors.

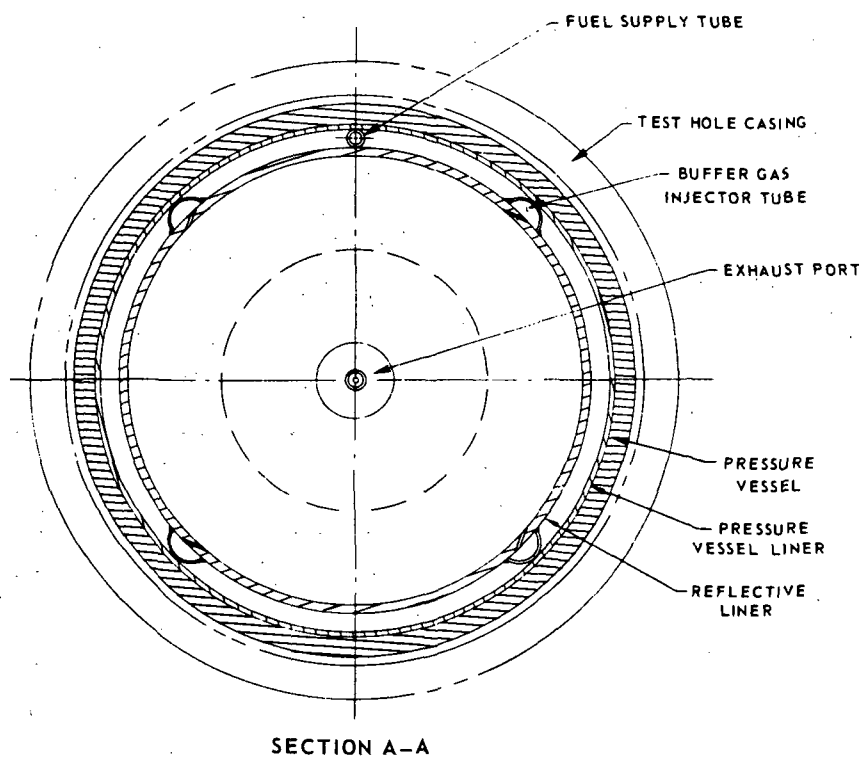
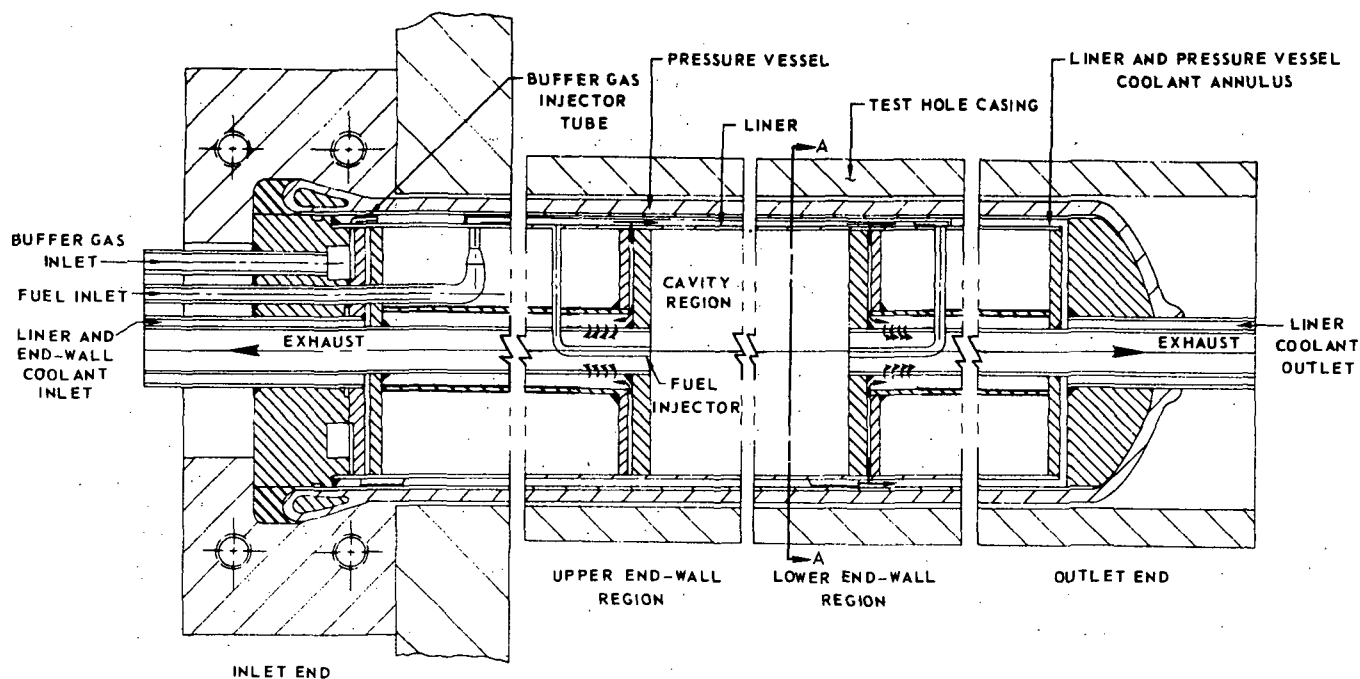
(e) Straight pipe substituted for model.

(f) Unloaded, no water in system.

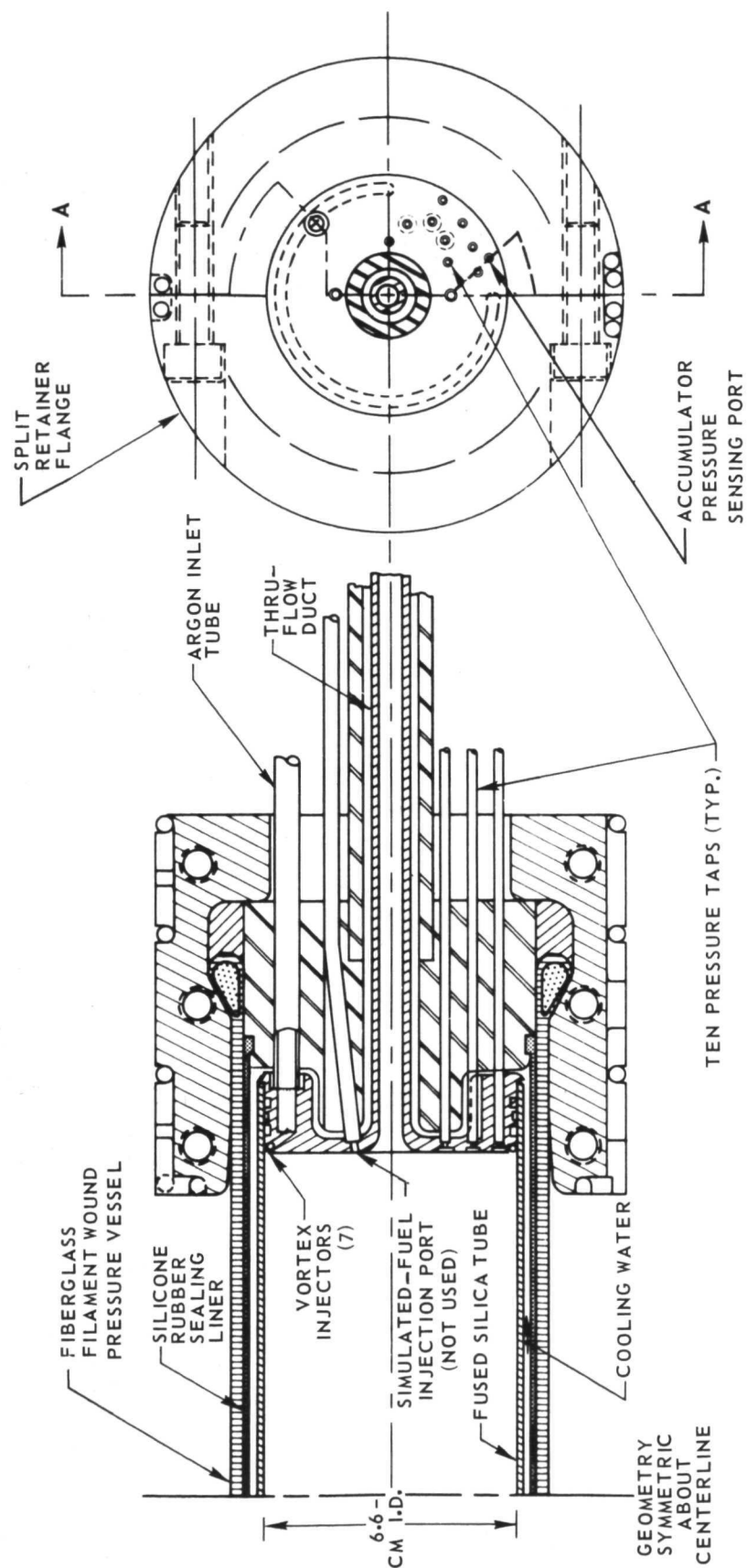
PRELIMINARY LAYOUT OF TEST CELL FOR NUCLEAR FURNACE IN-REACTOR TEST

ID OF TEST HOLE CASING - 8.4 CM

DIMENSIONS OF CYLINDRICAL CAVITY REGION: 6.6-CM I.D. X 17.8-CM LONG



SKETCH OF 500 ATM TEST CONFIGURATION



PHOTOGRAPH SHOWING INSTALLATION OF 500 - ATM TEST MODEL

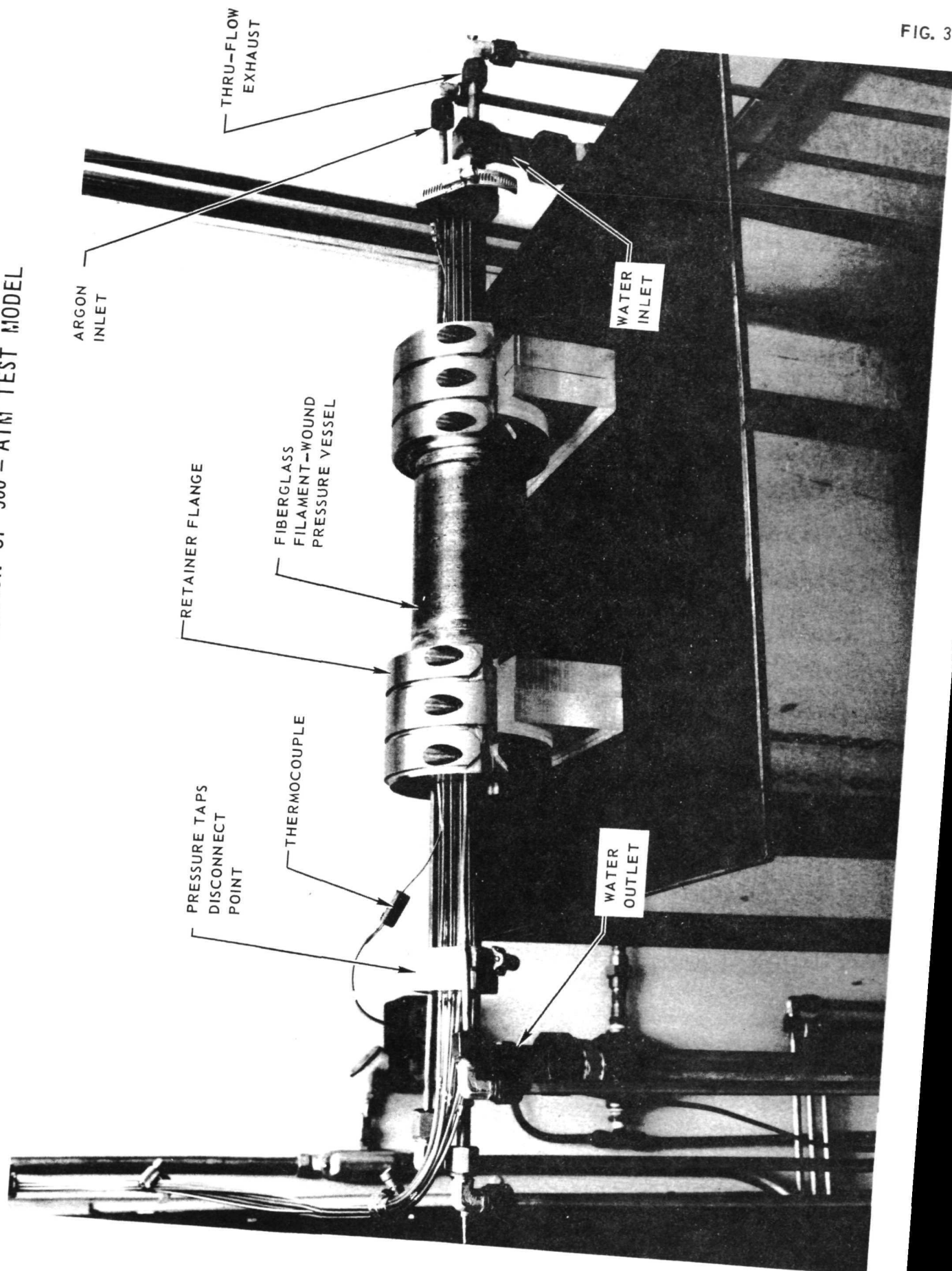
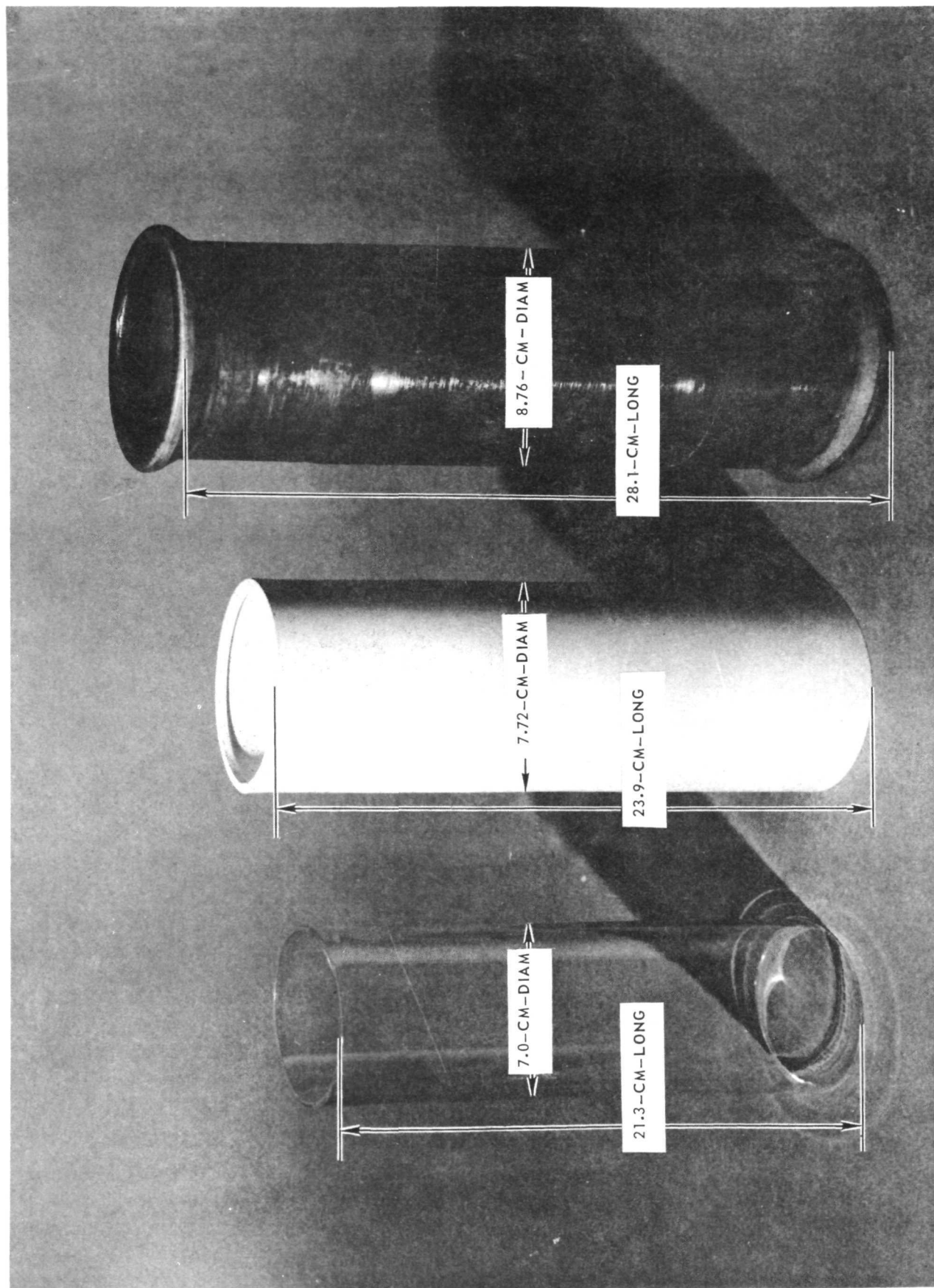


FIG. 3

PHOTOGRAPH OF 500-ATM COLD-FLOW TEST COMPONENTS



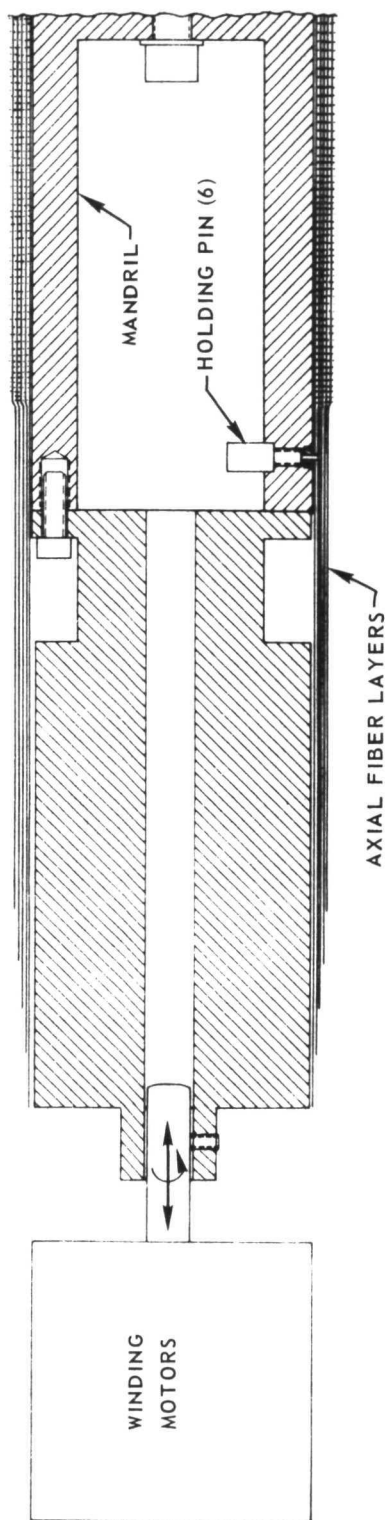
PYREX TUBE
2-MM WALL

SILICONE RUBBER
SEALING LINER

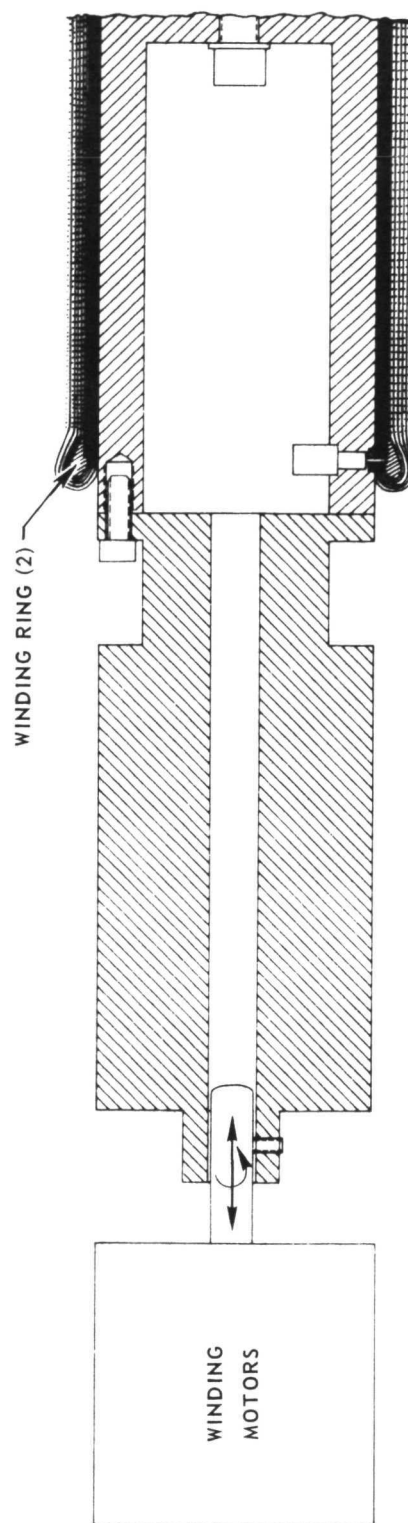
FIBERGLASS FILAMENT-WOUND
PRESSURE VESSEL

SKETCHES OF FILAMENT WINDING FIXTURE AND ILLUSTRATION OF WINDING TECHNIQUE

(a) WINDING CONFIGURATION - FIRST TEN LAYERS



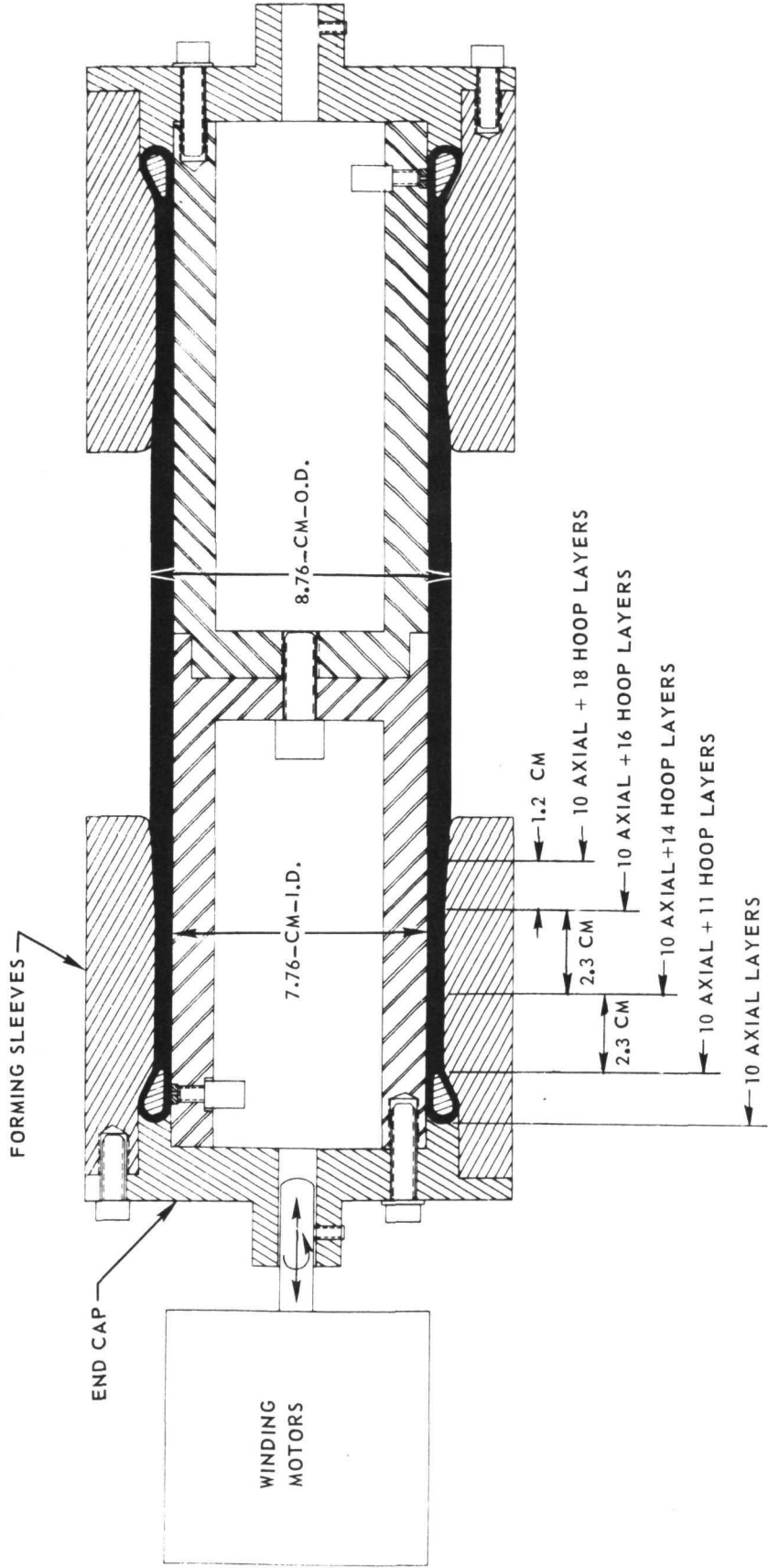
(b) WINDING CONFIGURATION WITH RINGS INSTALLED - SECOND TEN LAYERS



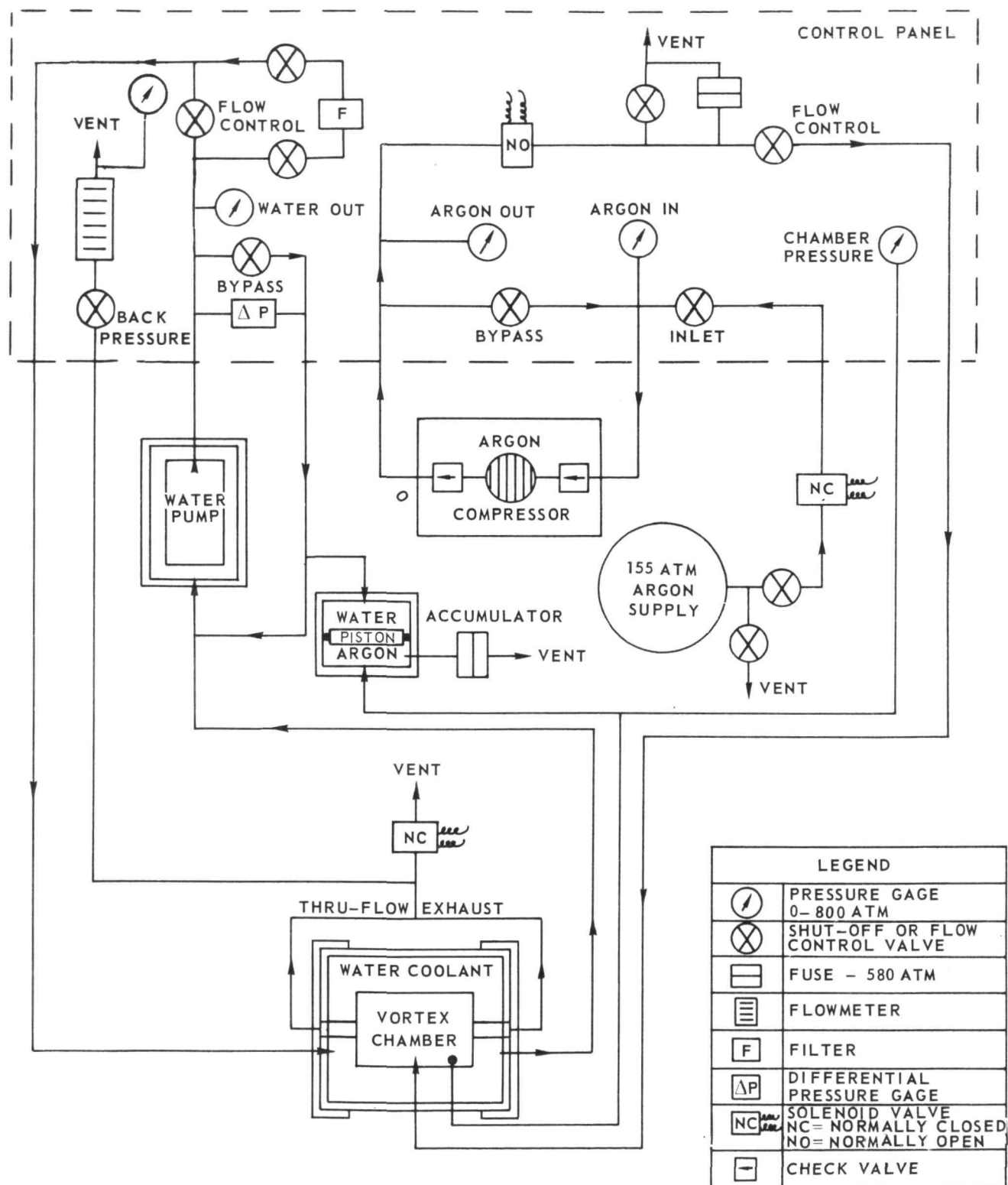
(CONTINUED)

SKETCHES OF FILAMENT WINDING FIXTURE
AND ILLUSTRATION OF WINDING TECHNIQUE (CONTINUED)

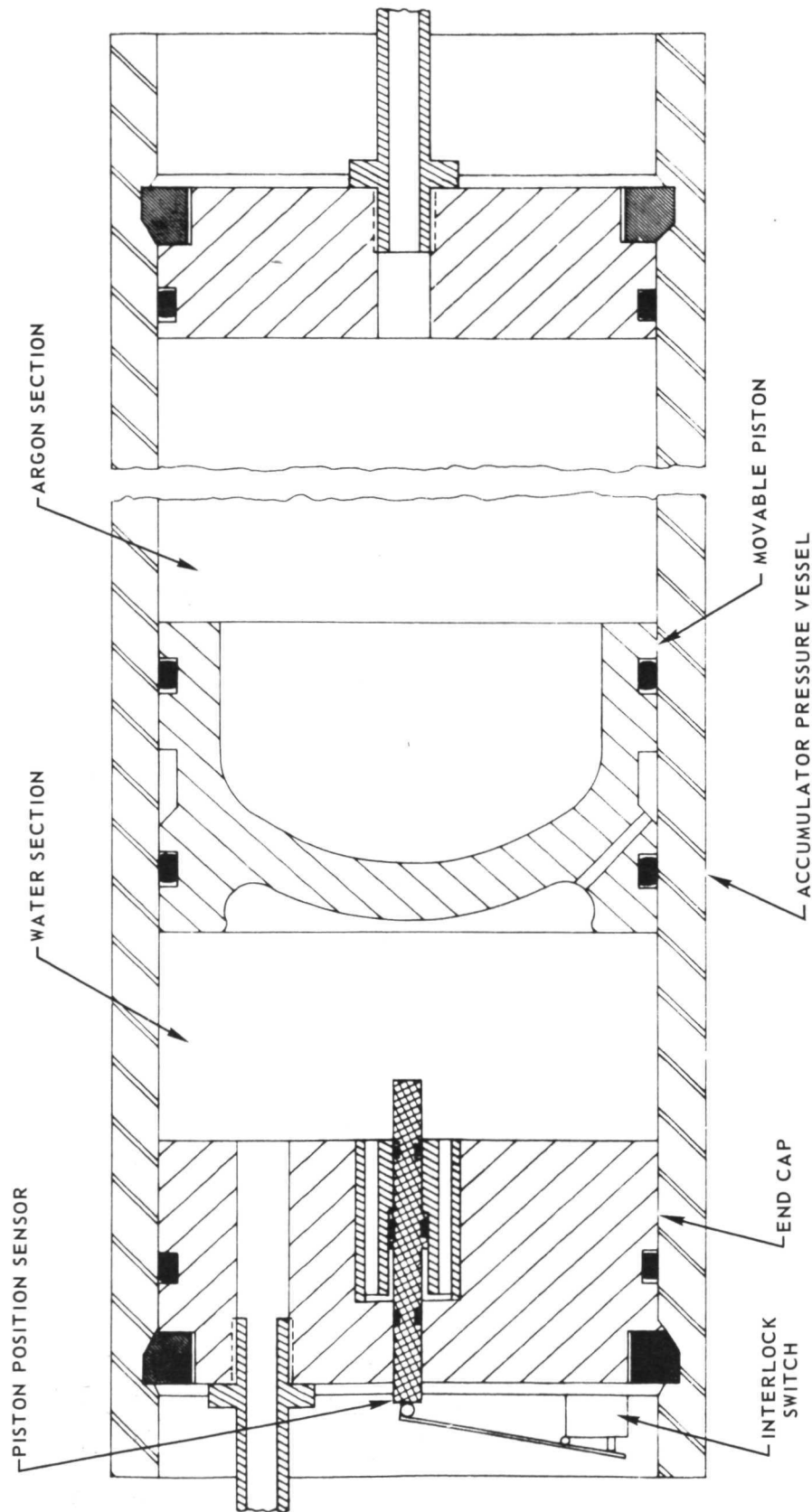
(c) FINAL WINDING AND FORMING CONFIGURATION



SCHEMATIC OF 500-ATM GAS AND WATER FLOW SYSTEM FOR COLD-FLOW TESTS



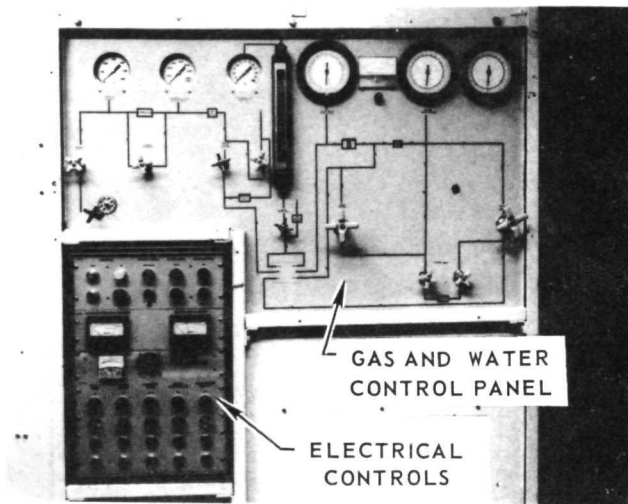
SKETCH SHOWING ACCUMULATOR WITH PISTON POSITION SENSOR INSTALLED



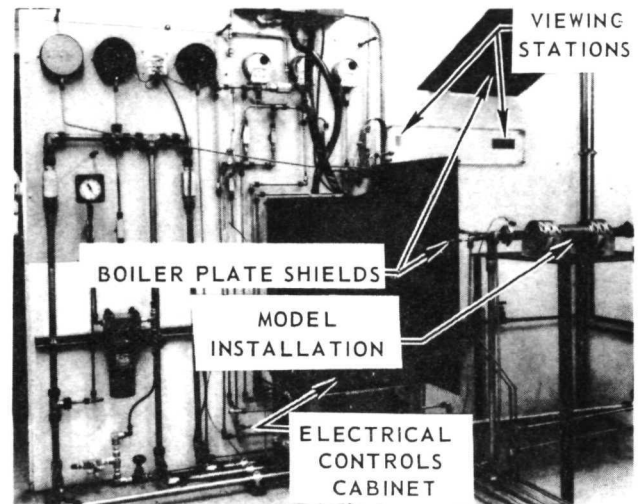
PHOTOGRAPHS SHOWING INSTALLATION OF MAJOR COMPONENTS IN 500 ATM TEST AREA

SEE FIG. 6 FOR SCHEMATIC OF FLOW SYSTEM

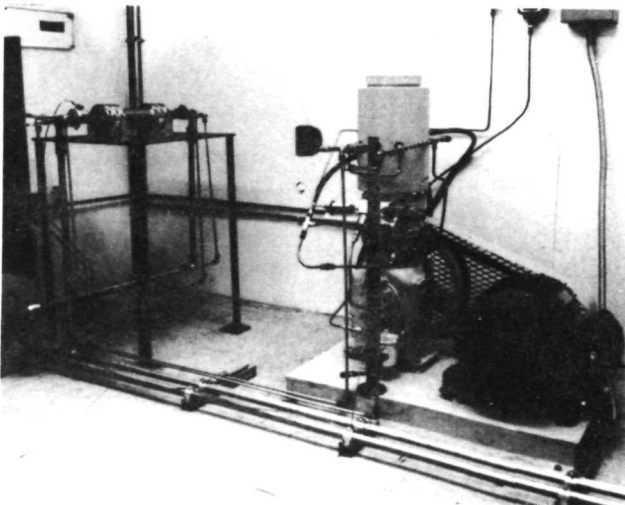
a) CONTROL PANEL FRONT VIEW



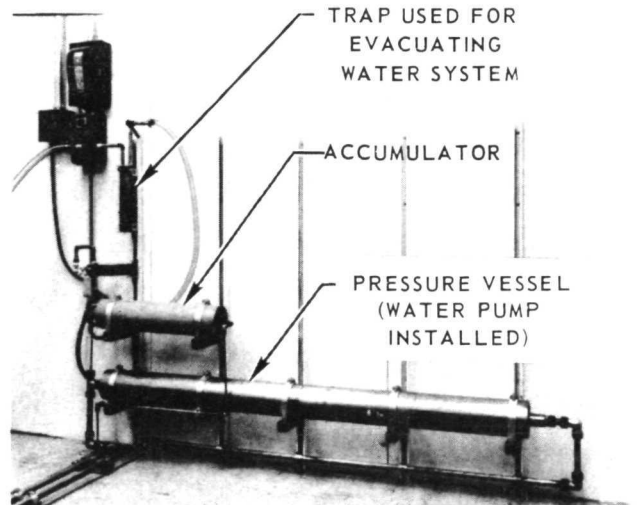
b) CONTROL PANEL REAR VIEW



c) COMPRESSOR INSTALLATION

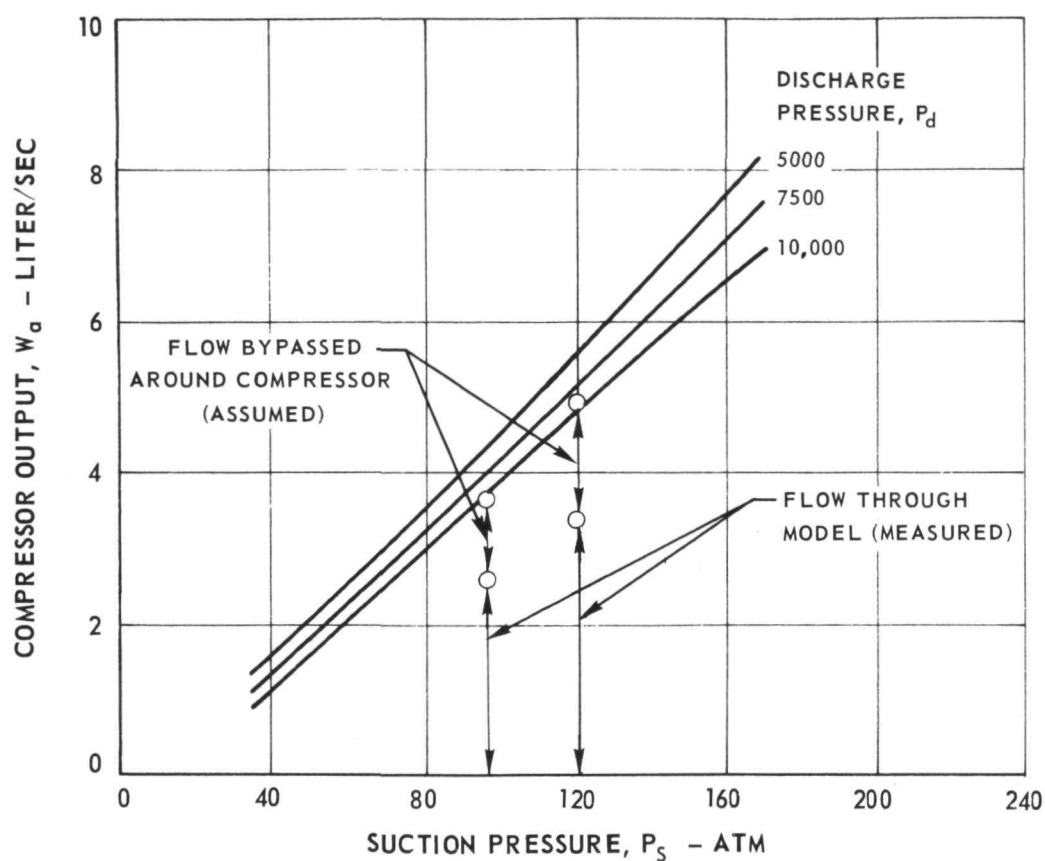


d) ACCUMULATOR AND PRESSURE VESSEL
INSTALLATION

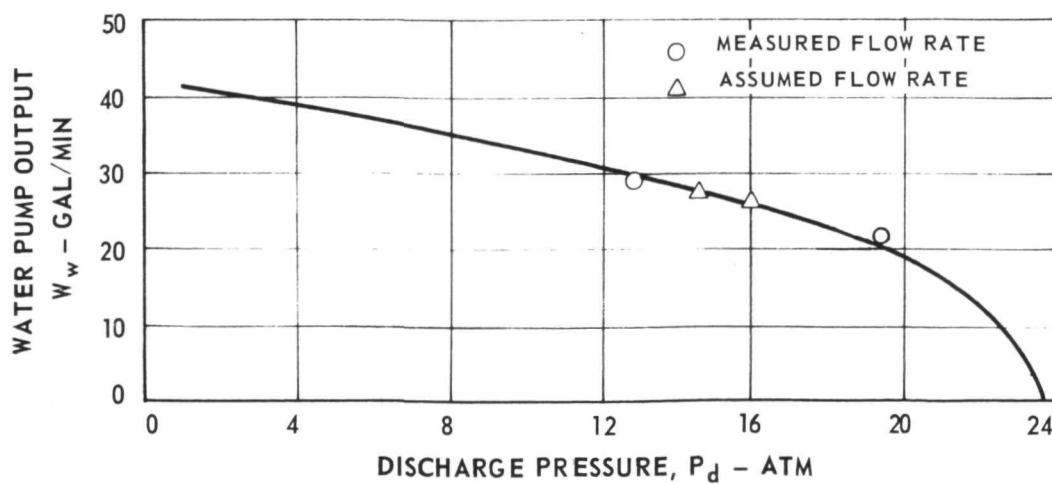


CALIBRATION DATA AND OPERATING POINTS FOR WATER PUMP AND ARGON COMPRESSOR USED IN 500 ATM TEST

(a) ARGON COMPRESSOR



(b) WATER PUMP



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