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PROOF-OF-CONCEPT ADVANCED NONPYROTECHNIC SMOKE GENERATOR* COMPONENT TEST REPORT

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ABSTRACT

One decade ago, Sandia National Laboratories designed and developed a nonpyrotechnic smoke generator capable of producing large quantities of low corrosivity, low toxicity chemical smoke to be used as a visual obscurant in access delay applications. Utilizing the same chemistry, a proof-of-concept advanced smoke generator is presently being tested. The testing is being conducted to evaluate two new concepts providing unique capabilities. Hemispherical stainless steel bladders are installed in spherically shaped chemical storage reservoirs. This provides positive displacement of the chemicals and permits orientation insensitive operation. Also, a specially designed nozzle/valve is being evaluated as a means of providing a multiple initiation capability. Cyclic operation could be accomplished via time delay circuitry, sensor input, or on demand from the control console. These new capabilities provide distinct advantages. Some advantages may be longer obscuration times, optimal volume obscuration, easier facility sizing, no organic seals in contact with the stored chemicals, and elimination of the requirement to use ultrahigh purity nitrogen as a propellant.

INTRODUCTION

Smokes, used as visual obscurants, provide effective access delay when used in conjunction with sight-related tasks. In the late 1970's Sandia identified an access delay application that required the use of nonpyrotechnic smoke. There are several chemical reactions that are capable of producing large volumes of nonpyrotechnic smoke. The system Sandia developed involves spraying titanium tetrachloride and ammonium hydroxide into the air through separate atomizing nozzles. In the air the two components react to form titanium dioxide, ammonium chloride, and water according to the following reaction:

$$TiCl_4 + 4NH_4OH \rightarrow TiO_2 + 4NH_4Cl + 2H_2O$$

When the two reactants are sprayed in the proper ratios, the smoke produced is chemically neutral minimizing corrosivity. The smoke is very white and can effectively obscure vision beyond 3 or 4 inches. The smoke has a high expansion ratio, approximately 50,000:1, that is the ratio of deployed volume to stored volume. Under test conditions the smoke products were determined not to be discernibly toxic to animals. Projections are that short term exposures to cold smoke products should have no pathological effects on humans. Cleanup of the settled smoke residue is easily accomplished by sweeping with a dust settling compound and collecting into a plastic bag. Disposal is not an environmental problem because the products are not toxic or hazardous.

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During the early 1980's, Sandia was very active developing smoke generator hardware. Many concepts were investigated and prototypes assembled and tested. Figure 1 shows the production unit of the Sandia developed nonpyrotechnic smoke generator. The generator was frequently referred to as the WADS (Weapon Access Delay System) generator. The unit contains one liter of $TiCl_4$, three liters of NH_4OH, and will effectively smoke 225 cubic meters (8000 cubic feet). One liter of ultra-high purity nitrogen at 1500 psi is the propellant for expelling the chemicals. The generators are available in two models; a booster which dispenses the chemicals in about 1.5 minutes for rapid obscurance, and a sustainer that dispenses the same quantity of chemicals in approximately 9.5 minutes. The smoke generator has an estimated reliability in excess of 99%. The technology has been transferred to industry, and the generators are commercially available.

The smoke generator suited the application for which it was designed; however, several shortcomings were identified that, if corrected, would result in a more versatile design. The explosive initiating valve is susceptible to premature initiation resulting from induced voltage pulses, i.e., lightning strikes. This was remedied by adding lightning protection circuitry to the control electronics and improving the grounding. The generators are also one-shot units that can not be turned off after initiation. The units are orientation sensitive, thus the applications and mounting configurations are restricted. There are numerous organic seals in the generator and they are of various compounds to be compatible with the chemicals. Organic seals can deteriorate with time and become potential leak sites. Because of the reactivity of the titanium tetrachloride, ultrahigh purity nitrogen MUST be used as the propellant. This can be a disadvantage in the field. The generators are only available in one size and therefore, depending on the volume to be smoked, the smoke concentration may be less than optimum.

THE ADVANCED SMOKE GENERATOR CONCEPT

Using the shortcomings as design requirements, we conceptualized an Advanced Smoke Generator. We proposed substituting an electromechanical initiation valve that requires a longer duration signal to activate for the presently used explosive valve that requires only a voltage pulse. This would eliminate the potential for inadvertent firings from spurious induced signals. We visualized a special nozzle/valve combination that would permit multiple initiations. The cyclic operation could be accomplished through time-delay circuitry, sensor input, or upon command from the control console. Cyclic operation also permits easier sizing to the facility, optimum obscuration, more efficient use of the chemicals, and possibly longer obscuration times. We investigated using hemispherical stainless steel bladders inside spherical stainless steel chemical storage reservoirs. This concept provides positive displacement of the chemicals for orientation-insensitive operation. It also eliminates the requirement for ultra-high purity nitrogen as a propellant because the propellant does not come in contact with the chemicals. It reduces significantly the use of organic seals by eliminating the gang valve assembly. Figure 2 shows a schematic diagram of the proof-of-concept Advanced Smoke Generator. The remainder of this report presents information on the design, fabrication, and testing of both individual components and the prototype Advanced Smoke Generator.

ELECTROMECHANICAL INITIATION VALVE

The electromechanical valve is a motor-driven device developed to eliminate premature initiation of the smoke generator resulting from spurious lightning strikes or other induced transients or surges. Sandia defined the specifications for the valve and provided them to various valve manufacturers. A competative bid purchase order was placed with Futurecraft Inc., City of Industry, CA, for two valves and numerous expendable replacement parts.

Figure 3 shows the Futurecraft valve. The valve is an electromechanical assembly incorporating a small, rare earth permanent magnet motor and a gear reducer. Upon receipt of a 28 volt dc signal, an internal mechanism activates and permits the 1500 psi gas to flow. The signal must be applied for the duration of 1.5 seconds. The valve was designed for a 20 year life. One of the primary requirements was for a leak rate not exceeding 10^{-9} cc/sec helium at STP across the valve inlet port that is continuously exposed to the 1500 psi gas. This was accomplished by making a one-piece pressure inlet/burst disc.

It is estimated that the valve would cost approximately $2500 each in production quantities of 250. In addition to being used in the Advanced Smoke Generator, the valve can also be retrofitted into the WADS generator.

SPECIAL NOZZLE/VALVE ASSEMBLY

A special design nozzle/valve to accomplish the multiple initiation capability of the Advanced Smoke Generator also was needed. Sandia provided the concept and operating specifications to several nozzle manufacturers. Delavan-Delta Inc., a Division of Colt Industries, in Lexington, TN, was awarded the contract. Four prototype nozzle/valves were built and tested, two with the proper flow capacity for spraying titanium tetrachloride, and two for the ammonium hydroxide.

The concept was to have a nozzle that exhibited the proper flow characteristics that would be capable of stopping the flow at the orifice. This is to prevent any moisture from reacting with the titanium tetrachloride and clogging the orifice. An orifice clean-out feature, a pin that protrudes through the orifice when the flow is turned off, is incorporated into the design as an additional measure to reduce the likelihood of clogging. The ratio of the flow rates of the two chemicals, using water as the fluid, must be between 1.99 and 2.13

(ratio of NH_4OH to $TiCl_4$) to produce neutral ph smoke products, thus minimizing corrosion problems. The nozzle is normally open, the fail-safe position assures smoke generation at the time of initiation, and requires air to close. The pneumatic pressure required to close the nozzle/valve is nominally 75 psi greater than the hydraulic pressure of the chemicals it is sealing. The nozzle/valve is constructed from 300 series stainless steel for compatibility with the chemicals.

Figure 4 shows the Delavan nozzle/valve. The nozzles produce an 80° hollow cone spray pattern. At 350 psi operating pressure the $TiCl_4$ nozzle has a flow rate of water of 0.22 gpm and a Sauter mean droplet diameter of 143 microns (micrometers). The NH_4OH nozzle has a flow rate of 0.46 gpm and a Sauter mean droplet diameter of 149 micons. The ratio of the flow rates is 2.09. Both nozzles are equipped with the clean-out pin on the end of the sealing rod. This feature was only required on the $TiCl_4$ nozzle. The shut-off capability works well at the nominal 75 psi differential specified, at the lower limit of 50 psi, operation is marginal. Operation of the shut off capability at lower pressure differentials will require replacing the return springs with springs having a lower spring rate. We conducted nozzle tests to measure the effects of pressure on the flow rate, to evaluate the shut-off capability, and to visually compare the spray patterns of the Delavan nozzle with the presently used Spraying Systems nozzle. One of the Delavan nozzles would not seal properly even at 100 psi pressure differential. A postmortem disassembly and inspection of the nozzle showed a deep indentation on the sealing surface of the orifice disc. Attempts to remove the indentation by polishing proved futile so a new disc was ordered to replace the damaged one. Other than this one minor problem, the Delavan nozzle/valve performed as specified.

HEMISPHERICAL STAINLESS STEEL BLADDER CONCEPT

The use of bladders inside the chemical storage reservoirs provide a positive displacement of the chemicals and thus is a technique for providing orientation-insensitive operation. The reactivity of the chemicals used in the smoke generator dictate the use of stainless steel for fabrication of both the bladders and the reservoirs. The metal bladder technology was developed primarily in support of weapons programs. Significant research and development has been conducted in the design of hemispherical metal bladders. The bladders, also frequently called hemi-shells or inversion shells, were designed using bladder simulation software developed by the University of New Mexico under contract to Sandia.

The inversion dynamics are affected by the thickness of the bladder and the roll radius. In this design, the bladder inverts by rolling from one side of the vessel to the other, beginning at the equator. The design objectives are to minimize the pressure drop across the bladders and to attempt to match the inversion dynamics of the two bladders. The latter objective is required to maintain the flow rate ratio between 1.99 and 2.13.

Los Alamos National Laboratories (LANL) fabricated one lot of each of the two sizes required, one size for $TiCl_4$ and the other for NH_4OH. Figure 5 shows the two sizes of inversion shells fabricated. The bladders were formed from annealed type 304 stainless steel sheet by hydrostatically forming it over a mandrel. Preliminary testing was conducted to measure the inversion pressure as a function of volume displaced and to evaluate the effects of roll radius on the inversion dynamics. After the first series of preliminary tests, LANL fabricated a second lot of each of the two sizes required. We reduced the material thickness of both bladders. The second lot of bladders exhibited lower inversion pressures overall and a lower pressure difference between the two bladder sizes. The remainder of the second lot of shells would be evaluated further in the actual prototype test system, where they would be installed in spherical reservoirs.

PROOF-OF-CONCEPT PROTOTYPE

Figure 6 shows the proof-of-concept Advanced Smoke Generator System. The system is comprised of a one gallon gas cylinder pressurized to 1600 psi. The compressed gas can be any gas compatible with the stainless steel cylinder. The compressed gas provides the energy to invert the bladders consequently expelling the chemicals and to close the nozzle/valves. A gas regulator, Victor model SR41, reduces the gas pressure to approximately 450 psi. A pressure relief device set at 550 psi protects the components from overpressurization. Two spherical chemical reservoirs fabricated from 300 series stainless steel are flanged at the equator to facilitate bladder replacement for testing purposes. O-rings are used to seal between the vessel flanges and the bladder flange. Envisioned production units would be expendable, thin-wall welded assemblies. The vessel volumes are approximately 1.5 liters for the $TiCl_4$, and 4.5 liters for the NH_4OH. This is a 50% increase in capacity from the WADS generator. Two Omega model PX302-500GV pressure transducers measure the pressure at each of the nozzles, and two Omega model FTB-504-1CK-5VDC high accuracy flow meters measure their flow rates. Two, double channel Yokogawa strip chart recorders were used to document continuously the pressure and flow data.

Figure 7 shows the pressure drop across the bladders as a function of volume displaced (%). The data were calculated by subtracting the pressure measured at the nozzle from the constant regulated pressure applied to the bladders. The data show a higher deformation pressure for the larger 4.5 liter bladder when compared to the 1.5 liter bladder and the pressure differential between them is greater initially and decreases as the volume is displaced.

Figure 8 shows the continuous flow rates for each of the two components as a function of volume displaced. The data suggest that the differential pressure observed in Fig.7 produced insignificant effects on the flow rates. The ratio of the flow rates was between 1.96 and 2.01 for the duration of the test. While the 1.96 is below the allowable 1.99, the range is well within the acceptable limits thus indicating that the bladder concept is a viable alternative for expelling the chemicals. The nozzle can be modified to bring the flow ratio from 1.96 to 1.99.

CONCLUSIONS:

After analyzing the test data we arrived at the following conclusions:

1. An Electromechanical Initiation Valve can be fabricated that would eliminate the premature firing of a smoke generator resulting from lightning or other induced voltage pulses. The valve is designed to meet the 10^{-9} cc/sec helium at STP leak rate specified, and the valve could be retrofitted into the WADS generator if required.

2. We have demonstrated that a nozzle/valve device can be fabricated that will meet the smoke generator flow characteristics and can effectively shut-off and restart the fluid flow at the orifice to prevent contamination of the chemicals.

3. Stainless steel bladders can be fabricated that when installed in spherical chemical reservoirs and pressurized with a gas expel the chemicals regardless of vessel orientation. When the bladder/vessel assemblies are coupled to the proper nozzles, they provide flow characteristics suitable for use in a nonpyrotechnic smoke generator.

4. A proof-of-concept system assembled using the nozzle/valves and bladders demonstrated that a smoke generator could be built that would be orientation-insensitive, provide cyclic operation, reduce the use of organic seals, permit optimum obscuration, and possibly provide longer obscuration times. However, it must be understood that this was the proof-of-concept phase, and that significant additional development, testing, and evaluation would be required prior to production fabrication.

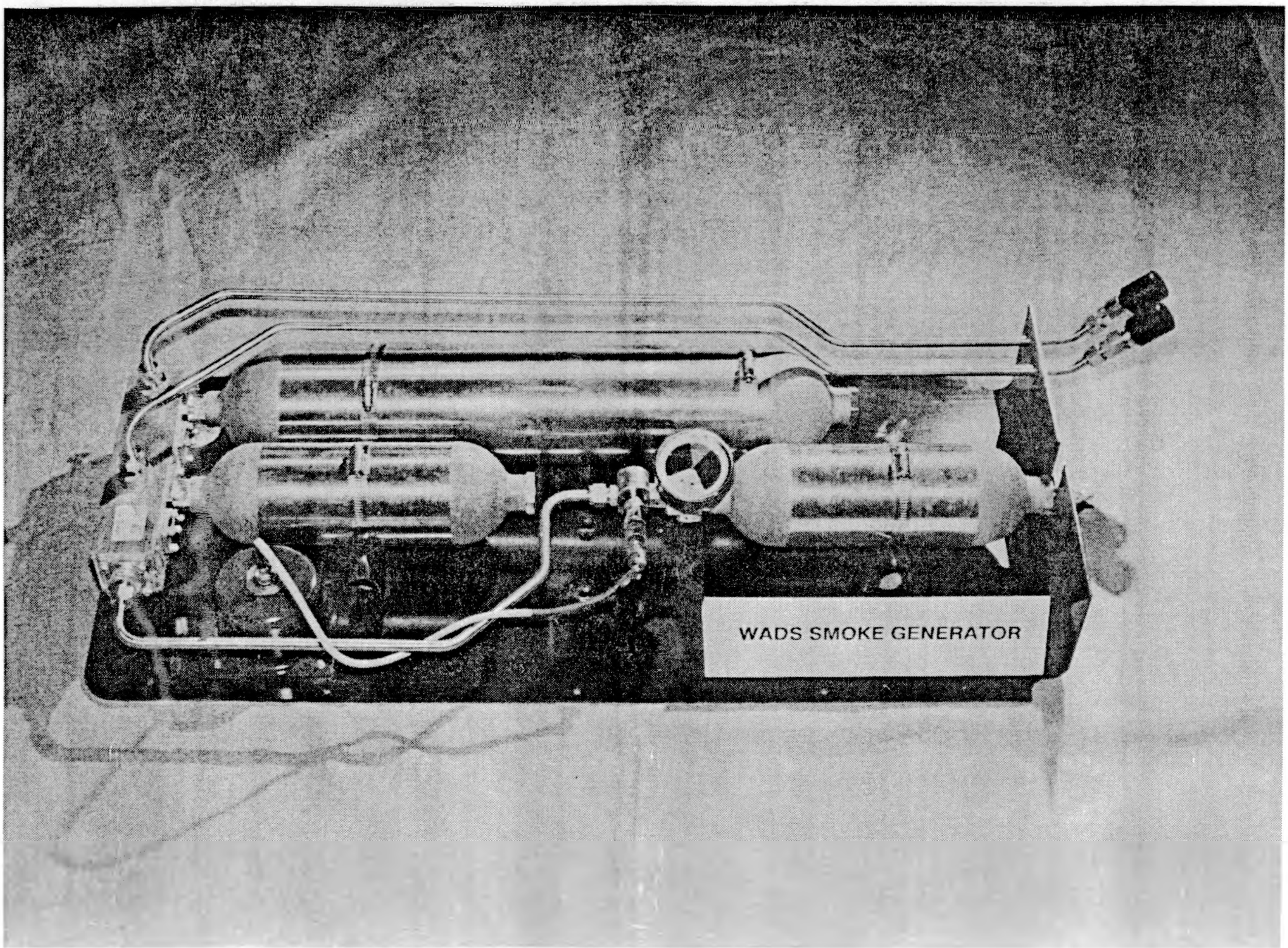


Fig. 1 Sandia-Developed Nonpyrotechnic Smoke Generator Production Unit

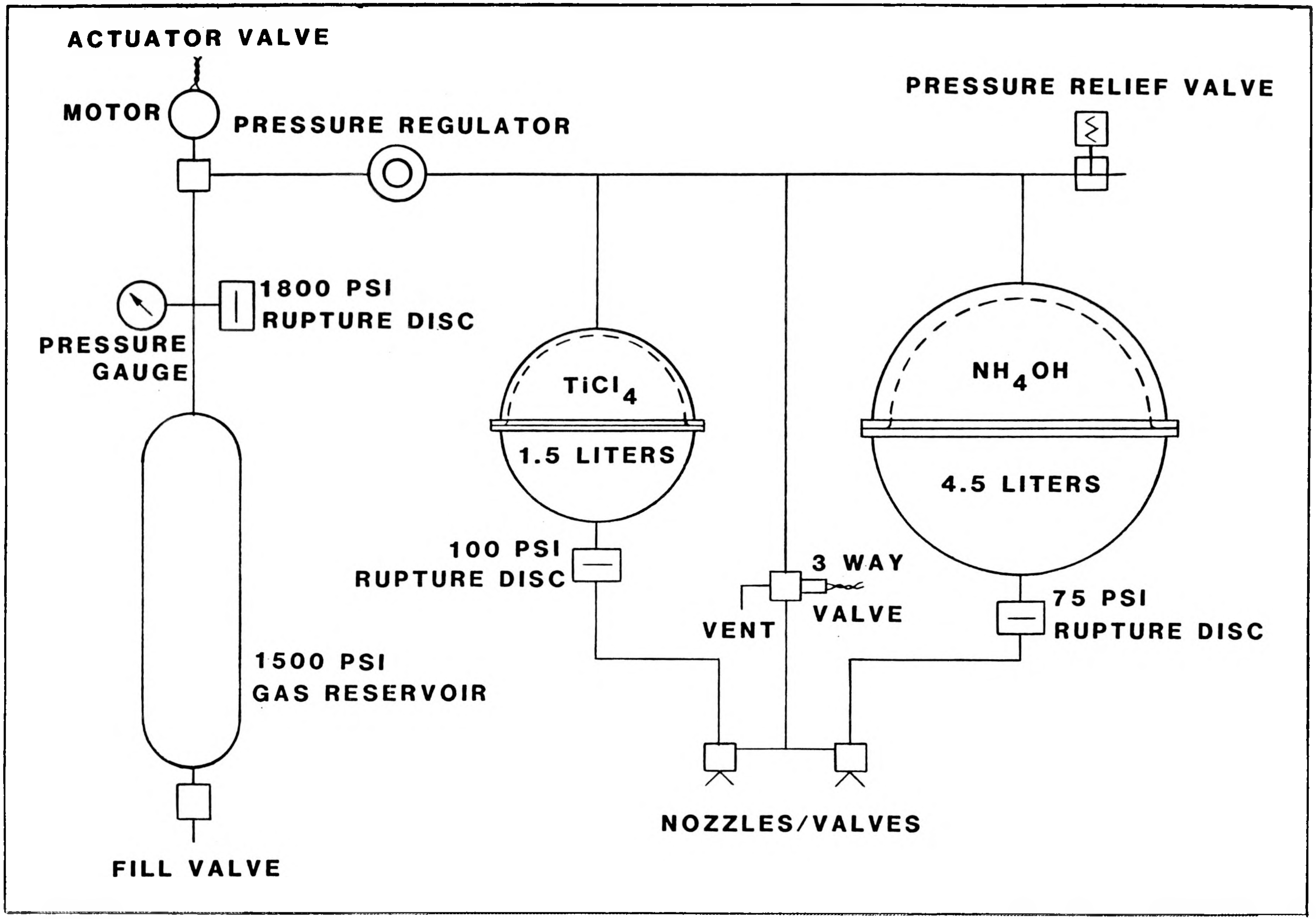


Fig. 2 **ADVANCED SMOKE GENERATOR SCHEMATIC**

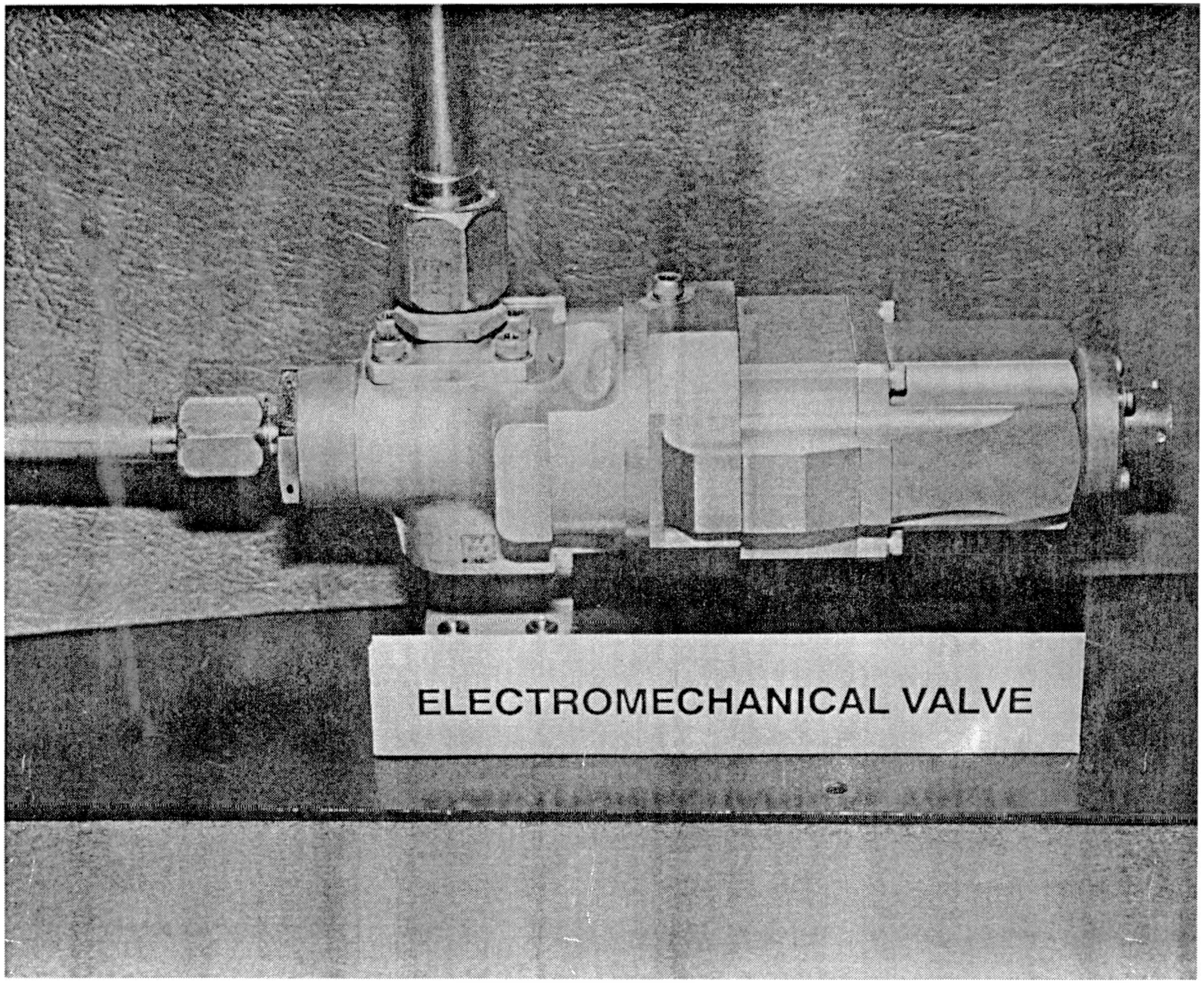


Fig. 3. Electromechanical Valve

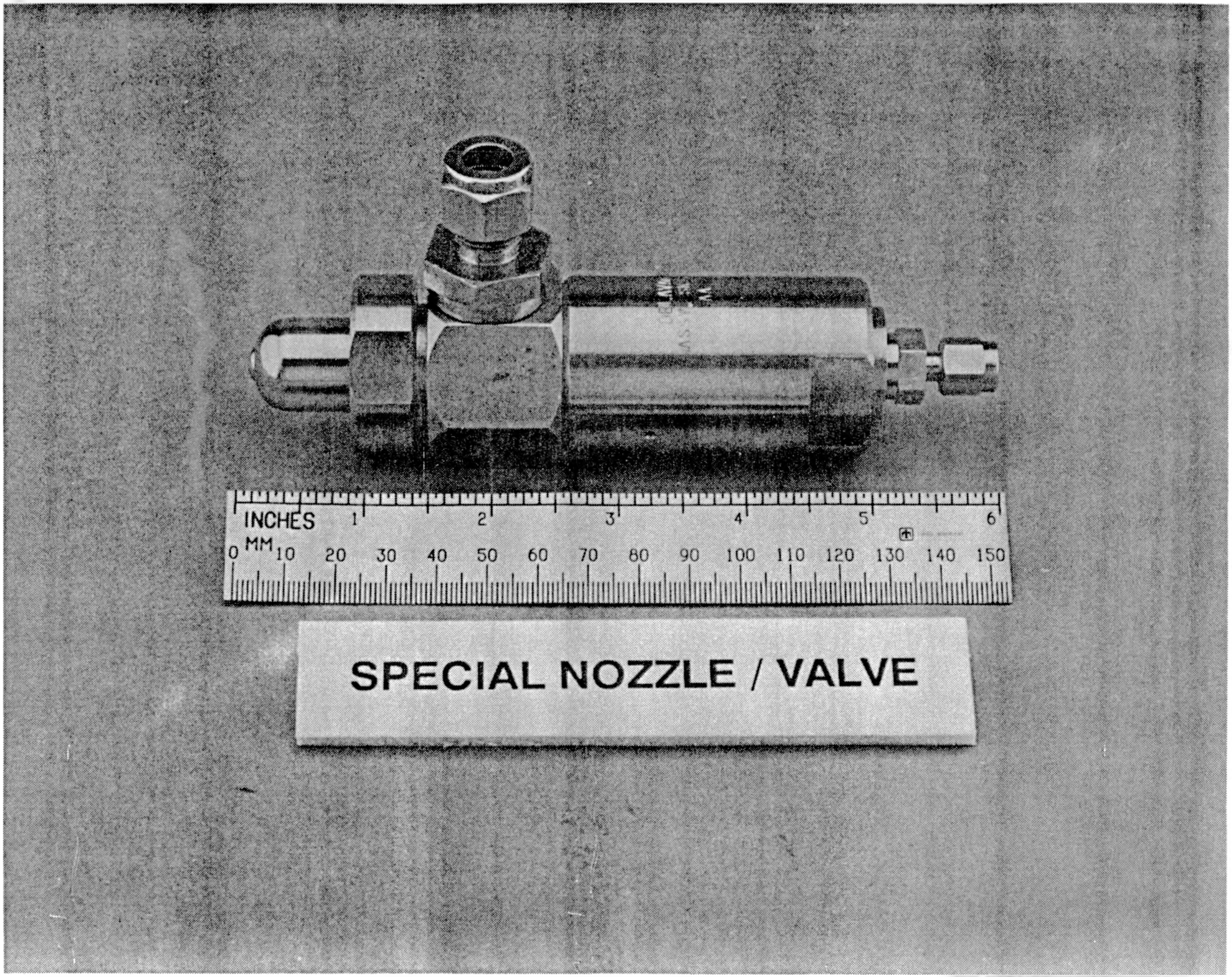


Fig. 4 Atomizing Nozzle with Shut-Off Capability

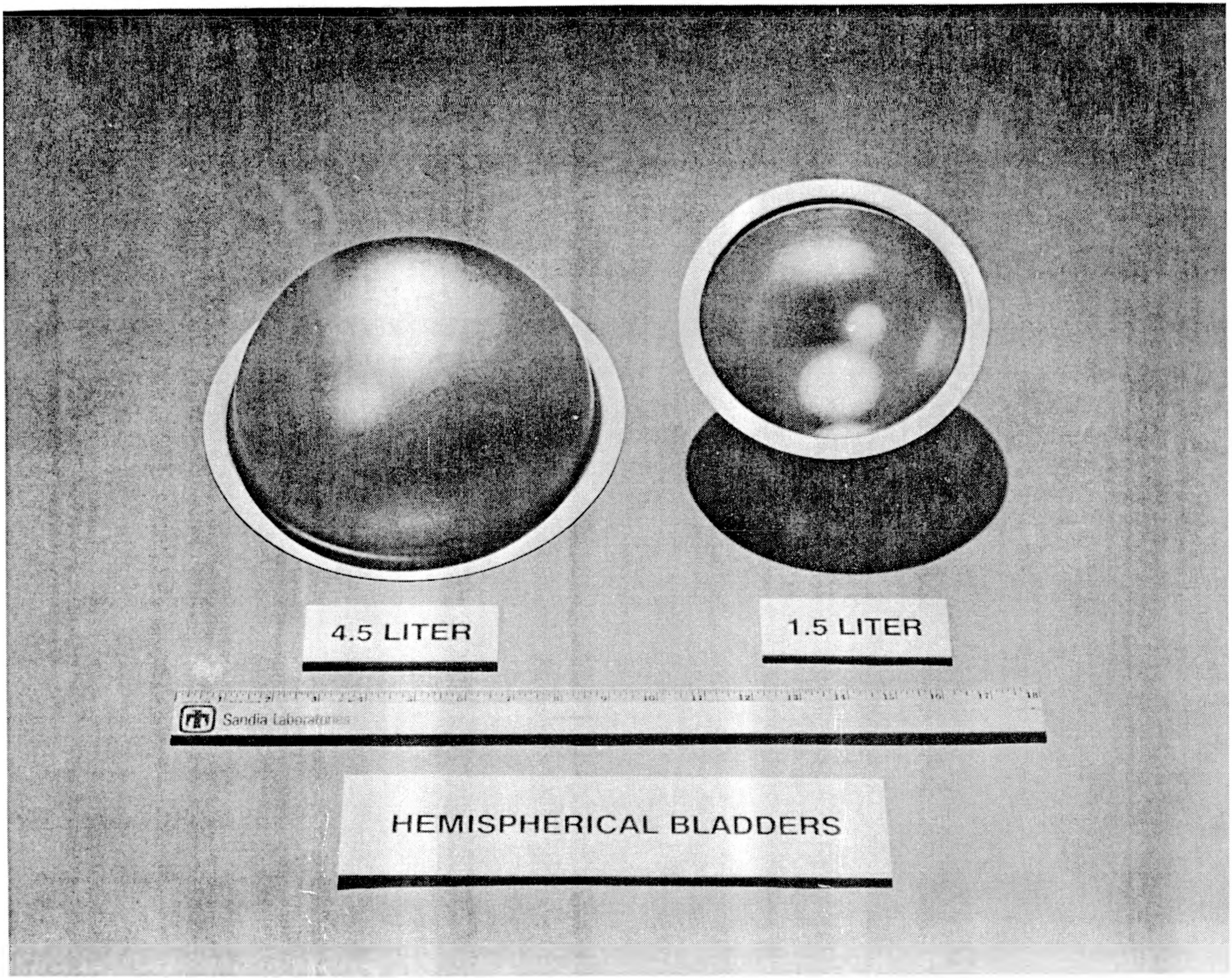


Fig. 5 Stainless Steel Bladders

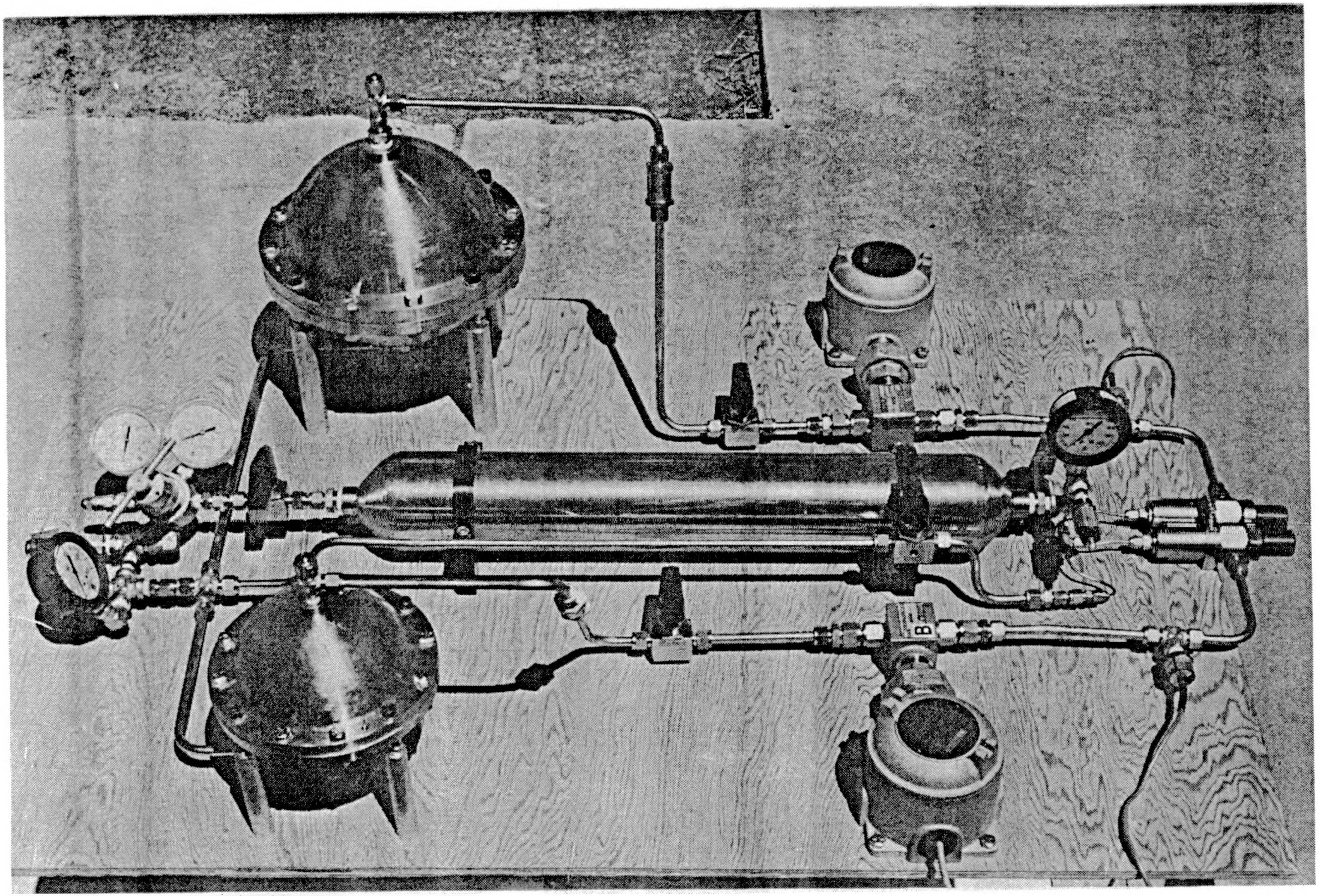
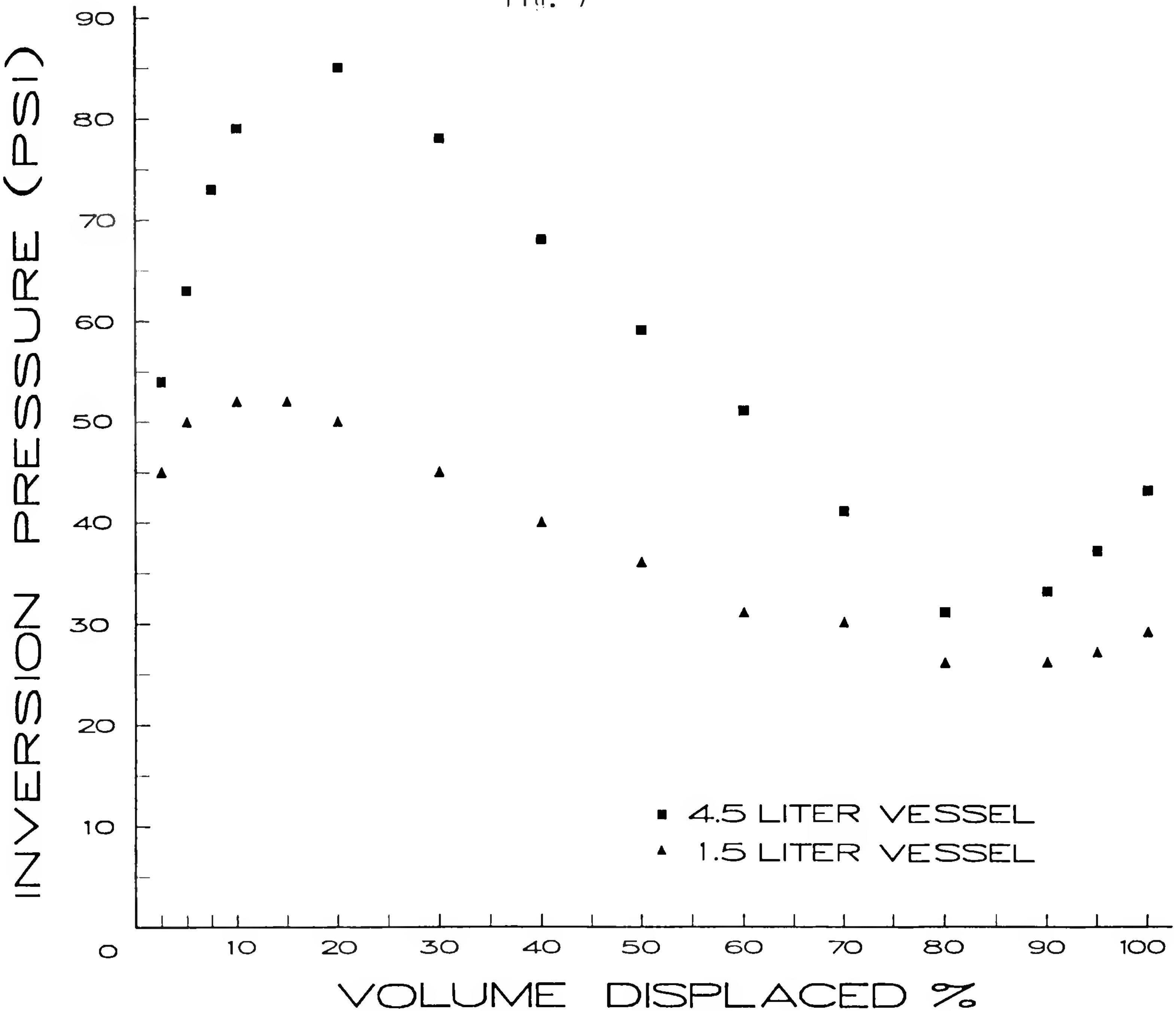


Fig. 6 Proof-of-Concept Advanced
Smoke Generator System

Fig. 7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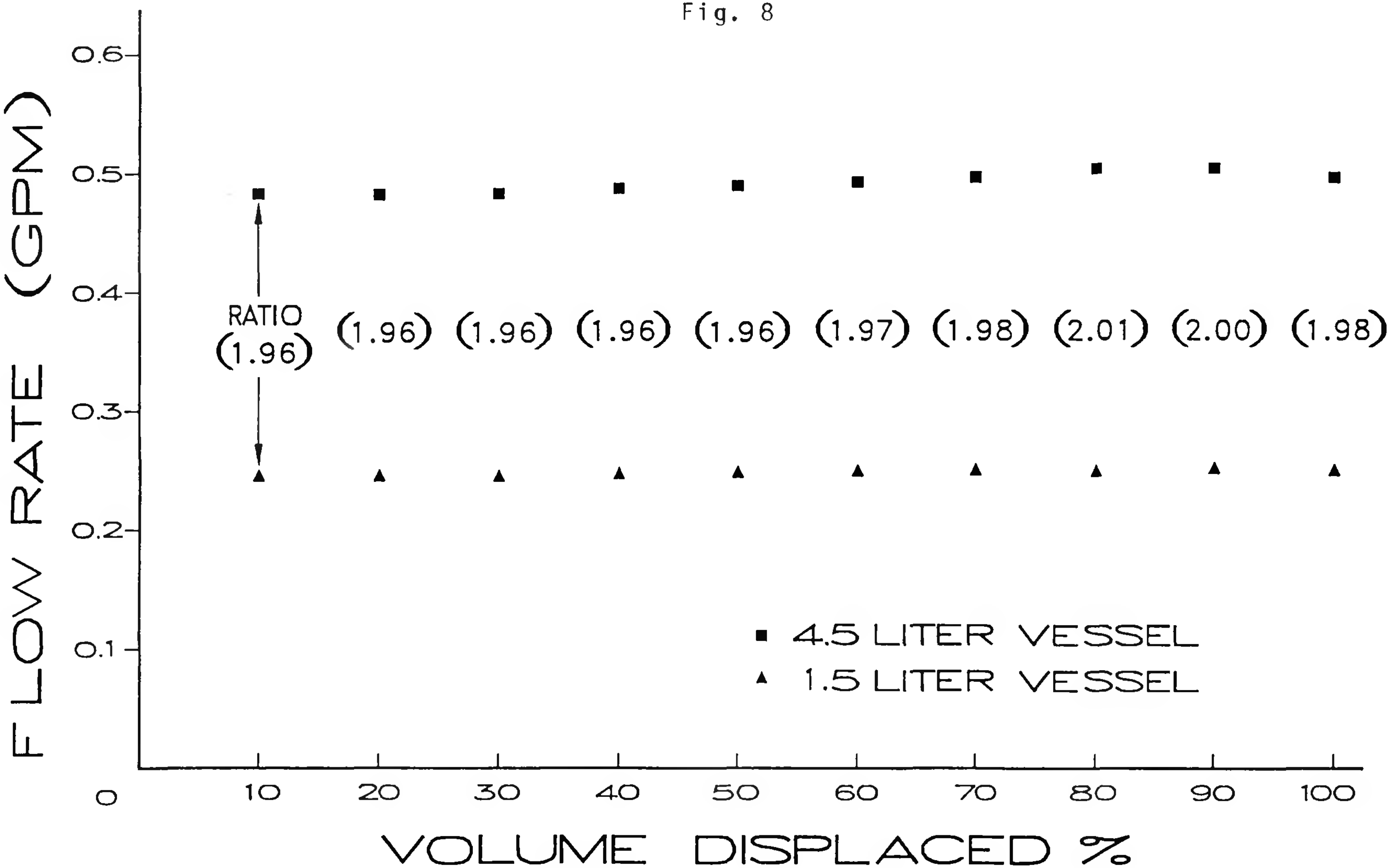
70
60
50
40
30
20
10
0
INVERSION PRESSURE (PSI)
10
20
30
40
50
60
70
80
90
100
VOLUME DISPLACED %
4.5 LITER VESSEL
1.5 LITER VESSEL

Fig. 8



0.6
0.5
0.4
0.3
0.2
0.1
FLOW RATE (GPM)
RATIO
(1.96)
(1.96)
(1.96)
(1.96)
(1.96)
(1.97)
(1.98)
(2.01)
(2.00)
(1.98)
4.5 LITER VESSEL
1.5 LITER VESSEL
0
10
20
30
40
50
60
70
80
90
100
VOLUME DISPLACED %