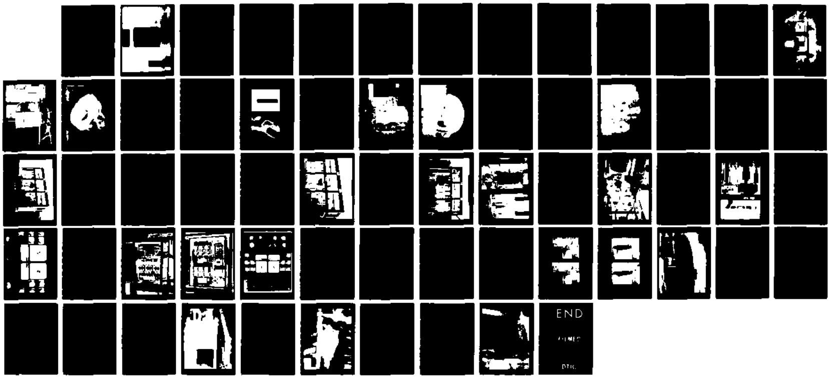
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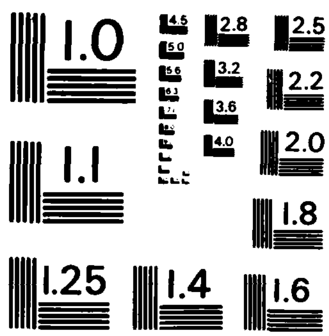

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

PROTOTYPE SALVAGE FOAMING SYSTEM

To

U.S. NAVY SUPERVISOR OF SALVAGE
WASHINGTON, D.C. 20362

November 4, 1985

FINAL REPORT

on

Contract No. N00014-84-C-0145

PROTOTYPE SALVAGE FOAMING SYSTEM

To

U.S. NAVY SUPERVISOR OF SALVAGE
WASHINGTON, D.C. 20362

November 4, 1985

by

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D.J. Hackman, and D.W. Caudy

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Columbus, Ohio 43201

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INTRODUCTION

Rigid polyurethane foam has been used in the past by the U.S. Navy to salvage sunken ships. This technique, which is known as foam-in-salvage, was used to raise the USS Frank Knox and Sidney E. Smith. Although other methods are available for providing buoyancy to refloat sunken ships, the density and strength of polyurethane foam, combined with its compact pre-blown form, make it a very advantageous method for ship salvage.

Unfortunately, state-of-the-art methods and equipment do not consistently produce good quality foam under water. In previous work for the Navy, Battelle investigated the state of the art in terms of both foaming machinery and foam chemical systems. Based on the results of those programs, Battelle has developed a prototype polyurethane foam machine for the Navy, so that materials and labor can be used with greater efficiency.

BACKGROUND

Polyurethane foam component chemicals can expand to as much as 30 times their original volume when combined. The foam has excellent rigidity and buoyancy; it can provide a buoyant force of 0.88 to 0.96 grams per cubic centimeter (55 to 60 lb/ft^3) in seawater. Foam has many advantages over other types of ship salvage such as compressed air or expandable polystyrene beads due to its compact pre-blown form, its ability to seal small openings and the fact that it does not shift position once it is in place.

Polyurethane foam is made by mixing MDI (polymeric diphenylmethane diisocyanate) and polyol together with a blowing agent such as freon, carbon dioxide, or nitrogen. This mixture expands, then hardens. The time for the entire process is determined by the chemical temperatures and the innate reaction time of the chemicals.

In 1980[(1)] and 1982[(2)], Battelle investigated developments in polyurethane foam formulations and emplacement equipment, to determine what technology could be adapted for underwater foaming. These studies concluded that the combination of high pressure impingement mixing technology (HPIM) and a fast reacting foam formulation would produce an improved foam under water.

SUMMARY

The first phase of this program began in March 1984 by upgrading a previously developed laboratory model foam machine for use at sea. Upgrading consisted of providing a larger motor, barrel handling equipment,

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(1) Myers, J.R., Hackman, D.J., Nikodem, L.F., "Evaluation of New Urethanes and Urethane Dispensing Equipment for Improving Foam-in-Salvage Plan", Battelle, 1980.

(2) Myers, J.R., Hackman, D.J., Nikodem, L.F., "Development of Rigid Polyurethane Foam Components for Foam-in-Salvage Applications", Battelle, 1982.

longer hoses and several high pressure impingement mixing (HPIM) dispensing guns. Development and experimentation centered around the dispensing gun design. This upgraded laboratory model was tested in-house and then taken to Tracor Marine's Port Everglades, Florida facility for at-sea testing. The dual purpose of these tests was to: prove that the impingement concept worked and collect necessary data for designing a full-scale prototype foaming system.

With the successful completion of Phase I in March 1985, Phases II and III were started. These two phases involved the development of a full-scale prototype foaming system based on the information gathered in Phase I and incorporating the most desirable features determined by the previous work. The full-scale prototype system features control and monitoring of chemical temperature, flow rate and pressure. Other features include chemical recirculation, automatic flushing and a weather-proof design. This research program also included a risk assessment of the foaming system which is covered in a separate report issued in July 1985. The issue of this report, a complete drawing package and an operation and maintenance manual in October 1985 completes the program.

CONCLUSIONS AND RECOMMENDATIONS

Based on the information and data gathered during the development of the laboratory model and full-scale prototype foaming machines, including the in-house and at-sea tests, the following conclusions are made:

- Making high quality foam underwater is feasible to depths of at least 100 feet. Foam densities of less than (10 pounds/cubic feet) can be obtained.
- The full-scale prototype foaming machine performs well and provides the high degree of control necessary or good foam making. The machine, with its automatic features, is safer to operate, requires less labor to operate and has less down time than previous models.

- In order to increase the efficient use of chemicals and prevent nozzle clogging, more development work is warranted in the gun and nozzle design. Future machines should use flow meters that are not affected by changes in chemical viscosity (temperature changes). The heater control system will require further investigation and possibly a re-design, to produce a more stable time/temperature profile.

Based on the above conclusions and bearing in mind the goals of the Navy's Supervisor of Salvage, the following recommendations are made:

- The Navy should continue with its long-term foam-in-salvage program. The basic concept of impingement mixing has been proven and requires only straightforward development efforts to further optimize and increase the efficiency and reliability of the process. Further development should focus on improved gun/nozzle design, better heater control and improved flow instrumentation.
- For large scale salvage operations, the foam chemical components should be supplied in large tanks rather than 55-gallon drums to reduce the size of the surface support crew and ensure continuous foaming operation.

RESEARCH/ENGINEERING ACTIVITY

The following sections describe the significant project activity and findings of this development program. The discussion is organized into three sections: the first two dealing with the design and fabrication of the two foaming machines (the upgraded lab model and the full-scale prototype) and the third dealing with the testing program. The risk assessment portion of this program is covered in a separate report issued in July 1985[1].

Upgraded Laboratory Model Foaming Machine

The laboratory model foaming machine was developed on an earlier program. It could deliver only about 7.6 liters per minute (2 gallons per minute) of foam chemical components from each pump due to the small motor and small diameter hoses. Furthermore, this laboratory model was not built to withstand the rigors of transportation and at-sea testing. However, before building a complete, full-scale foaming system (with heaters, automatic head flushing and precise controls), it was necessary to prove the feasibility of the impingement mixing system in actual seawater trials. It was also desirable to learn more about the system in terms of heat transfer in the hoses, continuous operation effects and human factors. For this reason the laboratory model foaming machine was upgraded and tested before the full-scale development was undertaken.

Pumping Module Design

Upgrading the pumping system consisted of installing an 11.2 kW (15 hp) electric motor that could drive the Vickers PVB-5 pumps closer to their full capacity of 19 Lpm (5 gpm) each, at the required pressures of 83 to 103 bar (1200 to 1500 psi). The foaming hardware was mounted on a heavy-duty platform truck which provided a strong but mobile base. The 220-volt, 3-phase motor was set up to be controlled by a 24-volt system. This arrangement would allow the 24-volt control switch to be transferred to the foaming gun (under diver control) if desired.

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(1) Vergara, R.D., "Risk Assessment of Foam-in-Salvage System", Battelle, 1985.

The upgraded foaming machine is shown in Figure 1, with the DOP (dioctyl-phthalate) tank on top of the motor. DOP is a plasticiser and was used to lubricate the pumps and to dilute any foam chemicals that leaked into the cases. Diluting the chemicals retards their tendency to harden. DOP was also used to flush this foaming machine at the end of the day. It should be noted that DOP is not a solvent but is a neutral agent. Thus, the two urethane chemicals must be kept separate, even in the presence of DOP. Once the urethane chemicals have mixed and have cured, there is no practical way to dissolve them.

Thirty-six meters (120 feet) of nylon-lined hydraulic hose was purchased for each of the high-pressure lines. The first 30 meters (100 feet) are 25 millimeter I.D. (1 inch) to reduce flow losses. The last 6 meters (20 feet) are 19 millimeter I.D. (3/4 inch) for easier handling. The foaming gun is attached to the end of the 19 millimeter (3/4 inch) section of hose. During the in-house tests, only the shorter, 19 millimeter I.D. (3/4 inch) hoses were used.

To eliminate the need for transfer pumps with this small machine, the foam was drawn directly from the 208 liter (55 gallon) drums by connecting them directly to the pumps with short sections of 25 millimeter I.D. (1 inch) hydraulic hose. The barrels were then inverted, using the barrel-handling devices shown in Figure 2. The barrels were vented with standpipes and the barrel outlets were raised higher than the pump inlets to keep feed pressure from dropping below 1 bar (0 psig).

Initial Foaming Gun Design

The foaming gun was designed to be as small and as simple as possible. The first gun designed is shown in Figure 3. The gun is made of stainless steel and consists of two O-ring ports for the hose connections and two impingement orifices on the other side. The orifices were originally 3 millimeters (.125 inch) in diameter and were designed to impinge at a 15-degree angle from the face of the gun. This offset angle, shown in Figure 4, was used to avoid the problems associated with orifices aimed directly at one another: if the pump

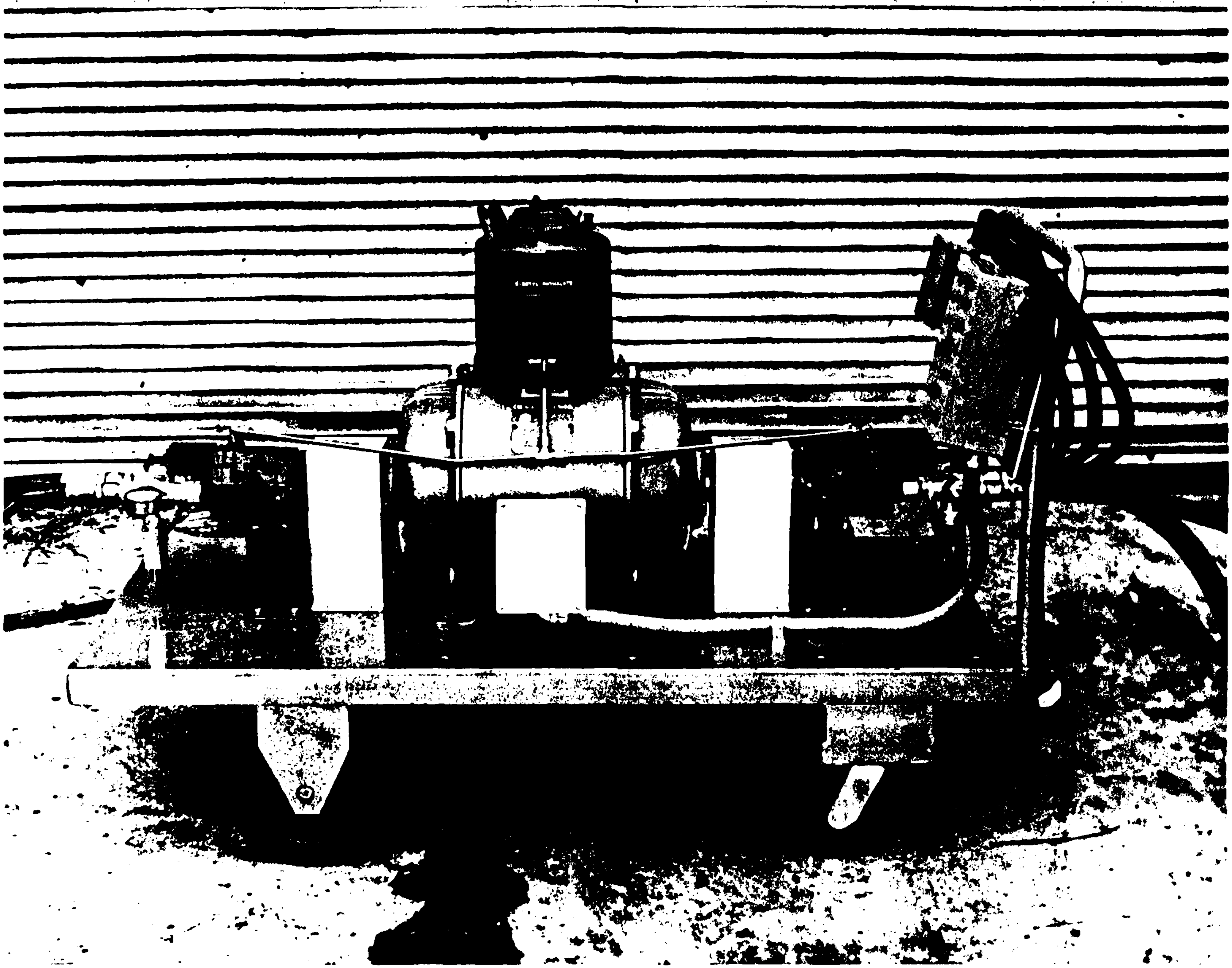

FIGURE 1. THE UPGRADED LABORATORY MODEL UNDERWATER FOAMING MACHINE

FIGURE 2. HANDLING DEVICES FOR CHEMICAL DRUMS

FIGURE 3. UNDERWATER FOAMING GUN (DESIGN NO. 1)

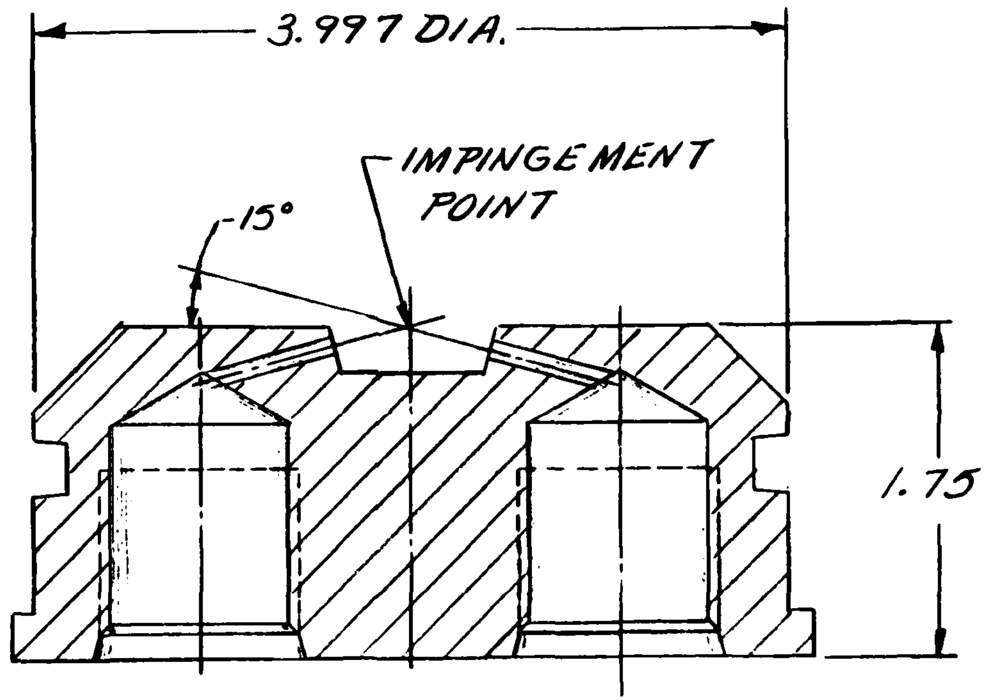

FIGURE 4. SKETCH OF FOAMING GUN (DESIGN NO. 1)

pressures are not closely balanced, one stream will enter the opposite orifice and flow backward up the supply hose. Using angled impingement rather than straight-on impingement) reduces the likelihood of this happening. However, best mixing occurs as the angles approach zero (straight on impingement), so there is a delicate tradeoff between the best mixing and reliable gun operation. Two other guns were built in an attempt to achieve this compromise. They are discussed in the next section.

The nozzle is a 10 centimeter I.D. (4 in.) PVC tube, held on with a hose clamp. It is inserted from the front of the gun over the O-ring as shown in Figure 5. The length of the nozzle can be adjusted to allow time for the foam chemicals to react and start to expand before they are exposed to seawater. If the flow rate or chemical temperature is changed, the length of the nozzle must be adjusted accordingly. This is important because a 6^{0}C (10^{0}F) rise in chemical temperature will double the reaction rate.

Nozzle length is a critical portion of the design. If the chemicals come in contact with the water too soon, the MDI reacts with the water and the foam will either not cure properly or not form at all. MDI has a greater affinity for water than it does for the polyol, so it must be kept isolated from water until it has reacted sufficiently. The nozzle is disposed of immediately after each "shot," as the foam will harden inside it within seconds.

An anodized aluminum handle was put on the first foaming gun, but later was removed. It was found that grasping the gun with one hand on the nozzle and the other hand on the hoses was sufficient at this stage of the development.

The upgraded foaming-machine/pumping module required a 220-volt, 40-amp, 3-phase power supply of 16 kVA. Except for the hoses and foaming gun, the foaming machine was not protected from the weather and ocean spray because it was only a lab model. The unit had no heat exchangers, so the chemicals had to be supplied at the proper temperatures to ensure good foam production. These temperatures depend on the particu-

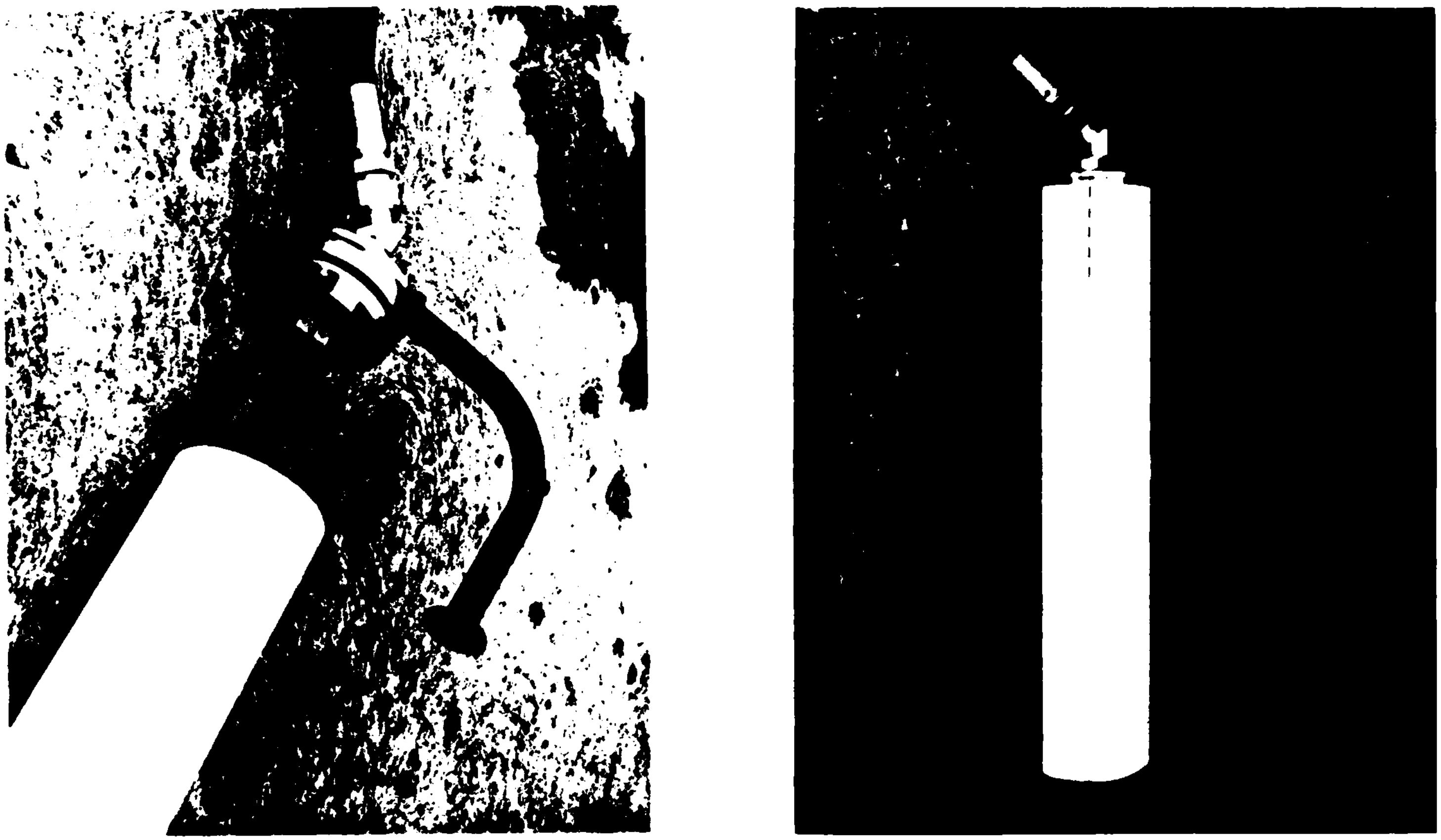

FIGURE 5. FOAMING TUBE ATTACHED TO FOAMING GUN

lar chemical composition being used and the environmental conditions, but are in the 21-38°C (70-100°F) range for the polyol. It is also necessary to use this machine only in relatively warm water; 10°C (50°F) or higher, to prevent the chemicals from cooling too much in the hoses.

Design Optimization

The operational tests were part of a design iteration procedure. Several design changes were indicated during these tests. The changes were implemented and then further tests were conducted until the machine was ready for the formal in-house and at-sea tests.

Operational tests were first run in air to check pump pressures, flow rates, proper mixing, etc. Then tests were run in the 1.8 meter deep by 1.6 meter-diameter tank (6 ft x 5-1/2 ft) shown in Figure 6. The tank was filled with fresh (tap) water. A porthole in the side of the tank allowed underwater viewing.

The no. 1 foaming gun (first design) made foam well in air, but the orifices were too large, reducing the impingement velocity and the quality of foam made underwater. To correct this problem, the orifices were welded over and re-drilled to 1.6 millimeter (1/16-inch) diameter. This resulted in a marked improvement in the quality of mix.

To further improve impingement mixing, a second foaming gun was designed (gun no. 2). This gun had 1.6 millimeter (1/16-in.) orifices also, but they were at a 3-degree impingement angle rather than the 15-degree impingement angle of gun no. 1. The orifices were also closer together (13 mm, rather than 22 mm). As shown in Figure 4, the orifices of gun no. 1 were raised on the face of the gun. Figure 7 shows the orifices of gun no. 2 entering from opposite sides of a 13 millimeter (1/2-in.-diameter) hole drilled into the face of the gun.

Recessing the orifices in a hole increases the turbulence and provides better mixing. However, as mentioned earlier, the tradeoff for better mixing is an increased likelihood of gun fouling (clogging) by having one stream enter the opposite orifice due to a slight pressure imbalance. Once the stream enters the opposite orifice, foam is made inside the gun and it becomes clogged.

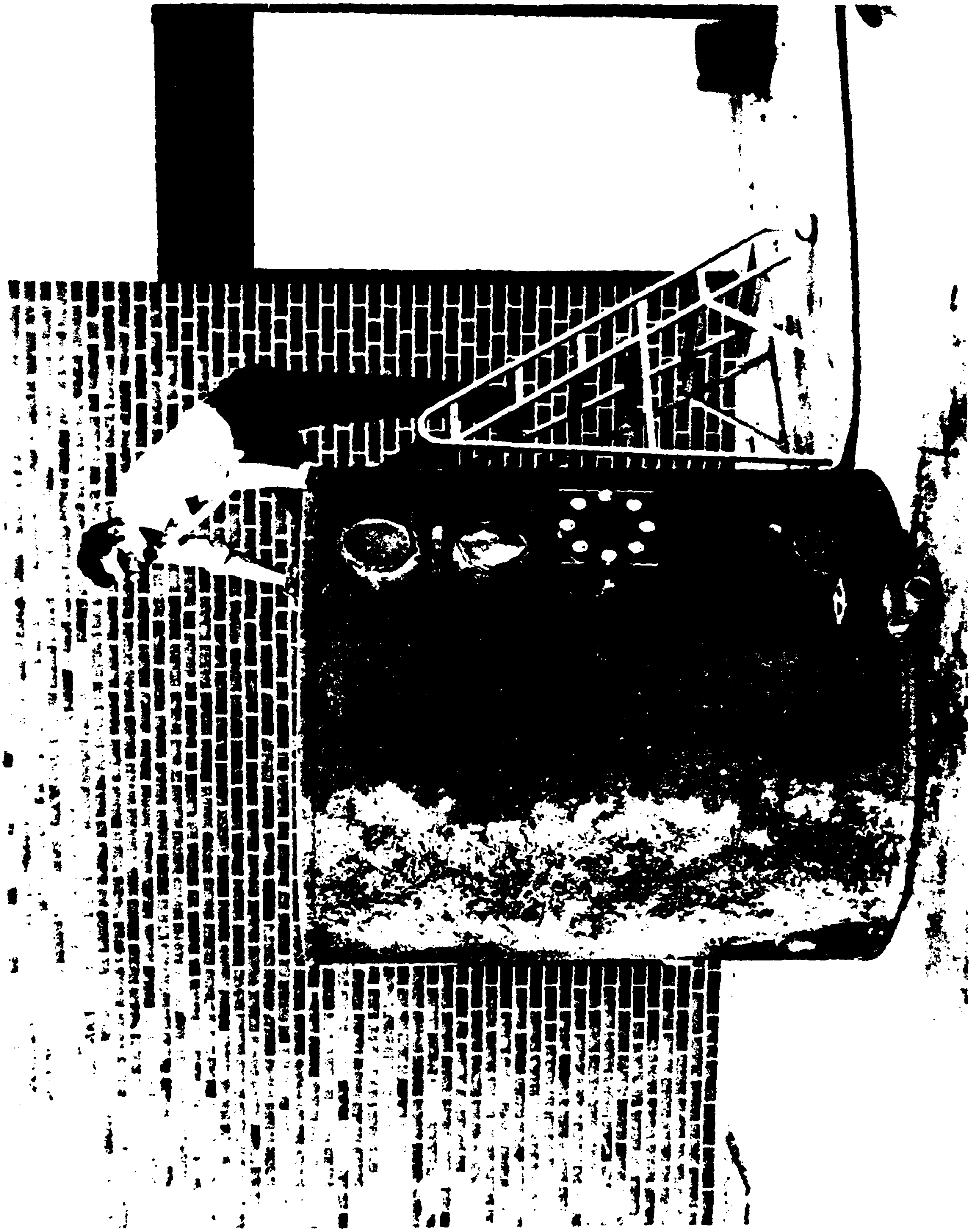

FIGURE 6. TANK USED FOR OPERATIONAL TESTING
(6 FT DEEP BY 5-1/2 FT DIAMETER)

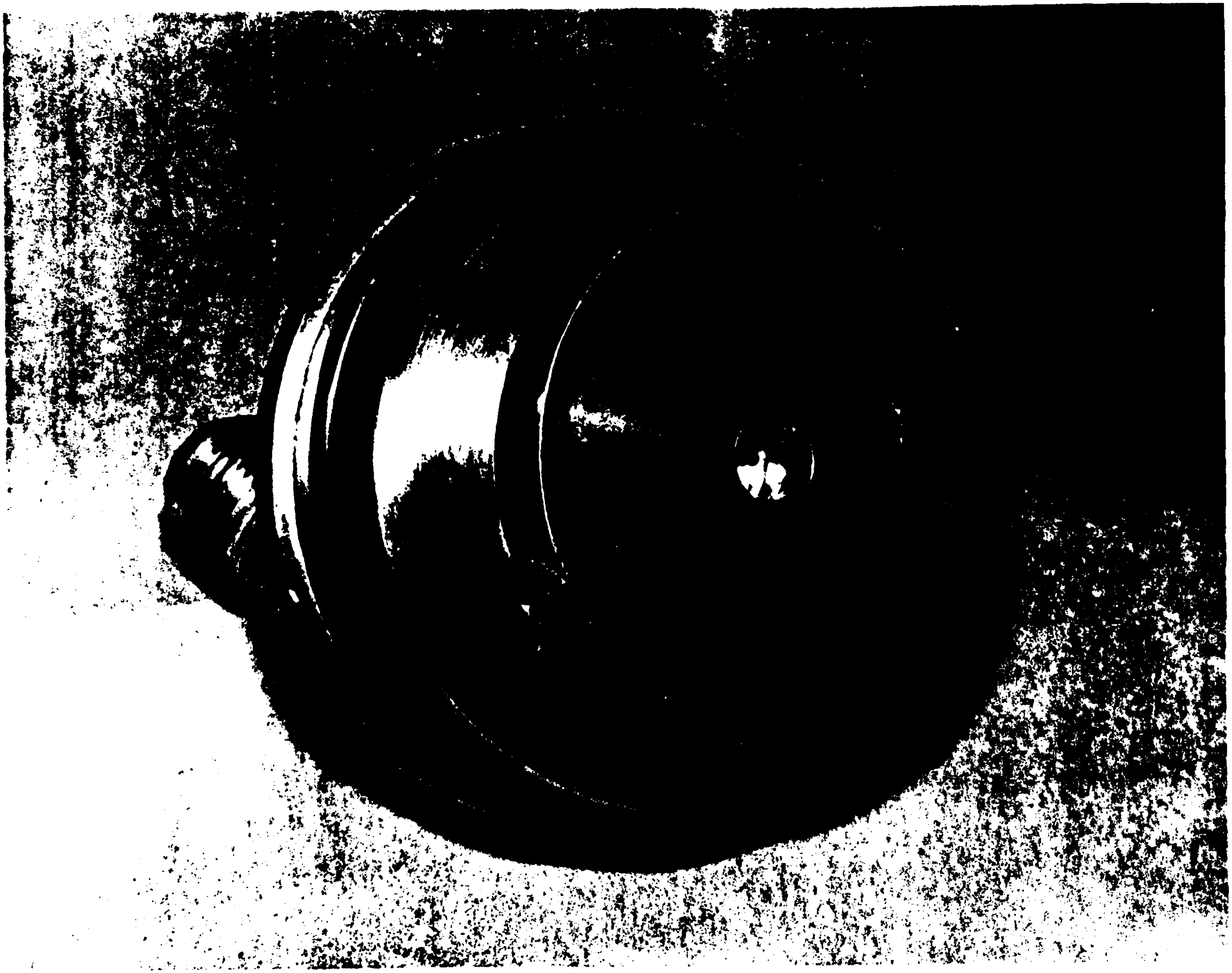

FIGURE 7. FOAMING GUN DESIGN NO. 2 SHOWING ORIFICE RECESSED IN HOLE

The no. 2 foaming gun produced excellent quality foam in air and underwater. However, the gun tended to foul. To maintain the high foam quality produced by gun no. 2 and to get the non-fouling character of gun no. 1, a third gun was designed and fabricated. Outwardly, gun no. 3 is similar to gun no. 2. The significant differences, shown in the cross-sectional sketch of Figure 8, are the 6-degree impingement angle of the orifices (instead of 3 degrees) and the addition of an air jet. The 6-degree impingement angle of gun no. 3 resulted in excellent-quality foam and reduced the fouling.

The air jet was added for experimental purposes in anticipation of using the gun at depth. As the foaming system is used deeper, and as pressure increases, the air jet may be necessary to froth or blow the foam. Freon, which is currently used, is depth-limited, as is the carbon dioxide used in "self-blowing" foams. Another possible use for the air jet is to clear the foaming nozzle of water before the pumping is started and thus producing good foam from the start. The jet may also greatly help in cleaning the gun after each run.

Control of the air input is accomplished with a needle valve on the rear of the gun and by a regulator at the source. At a foam flow rate of 38 liters per minute (10 gpm), the gas required is 30 times this, or 1136 liters per minute (300 gpm). Therefore, the supply must be 1100 Lpm (40 cfm) at the ambient pressure of the gun (not at the surface). The orifice must be sized to keep the gas velocity low enough not to be detrimental to the impingement process.

Check valves were installed in both chemical supply lines at the foaming gun. When the pumps are off, water can enter the MDI line and react with it, crystallizing the chemical and clogging the hose. The check valves prevent this water/MDI reaction by preventing water from traveling up the hose. Also, the check valves prevent the hoses and pumps from fouling when the pressures are very imbalanced. The farthest that the system can foul is up to the check valves, which are installed inside the hose fittings on the back of the gun (see Figure 9). The check valves have no effect on the foam quality.

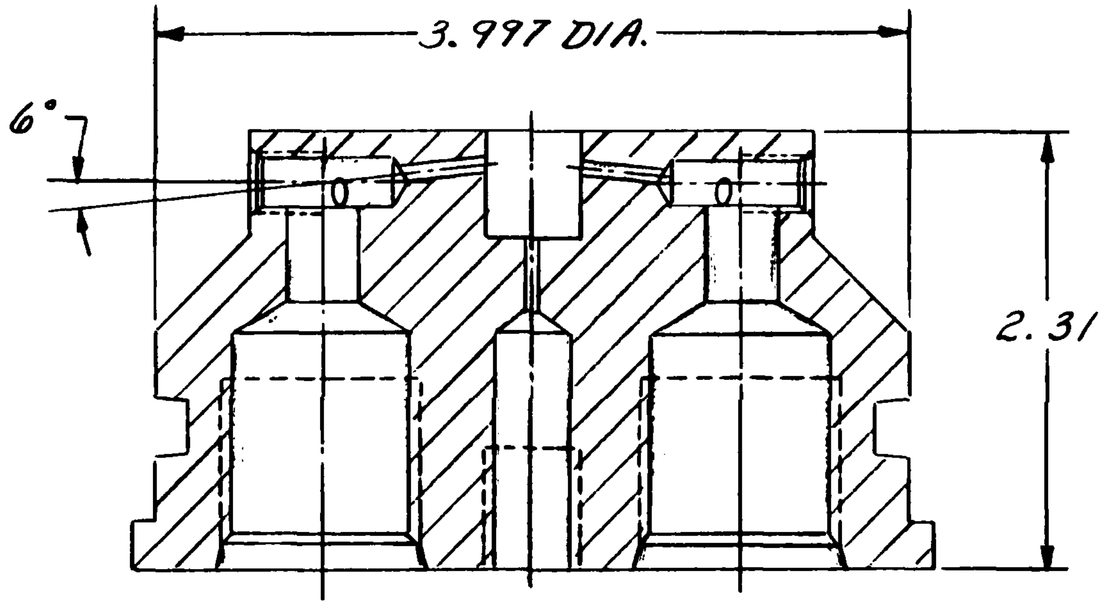

FIGURE 8. CROSS SECTIONAL VIEW OF FOAMING GUN NO. 3

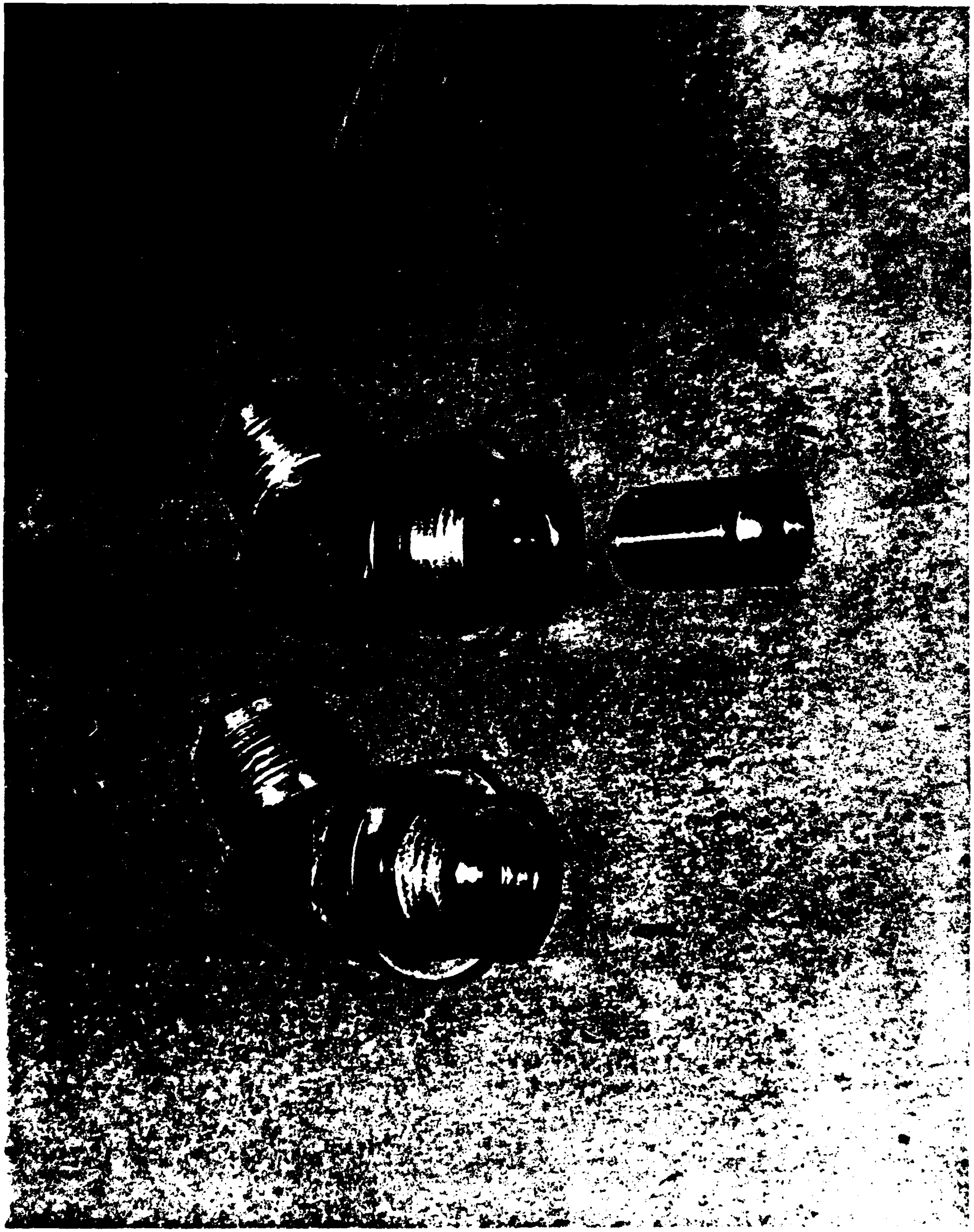

FIGURE 9. CHECK VALVES IN FOAMING GUN HOSE FITTINGS

The foaming gun tended to weep small amounts of the chemicals when the pumps were turned off. Also, the pumps did not always reduce pressure at the same rate when shutting down. For these reasons it was possible for foam to be made in the recessed hole or in the orifices and thus clog the gun. To prevent this, a flushing system was added to the foaming gun. This flushing system, using DOP as the flushing agent, was maintained at a pressure of 2.8 bar (40 psig). The DOP entered the gun just behind the orifices. When the pumps were off, the DOP flowed through this area and out the orifices to flush away the chemicals. When the chemical pumps were on, two check valves prevented the chemicals from backing up into the flushing system. Thus, as long as the pressurized DOP supply was maintained, the flushing was automatic.

Full-Scale Prototype Foaming System

As a result of the success of the upgraded laboratory foaming machine, work was started on designing and building a full scale, prototype foaming system for at-sea use ("System" implies the foaming "machine" and the foaming gun/nozzle). It was to be based on the previous designs, but was also to include all the necessary additions to make it practical for actual duty, such as chemical heaters, automatic head flushing, full control systems for temperature, flow rate and pressure and a sturdy, weatherproof design.

There was little control over the operating parameters with the upgraded laboratory model machine and that made it difficult to optimize the foaming gun design. Without very accurate control of chemical temperatures, flow rates and pressures, test results on the gun were inconclusive. Thus, the full-scale prototype machine would not only be a development step in producing a production machine for Navy use, but would also provide the degree of control necessary for further foaming gun testing and design optimization. These activities are discussed in the following sections.

A significant difference between the full scale machine and the lab model is in what happens to the flow of the MDI and the polyol when foaming stops. In the lab model machine, the motor and pumps stop when the foaming stops. This can lead to head clogging problems if the pumps do not lose pressure at exactly the same rate when shutting down. In contrast, the full-scale machine motor and pumps run continuously. The MDI and polyol are recirculated through their respective systems, when foaming ceases. Since the pumps are always running, they can be adjusted to produce equal pressures, and thus minimize potential head clogging.

Another important difference between the two machines is the head flushing system. In the laboratory model, the flushing chemical is DOP. Since DOP is not a true solvent of polyol and MDI, polyurethane foam can form in the presence of DOP. In the full-scale machine, the head flushing chemical is methylene chloride. Methylene chloride is a solvent of the polyurethane component chemicals, and hence, provides a better flush.

Full-Scale Module Design

The Full-Scale Prototype Foaming System is considerably more complex than the previous lab model. The additional hardware provides a high degree of control over the chemical process necessary for producing better quality foam, resulting in more efficient use of chemicals. The Full-Scale Prototype Foaming System is shown in Figures 10 and 11. In the following section the overall flow schematic is described. In subsequent sections the major hardware components are discussed in detail.

Flow Schematic. The foam machine flow schematic (Figure 12) is composed of two similar flow paths, one for the MDI and the other for the polyol. In addition, there are several components which serve both sides of the system. Due to the similarity between the two flow paths, only one path will be described here in addition to the common components.

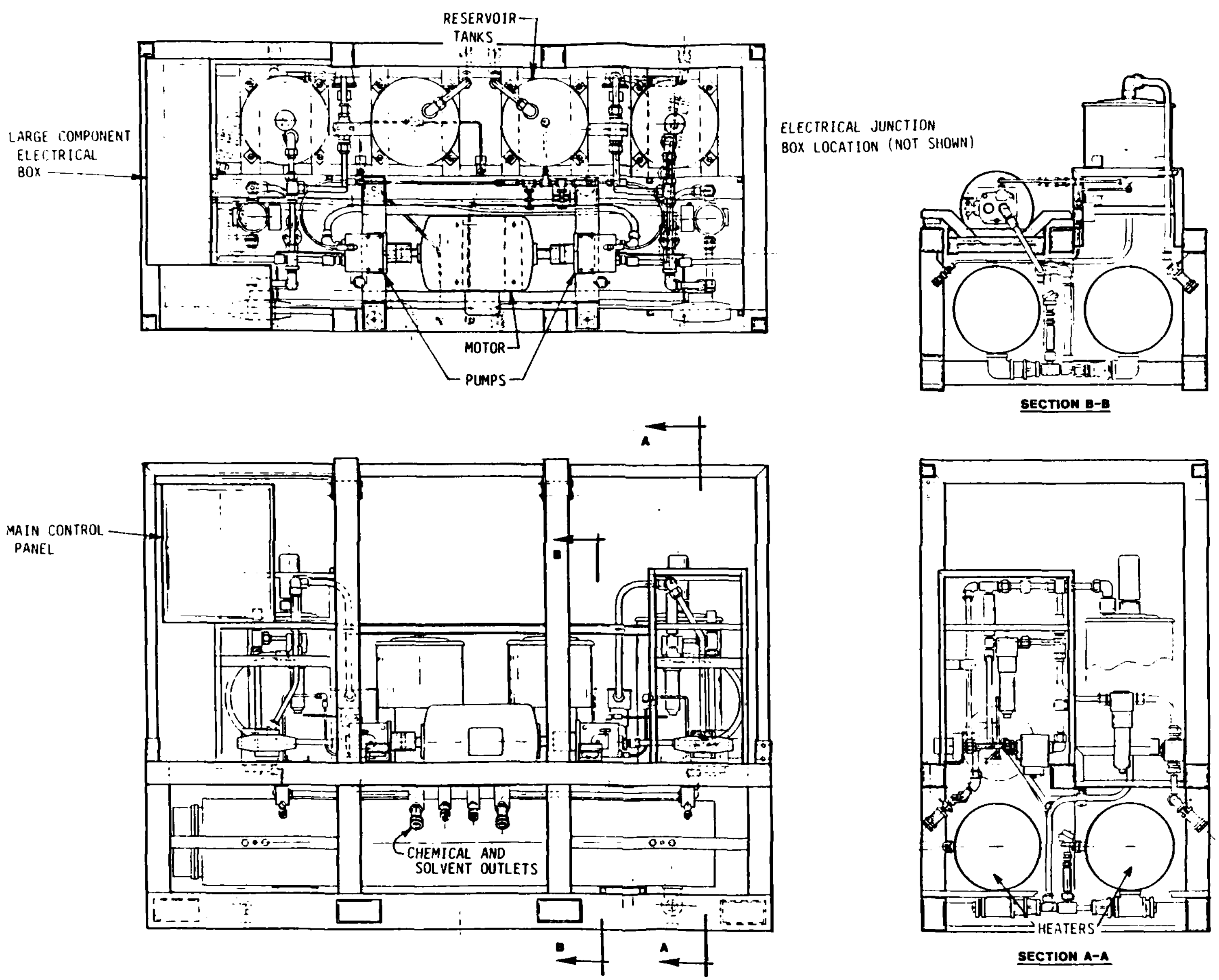

FIGURE 10. PROTOTYPE FOAMING SYSTEM ASSEMBLY DRAWING

FIGURE 11. FULL-SCALE PROTOTYPE FOAMING SYSTEM

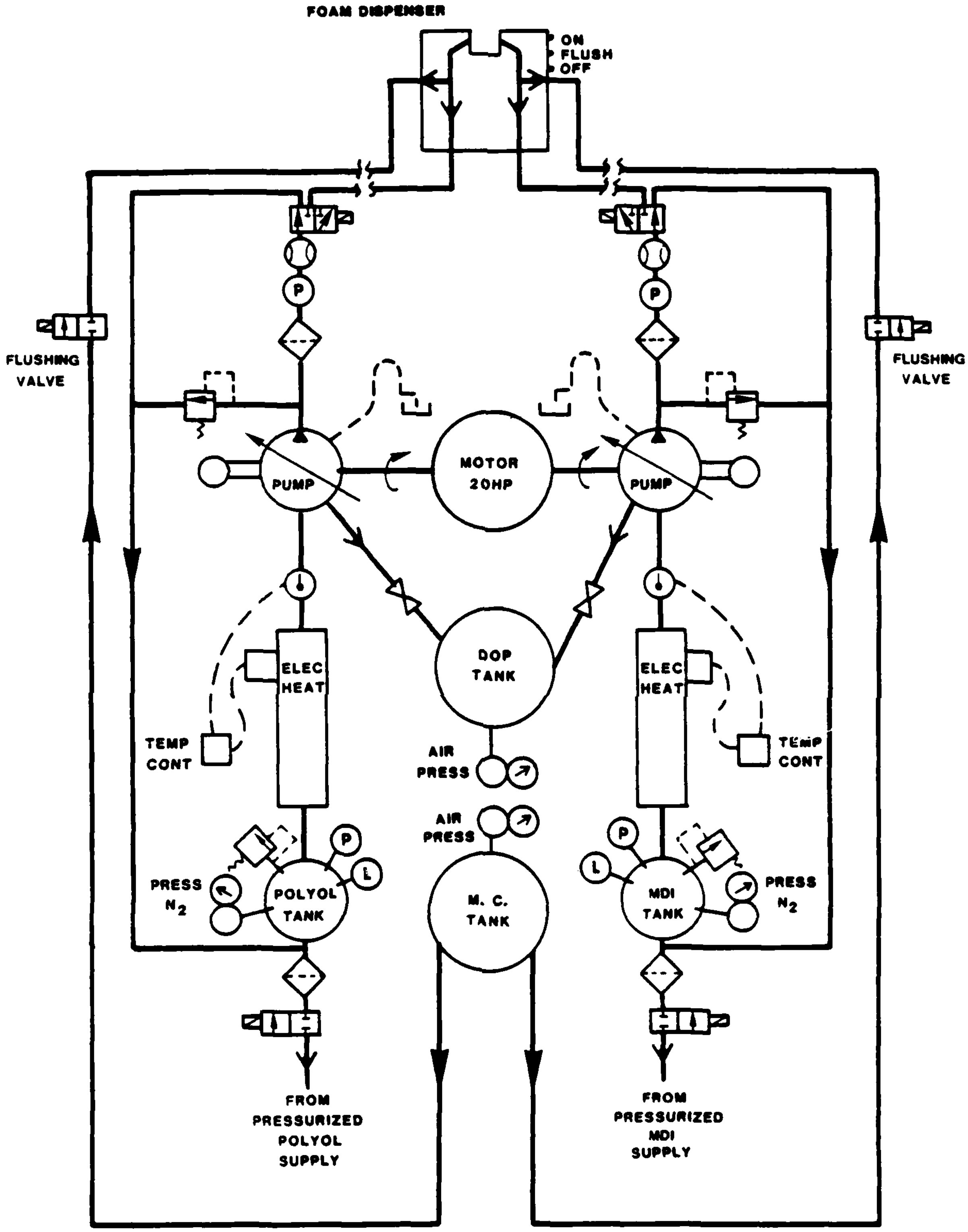

FIGURE 12. SYSTEM FLOW SCHEMATIC

The schematic begins with an inlet through which the pressurized MDI flows from the main chemical supply. (This currently comes from transfer pumps in 55 gallon drums, but may be supplied by large pressurized chemical tanks). From the main supply, the MDI flows first through a check valve, next through a solenoid valve, then through a filter, and finally into the pressurized reservoir tank. This tank is pressurized with nitrogen and is equipped with an automatic level controller and a relief valve. The automatic level controller opens and closes the inlet solenoid valve to fill the pressurized reservoir tank. The check valve prevents any accidental flow of chemicals from the machine backward to the sources.

From the reservoir tanks, the MDI flows to an electric heater. Two temperature controllers are used to control this heater. One temperature controller is used as a process temperature controller. This temperature controller is a PID (proportional integral derivative) type controller. Its input is a signal from an RTD (resistive temperature detector) which is inserted into the tubing just downstream of the heater. The RTD signals the controller which in turn activates an SCR (silicon controlled rectifier)* which controls the heaters. The SCR varies the electric power to the heater, thus varying the amount of heat energy put into the fluid as it flows through the heater.

The second temperature controller is an over-temperature controller*. It monitors the temperature of the heater elements by way of a thermocouple welded to the heater element bundle. If the temperature of these elements goes over the set point, power to the heater is cut off. The purpose of the over-temperature controller is to prevent localized hot spots that could raise the chemical temperature beyond its flash point.

From the heater, the MDI flows to the piston pump. At the outlet of the pump the fluid can go in two directions. If the pressure of the fluid is over 120 bar (1750 psi), a pressure relief valve will open, directing the MDI back to the reservoir tank. Normally, when

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*Not shown on schematic.

the pressure is less than 120 bar (1750 psi), the fluid will continue along a path which takes it through a second filter, a pressure transducer, and a flow meter to a 3-way valve.

The 3-way valve directs the MDI either to the foaming gun via 30 meter-long (100-foot) hoses or recirculates it back to the reservoir tank. The 3-way valve is controlled by a switch on the foaming gun (it can also be controlled by a button on the main control panel). The valve default position will cause the MDI to recirculate back to the reservoir tank. Only when the switch on the gun (or on the control panel) is depressed, will the material flow to the gun.

The flow path and components for the polyol are the same as those just described for the MDI. Several components supply both the MDI and polyol sides of the schematic. A tank of solvent (methylene chloride) supplies solvent to flush the head. This tank is pressurized with nitrogen. Two lines exit from this tank. Each line goes to a 2-way valve, and then on to the head. The 2-way valves are normally closed. When the diver releases the foam switch (the switch that starts/stops the flow of foam to the gun), the 2-way valve automatically opens for a preset amount of time permitting the solvent to flow into the head and flush it. The amount of time that the valve remains open is variable from 2 seconds to 3 minutes. A DOP reservoir tank is also included on the machine. This tank is also pressurized with nitrogen. The DOP is used to lubricate and flush the piston pumps.

Another component common to both sides of the schematic is the 15 kW (20 hp) electric motor which drives the pumps. Since both pumps are directly coupled to the same motor, they will both run at the same speed.

Heating System. The chemical heating system was designed to meet several criteria. The system must accept chemicals at 0 degrees Celsius (32°F) and heat them to proper operating temperature, which ranges from 20 to 50 degrees Celsius (70°F to 120°F). At flow rates of 23 Lpm (6 gpm), this requires a fairly high power input and thus large heaters. Two-stage heating was considered, where the first stage would be heated chemical reservoir tanks and the second stage would be an in-line heater. The bulk of the heating in this scenario would be done in the reservoir tank. However, to reduce the system complexity and cost and to provide more uniform heating, single stage heaters were chosen at the expense of increased size.

There was concern about the type of heat source to be used to heat the chemicals. Water-to-chemical heat exchangers were considered, but this idea was discarded because a separate system to heat and circulate the water for the heat exchangers would be needed. The electric heaters were chosen because they are for less complex and the only input required is electricity which is readily available on most ships. Water based heat exchangers are less likely to scorch or cause the chemicals to ignite, but with the electric heaters, over-temperature controllers assure that the chemicals are not heated to their flash point and the selected heaters are low energy density types which add the heat energy at a moderate rate.

The electric heaters pictured in Figure 13 are Chromalox circulation heaters. They are rated at 45 kW and 480 V. The heaters are normally mounted vertically, but because they are 2.7 meters (9 ft) long, they have been installed horizontally with the inlets and outlets facing vertically downward. This orientation facilitates draining the heaters when the system is to be stored or overhauled. A vent at the top of each heater allows the venting of air when the machine is first filled.

Each heater has a thermocouple welded to the top side of the heater elements. This thermocouple provides the input to the over-temperature controller. The over-temperature controller is a safety device which will not activate in normal operation.

The main temperature controller is a Chromalox PID controller. It operates by sensing (with an RTD) the temperature of the fluid coming out of the heater.

Reservoir Tanks. All four tanks on the foam machine are Graco steel tanks rated for pressures up to 7 bar (100 psi). The tanks used

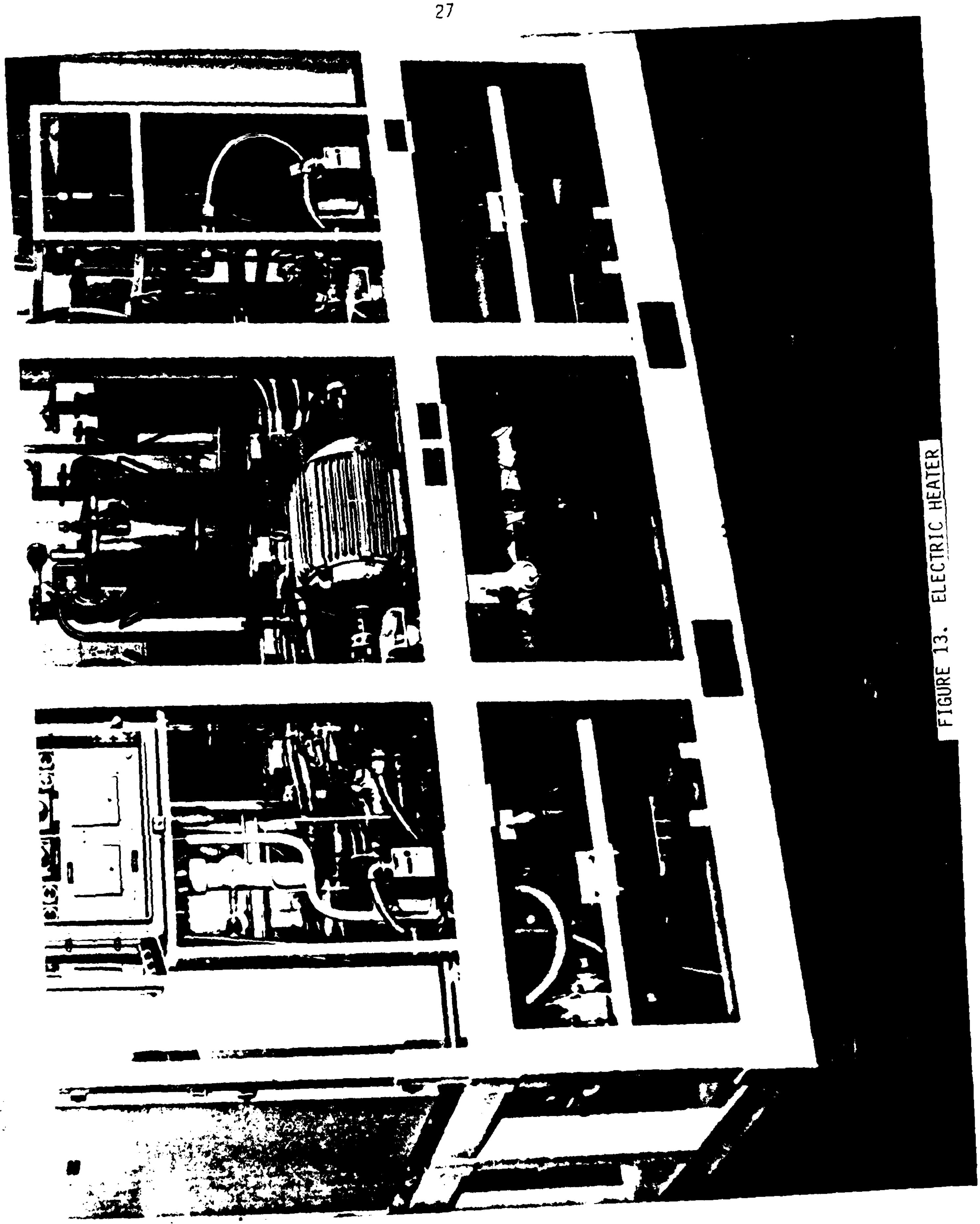

FIGURE 13. ELECTRIC HEATER

for the MDI and polyol reservoirs are 38 liter (10 gallon) tanks, while the DOP and solvent reservoirs are 19 liter (5 gallon) tanks. The tanks are equipped with pressure relief valves for safety and pressure regulators so they can be pressurized with air or nitrogen. The inlet to the tanks is through the top lid of the tank and the outlet is from the center of the bottom. With this arrangement, gravity assists the flow of the chemicals. All of the tanks can be filled without removing the tank covers. The MDI and polyol tanks have automatic level controllers which control the inlet line solenoid valves. The DOP and the solvent tanks have liquid level sight gauges on the sides of the tanks and are manually filled by using a transfer pump at the start of a mission.

The Graco tanks, shown in Figures 14 and 15, were modified slightly from their as-manufactured condition. Mounts were welded onto the tank skirts in order to attach the tanks to the frame, and the lid was modified to accept the automatic liquid level gauges and inlet piping. The tanks came from the factory with thiokol gaskets. Except for the solvent tank, this material held up well during our tests and was not replaced with PTFE as was originally planned. The methylene chloride attacked the thiokol material after several weeks so this tank gasket was replaced with a Viton® gasket.

The liquid level sight gauges are cadmium-plated steel with a glass, sight-gauge. The O-rings were originally Buna-N, but have been changed to Viton®.

<u>Automatic Level Controllers</u>. The automatic level controllers (Figure 15) are Ball Products level switches. They are composed of a rod and a sliding float which slides up and down on the rod. When the float hits the low limit on the rod, it activates a microswitch. The wetted parts of the level controller are made out of Type 316 stainless steel. The electrical housing is weather-tight.

<u>Filters</u>. The filters serve a dual purpose; they remove particles from the chemicals which could wear or damage the piston pumps and they protect the orifices in the head by removing particles large enough to clog them.

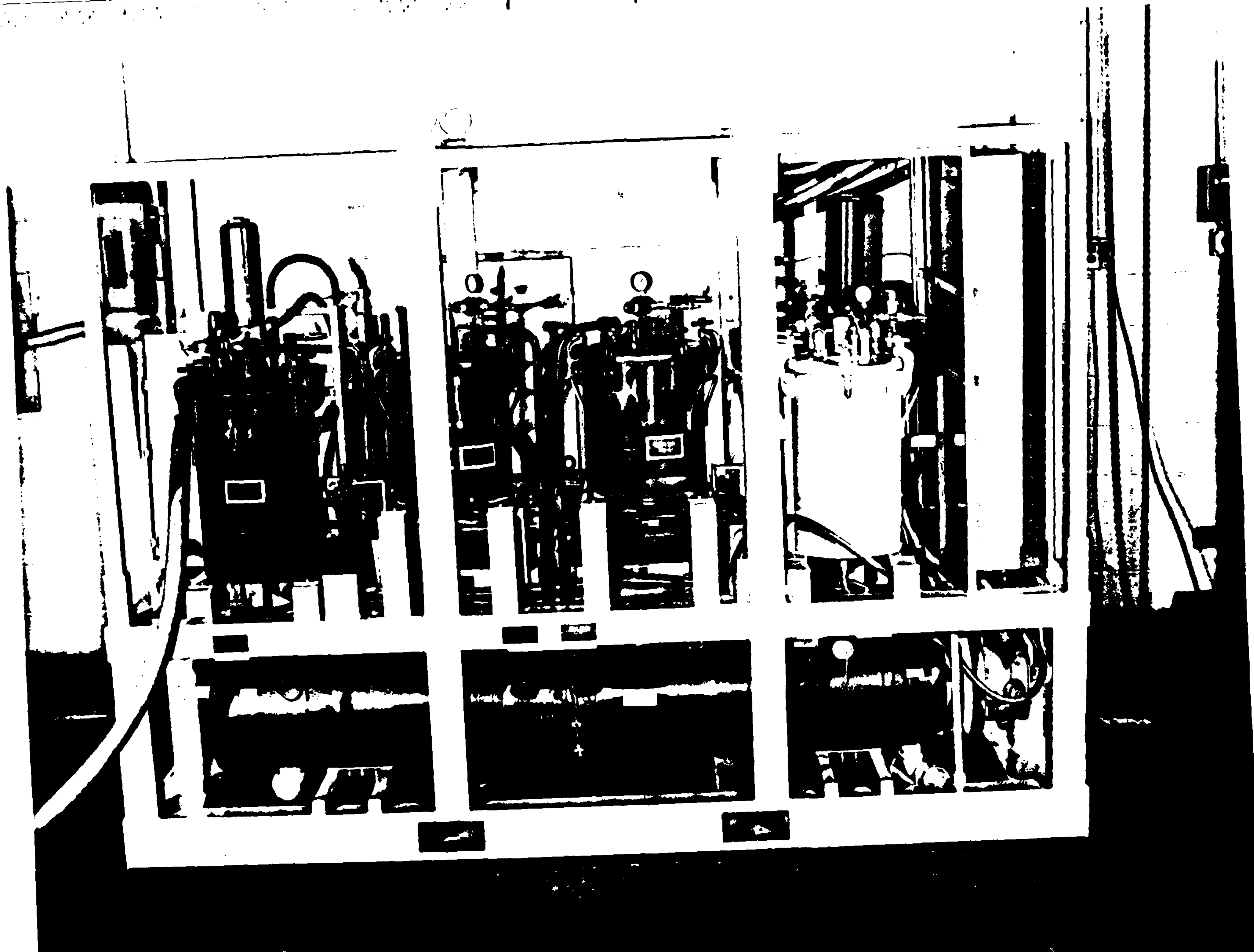

FIGURE 14. HOLDING TANKS FOR MDI POLYOL DOP AND SOLVENT

FIGURE 15. SOLVENT TANK AND MDI TANK WITH AUTOMATIC LEVEL CONTROLLER

The filters (Figure 16) used on the foam machine are Purolator hydraulic filters. They are rated at 400 bar (6000 psig) with a nominal flow rate of 115 Lpm (30 gpm). The filter element is a stainless steel mesh filter element (also known as a wire cloth type element). The degree of filtration was originally 25 microns, but has subsequently been changed to 300 microns. For ease of maintenance and stocking of spare parts, all four filters in the system are the same type even though two of the filters are used on the low pressure side. Modifications to the filtering system were made during the operational and in-house testing programs (see subsequent sections of this report).

Valves. Two-way (open/closed) Asco solenoid valves are used to control the chemical inlets to the foaming machine. They are controlled by the previously described automatic level controllers. These valves have a stainless steel body, PTFE diaphragm, and ethylene-propylene seals. The solenoid enclosure on the valve is watertight and explosion proof.

To direct the high pressure foam chemicals to the foaming gun or back to the reservoir tanks, two 3-way Rexroth directional control valves are used. These valves are rated at 100 Lpm and 320 bar (26 gpm and 4,600 psi). The materials of construction are cast iron and steel with Viton® seals.

Pressure relief valves are installed at the pump outlets to regulate line pressure to the foaming gun. These valves dump fluid back into the reservoir tanks. The valves are Teledyne Republic direct acting relief valves with hard seats, PTFE seals and stainless steel bodies.

Check valves are installed in the MDI and polyol inlet lines. There are also check valves in the lines leading from the DOP tank to the pumps. The check valves in the DOP lines prevent MDI and polyol from entering the DOP tank and mixing there to make foam.

Various other manually operated valves are used on the foaming machine to allow venting, draining, flushing and so on. Proper use of these valves is covered in the Operation and Maintenance Manual.

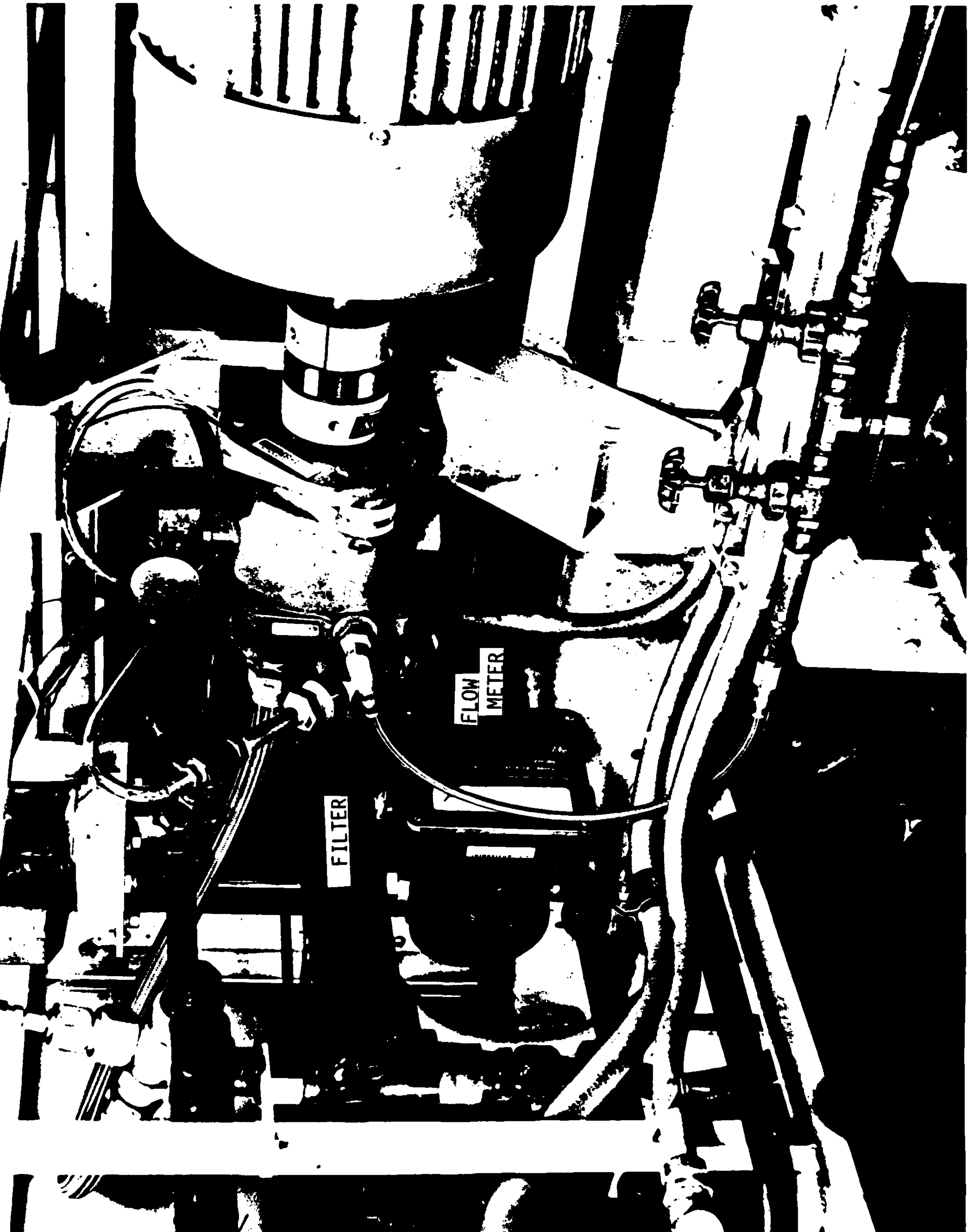

FIGURE 16. FILTER AND FLOWMETER

Pump and Motor Unit. The pumps are variable displacement Vickers piston pumps with hand wheel displacement controls. These PVB-10 pumps are capable of pumping 40 Lpm at 207 bar (10 gpm at 3000 psig). The pumps are steel construction with Viton® seals. The pumps are directly coupled to the motor shafts with spider couplings. The motor is a 15 kW (20 hp) three-phase induction motor.

The pumps and motor, shown in Figure 17, are mounted on a cradle that is attached to the main frame with vibration isolation pads. Flexible hoses are used to connect the various lines to the pumps. This significantly reduces noise and minimizes vibration induced problems such as metal fatigue and loose fasteners in the rest of the hardware.

Plumbing. Steel tubing and tube fittings are used throughout the foaming machine for chemical transport. For vibration isolation, PTFE lined hose is used to connect the various lines to the pumps.

Connecting chemical lines improperly can result in serious and expensive fouling of the machine components. Thus, a design goal was to keep the polyol plumbing at one end of the machine and the MDI plumbing at the other end. This simplifies maintenance and avoids accidental mixing of the two chemicals. In addition, the polyol lines and many of the polyol components are painted green for easy identification. MDI lines and the major MDI components are painted yellow.

To avoid the high cost of PTFE lined hose between the foaming machine and foaming gun, standard grade hydraulic hose is used. This type of hose is also much more resistant to kinking than PTFE or nylon lined hose (a problem in the past). The synthetic rubber liners of these hoses do not stand up to long term MDI and polyol exposure as well as PTFE lined hoses would, but these particular hoses are considered mission expendable and should be satisfactory for several weeks use. The hoses from the machine to the gun are considered mission expendable because they see the most abuse and usually get heavily covered with foam. Rather than drain, clean and store these 30 meter (100 feet) hoses at the end of a mission, it is more expedient to replace them.

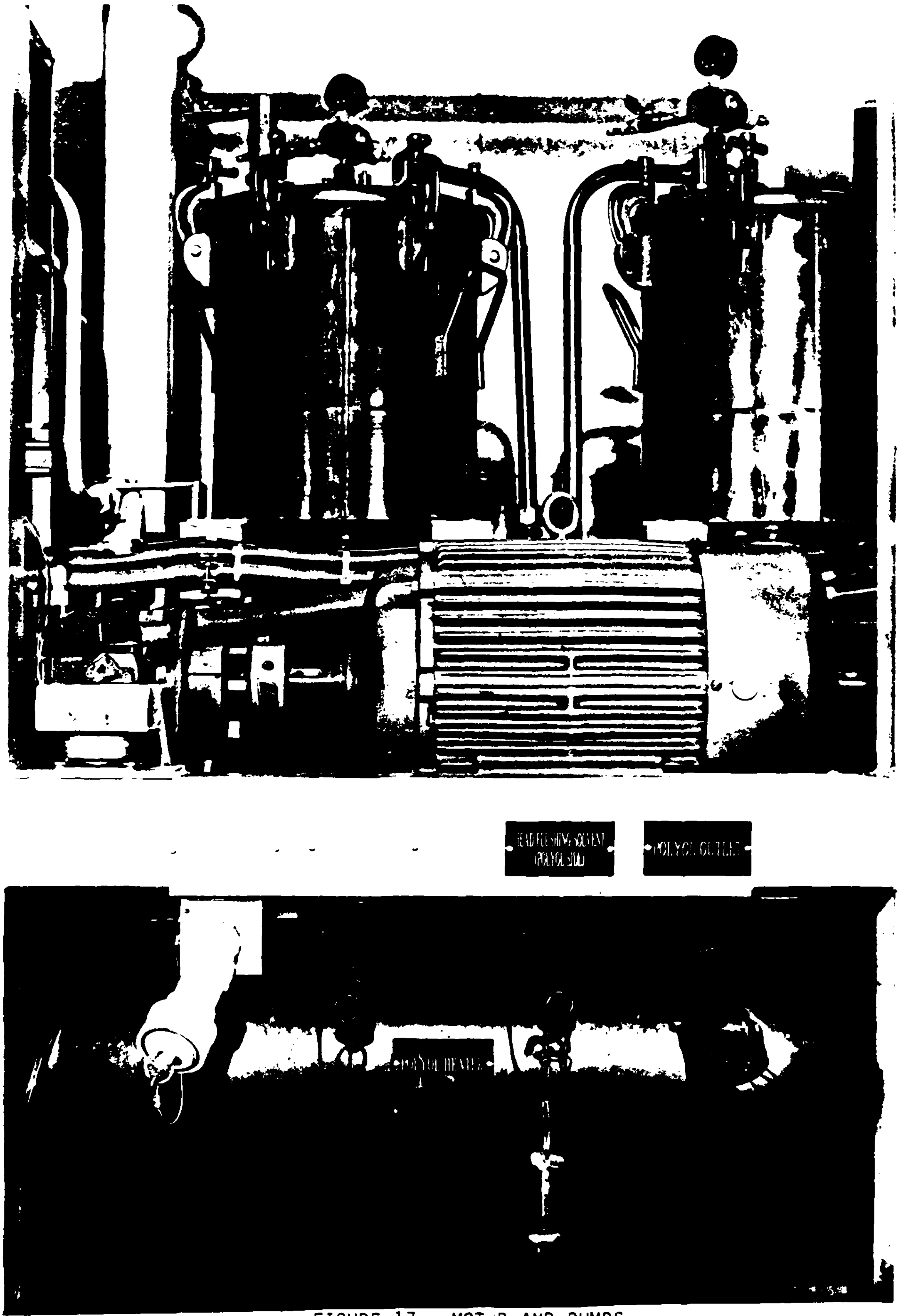

FIGURE 17. MOTOR AND PUMPS

The gun flushing solvent (methylene chloride) flows through flexible polyethylene tubing to the gun. This tubing and the two hydraulic hoses are bound together into a single hose bundle using nylon ties.

Frame. The frame is constructed of welded, steel, square tubing that has been painted with an epoxy paint suitable for equipment used at sea.

There are integral forklift lift slots on the frame so that it can be easily moved around by forklift. There are also eyelets on the top of the frame for a custom built lift sling so that the machine can be lifted on or off of a ship by crane. The total module weight is approximately 2720 kilograms (6000 pounds).

Instrumentation. Three chemical variables must be controlled for good foam making; temperature, pressure and flow rate. For this reason the foaming system is designed to have a high degree of control over these parameters. The controls for temperature, pressure and flow rate are automatic, but they must be set properly and monitored regularly. The following instrumentation supports the monitoring function.

The polyol and MDI temperatures are displayed on the temperature controllers (Figure 18) and are sensed with the RTDs. Temperature control is automatic once the desired temperature has been set.

Pump pressure is monitored with Sensotec pressure transducers. The range of these transducers is from 1 to 140 bar (0 to 2000 psig) with an accuracy of 1 percent. They are strain-gage type transducers with stainless steel diaphragms. The pressure is determined chiefly by the flow rate (pump displacement) and gun orifice size.

Flow rate is monitored by two Universal Flow Monitor flow meters. These meters measure flow rate from 0 to 57 Lpm (0 to 15 gpm) and feature a directly coupled mechanical readout at the sensor. They also have potentiometers which provide a signal to two Weston digital voltmeters on the main control panel. The flow meters, which were shown in Figure 16, are 304 stainless steel with seal materials of PTFE (Teflon®) and Kalrez®. Kalrez® is an elastomeric grade of PTFE.

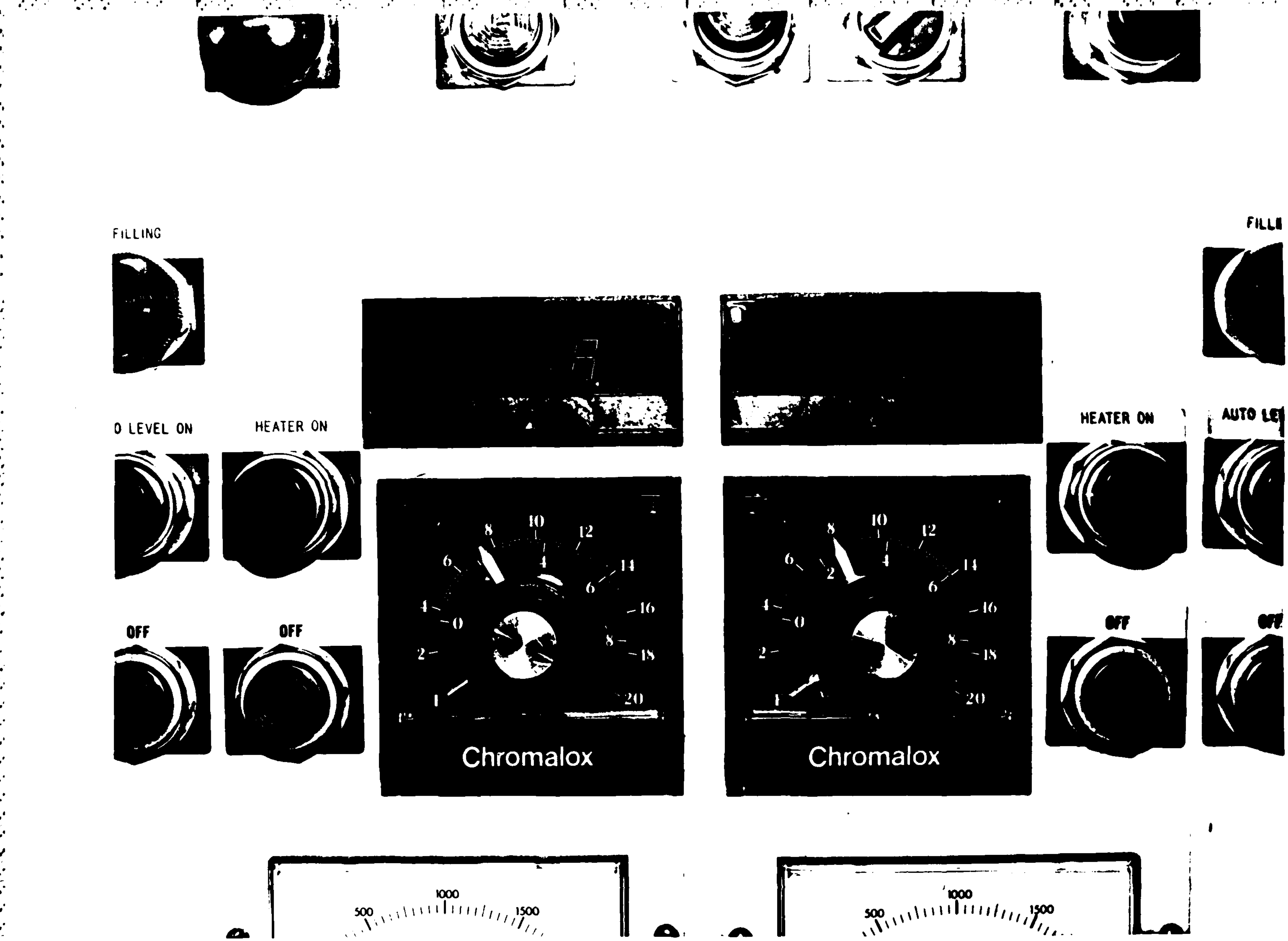

FIGURE 18. PROCESS TEMPERATURE CONTROLLERS

Electrical and Control Sytems. The solenoid valves, motor, heaters and much of the instrumentation and controls are electrically powered. The foaming machine has three boxes to house the electrical hardware: the main control box, the junction box and the large component box.

The junction box (Figure 19) is where the external electrical power source is connected. In this box are terminal blocks where either one 140 amp, 480 volt, 3-phase power cable can be attached or three smaller cables can be attached. This arrangement allows the foaming machine to be powered by one high capacity source if available or by three smaller electrical sources such as portable generators. When three separate power inputs are used, the motor and two heaters are each powered independently. Lower voltage, auxiliary power for the valves and control panel is provided by a transformer connected to the motor source.

Three separate phase checkers are wired into the junction box to signal the electrician when the phases are connected in the right order. Also provided are three fused disconnect switches. The correct sequence of phases is extremely important both for the heaters and for the motor. If the sequence was incorrect for the motor, the pumps would be driven backwards. This would cause damage not only to the pumps, but also to the rest of the foam machine. If the phases going to the heaters are out of sequence, the SCRs will not fire properly. Proper connection procedures are provided in the Operation and Maintenance Manual.

The large component box, pictured in Figure 20, houses the heater SCRs, the motor starter, the over-temperature controllers, the flush timer, the control relays and the transformers. This box contains the most expensive and delicate electrical components and need not be opened under normal operation.

The main control box (Figure 21) has a clear polycarbonate door and contains the main control panel and some small electrical components. The main control panel is powered by a 2-phase, 110 volt source. This source is provided by a step down transformer connected to the

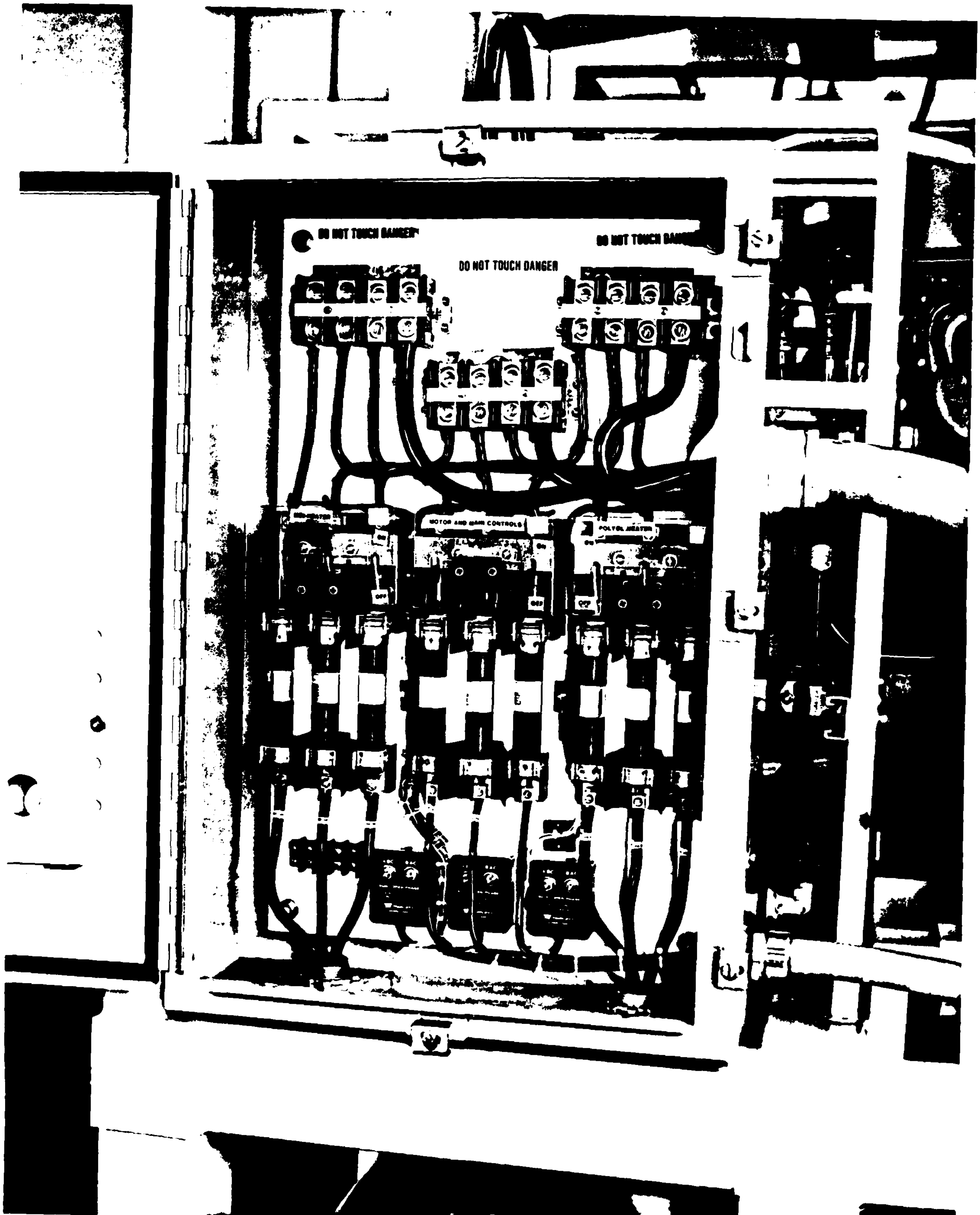

FIGURE 19. ELECTRICAL JUNCTION BOX

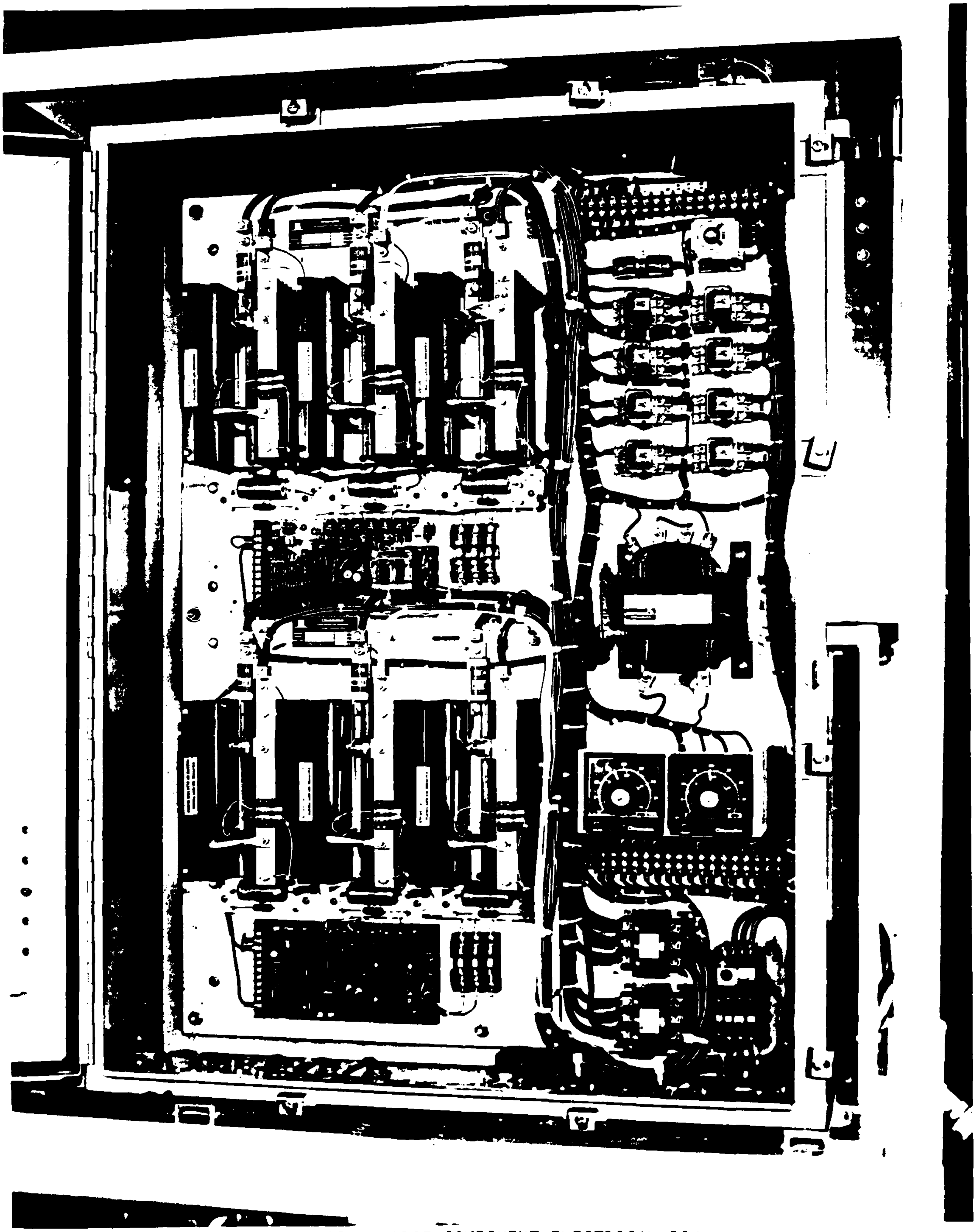

FIGURE 20. LARGE COMPONENT ELECTRICAL BOX

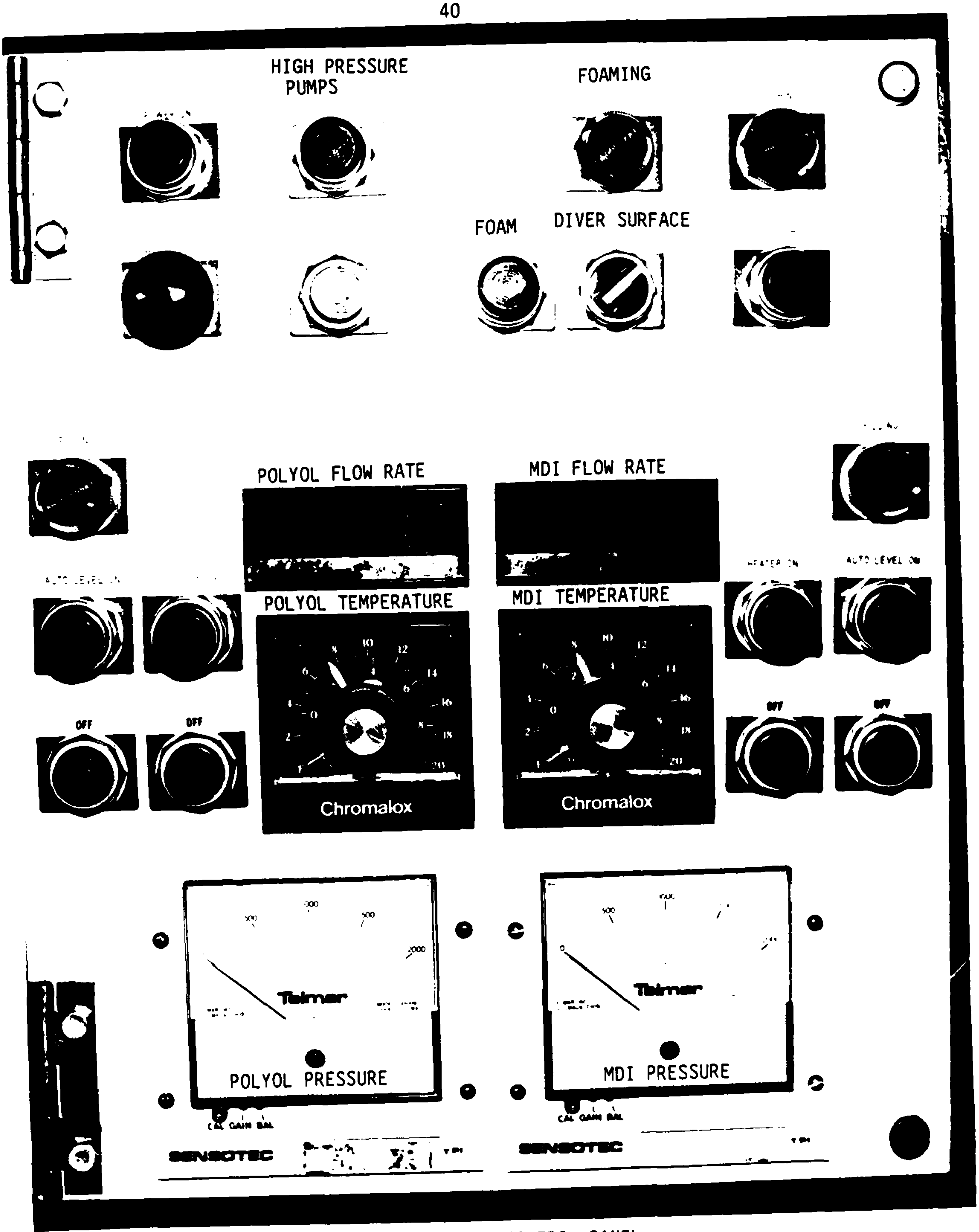

FIGURE 21. MAIN CONTROL PANEL

480-volt motor lines. For safety reasons, the control switch circuit is configured to provide proper system defaults. For instance, the heaters will not operate unless the pump motor is running. Also, if power is interrupted, the switches all default to the off position and the start-up procedure must be manually repeated.

The control panel and its use are fully described in the Operation and Maintenance Manual, but briefly there are: a main power on/off control, heater enable controls, pump motor on/off control, automatic flush system control and foaming control. All switches have green lamps to indicate the on position and red status lamps indicate system status such as "foaming" and "flushing". The button that activates foaming (flow to the gun) is a momentary switch that operates on a 12-volt relay circuit. A second switch can be mounted on the foaming gun to be controlled by the diver. A selector switch on the control panel allows either the diver's control or the panel mounted "surface" control to be operable. Also on the main control panel are instrument gauges providing flow rates, pressures and temperatures for each of the two component chemicals. All three electrical boxes are NEMA class 4 boxes, meaning they are weatherproof.

Operational Tests

Operational tests were conducted on the Full-Scale Prototype Foaming Machine to verify the machine performance, calibrate instruments and perform any necessary de-bugging.

Machine Testing. The most time consuming task was calibration of the instruments. The flow meters did not supply the linear output signal necessary for most common digital displays. The manufacturer recommended using a needle type, panel meter with a non-linear printed scale. As was not acceptable, a circuit was built to convert the non-linear signal into a simulated linear signal. This signal was then supplied to digital displays (Weston voltmeters). Because of the linearizing circuit, the displays read 1.0 gpm at zero flow, but are accurate from 2 to 10 gpm which includes the normal operating range of 6 gpm.

The heater controlling mechanism consists of an RTD (resistance temperature detector) located downstream of the heaters and a PID (proportional integral derivative) controller. The PID controller can be adjusted to react quickly. Due to the slow response of the RTD, temperature oscillations about the set point occur, and take about 5 minutes to die out. Much time was spent fine tuning the heater control system to avoid excessive overshoot and obtain quick temperature stabilization. Although the present system provides satisfactory performance, future designs might utilize either faster temperature detectors, dual temperature detectors (upstream and downstream) or a 2-stage heating system.

The original filters contained 25 micron stainless steel mesh elements. The viscosity and surface tension of the polyurethane chemicals caused these filters to have excessive back pressure resulting in a continuous bypass flow. The elements were subsequently replaced with units of higher micron value to eliminate this problem (200-300 micron).

Other minor leaks and adjustments were made before the first foam was made.

Operational Foaming Tests. The Full-Scale Prototype Foaming Machine presented the first opportunity for Battelle engineers to know precisely what temperature, pressure and flow rates were being generated. The MDI is more viscous than the polyol (if they are at the same temperature) and, as expected, when you have identical-sized orifices, the pressures and flow rates cannot both be equal. If the polyol and MDI flow rates are set equal, then the MDI line would show greater back pressure. Because the control panel instrumentation shows pressure at the pump outlet it does not reflect the actual pressure at the gun. Pressure gauges at the gun showed pressures to be within 50 psi and since unequal pressures were not causing the head to clog by having one fluid stream enter the opposite orifice, it was decided to set flow rates equal for the best foam making and allow the pressures to be slightly unbalanced. Heating the MDI in later tests reduced its viscosity and equalized component pressures.

A significant benefit of the full-scale prototype foaming system is that many more experimental "runs" can be made in a given time period due to the automatic filling and self-cleaning aspects of the machine. Also, there is significantly less exposure of the operating personnel to the various chemicals with this machine which provides a much safer working environment. The net result is that more time could be spent conducting research and less on machine operation labor compared to the laboratory model machine.

Testing Program

Both the laboratory model and the full-scale prototype foaming system have received significant testing. The testing program consisted of in-house tests conducted in the 2 meter (6 foot) diameter tank and seawater tests at Tracor Marine's Port Everglades facility. The following sections outline these two testing programs.

In-House Tests

Both the Laboratory Model and Full-Scale Prototype Foaming Machines were put through a series of formal in-house tests following their respective operational tests. The following sections describe the results of these two testing programs starting with the Laboratory Model Foaming Machine.

Laboratory Model Foaming Machine In-House Test Results. Guns number 2 and 3 were tested in the tank. The data recorded for each run are in Appendix A. During some tests, the gun was aimed up and for others it was aimed down. In both cases, guns number 2 and 3 worked well, producing high-quality foam. The "shots" were usually about 20 seconds duration, and the best nozzle length was 84 centimeters (33 in.). The chemicals were approximately at room temperature.

The check valves in the chemical lines worked well, but they reduced the total flow rate in both hoses from 45 liters per minute to 28 liters per minute (12 gpm to 7-1/2 gpm). These flow rates are based on running DOP, not the actual chemicals. The flow rate of the foam chemicals is somewhat lower because they are more viscous than DOP.

The air jet was turned on for some tests, but it produced no difference in foam quality. At the shallow depths of these in-house tests, air was not expected to contribute to the process.

A board was fastened at the top of the tank to keep the foam submerged during cure. Good-quality foam resulted, with densities ranging from .03 to .08 grams per cubic centimeter (2 to 5 lb/ft^3). The outermost layer of foam cured while exposed to the water. This layer, from a fraction of an inch to several inches, was somewhat crumbly and of inferior quality. This is to be expected.

Figures 22 through 24 show a sequence from a typical foaming test and the resulting cured foam after removal from the tank. Some head fouling was still experienced, but the head could be easily cleaned because of the presence of the check valves.

Full-Scale Prototype Foaming Machine In-House Tests. The first in-house tests on the Full-Scale Prototype Foaming Machine were run using 30 meter (100 feet) long hose of 2.5 centimeter (1 inch) I.D. Gun no. 3 (6 degree impingement angle) was used as it had the best demonstrated performance in earlier tests. Pressure gauges and thermometers were connected to the plumbing just behind the gun. As previously discussed, the gun flushing system was automatic and used the solvent, methylene chloride.

The first few tests were run in both air and water with the chemical heaters off and produced foam of the same quality as the Laboratory Model. A 10 centimeter (4 inch) I.D. nozzle of PVC was used and 18 inches appeared to be a good length. Flow rates were approximately 23 Lpm (6 gpm) each side, with a pressure of about 120 bar (1750 psig) at the pump outlet. Pressure gauges at the gun indicated a 4 to 7 bar

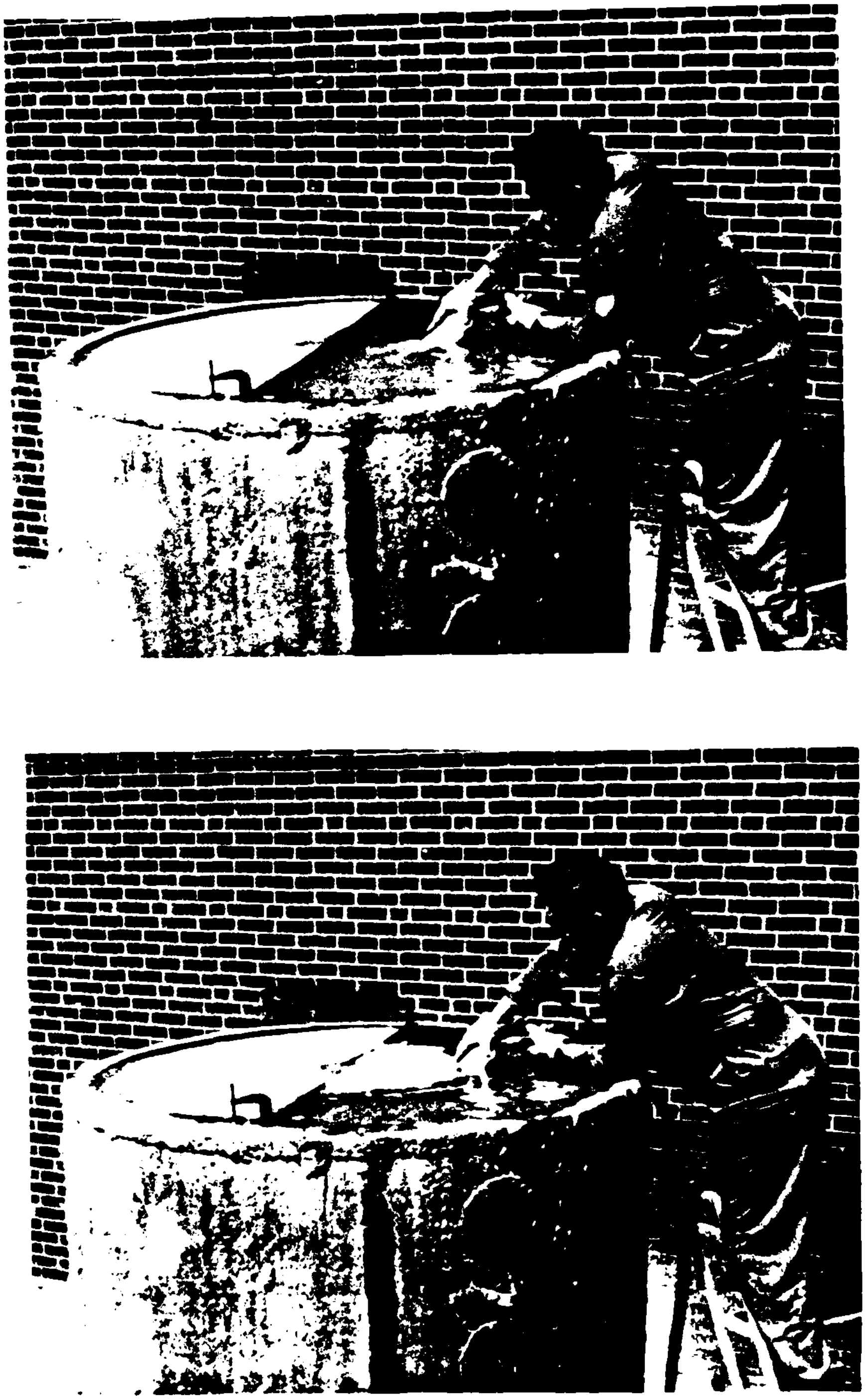

FIGURE 22. TYPICAL FOAM TEST: SEQUENCE 1 AND 2

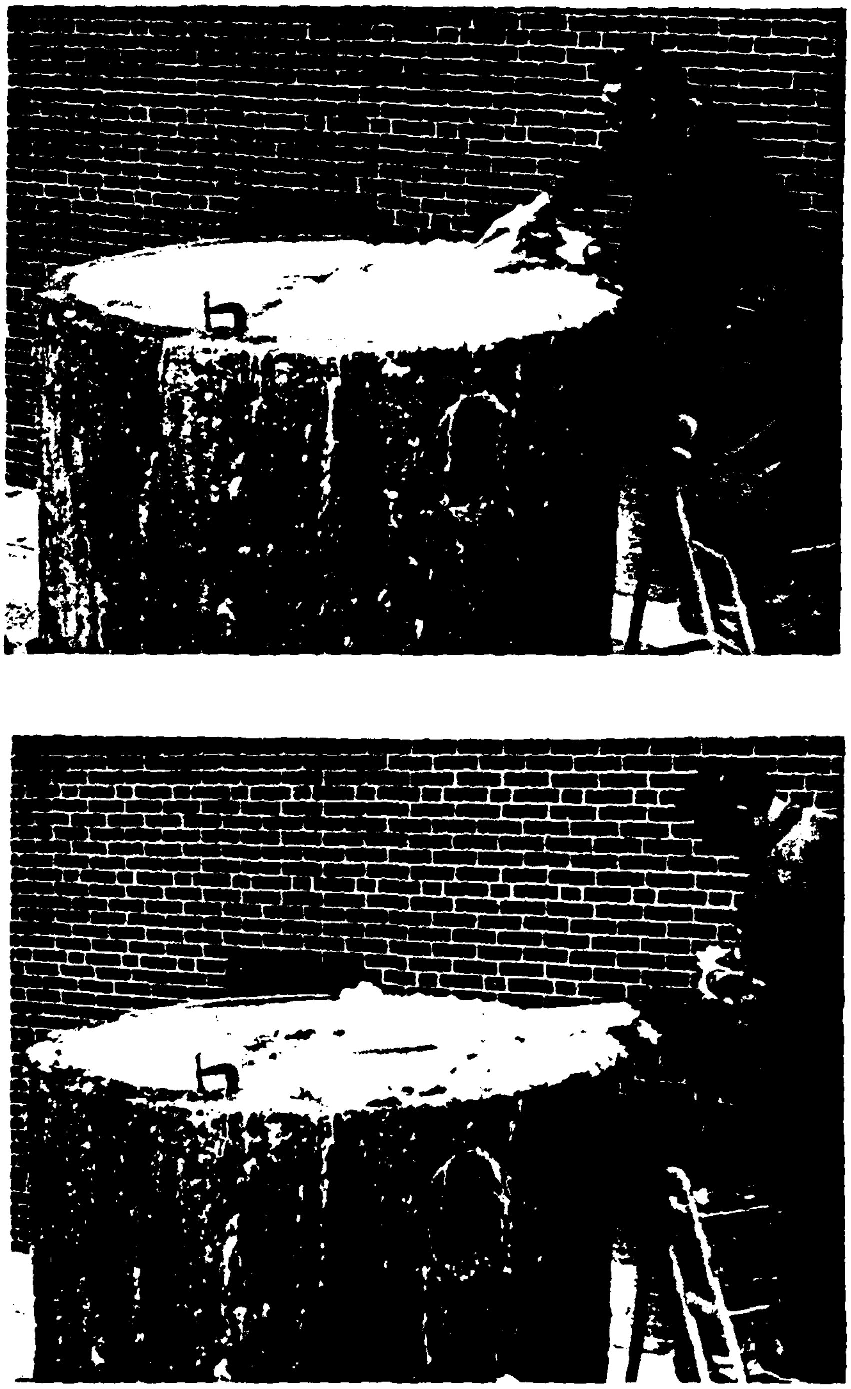

FIGURE 23. TYPICAL FOAM TEST: SEQUENCE 3 AND 4

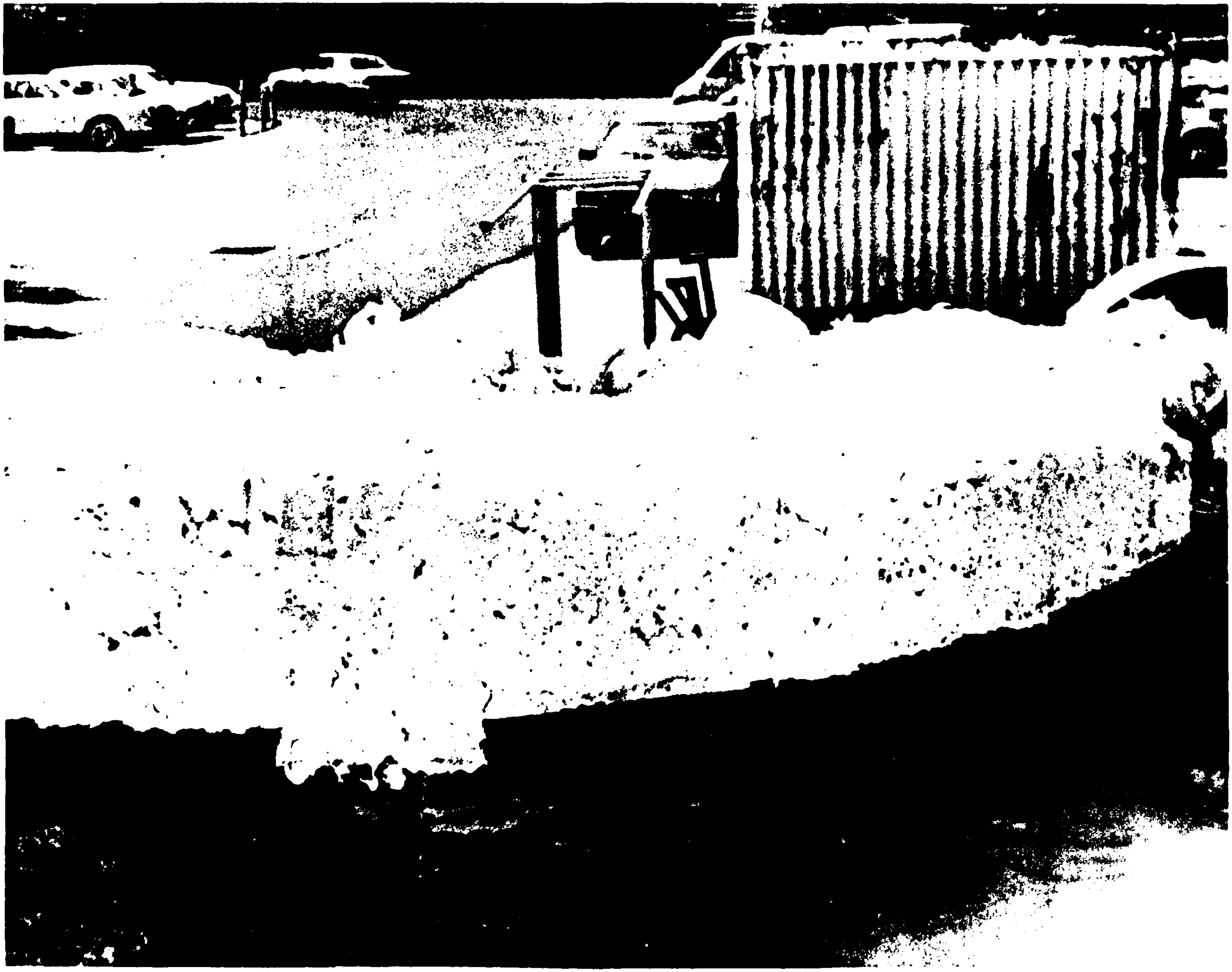

FIGURE 24. FOAM MADE UNDERWATER DURING TEST

(50 to 100 psi) flow loss in the hose. Runs of 10 to 30 seconds were made using PPG SC 43-60 Selectrofoam for the polyol and Mobay Mondur MR for the MDI. Chemical temperatures were at a nominal 22 degrees Celsius (72 degrees Fahrenheit).

The 25 micron elements in the filters were too fine for chemicals of this viscosity and immediately started bypassing. Filters with 200 or 300 micron elements were ordered.

The Vickers PVB-10 piston pumps are handwheel adjustable and utilize a small worm gear train. This gear train has a considerable amount of backlash in it and allowed the flow rates to vary after being set. This problem was minimized by adjusting from the direction that the pumps tended to drift and thereby taking up the backlash. Future machines should use an alternate adjustment method (if one is used at all).

In general, the performance of the foaming machine itself was quite satisfactory. The machine controls made the unit easier to operate than the laboratory model machine. There was a reduced need for breaking chemical lines and less atmospheric contamination resulting in a safer working environment. The machine automatically fills itself from 210 liter (55 gallon) drums, automatically flushes the foaming gun, utilizes solenoid valves to perform certain functions and is otherwise easily controlled.

Two significant but easily corrected problems were encountered with the present machine design. The first was the heater control system. The chemical temperatures are sensed at the heater outlets with a sheathed RTD (resistance temperature detector). The RTDs signal PID (proportional integral derivative) controllers. These controllers can sense a rate of change in the chemical temperature and thus start corrective action before the RTDs fully detect it. A good deal of time was spent adjusting the system for optimum performance. Temperatures are fairly stable after 2 to 5 minutes of recirculation. For actual salvage operations this transient behavior should be acceptable since the temperatures can be stabilized during recirculation, causing only a 5 minute delay in foaming startup. We have seen no tendency toward head clogging due to chemical temperature variation. If faster responding RTDs or precision calibrated thermocouples were used to detect chemical temperature, the response time would be reduced and this would greatly assist the PID controllers in stabilizing the temperatures sooner. Further improvement would involve the use of multistage heating with a temperature controller for each stage. This would increase the cost of the system, but should be considered for future foaming machine designs. Temperature controllers which have upstream and downstream sensors are not commonly available, but still may bear investigation.

The other significant problem involved the type of flow meters used on the Full-Scale Prototype Machine. The flow meters use a paddle type mechanism that turn out to be strongly dependent on chemical viscosity. The flow meters were calibrated with the correct chemicals, but as the chemicals are heated the viscosity can vary by as much as 2400 centipoise. This causes flow meter errors of up to 11 Lpm (3 gpm). Because the gun orifices behave like sharp edged orifices, the line pressure of the chemicals is a function of just the flow rate and orifice size. Thus, if the line pressure and orifice size are known then the flow rate can be deduced. This method is fairly insensitive to chemical temperature (viscosity) and was used in place of the malfunctioning flow meters. Flow measurement methods which do not depend on the chemical viscosity should be utilized in future designs. In fact, flow meters could be eliminated from future designs, since the flow through a given orifice size at a given pressure can be experimentally established. For operation, line pressures can then be matched using the knowledge of the corresponding flows.

Tests run with heated chemicals produced better quality foam due to the faster reaction time. The fast reaction reduces the amount of water contamination. In addition, the extra heat increases the degree of blowing or cell creation which causes the foam to expand. The cells are formed by freon which is boiled to a gas during the reaction.

Typically, only the MDI is heated because the freon is in solution in the polyol and will turn to gas at temperatures slightly above room temperature. This off-gassing can cause vapor lock and pump cavitation in the foaming machine. The MDI is over-heated enough to yield a net mix temperature equivalent to that desired. Typical MDI temperature was 37 to 50 degrees Celsius (100 to 120 degrees Fahrenheit). Polyol temperature was 22 to 29 degrees Celsius (72 to 84 degrees Fahrenheit) during the in-house tests. For use on warm days, in future designs, the polyol should have a cooling loop to keep temperatures within manufacturer recommendations.

Because the Full-Scale Prototype Foaming Machine was intended to operate at 23 Lpm (6 gpm) from each component, the original foaming gun orifice size of 1.6 millimeter (1/16 inch) produced line pressures of greater than 120 bar (1750 psi). This is the pressure at which the relief valves open and, therefore, an unknown volume of chemical was being relieved back to the reservoirs. The foaming gun orifices were subsequently drilled to 2.4 millimeters (3/32 inch). This allowed the machine to be run at 23 Lpm (6 gpm) with a line pressure of approximately 103 bar (1500 psig).

During all of the runs there was no problem with clogging of the outlet orifices or passages within the gun (not to be confused with nozzle clogging). The automatic flushing system using methylene chloride worked very well. Because of this, the check valves that were installed in the foaming guns to limit the degree of fouling were removed. The guns did weep foam chemicals after a run with or without the check valves, but did not clog as long as they were flushed periodically. Ball valves were installed between the hoses and the foaming gun to prevent the weeping and they performed as intended. The ball valves are rated for use at 2000 psi. Opening and closing the ball valves should be coupled to the electric switch that activates the foaming process for single step gun operation in future designs. In any event, the valves must be connected together so that they open and close simultaneously.

One of the purposes of the Full-Scale Prototype Foaming Machine was to provide enough control of the chemical states that meaningful research could be conducted on optimizing the gun and nozzle design. Both gun nos. 2 and 3 were tested and provided a good mix and no clogging. The lack of internal gun clogging was a result of the more controlled pumping and pressure aspects of the machine and the new flushing system. Therefore, no improvement in the mixing area was warranted. However, as discussed below, the outlet nozzles were clogging with the Laboratory Model Foaming Machine and this behavior continued with the Full Scale Prototype.

The nozzle fits over the foaming gun as shown previously in Figure 5. The purpose of the nozzle is to protect the foam from water contamination from the time it is mixed until it is starting to rise. The foam must be dispensed before it rises too far or it will harden in the nozzle. Dispensing the foam too soon will cause poor quality foam and wasted chemicals because of reaction with the water. The optimum nozzle length can be determined if the flow rates, chemical reaction rates and chemical temperatures are fixed, as is the case with this machine.

Nozzle clogging is a result of the boundary layer fluid moving slowly enough to rise, harden and stick along the nozzle walls. This process continues and reduces the nozzle I.D. causing two problems. The first problem is that as the I.D. of the nozzle decreases, the fluid velocity increases. Thus, before long the foam mix is being expelled into the water before it has had sufficient time to rise. This results in poor foam quality or no foam formation at all. The second problem is that the nozzle may completely clog and the foam will cease to flow.

Several attempts were made to eliminate this problem. The first attempt was to coat the nozzle interior with a mold release agent. Although this seemed to delay the phenomenon it did not prevent it. Coating the nozzle and gun face with a lubricant such as Aqua-Lube® grease kept the gun face clean but tended to wear off.

A second method for preventing nozzle clogging was to increase the turbulence in the nozzle by using one of smaller I.D., but longer length (to provide sufficient time for the foam to rise). The 10 centimeter (4 inch) diameter nozzle was replaced with an 8 centimeter (3 inch) diameter one. This nozzle was also coated with Aqua-Lube®, but did not eliminate the clogging problem.

The last in-house tests used a 5 centimeter (2 inch) Gooch tube for a nozzle. Gooch tubing is an elastomeric tube that naturally lays in a flat, closed position. When the foam is injected into it, it opens as required and no more. The outlet end remains closed until the first amount of foam reaches it, thus reducing the amount of water exposure. This nozzle configuration made high quality foam in our tank and left the tank water relatively clear, suggesting a high chemical efficiency.

At-Sea Tests

Immediately after the in-house operational tests, the laboratory model foaming machine and ancilliary equipment were shipped to Florida for the at-sea tests. The tests were postponed for 7 months while NAVSEA-00C arranged for support for these tests. In January, 1985, Battelle engineers trav-eled to Tracor Marine, Incorporated, in Port Everglades, Florida, for the at-sea tests.

The first day at Tracor was spent getting the equipment on board the R/V G.W. Pierce II and connecting the necessary utilities. Because the foaming machine had been idle for so long, Battelle engineers had to check its operation and refurbish it. When both the foaming system and the other shipboard support equipment were operational a complete dry run was made. This dry run included running the machine with DOP instead of foam and sending divers and the foaming object into the water for practice. All personnel and equipment were then ready to begin the actual tests.

The foaming object constructed by Tracor was a steel box, 1.4 x 1.4 x 1.2 meters (4-1/2 x 4-1/2 x 4 ft), with an open bottom, legs, and a weight. Pictured in Figure 25, the box had a removable top, and the sides angled slightly outward toward the top. The removable top and angled sides were to facilitate foam removal. The legs allowed a diver to enter the object from below, and the weight prevented the object from ascending even when completely filled with the buoyant foam.

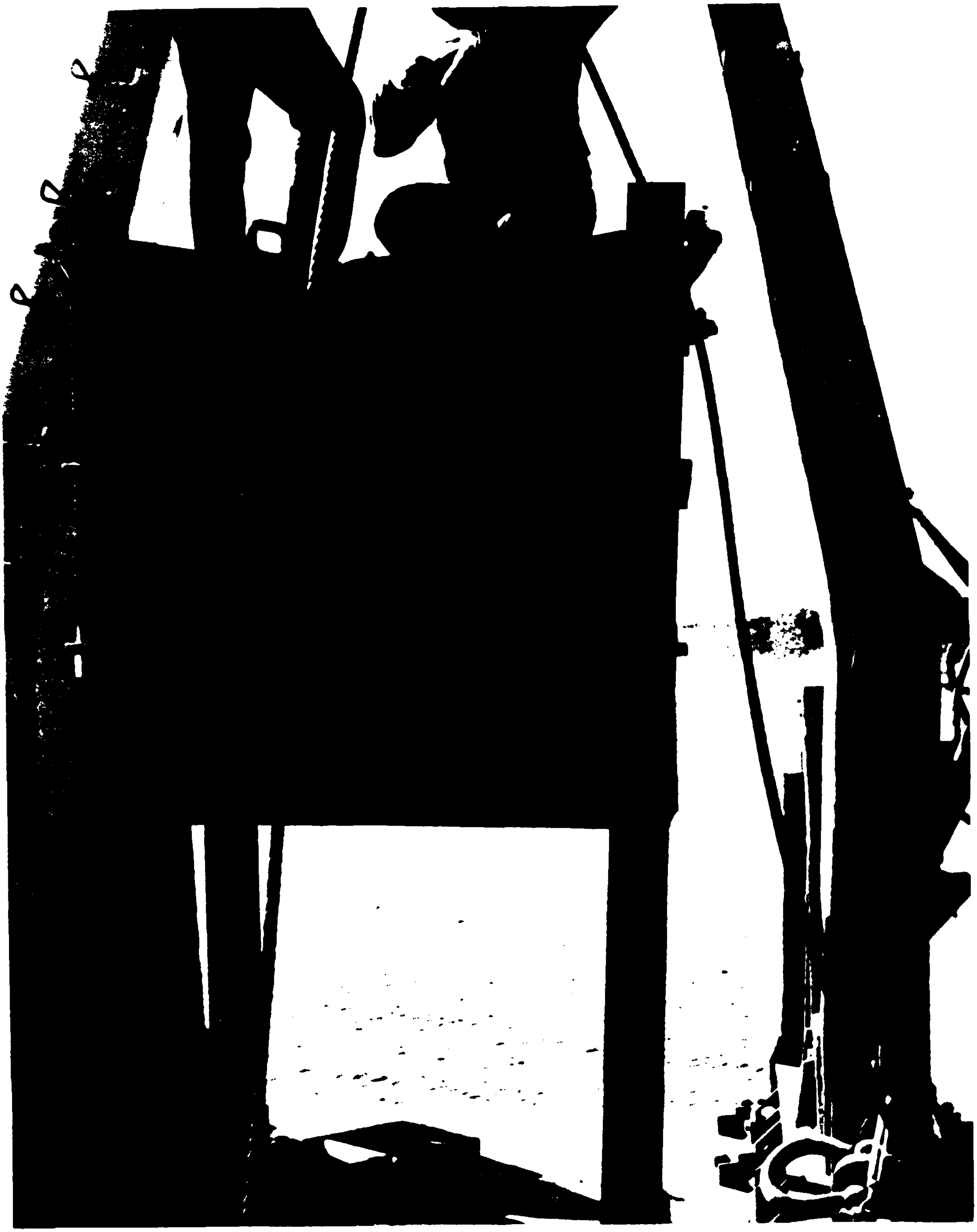

FIGURE 25. FOAMING OBJECT (BOX)

The object was loosely lined with vinyl sheeting during the first few tests, also to facilitate foam removal.

Five tests were run in 13 meters (42 ft) of seawater off the stern of the ship while it was docked (dockside tests). On the following day (day four), the R.G. Pierce II was taken out to sea and three tests were made at 16 meters (52 ft) in calm seas.

The detailed data sheets from the at-sea tests are contained in Appendix B but are summarized here.

An on-deck test was run just to check the machine operation. This run (Run no. 1), produced excellent quality foam, with about 0.03 grams per cubic centimeter (2 lb/cu-ft) density. The pumps came up to pressure equally, and there was no gun fouling.

Dockside Tests. The first test in seawater (Run no. 2) was a 2-minute, 48-second run. The object gained 544 kilograms (1200 lb) of buoyancy and produced good quality foam with a density in the center, of 0.091 grams per cubic centimeter (5.7 lb/cu-ft) and 0.19 grams per cubic centimeter (11.8 lb/ft^3) at the outside layer. The water temperature was $31^{o}C$ ($70^{o}F$), the air temperature was $16^{o}C$($60^{o}F$), and the nozzle length was 86 centimeters (34 in.). The object was retrieved after this run and was placed on deck. When the top was removed, the vinyl sheet allowed the foam to come out with it. A cable running down from the center of the top was all that held the foam to the top (see Figure 26).

Because the laboratory-model foaming machine did not have flow meters, it was difficult to determine flow rates and efficiency. Efficiency is defined here as the amount of solid foam formed underwater, divided by the amount of foam dispensed at the gun. Calibration of the machine before a run is not an accurate method of determining amount of foam dispensed at the gun because pressure at depth and any flow restrictions occuring during a shot will reduce the flow rate. Based on very rough estimates and assumptions, we believe the efficiency ranged between 20 percent and 40 percent.

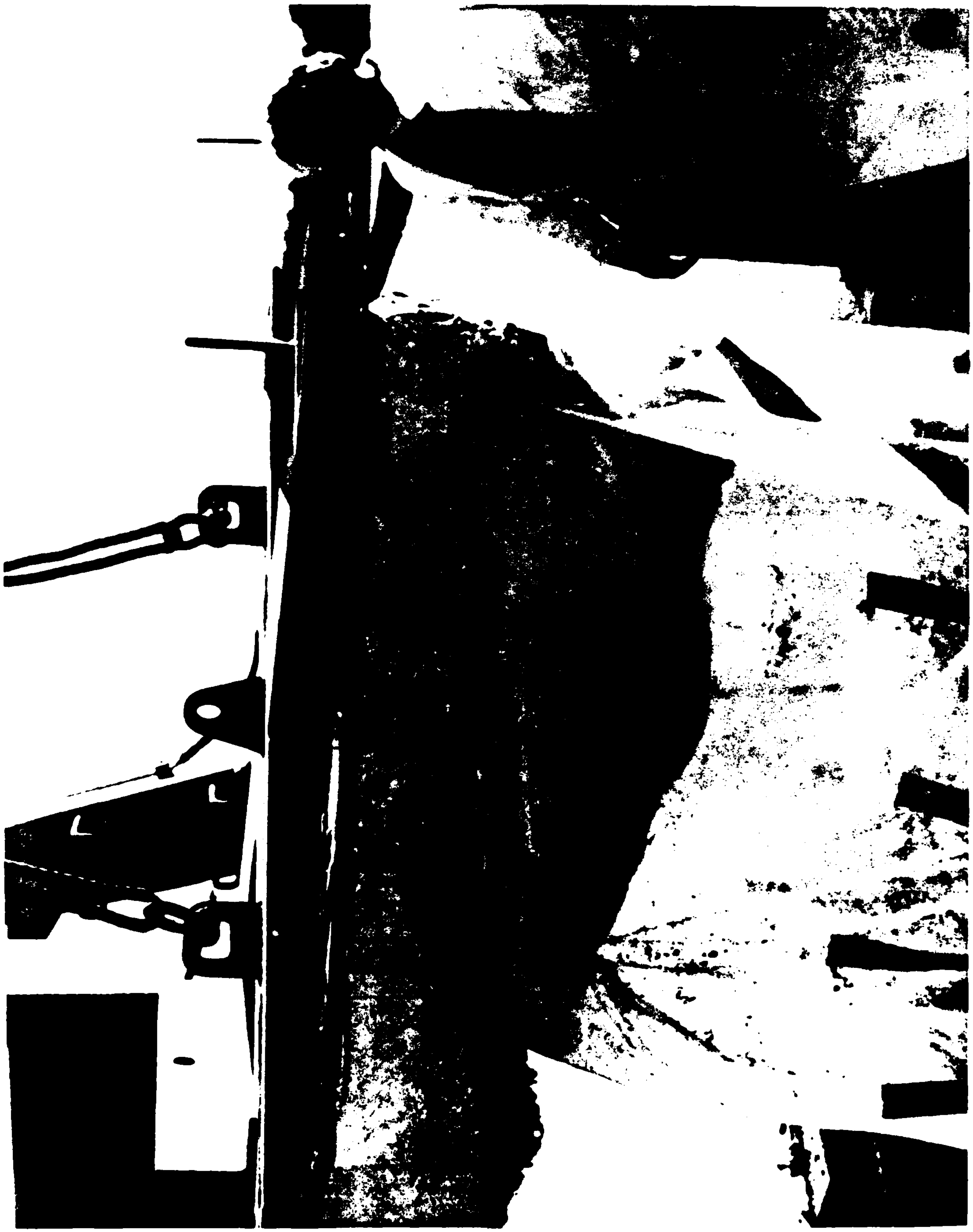

FIGURE 26. FOAM FROM RUN NO. 2

The divers noticed the water turning milky in the immediate foaming area, which indicates some loss. However, losses are a natural occurrence when making foam underwater; they are not necessarily a cause for concern. The intent is to quantify the amount of loss and to keep it to a minimum. There was little indication of the milky water from the surface, but the volume of water in the area must be considered. A small amount of hardened foam came to the surface, was contained in the oil boom, and was netted off.

The second underwater test (Run no. 3), was similar to the first, but with a 114 centimeter (45-in.) nozzle. This nozzle was too long and resulted in foam hardening in the tube and stopping flow after 3 minutes and 10 seconds. Run no. 4 used a 58 centimeter (23-in.) nozzle and ran for 2 minutes and 42 seconds before clogging with hardened foam. The isocyanate was at 38°C (100°F) during Run no. 4, which was 6°C (10°F) warmer than in Run no. 3. Thus, even the shorter nozzle was not short enough as the reaction rate had doubled.

The foam barrels were being heated with electric drum heaters (band type), as was mutually agreed upon before the tests. The only temperature control was the uncalibrated thermostats on the heaters themselves. Thus, it was difficult to maintain any consistent temperature control. This was a major problem during the tests as the nozzles must be adjusted to the chemical temperature. During the dockside tests, only the isocyanate had to be heated, because the polyol was in the 16 to 21°C (60 to 70°F) range (ambient temperature). During the tests at-sea, however, the polyol had to be heated also. Due to the lack of temperature control, the polyol was overheated, causing the freon to come out of solution. This was remedied by pressurizing the polyol barrel with air at 0.7 bar (10 psi).

Run no. 5 used a 28 centimeter nozzle (11-in.), but the run was aborted because the gun was clogged. The clogging nozzles may have caused the clogged gun to clog by not allowing room for the expanding foam to escape. Closer inspection revealed that only the isocyanate orifice had clogged. A piece of a broken drill bit found in the orifice was probably the cause of clogging. Run no. 5 was the last dockside test.

At-Sea Tests. The Pierce was taken out to 15 meters (50-ft) deep waters and put into a two-point moor. The foaming object was not lined with the vinyl sheet because foam removal had not been a problem and we wanted to see how the foam adhered to the bare steel. The water temperature was approximately 18^{O}C (65^{O}F), and the air temperature was in the low-20s (70s^{O}F).

The first at-sea run, Run no. 6, lasted for 4 minutes, after which time the diver signaled to stop. The diver thought all the foam was escaping through cracks in the foaming object. A second attempt was made (Run no. 7) using the same 73 centimeter (9-in.) nozzle, but the diver again signaled a stop for the same reason. Subsequent investigation revealed that foam was indeed being made, but visibility prevented the diver from noticing. The chemical temperatures were found to be excessively low during runs no. 6 and 7; thus, efficiency may have been low, resulting in poor visibility.

Both of the chemicals were heated, and the polyol barrel was pressurized before Run no. 8. The longest continuous shot was achieved during this run, lasting 4 minutes and 30 seconds before the nozzle plugged. Over 360 kilograms (800 lb) of buoyancy was added to the object during this run. The object was retrieved and was found to contain high-quality foam with densities of just under 0.16 grams per cubic centimeter (10 lb/cu-ft). The individual layers from each run (nos. 6, 7, and 8) could be identified in the large chunk of foam retrieved. Figure 27 is a photograph of part of the foam chunk (a piece broke off and drifted away).

Because the objective of the seawater tests was to prove that good-quality foam could be made at sea using the impingement process, the tests were considered a success and were halted. It would have been desirable to experiment further, but little more could be learned without accurate flow data and controlled chemical temperatures.

FIGURE 27. FOAM CHUNK FROM AT-SEA TESTS
(RUN NOS. 6, 7, AND 8)