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AD-B086 978

DTIC ACCESSION NUMBER

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Final Rpt., Apr.'81 - Mar.'82, Rpt. No. J520-82-2228
Yu, H.-Y. James; Vesel, Edward J.
Contract DAMD17-81-C-1059
July'82

DOCUMENT IDENTIFICATION

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A PROPOSAL TO BUILD A LABORATORY BLAST OVERPRESSURE TEST SIMULATOR; Subtitle: The Development of a Water Jet Impactor

Final Report

by

James H.-Y. Yu
Edward J. Vasel

July 1982

Supported by

U. S. Army Medical Research and Development Command
Fort Detrick, Frederick, Maryland 21701

Contract No. DAMD17-81-C-1059

JAYCOR
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) A PROPOSAL TO BUILD A LABORATORY BLAST OVERPRESSURE TEST SIMULATOR; Subtitle: The Development of a Water Jet Impactor		5. TYPE OF REPORT & PERIOD COVERED Final Report April 1981-March 1982
		6. PERFORMING ORG. REPORT NUMBER J520-82-2228F
7. AUTHOR(s) James H.-Y. Yu, Edward J. Vasel		8. CONTRACT OR GRANT NUMBER(s) DAMD17-81-C-1059
9. PERFORMING ORGANIZATION NAME AND ADDRESS JAYCOR 11011 Torreyana Road San Diego, California 92121		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62777A.3E162777A878.AB.001
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Medical Research and Development Command Fort Detrick Frederick, MD 21701		12. REPORT DATE July 1982
		13. NUMBER OF PAGES 98
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Blast overpressure
Jet impact
Pulmonary and gastrointestinal tract injury

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In order to establish a damage risk criteria (DRC) on pulmonary and gastrointestinal injury for the operating crew who fire heavy artillery, direct information that links the critical blast overpressure parameters and the degree of injury is necessary. Although field tests can be performed to provide the data, they are not amenable to speedy post-mortem analyses and sophisticated instrumentation. A laboratory test facility that is capable of generating the equivalent blast overpressure signal will serve the purpose and

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20. ABSTRACT (cont'd)

greatly facilitate the test procedure. It will also help to provide an environment for systematic and controlled experiments to quantify the relationship between blast and injury.

However, for various reasons, most conventional approaches in generating the blast overpressure or its equivalent are not suitable for a laboratory setting. The idea of using a jet impactor to generate the impact signal was conceived. This report summarizes the process of the development of such an apparatus. The first part focuses on the proof of the principle and identification of key elements and parameters. The second part is mainly devoted to the design and development of the prototype system.

The system developed in this project is able to deliver a peak pressure of 25 psi over 100 in.^{2} target area. It has a rise time of about 1 ms, and the shots can be repeated at four shots per minute for an infinite number of shots. After a series of calibration tests, the unit was delivered to the Walter Reed Army Institute of Research for animal impact tests.

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THE DEVELOPMENT OF A WATER JET IMPACTOR

Final Report

by

James H.-Y. Yu
Edward J. Vasel

July 1982

Supported by

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1. INTRODUCTION

Evidence of pulmonary and gastrointestinal injuries in animals from intense blast overpressure (BOP) and the general distress to the operating crew of the extended range M198 towed howitzer prompted the Army to conduct detailed research work to define a damage risk criteria (DRC) for humans in a blast environment. In order to facilitate the clinical test, an on-site apparatus that would generate a similar BOP or its equivalent was required. In addition, this apparatus must be able to provide certain special features. A general guideline about these features was provided by WRAIR. These include:

1. Small overall dimensions so that it can be installed in a normal size room for clinical usage.

2. Capability of delivering a uniform pressure, up to 25 psi, over a 100 $in.^2$ target area.

3. Repetition rate of 4 shots per minute for infinite number of shots.

4. Lack of nuisance or hazard to operating personnel and surrounding residents.

5. Ease of operation and convenience of use.

As a result of these requirements, it was apparent that the conventional approaches would not be suitable for this application. For example, the approaches of using gun blast, shock tube and the detonation of TNT would not be appropriate for a clinical laboratory setting. Mechanical impact with controlled velocity and displacement on impact to simulate the blast effect was used extensively by Clemedson. However, the apparatus was too large to be used indoors and the repetition rate was slow. Moreover, it was questionable whether the crushing effect of the mechanical impact would faithfully reproduce the effect of the shock wave. The uncertainties and drawbacks associated with the existing approaches suggested that an alternative approach was required.

One of the plausible approaches was to use pulses of high velocity water jets to hit the target. Since this approach had no shock noise, was nonmechanical, and could be easily tailored for different pressures, it became an attractive candidate. This report details the rationales and procedures of the development of such a jet impactor system.

Because this project involved the development of a new product, considerable uncertainties were present. To reduce the risk and minimize the impact to the overall program, the project was divided into two phases with the proof-of-principle as the milestone of the first phase. Once the concept was proved to be feasible the next phase would then be continued and a prototype system designed and fabricated. Otherwise it would be terminated and alternatives sought.

This report summarizes the design concept, the major hurdles, and the approaches we took to alleviate such hurdles. It is divided, in accordance with the two phases of the project, into two major sections with the next section devoted to the conceptual verification and parametric study of a single valve system while the section that follows concentrates on the development of the prototype system. Detailed installation and maintenance manual, parts and vendors lists, and the engineering drawings are appended for reference.

2. THE JET IMPACTOR MODEL

2.1 SELECTION OF THE APPROACH

A typical BOP signal has a sharp pressure rise followed by an exponential decay and rarefaction. The objective of this phase was to construct a model apparatus that would deliver a short pulse of water and generate a signal similar to that of a BOP.

A number of ideas were conceived and their pros and cons weighed. It was concluded that the approach of using a fast cycling valve to deliver the desired pulse of water would be most desirable and involve the least amount of development work. When such a valve is combined with a properly designed distributor plate, a bundle of uniformly distributed jets can be delivered to the target and generate the impact pressure over the desired area.

Since time required for development was of utmost concern and this approach used existing hardware and thus less development work, it was chosen as the candidate approach. The following subsections are centered around the development of this concept.

2.2 DESIGN CONSIDERATIONS AND PROVISIONS

The first question to be asked in the design of a test jet impactor was the design capacity: the design pressure and the design flow rate. Once these parameters were determined, the rest of the system components would fall into place accordingly.

Since the main objectives of the first phase were to prove the principle, learn about the system performance, and develop a unit that can be used on a small test animal, a system that would impact a 4 in. diameter area was chosen. Since a 25 psi peak impact pressure was required, the system pressure was estimated on the order of a few hundred psi. The exact value depended on the amount of discharge and, more importantly, on the performance of the valve.

For an impact signal of 25 psi, 5 ms duration, and a 12.5 in.^{2} coverage area, an equivalent flow rate of 600 gpm at a line pressure of 100 psi would be required. This high flow rate calls for a very large pump-and-motor system, and even at considerably higher line pressure, the size is still prohibitively large. For a prototype that was eight times larger, the approach would hardly be practical.

To alleviate this difficulty, a high capacity, high discharge rate accumulator was designed into the system. The large discharge port and high volume capacity, allowed a large volume to be delivered in a short time and without "starving" the system. The high pressure pump would only serve to recharge the accumulator to its test setting and would have little effect on the jetted water. For this purpose, a positive displacement pump, model 430 triplex CAT pump, was chosen for its high capacity (up to 1000 psi in pressure, 5 gpm in flow rate) and minimal pressure fluctuation. A 2 HP Baldor TEFC motor was selected to drive the pump.

For different impact pressures, different line pressures were required. This adjustment was done with a pressure regulator. For each setting, part of the flow would be delivered downstream of the regulation and part would be bypassed back into the supply tank. As water fills up the accumulator, its pressure increases and thus decreases the pressure difference across the pressure regulator. This reduction reduces the flow into the accumulator and forces more flow into the bypass. In this way, the set pressure is achieved asymptotically.

For each shot, water is dumped out of the accumulator, the system pressure decreases and the recharge cycle restarts.

The amount of pressure reduction in the accumulator affects the amount of recharge time and the allowable period between shots. For a large capacity accumulator, the amount of water ejected per shot would only be a small percentage of the accumulator and hence less pressure reduction in the system. However, a large accumulator increases the volume of the total system and thus installation difficulty and cost. An initial estimate based on the amount of water delivered, and the nominal accumulator air/water volume ratio indicated that a 2.5 gallon accumulator would give a pressure variation of less than 5%

per shot. This capacity was chosen and was also used as the basis of estimation for the later prototype design.

A side benefit of the installation of an accumulator in a pump system was that it significantly reduced the amount of pressure pulsation caused by the cyclic action of the pump; otherwise, a pulsation damper was recommended by the manufacturer.

The most critical element of the impactor system is undoubtedly the control valve. In principle, it should have a fast pressure rise, short duration, be capable of covering a large area with high pressures, and be capable of being installed in any orientation. To meet these requirements, we needed a large diameter, fast cycling time, high pressure rating valve to deliver the impact. However, these features were not mutually inclusive and most of the valves had only one or two of the desirable features.

In general, large, high pressure valves are bulky and slow, while those that are fast and light are small, but suitable for low pressure, low flow applications only. Moreover, the vendors usually do not have the performance information needed for this task except in very general terms. The only way to qualify the performance of candidate valves was direct in-house calibration.

In conjunction with the pressure regulator, a check valve was installed to insure a one-way flow. This valve kept the water in the system when the pump was turned off.

A water tank with an automatic float shut-off valve was used as the supply reservoir for the pump. It was connected to a tap water outlet.

To prevent rust formation in the system, materials used in the systems were limited to brass, stainless steel or plastic. For the cases where these materials were not practical, the surfaces in direct contact with water were coated with epoxy paint.

In order to effectively control the valving cycle, a Xanadu Universal Programmable Timer was used. This timer has 10 channels with the capability to control 10 valves. For each channel, pulses of different durations and intervals can be independently controlled.

Rise time, pressure magnitude and pressure distribution uniformity were the three key requirements of the jet impactor. In order to evaluate these parameters accurately, piezoelectric transducers were used for pressure and force measurements. The pressure transducer was used to monitor the uniformity of the pressure distribution while the force transducer was used to monitor the total force over the entire target area. The outputs from these transducers were displayed on a Nicolet digital oscilloscope. Since this scope displays the digital information at each time step, very detailed information on the impact signal was obtained.

2.3 DEVELOPMENT OF THE SINGLE VALVE JET IMPACTOR

Based on the above design considerations, the single valve jet impactor was designed as shown in Figure 1, and the fabricated setup shown in Figure 2.

The initial concept assumed that a uniform jet front, and thus a fast pressure rise, would be achieved by using a head reservoir combined with a large full target area orifice plate. Therefore a 4 in. diffuser cone was installed between the valve and the orifice plate (Figs. 3 and 4) so that a uniform flow would be achieved before jetting out. However, this arrangement was later found not feasible for two reasons: (1) it was not suitable for horizontal installation because water would be drained out of the cone; and (2) it would not generate high enough impact pressure because of its large cone volume and large orifice openings. The large orifice openings prevented the formation of sufficient backpressure that is essential for high impact pressure. Thus, instead of the straight jet and diffuser chamber combination, it was replaced later by a small cavity and orifice plate of fanning nozzles combination. A more detailed description of this design will be given later.

A major concern of the project was the valve cycling time, and much emphasis was placed on the impact duration. Since smaller valves activate faster, valves as small as 0.5 inch in diameter were tested. Other sizes tested included 1, 1.5, and 2 inch.

After considerable effort was expended in searching and testing, we found that only the ASCO normally-closed, 1-1/2 inch DC valve possesses most of the desirable characteristics. This valve has a safe working pressure of 250 psi (with a burst pressure five times higher), has an adequate size and discharge coefficient, is reasonably priced, and has the smallest overall dimensions among comparable valves. Though the response time is relatively slow, 40 ms to

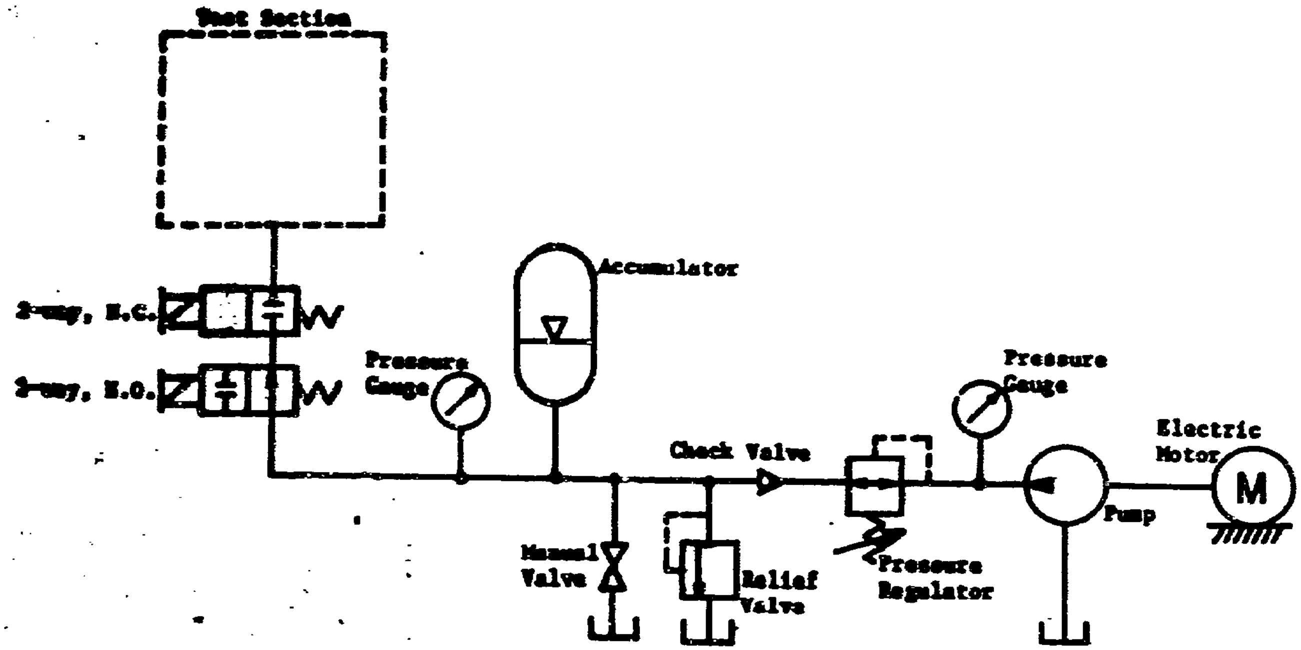


Figure 1. Schematic of Jet Impactor Test Setup

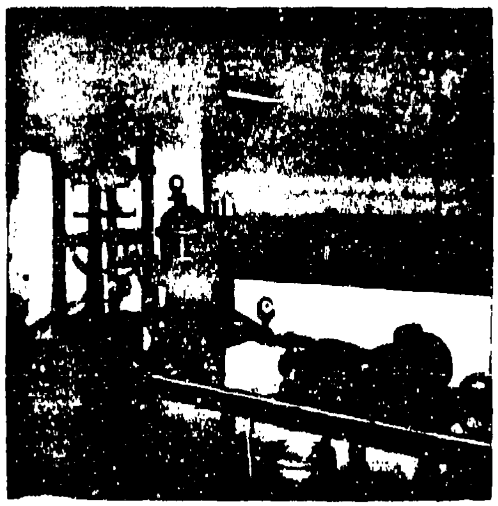


Figure 2. Single valve jet impactor test setup - vertical impact model

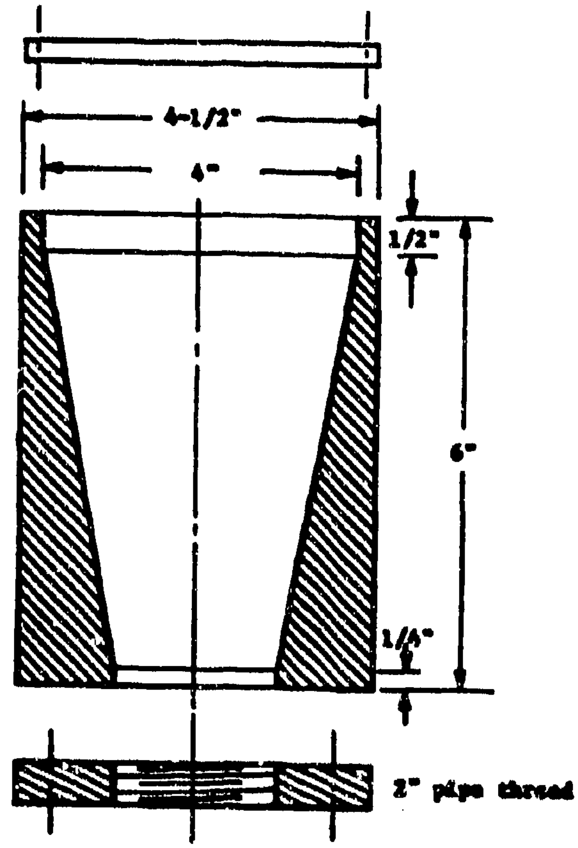


Figure 3. Diffuser cone geometry.

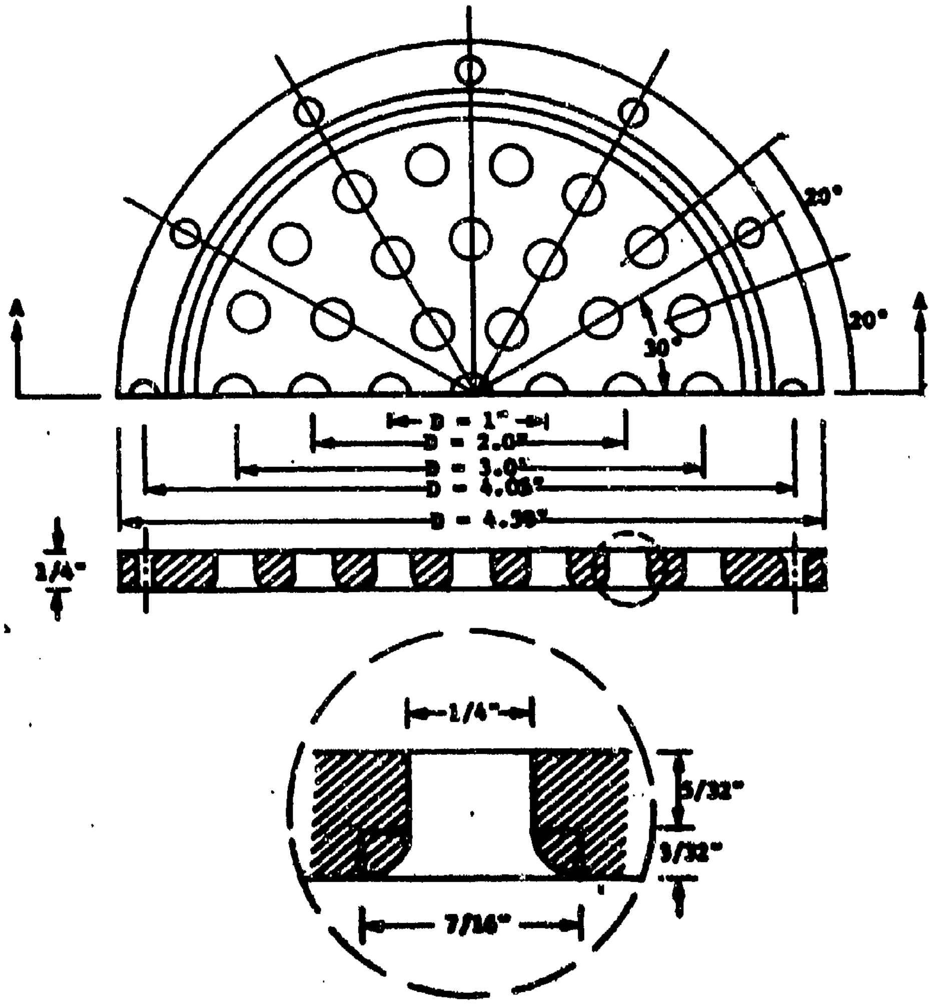


Figure 4. Orifice plate nozzle pattern of the vertical jet impactor.

open and 80 ms to close, it is the fastest among all similar size valves we tested. Therefore, this valve was chosen as the primary unit.

The results of the valve qualification tests indicated that besides long signal duration, for all the valve sizes all the impact signals were weak. This latter problem was a more critical one. Effort was concentrated on improving the impact signal.

As a first step, changes in orifice plate design were made. By systematically reducing the orifice size, increasing the number of jets and at the same time varying the plate thickness, optimal geometry was achieved. By reducing the hole size, less flow escaped immaturely from the cavity and a higher back pressure was created. This higher back pressure produced some more powerful jets. Nevertheless, the improvement was still not sufficient.

Additional improvements were achieved through the change in standoff distances; much stronger signals were found to result at certain optimum standoffs. When we combined the optimal distance with the optimal orifice diameter a threefold improvement in total impact strength was achieved. As an example of the development procedure the results of this set of tests are given in Table 1.

The uniformity of pressure distribution at the target was measured along two perpendicular diameters. As shown in Figure 5, though the distribution was uniform the magnitude was too low.

During this period, a changeover from vertical to horizontal impact was made. This was required because in clinical tests, sheep will be tested in standing position. It was found that when a sheep is laid on its side, it tends to tense up and cause different pulmonary stresses compared to those in the normal standing position. Thus, in order to generate the data in a more natural state, the impact must be horizontal.

One of the main concerns of developing a horizontal unit was how to keep the water in the cavity behind the orifice plate. We believed (incorrectly) that a full cavity was essential to achieve the highest impact force. The large volume cone reservoir was abandoned and nozzles with long aspect ratios (length to diameter) were designed and tried. A number of other ideas were also ready to be tested. However, we found that the signal would not

Table 1. Summary of Experimental Results

Item	System Components: Valve Size* (in.)	System Components: Orifice Plate (no. of holes)	Variables: No. of active jets	Variables: Line Pressure (psi)	Variables: Valve Cycle Time (ms)	Variables: Target Distance (in.)	Output: Force/Rise Time (lb/ms)	Output: Pressure/Rise Time (psi/ms)	Comments
1	0.5	61	1	180	50	7.25	—	12/0.2	1. A straight cylinder is used as the head reservoir. 2. This is the baseline information for subsequent tests.
			1	150	50	7.25	—	6.5/0.2	
			1	120	50	7.25	—	5/0.1	
2	0.5	37	1	180	50	7.25	—	60–120/0.04–0.1	1. A diffuser-cone-type head reservoir gives better results. 2. Single jet gives good signal. 3. Total signal is weak; need larger valve.
			37	180	70	7.25	9/3.5	1.0/1.4	
3	2.0 (Magna-trol)	37	37	180	250	7.25	—	2.3/2.0	The Magnatrol valve can sustain higher line pressure but requires long cycling time, has slow rise, and a weak signal.
				250	250	7.25	27/6	2/2.7	
4	1.0	37	37	150	90	7.25	22/1.5	—	1. Orifice plate #61 better than #37. 2. ASCO 1.0" DC valve is better than 2.0" Magnatrol valve.
		61	1	120	40	7.25	—	27/0.3	
		61	1	120	50	7.25	—	80–270/0.03–0.5	
		61	61	120	80	7.25	15/5	3/1.0	
		61	61	150	90	7.25	30/2	—	
5	2.0 (A.C.)	37	1	120	120	7.25	—	8/0.5	1. ASCO 2.0" AC valve is not as good as 1.0" DC valve. 2. Orifice plate #61 is better than #37.
		37	37	180	180	7.25	7/5.0	1.2/0.5	
		61	61	180	180	7.25	15/2	—	
6	1.5	61	1	150	50	7.25	10/0.7	—	1. The 1.5" valve gives the best result so far. 2. In order to achieve project objective we need some substantial improvements.
			61	150	100	7.25	40/2.2	—	
7	1.5	221 (1/4)†	221	150	90–130	7.25	30/3.5	—	1. Using more small holes did not change much on output signal. 2. Check on system O.K.
		221 (1/8)	221	150	80–150	7.25	30/3.0		
		221 (1/16)	221	150	90–150	7.25	30/3.0		
		61	61	150	120	7.25	40/1.8		

Table 1. (Cont'd)

Item	System Components: Valve Size* (in.)	System Components: Orifice Plate (no. of holes)†	Variables: No. of active jets	Variables: Line Pressure (psi)	Variables: Valve Cycle Time (ms)	Variables: Target Distance (in.)	Output: Force/Rise Time (lb/ms)	Output: Pressure/Rise Time (psi/ms)	Comments
8	1.5	221 (1/16)	221	150	110-130	24	85/6.4	—	Increasing target distance improves output significantly.
9	1.5	221 (1/16)	221	150	120	30	77/6.0		Test optimal target distance.
						24	77/4.5		
						18	60/4.5		
						12	45/4.5		
						7	30/3.0		
						7	17/6.7		
10	1.5	61	61	150	120	24	2.5/55		1. #221 orifice plate is better than #61. 2. The optimal target distance for #61 is around 7".
						18	6/15		
						12	23/6		
						7	25/2		
						4	30/1.8		
						7	40/2.2		
11	1.5	221 (1/16)	221	250	120	24	140-200/ 3-6	—	Increasing line pressure significantly improves the output signal.
12	1.5	221 (1/4) (0.1" diameter holes)	221	150	150	18	14/12	—	1. Increasing the diameter of the holes (compare with item 7) improves the signal output. 2. The optimal target distance for this orifice plate is 12".
					170	12	70/2.5	—	
					130	7	60/2.2	—	
					150	10	60/2.5	—	
				250	150	12	100/2.7	—	
13	1.5	221 (1/4) (0.1" holes)	221	250	150	12	—	15/1.0	The mean pressure over the target area is 15 psi with an average rise time of 1.0 ms. Detailed distribution is shown in the attached figure.

*All valves except as noted are ASCO DC valves.

†Numbers in parentheses represent the nozzle length. All holes except as noted are 1/16" diameter holes.

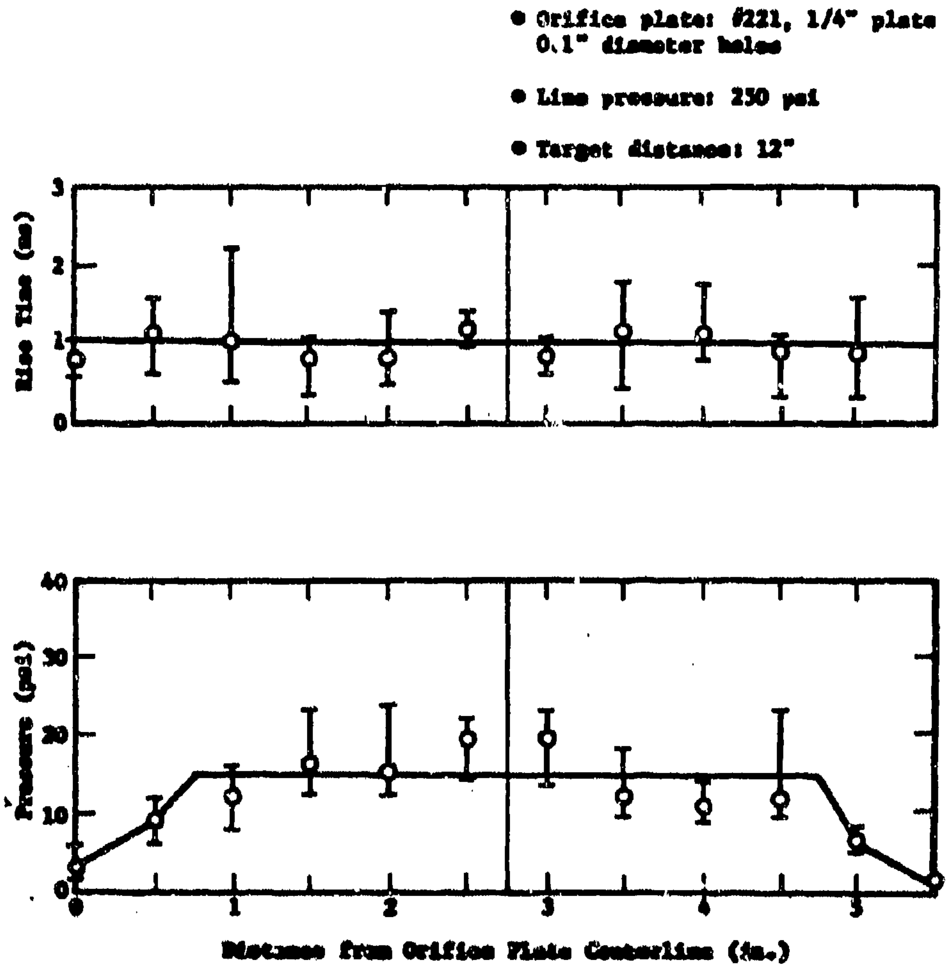


Figure 3. Pressure and rise time distribution across a target plate for a 4 in. nozzle head.

deteriorate when the cavity was not full. As a matter of fact, for certain cavity sizes and orifice plates, an empty cavity generated even stronger signals. This was an important discovery; it eliminated one of the major concerns and freed us for more direct pursuit of signal improvement.

The horizontal single valve impactor setup is shown in Figure 6. An extensive series of tests was conducted using this setup. The parameters tested include the nozzle head geometry (Figure 7), cavity sizes, and valve sizes and brands.

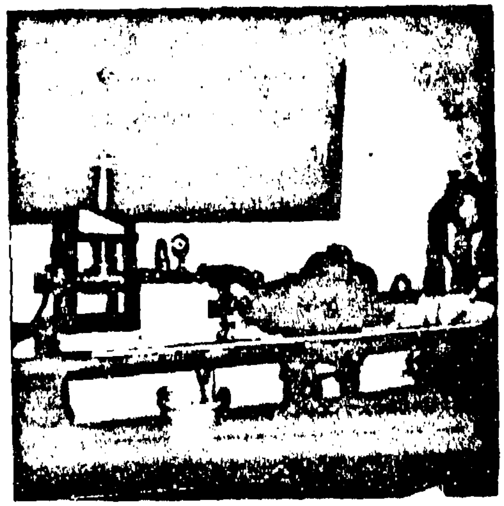
The valve cycling time was also a critical parameter. Though we would like to operate the valve in as short a duration as possible, there was a threshold value under which the valve would not fully open and this resulted in a lower magnitude signal.

Through an extensive series of tests the design parameters were systematically optimized to produce the right combination of orifice plate geometry, number of jets, cavity size, standoff distance and valve cycling time, and an impact force of 325 lbs was finally achieved! As shown in Figure 8, this signal had a rise time of about 1 ms, and a main lobe duration of about 4 ms. Though there was a trailing pressure caused by the slow valve closure, numerical modeling shows that it contributed little to total chest wall signals (see Section 2.4). The critical parameters that contributed to the high impulse were therefore used in the design of the large prototype system.

Instead of fixed nozzles, it was decided that a desirable feature on the prototype impactor would be to have the nozzles attached to the ends of flexible hoses. This feature would allow freedom in arranging the nozzles in a variety of patterns and generate different blast loading conditions. To implement this idea and to assure its feasibility a section of the designed hose was purchased and installed ahead of the single valve impactor nozzle for test. Since there was no observable effect on the impact signal, flexible extension hoses were designed into the prototype system.

2.4 PERFORMANCE AND DISCUSSION

A typical impact signal generated by the single valve model is shown in Figure 8. It has a rise time of 1 ms, a peak force of 325 lb, a main lobe of 4 ms duration, and it can be generated at a rate of four shots per minute. In



(a) Horizontal impact model

(b) Valve and nozzle head assembly detail

Figure 6. Single valve jet impactor test setup

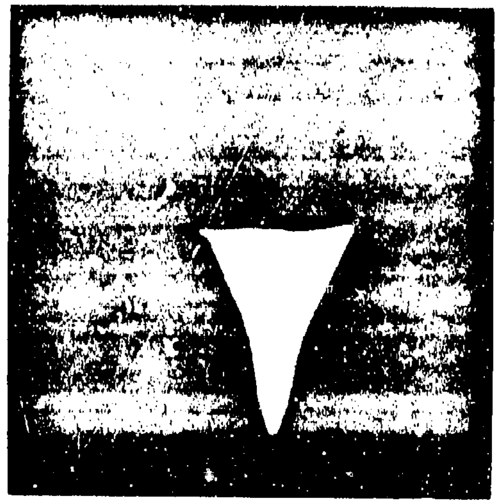


Figure 7. Nozzle head configurations tested

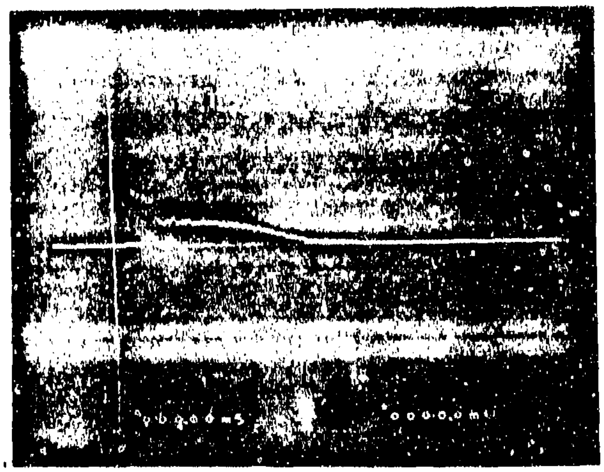


Figure 8. Jet impact signal

short, this system satisfies most of the design features. The only objection is the trailing pressure after the main impulse.

As we mentioned before, the ASCO valve has a minimum cycling time of roughly 120 ms (40 ms to open and 80 ms to close). This cycling time creates a total signal duration on the order of about 80 ms. Further reduction in cycling time would cause the valve to open only partially and reduce the magnitude of the impact signal. Cutting cycling time is apparently not an acceptable approach to reducing the duration of the signal.

A number of other ideas were tried to alleviate this problem. In general, they are based on two concepts: relieve the driving pressure or cut off the water supply after the main impulse.

The pressure could be relieved either upstream or downstream of the control valve. Because the cavity size between the valve and the orifice plate was small, only a small valve (1/2 in.) could be installed downstream of the control valve. The amount of relief was not enough to be effective. When a large valve was used in conjunction with a large cavity, the increased cavity volume reduced the signal magnitude. Another alternative was to install a bypass valve upstream of the main control valve. This reduced the signal duration slightly but it also reduced the magnitude of the impact signal.

Two ways to cut off the water supply were tried: one was to install an extra valve in series with the control valve, and the other was to critically charge the accumulator so that only the amount of water to be expelled per shot was kept in the accumulator. The former method required a normally-open valve so that it cut off the supply at the peak of the valve opening of the first valve. However, it was found that the second valve would not close any sooner and it also reduced the signal magnitude due to the additional flow restriction imposed by this second valve. The latter method allowed no fluid to be left in the accumulator at the end of the shot and thus terminated the signal without magnitude reduction (Figure 9). However, as the accumulator dumps out its contents it also causes the valve inside the accumulator to hammer at the seat. Continued impact was suspected of potentially causing significant damage to the accumulator. In addition, since the volume control of the water content in the accumulator was very sensitive to the setting of the pressure regulator, which has a resolution on the order of the pressure differential between the bladder pressure and the line pressure, identical shots were hard to achieve. A differential pressure gauge setup between line and accumulator would be able to solve this problem.

To quantify the exact effect due to the trailing stagnation pressure, numerical calculations were performed. Since in most cases, the "humps" were on the order of 10% of the peak value, a simplified profile with a rise time of 1 ms then fall to 10% peak value at 5 ms and remaining constant for 80 ms was used for the calculation. The results for the cases of both with and without the hump are compared in terms of chest wall acceleration, chest wall velocity, and chest wall displacement for peak pressures of 3, 10, 25 and 50 psi. As shown in Figures 10 to 13, the differences between each set of test conditions were within 2 to 4 percent. This variation is so small that it is unlikely to have any influence on injury.

Since the jet impactor model was able to capture all the essential features we specified earlier, the adopted approach was shown to be a viable one. Without further delay and upon the approval of WRAIR the next phase of the project, fabrication of the prototype impactor, proceeded.

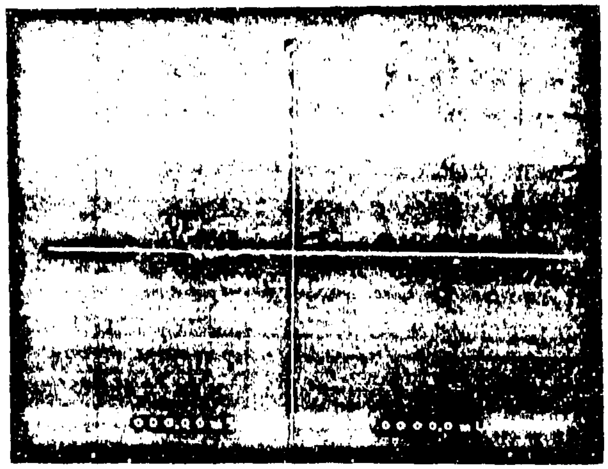
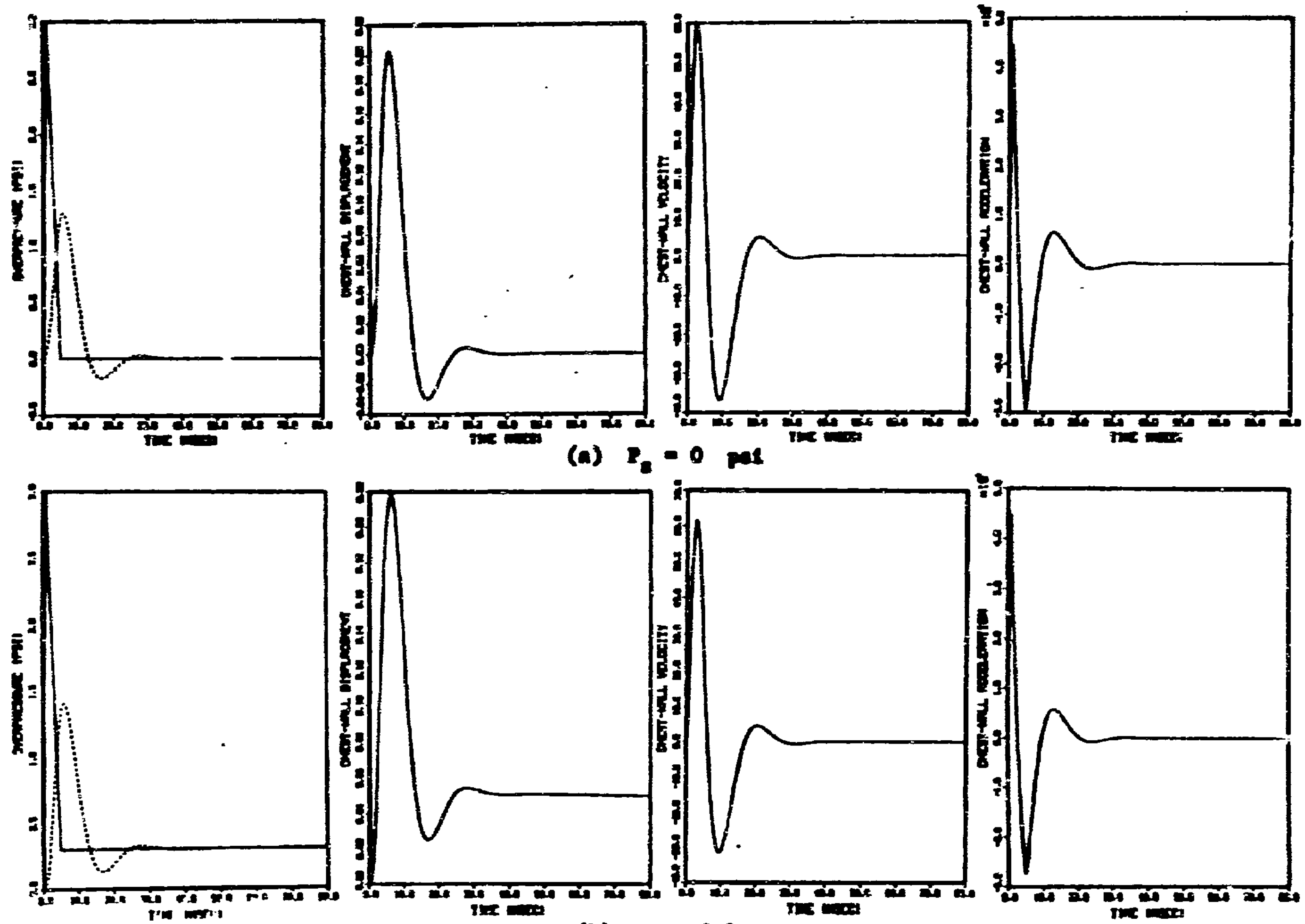


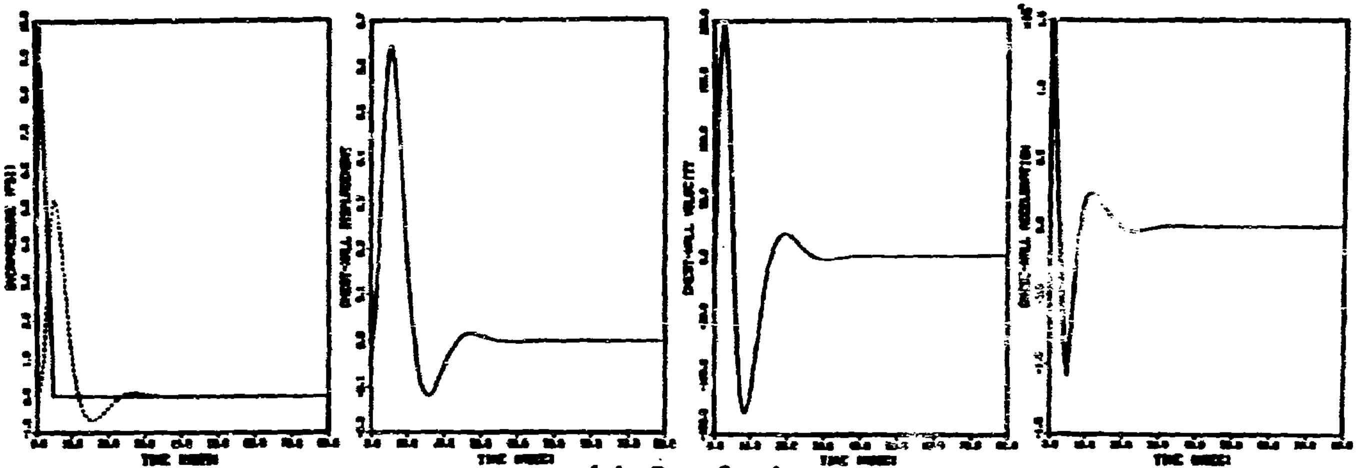
Figure 9. The impact signal from a critically charged accumulator



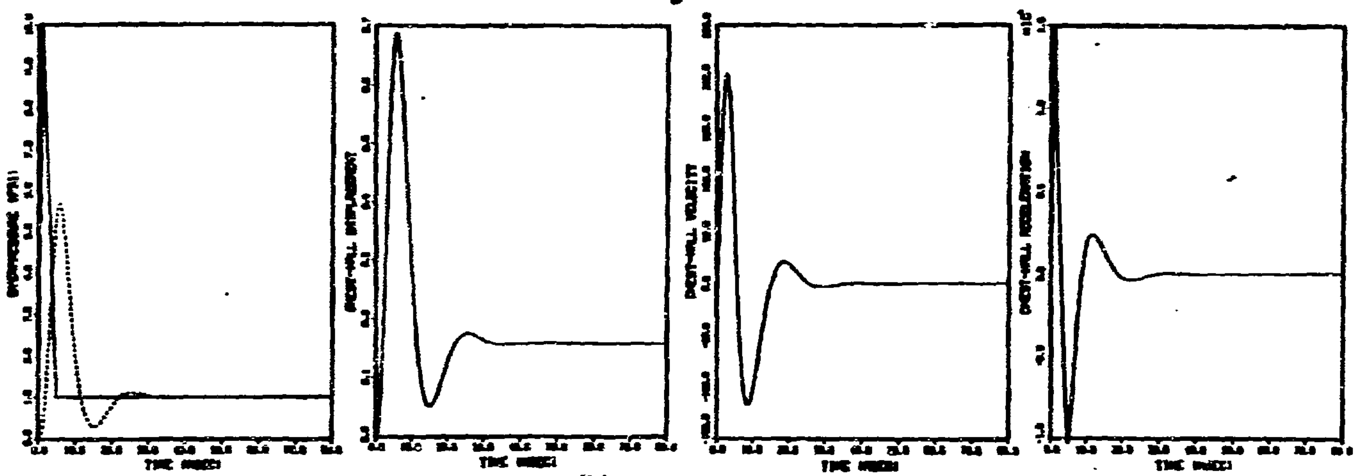
(a) P_s = 0 psi

(b) P_s = 0.3 psi

Figure 10. Comparison of the effect of trailing stagnation pressure on chest wall displacement, chest wall velocity, and chest wall acceleration for P_{max} = 3 psi

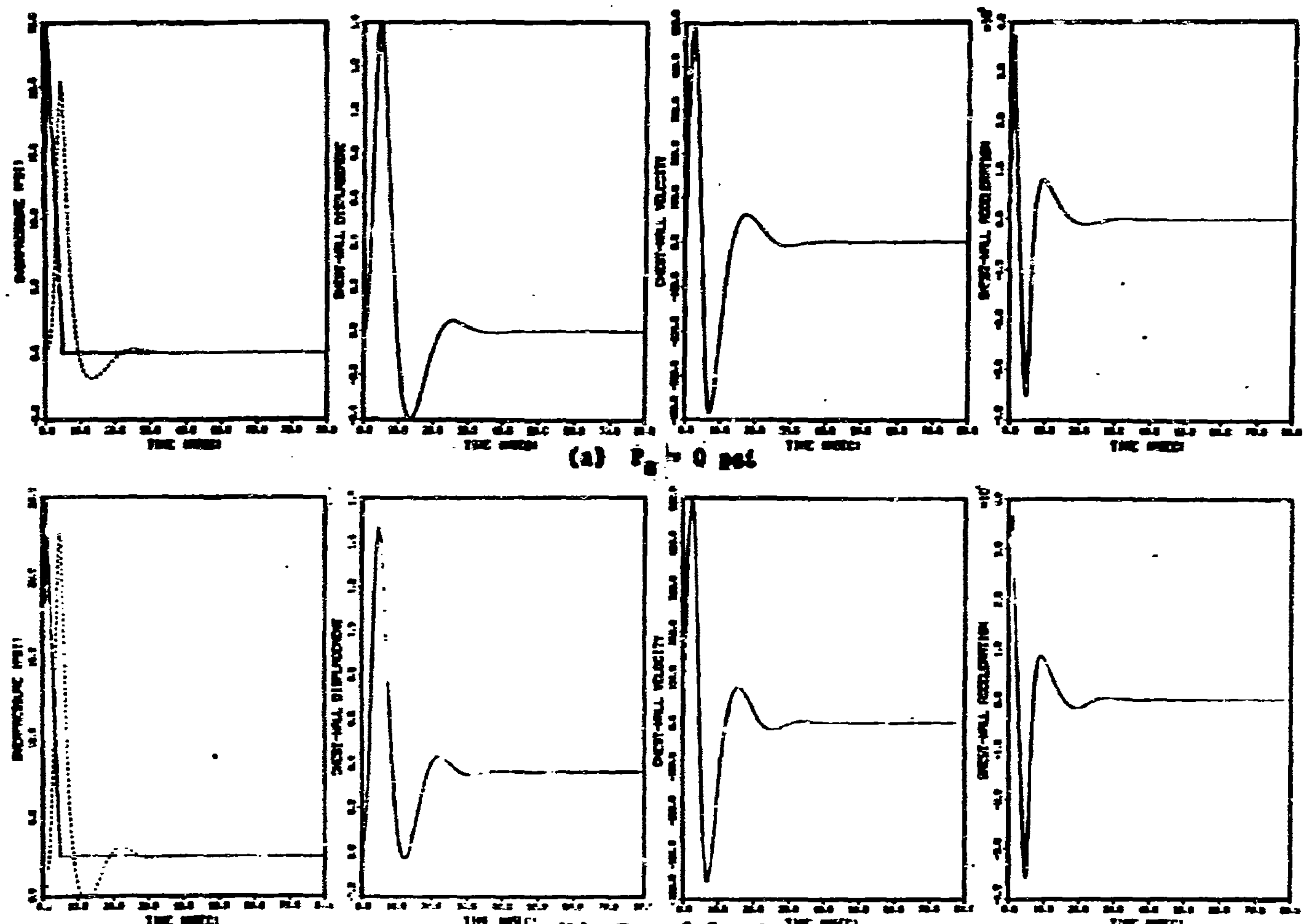


(a) P_s = 0 psi



(b) P_s = 1.0 psi

Figure 11. Comparison of the effect of trailing stagnation pressure on chest wall displacement, chest wall velocity, and chest wall acceleration for P_{max} = 10 psi



(a) P_s = 0 psi

(b) P_s = 2.5 psi

Figure 12. Comparison of the effect of trailing stagnation pressure on chest wall displacement, chest wall velocity, and chest wall acceleration for P_{max} = 25 psi

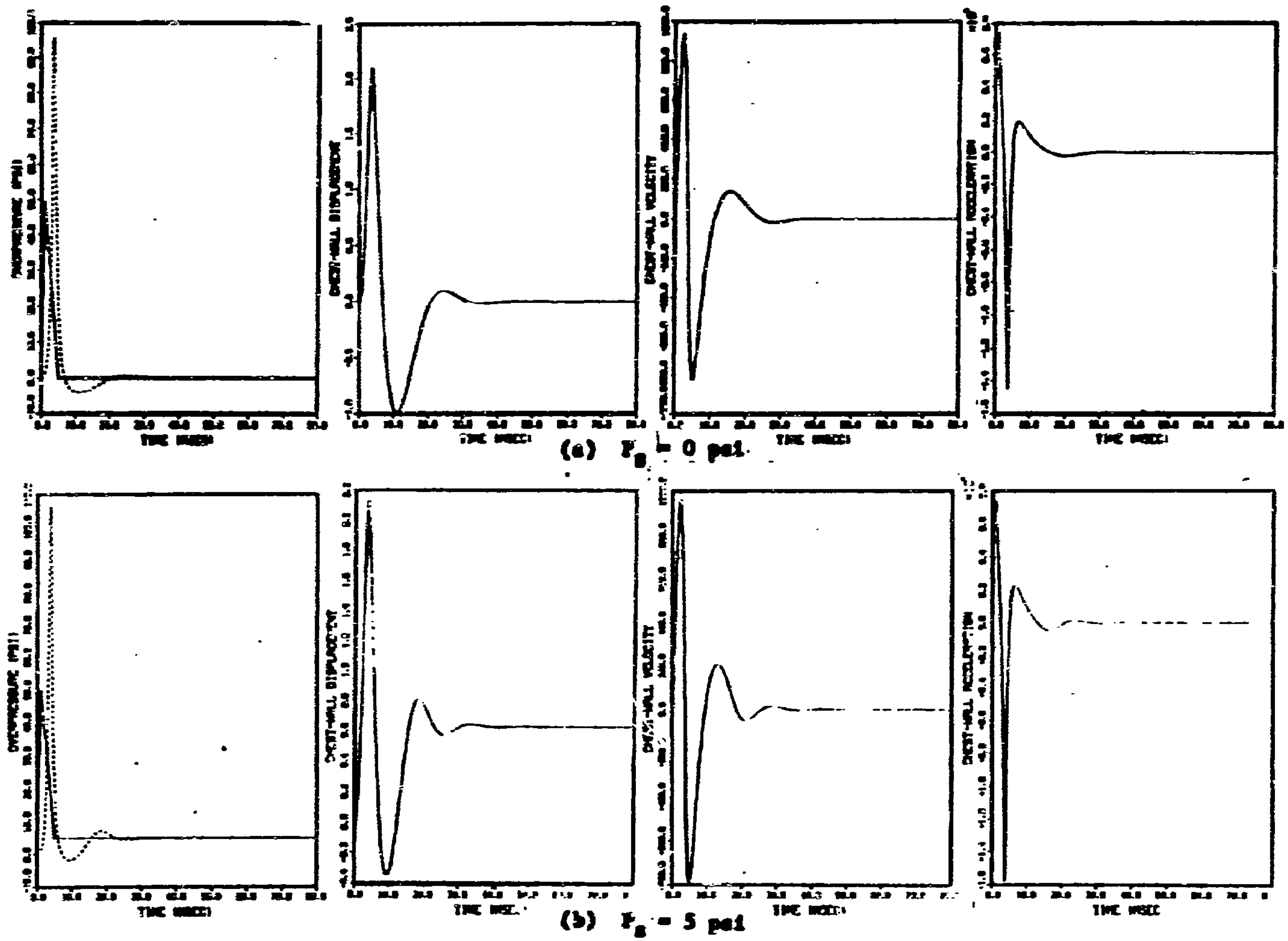


Figure 13. Comparison of the effect of trailing stagnation pressure on chest wall displacement, chest wall velocity, and chest wall acceleration for P_{max} = 50 psi

3. THE PROTOTYPE SYSTEM

The design considerations of the prototype system, the specific system components, and the system performance are given in this section.

3.1 DESIGN CONSIDERATIONS AND PROVISIONS

As we learned earlier, the heart of the jet impactor is the nozzle/control valve system. Since the maximum achievable impact force for each valve is about 325 lb, an eight-valve system would be required to generate the specified loading of 2500 lb. To cover the 100 $in.^2$ target, these valves were arranged in an 8 inch valve circle. This was the most compact arrangement for the eight ASCO valves. Since each valve has an outlet area of 1.77 $in.^2$ (1-1/2" diameter), the jet stream must be fanned out to cover its share of the target (12.5 $in.^2$). Moreover, the jets from all the valves must hit the target simultaneously to achieve the best rise time.

To satisfy the coverage requirement, a direct solution was for each valve to cover a sector equal to one-eighth of the circle. Simultaneous jet arrival, however, was not as straightforward to achieve. Since all the jets initiated from the 1-1/2 in. diameter valve need to cover a 45° sector uniformly, a 45° nozzle pattern was a natural choice. Within this region, each jet had its own inclination for hitting its designated target. Because the target is 12 inches in diameter and the valve circle is 8 inches, the jet patterns were skewed. Figure 14 shows the different jet traveling distances and jet angles along the bisecting diameter of two orifice plates.

Since the pressure in the cavity behind the orifice plate was the same for all the jets, all would have the same velocities. Thus for different traveling distances, they would have different arrival times at the target, and consequently longer pressure rise times.

To compensate for this effect, we needed to slow down the jets that travel shorter distances. This can be achieved by increasing the nozzle resistance either by smaller nozzle diameter or by longer nozzle length. Aware that we were at the threshold performance of the orifice plate and too much

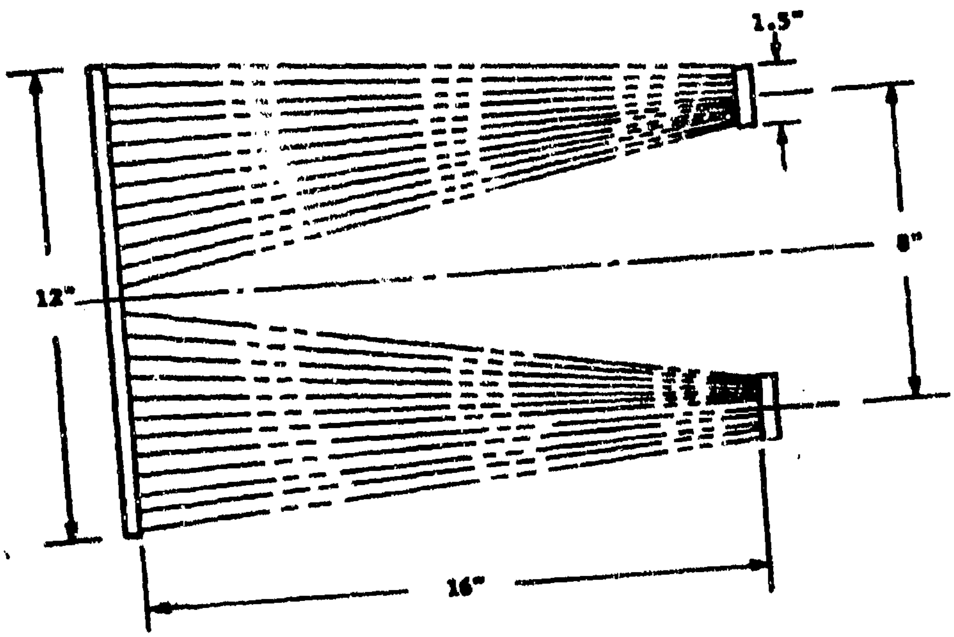


Figure 14. Jet trajectories in the plane bisecting the two orifice plates.

resistance would decrease the impact pressure, we chose to use variable nozzle lengths to balance the jet velocity. This was achieved by contouring the orifice plate in a cone shape so that the length decreases from the center toward the periphery. Through this arrangement, all the jets will be modulated in proportion to their inclinations so that they will arrive at the target plate close to the same instant and thus improve the magnitude and rise time of the impact signal.

Another consideration was the jet density. Obviously, the higher the density the less spiky the pressure distribution. However, because of the limited size of the valve, orifice spacing was limited. The jet density we designed has a jet-to-jet distance of about 0.5 inch on the target for the 16 inch standoff distance.

Based on these considerations, a number of orifice plates were designed and tested. The final choice was based on the best performance in signal rise time and impact force. High speed movies were used to help the selection. The final design of the orifice plate is shown in Figure 15. The valve arrangement pattern on the valve support plate is given in Figures 16 to 18.

The corresponding jet impact force of the single valve versus the standoff distance for various line pressures is shown in Figure 19, and the corresponding signal rise time is shown in Figure 20. From these figures, the optimal standoff distances for the various line pressures can be summarized as shown in Figure 21. For any target impact pressure, the required system pressure and target standoff can be read off directly. For example, in order to achieve an impact pressure of 17 psi, it is necessary to use a line pressure of 188 psi and a standoff distance of 15.7 inches. Since the jets are fanning out from the nozzle head, the coverage area increases with standoff distance. The exact impact pressure should therefore be calculated based on the total area coverage by the jets. The area coverage of a single valve for different standoff distances is shown in Figure 22.

The dimensions of the system were specified as such that neither the unit as a whole nor its separated parts should be larger than 4 ft wide, 8 ft long and 6 ft high. This provision was required so that there would be no problem in moving through doors or hallways. In addition, we designed the system in such a way that its major components were all installed on a heavy duty cart

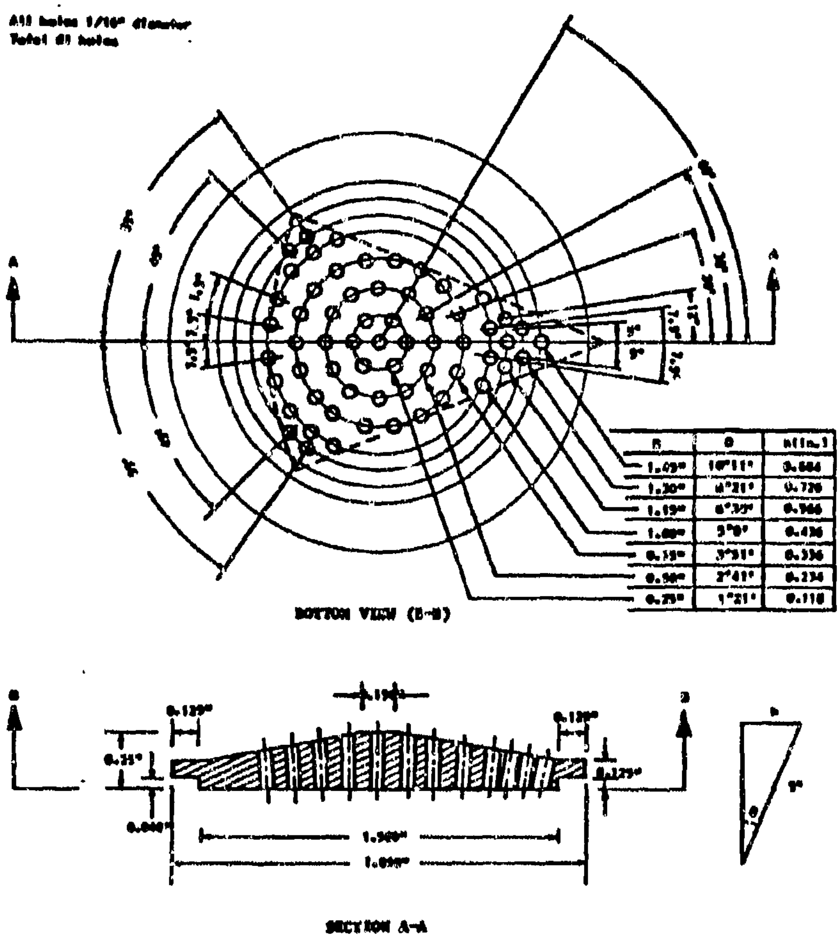


Figure 15. Orifice plate configuration and hole pattern

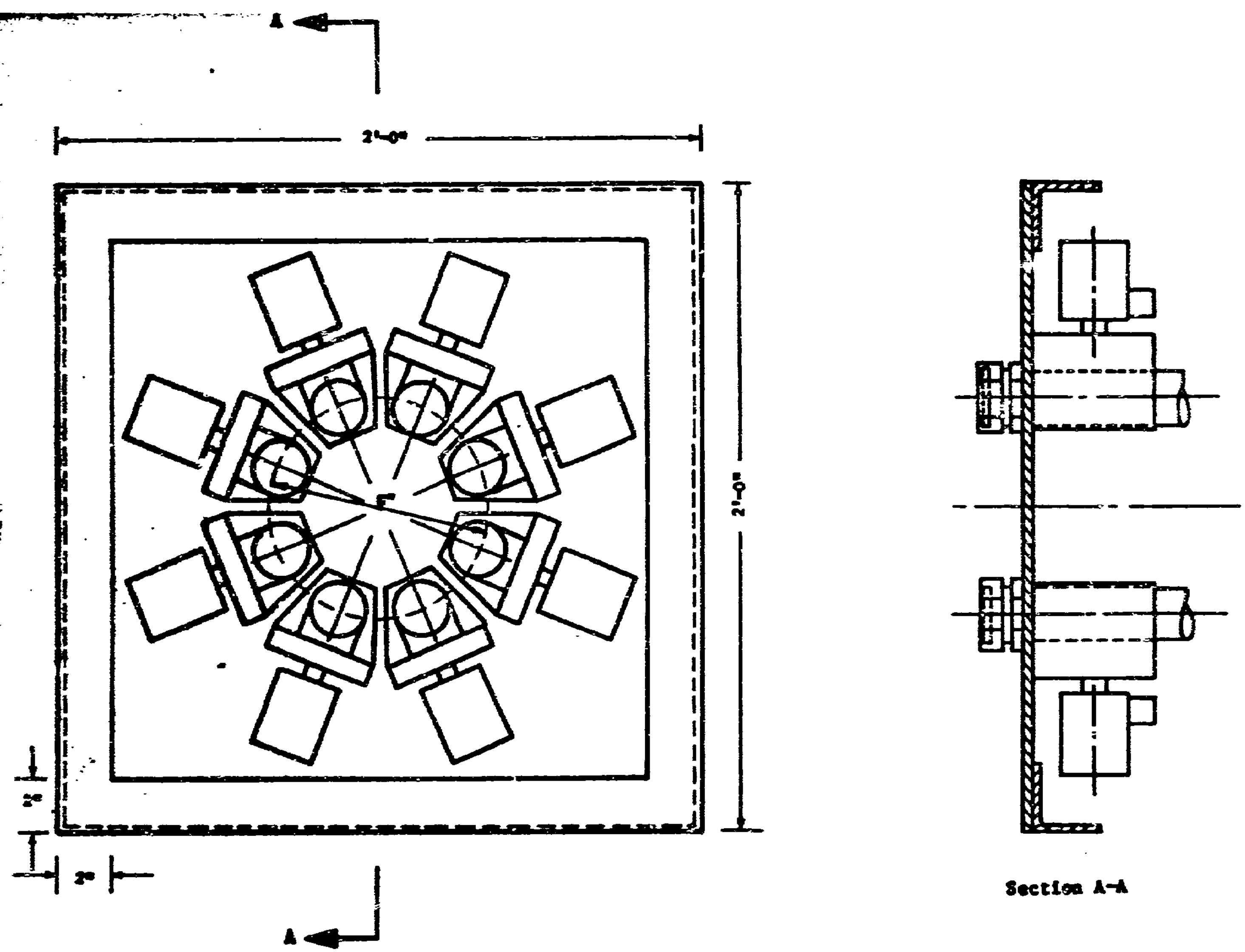


Figure 16. Nozzle head configuration

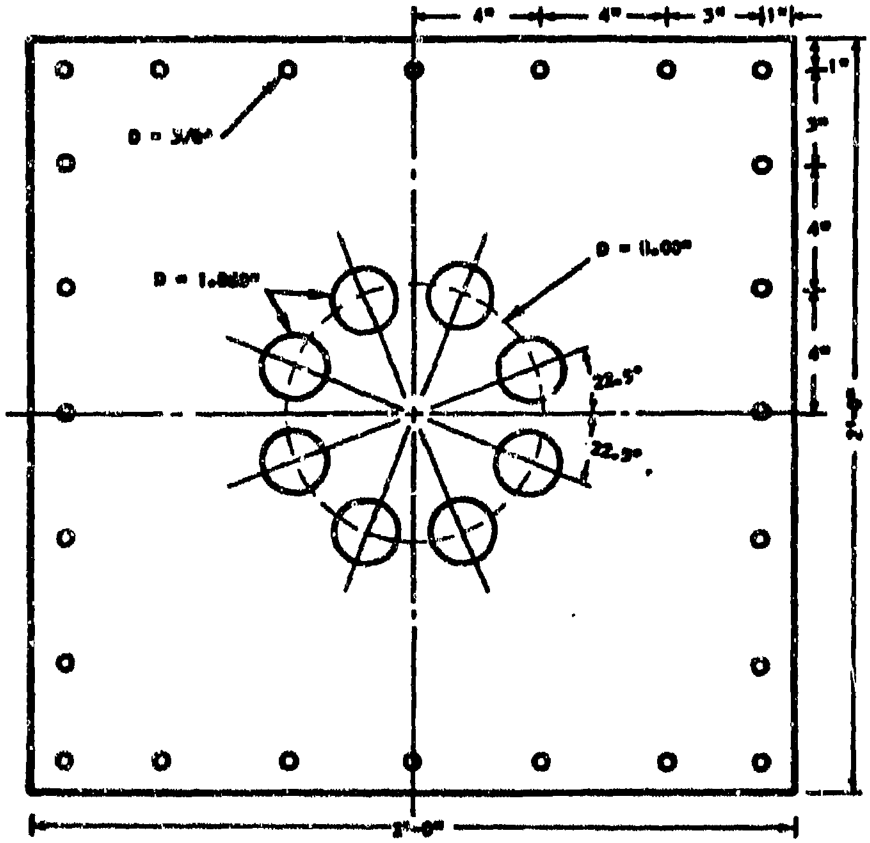


Figure 17. Valve mounting plate

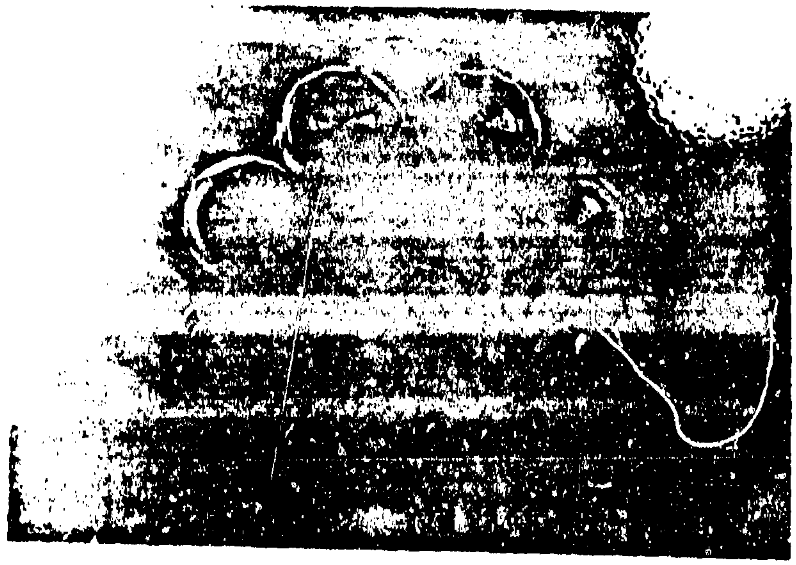


Figure 18. The nozzle head arrangement on the mounting plate

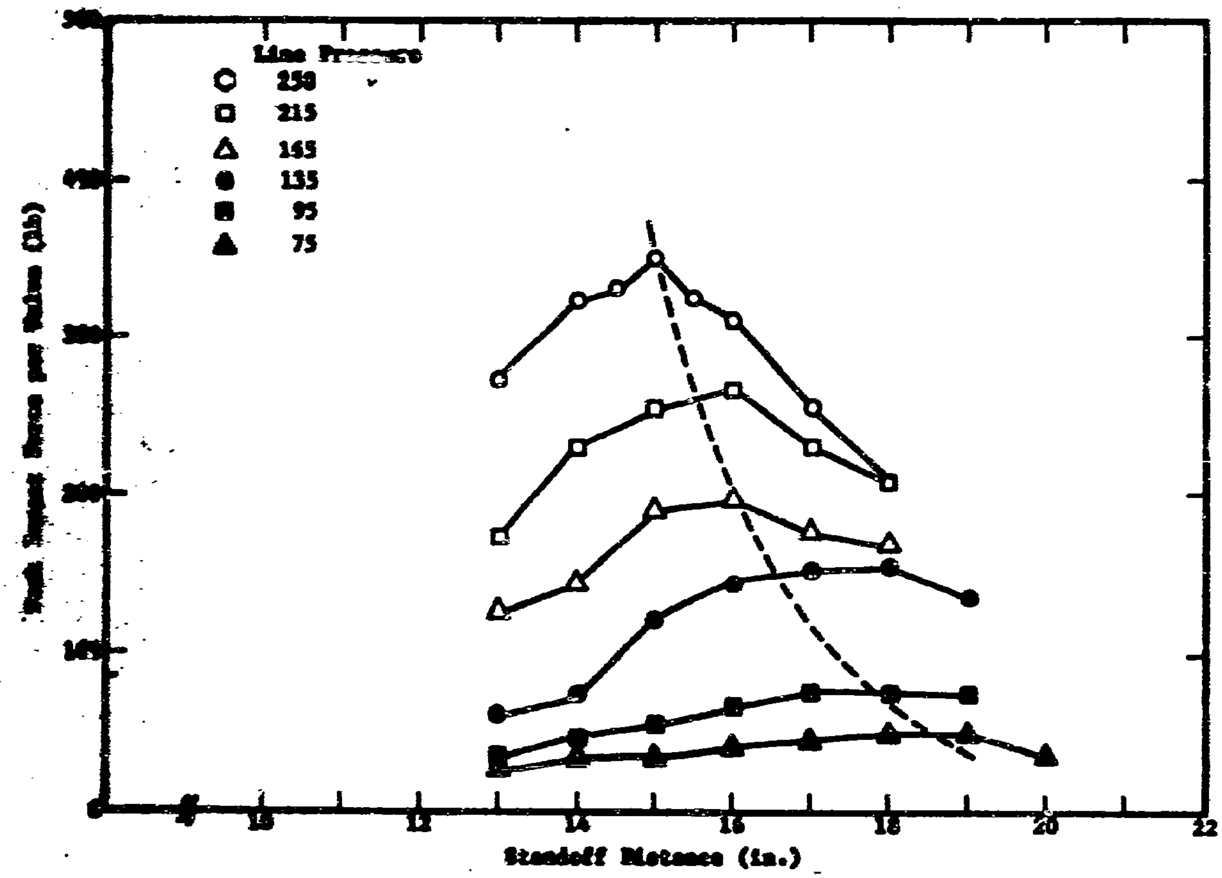


Figure 19. Impact force vs standoff distance for various line pressures.

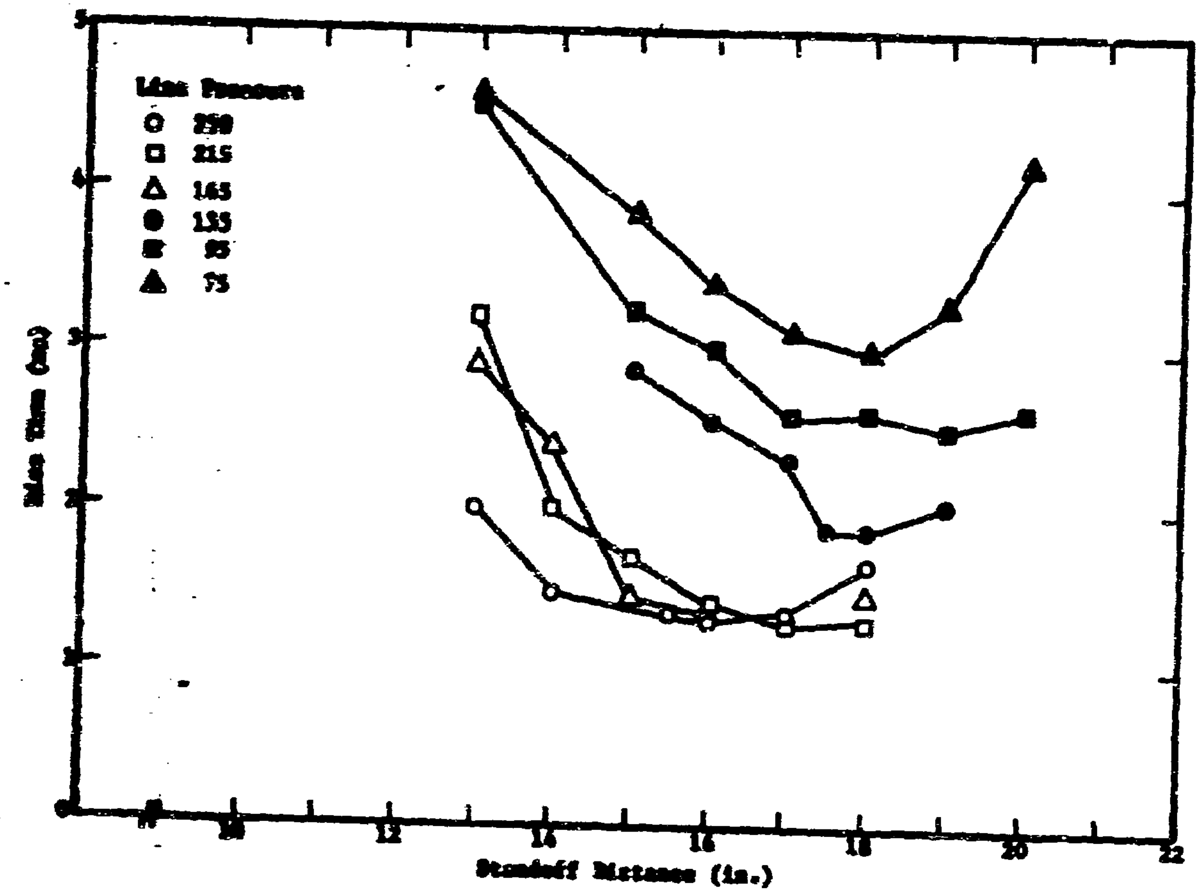


Figure 20. Rise time vs standoff distance for various line pressures.

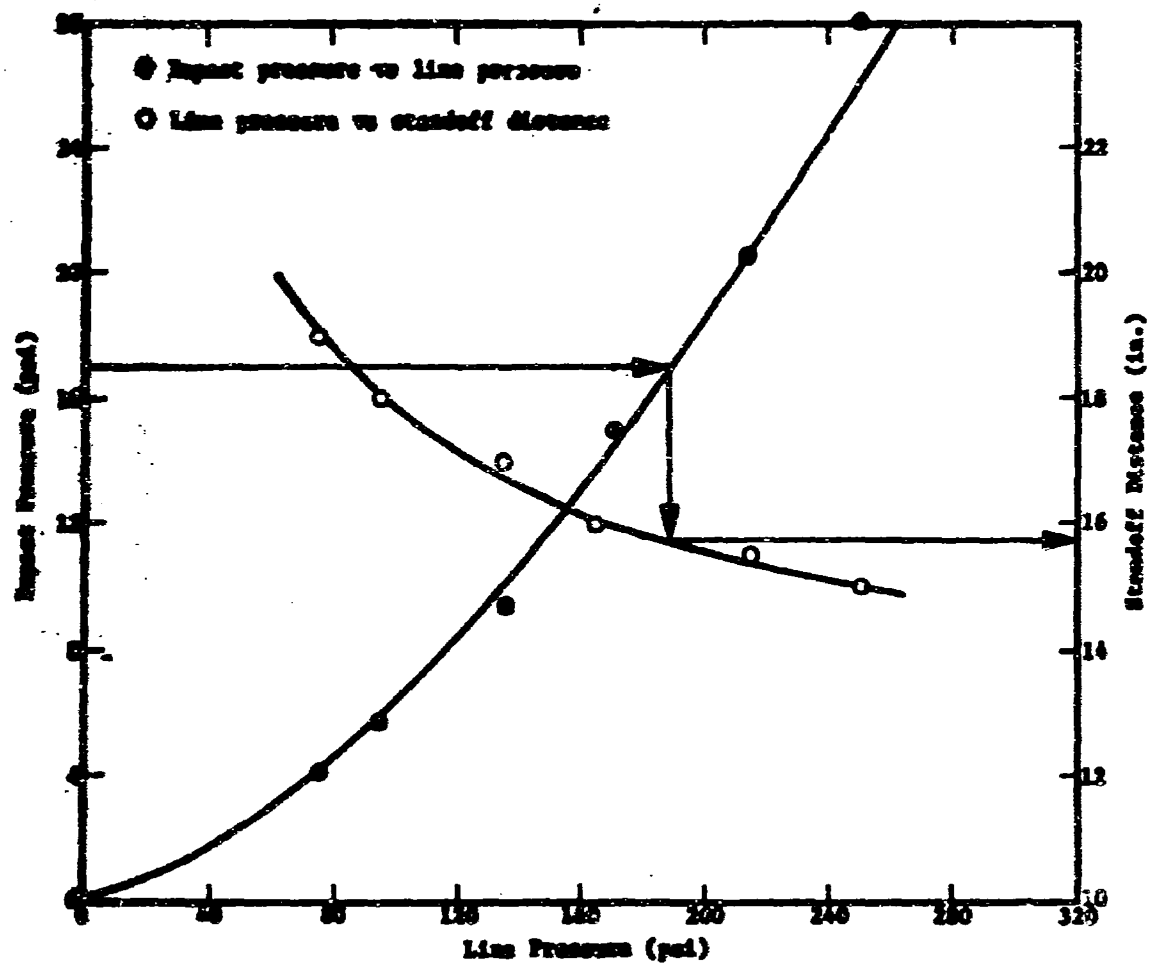


Figure 21. Impact force vs line pressure at the optimal standoff distance.

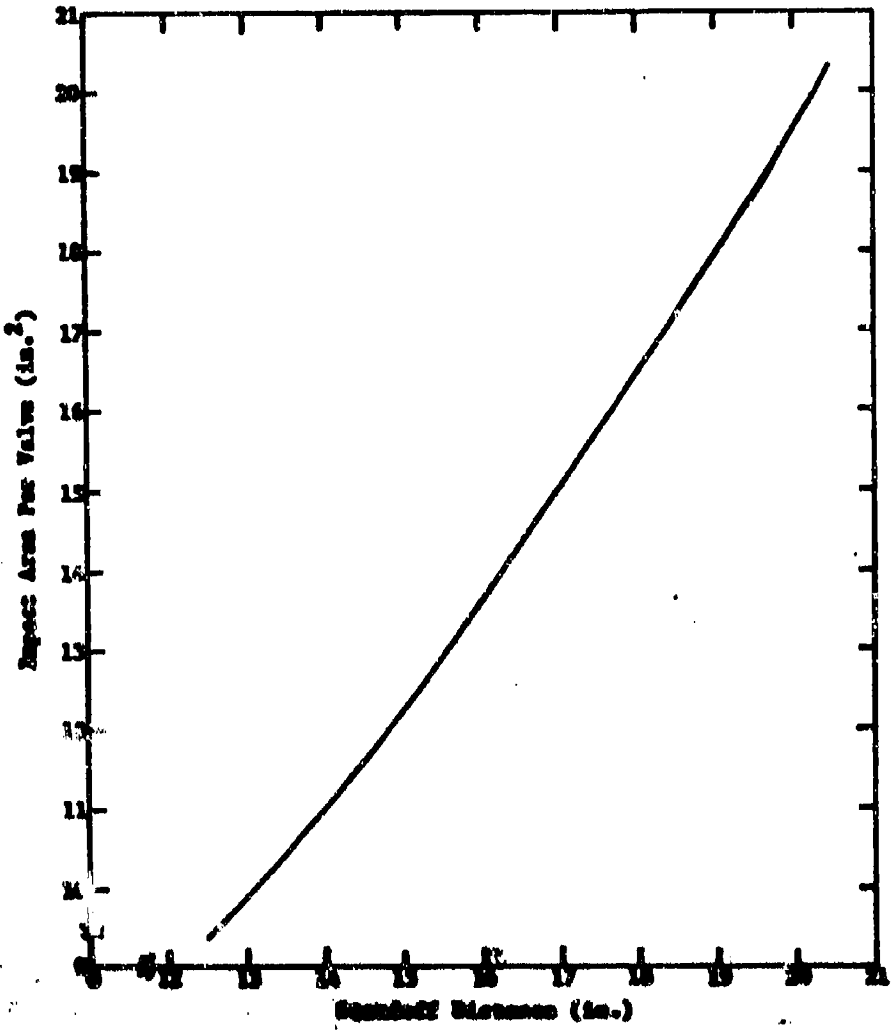


Figure [illegible]. Impact area per valve as a function of standoff distance for ease of position adjustment. The valve supporting frame and the calibration target mounting frame were designed as two separate units to allow freedom in standoff distance adjustment. The supporting plates for both frames can be adjusted to different impact heights.

A 15 HP Baldor TEFC motor was used to drive a Model No. 2520 CAT pump. This pump has rated capacities of 25 gpm and 700 psi. Both the motor and the pump were mounted on the lower shelf of the heavy duty service cart. A 1/2 in. aluminum plate was used to reinforce the lower shelf to reduce the amount of vibration. The pump supplied water to a reservoir which was connected to the four 5-gallon Hydrodyne accumulators. This arrangement allows a fast charge and discharge rate of the accumulators. The 20 gallon total capacity was necessary to maintain a pressure drop less than 5% for each shot.

As in the single valve setup, a check valve and a pressure regulator were provided to serve the same functions. A pressure gauge was mounted on top of the tank reservoir to monitor the system pressure, and a bleed valve was installed to vent the air accumulated in the system during initial pump-up.

Originally, the accumulators needed to be charged separately. This was modified by connecting their charging ports together so that a common air valve could be used (Figure 23). This provision simplified the charging process and helped to equalize the pressures of the accumulators.

As mentioned earlier, it was desirable to have flexible hoses designed into the system so that different valve patterns for different impact tests could be made. To meet this requirement, eight 2-ft long Flexonics stainless steel hoses were used to connect the valves with the reservoir tank.

The mounting plates for both the target plate and the valve/nozzle systems were made of 6061T aluminum plate. For the valve/nozzle plate, eight precise mounting holes were drilled to fix the locations of the valves. A 1-1/2" diameter short nipple was threaded into each valve and then fed through the mounting hole. Each unit was then locked in place by a lock nut.

Once the valves were fixed in place, orifice plates were installed. Because each orifice plate had its own designed orientation, freedom of adjustment was designed into the system for proper alignment. The orifice plates were designed such that they could be rotated at the end of the pipe nipples.

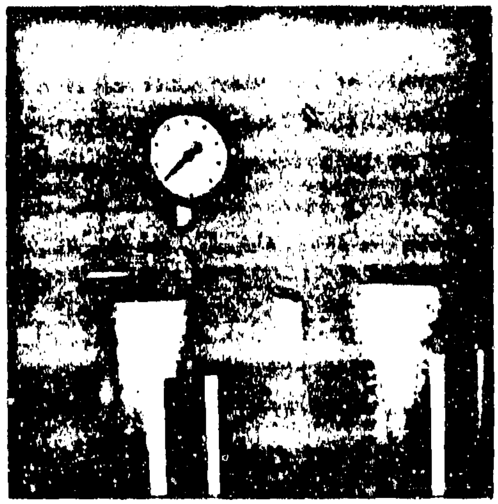


Figure 23. Accumulator charging system

Mason-jar-type rings were used to fix the orifice plates in place. The large ring openings allow all the jets to pass through freely. The exact orientation of the orifice plates were adjusted before completely tightening down the "jar rings." This was achieved by aligning the bisecting lines of the orifice plates with the guiding grooves on the mounting plate.

The target plate was mounted on a steel channel support frame. The center was aligned with the center of the valve group. Parallelism and exact distance between the two were fixed by four Unistruts mounted on the sides of the two support frames. This arrangement also keeps the target in place during calibration shots.

The impact load was measured by a force transducer, center-mounted behind a target plate. Three guiding bolts hold the target plate to the mounting plate. These bolts were used to minimize the amount of tilting of the target plate during the shots. Oil impregnated brass bushings were used to guide the movement of the bolts. Because of the bushings' low friction, little resistance was generated between the bolts and the bushings. This allows the force transducer to absorb and measure all the impact loading delivered by the jets. Rubber washers were inserted between the nuts and the mounting plate to minimize the amount of target plate vibration induced by the impact.

A 2 × 1.5 × 1.5 ft plastic tank was used as the water supply reservoir. Tap water was connected to the tank as the source. A float valve was used to control the water level in the tank. A screen filter was installed at the inlet of the suction pipe to prevent debris from getting into the system. The UP-timer was used to synchronize the operation of the valves.

3.2 QUALIFICATION OF THE SYSTEM PERFORMANCE

After the system was fabricated, a complete system shakedown and calibration was made. The objectives were to evaluate the system performance and to identify and eliminate any trouble spot so that a reliable system would be achieved. One of the key factors that dictated the performance of the system was the synchronization of the valves. It was crucial that all eight valves open simultaneously so that the jets would arrive at the target at the same time. Any misfire would result in delayed rise time and reduced impact.

To synchronize the valve operation, eight transducers would be required to monitor the jet arrival time of the eight valves. The average time-delays for each would then be corrected by adjusting the corresponding activation times on the control card of the UP-timer. This was a preferred approach. However, because of time and budgetary constraints this approach was not adopted during the development phase. Instead, an alternative approach was used.

If the jets from two different valves do not arrive at the single force transducer target plate at the same instant, two distinct impact signals will be generated. By measuring the time delay between the two peaks and adjusting the control card accordingly, the delay between them can be eliminated. Using the same valve as a reference, we could therefore eliminate the time delays for all the valves. This was the approach we used. Though there were variations among shots, a half dozen to a dozen shots usually result in a good average value. A sample output of an eight valve impact signal is shown in Figure 24.

The major defects of this approach were that it was a time-consuming process, and the results obtained from a pair of valves might be different from those when all eight valves were firing. In addition, using two valves tended to create unsymmetrical loading that might damage the target transducer and impair the system. We therefore recommend the use of eight transducers to time the eight valves.

To calibrate the uniformity of the impact pressure, two small target plates were designed and fabricated as sensor probes. One had an area of 5 $in.^2$ and the other had an area of 2 $in.^2$ The smaller target was used to measure the distribution of the higher pressure shots to achieve a "point-like" measurement without much smearing effect. The larger one was used for low pressure conditions to increase the signal-to-noise ratio.

The experiments were conducted by firing all eight valves simultaneously while the force was measured at the sensor target. The target was mounted on a guiding plate which was inserted in a Unistrut for ease of translation. The target was slid along the Unistrut to traverse across the diameter of the impact area. For each test pressure, data at every inch across four perpendicular diameters were taken. At each location, five shots were made to get the average value. The results for the 10, 15 and 25 psi tests are shown in

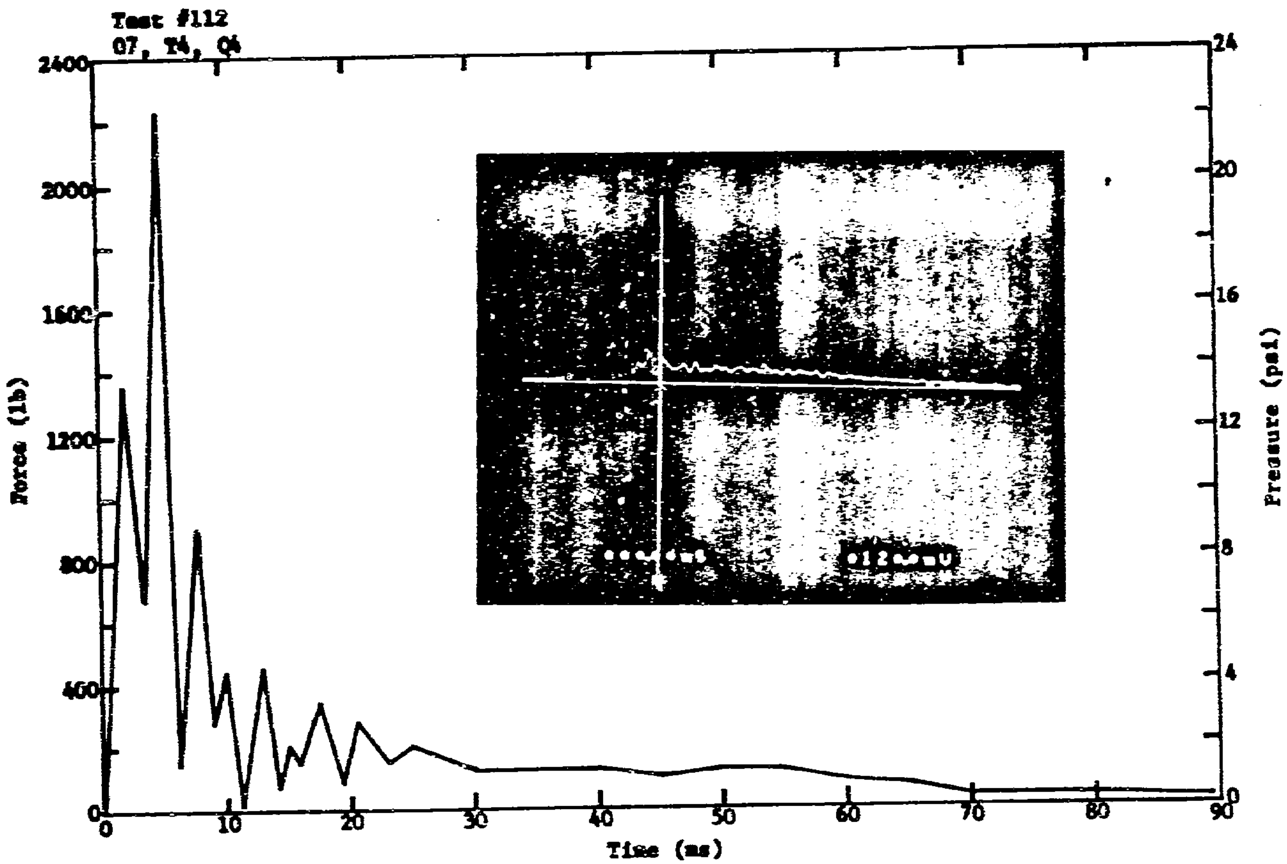


Figure 24. The prototype jet impactor impact signal

Figures 25, 26, and 27. These results were also plotted in terms of distance squared to simulate the area coverage effect and are shown in Figures 28 to 30. As shown, there is a low pressure region near the target center caused primarily by the relatively sparse jet density at the apex of the orifice plate. The pressure distributions over the rest of the target are relatively uniform.

Sample local impact signals are shown in Figure 31. These are the output from a 2 in.^{2} sensor target. They all exhibit short rise times and short durations, implying that locally they are very similar to the blast overpressure signal.

3.3 CONCLUDING REMARKS

After an intensive system life test and modification and/or replacement of all troublesome parts, the prototype impactor as shown in Figure 32 along with the parts and vendors list, engineering drawings and a detailed installation and operation manual as shown in the appendices were delivered to WRAIR to be used for pulmonary injury study.

To achieve the designed impact effect it is essential that all the valves deliver the impact to the target simultaneously. In order to achieve the synchronized valve operation the most direct approach would be to have eight individual sensors at the target to measure the jet arrival time and make the proper correction accordingly. Presently, WRAIR personnel are fabricating such a calibration target. Since there might be some variation among startups, it would be worthwhile to make some periodical calibrations to ensure the proper results.

Irrespective of the straightforwardness of the procedure in synchronizing the valves, it is still preferable to use as few valves as possible when the test conditions so warranted. Such would be the case for low pressure tests. For example, it would be desirable to use just four valves for pressures less than 10 psi and two valves for pressures less than 5 psi. In both cases, new orifice plates would be required.

The relatively low impact pressure near the center of the target area can be improved by some simple modification of the orifice plate. A few judicially added nozzles at the apex region will achieve this objective.

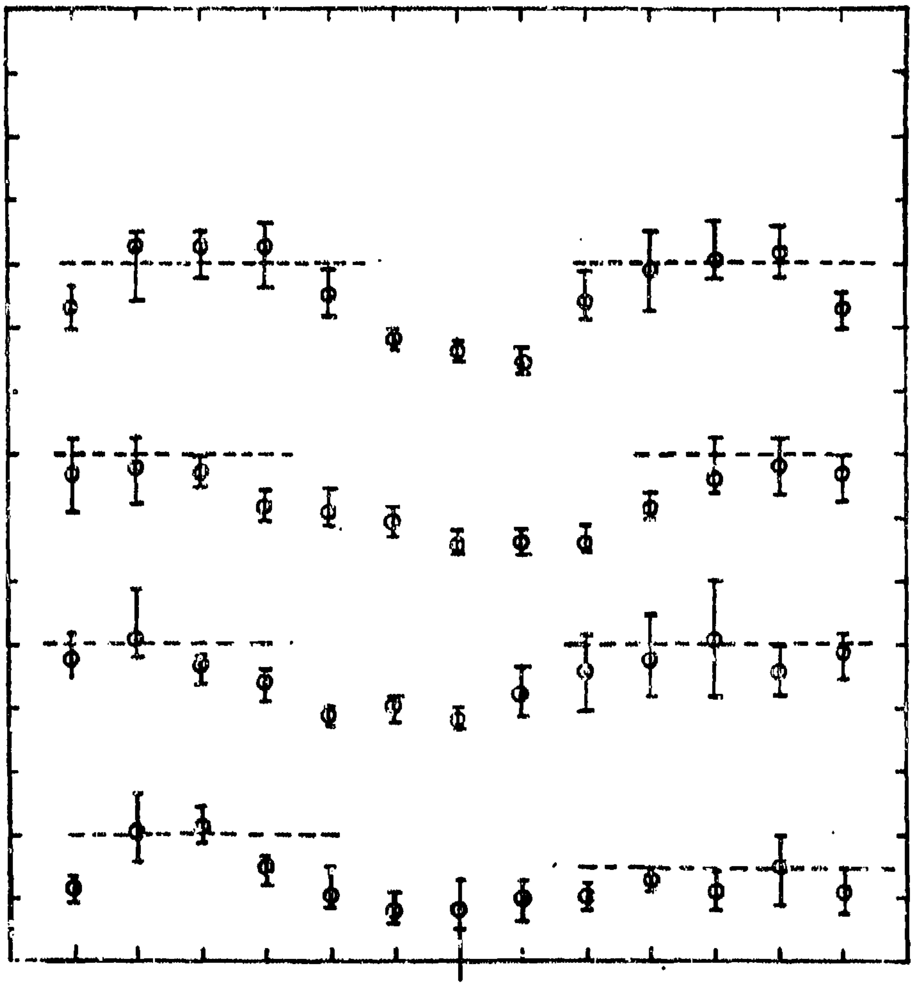


Figure 25. Pressure distribution along four perpendicular target diameters: $\bar{p}$ = 10 psi; standoff distance = 17"

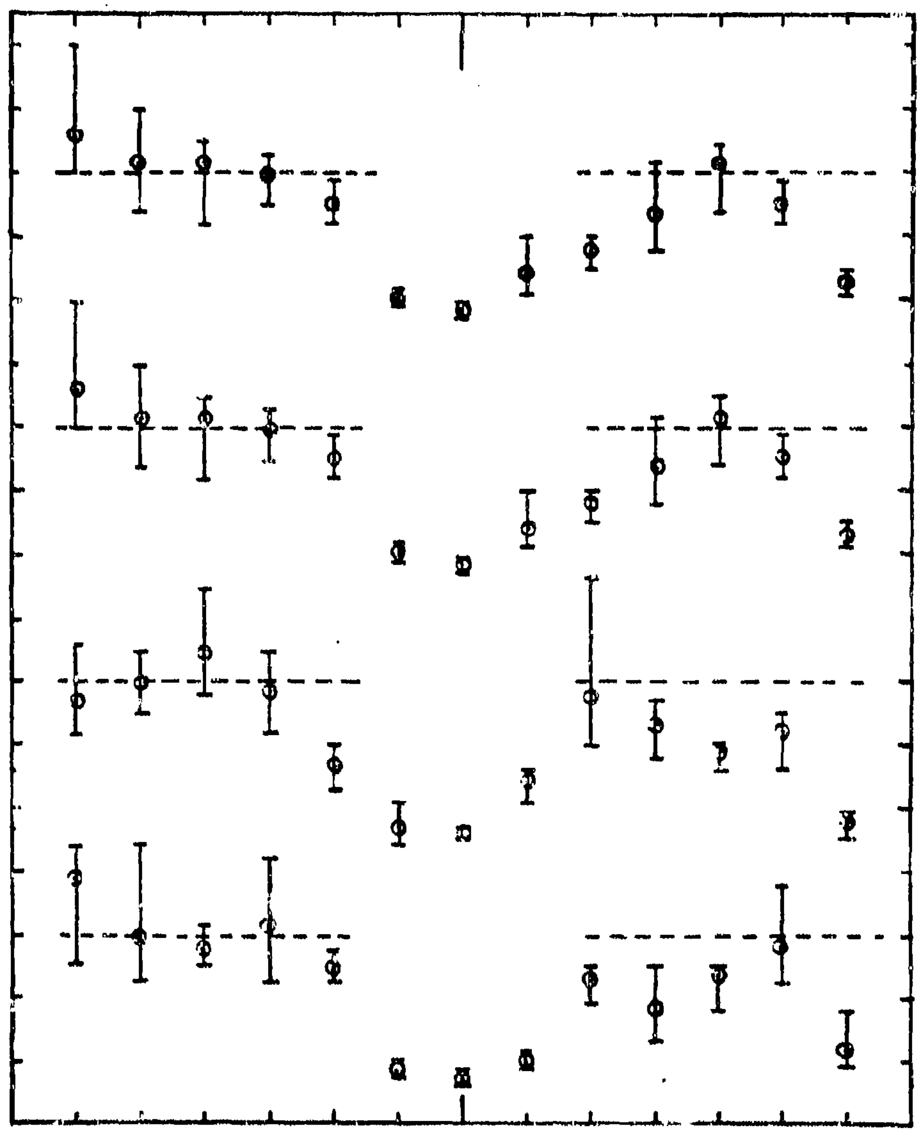


Figure 26. Pressure distribution along four perpendicular target diameters: $\bar{p}$ = 15 psi; standoff distance = 16"

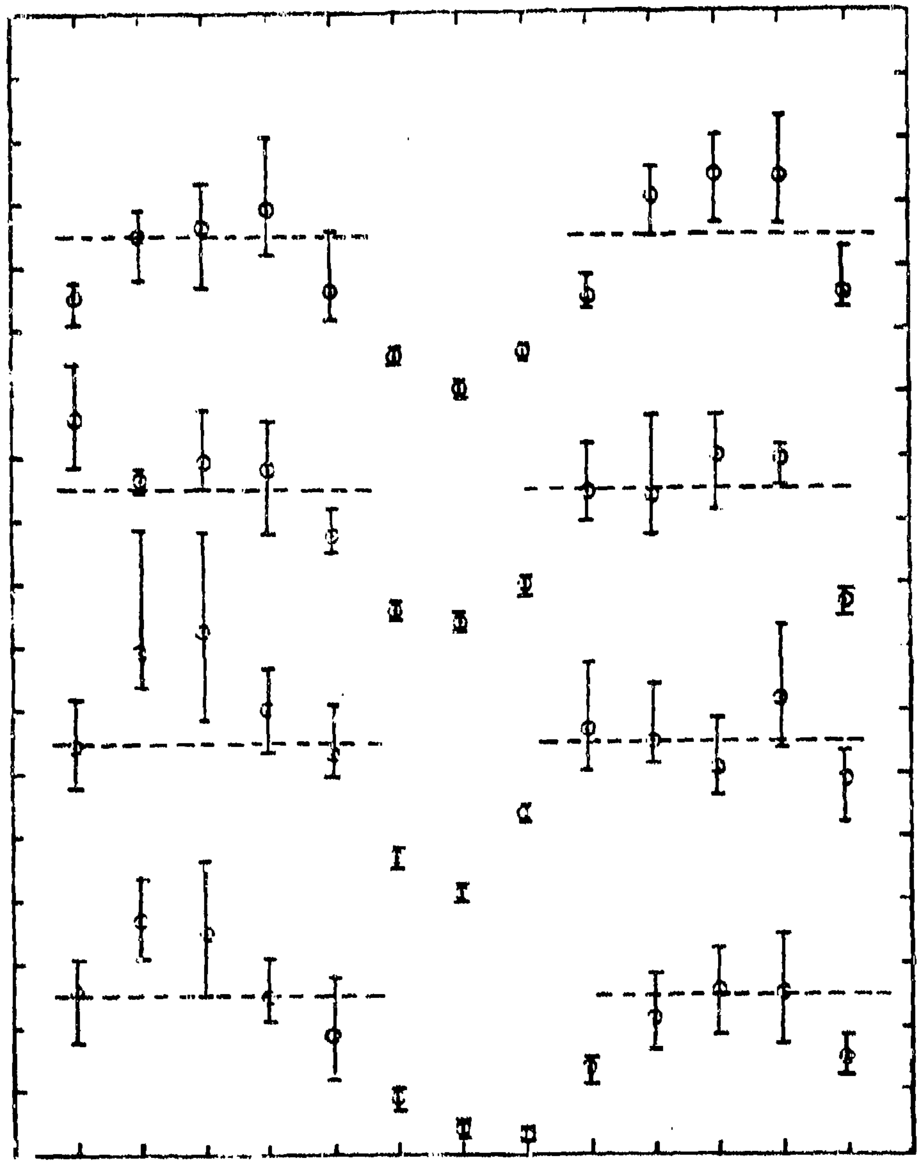


Figure 27. Pressure distribution along four perpendicular target diameters: $\overline{p}$ = 25 psi; standoff distance = 15"

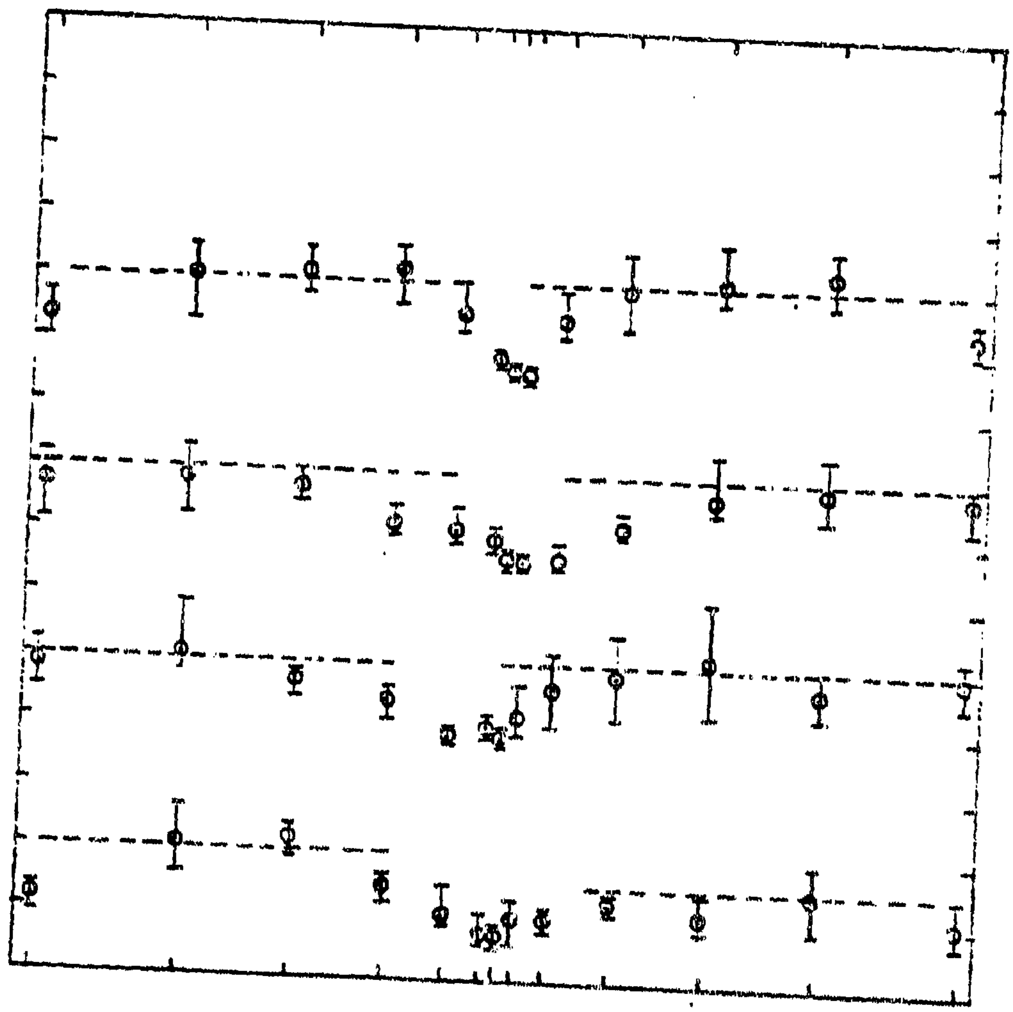


Figure 28. Pressure distribution in terms of r^2; $\bar{p}$ = 10 psi; standoff distance = 17"

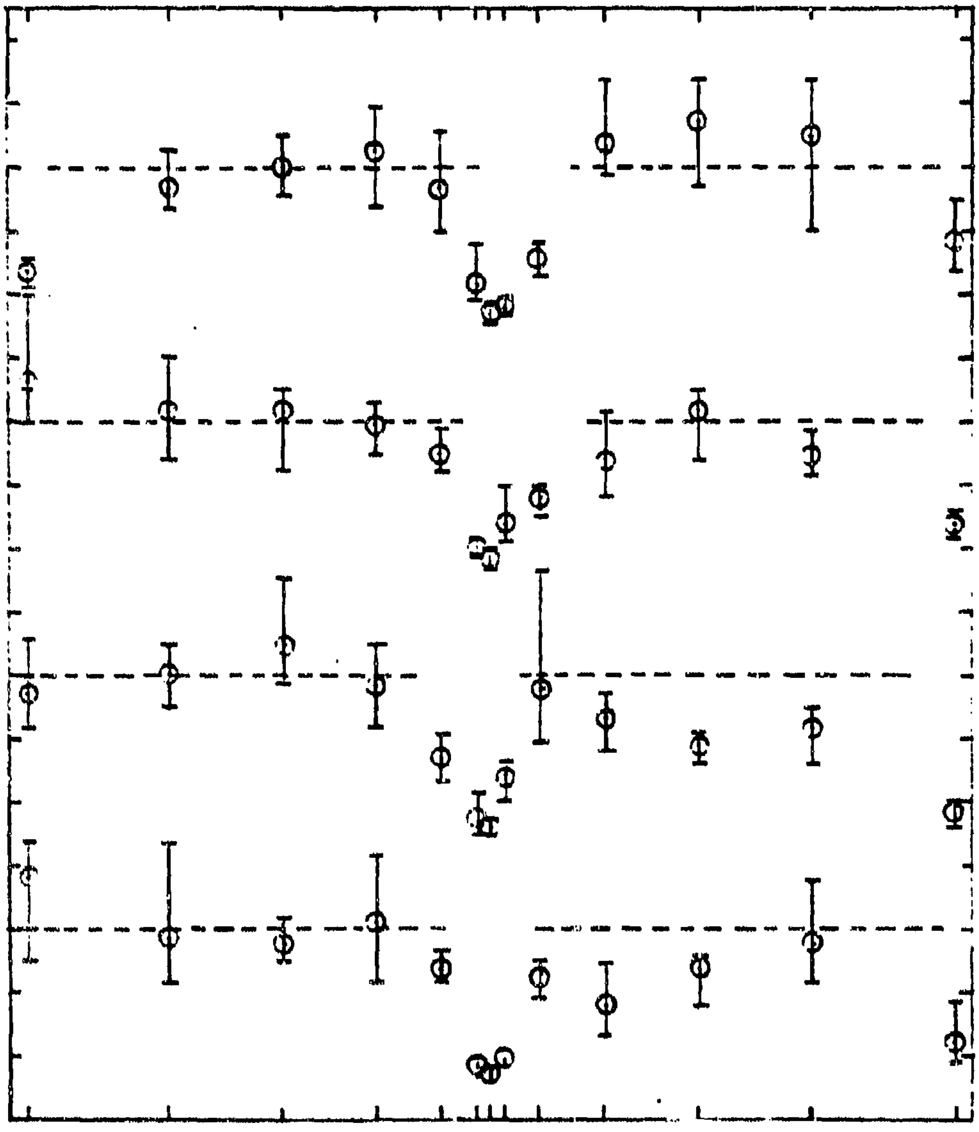


Figure 29. Pressure distribution in terms of r^2; $\bar{p}$ = 15 psi; standoff distance = 16"

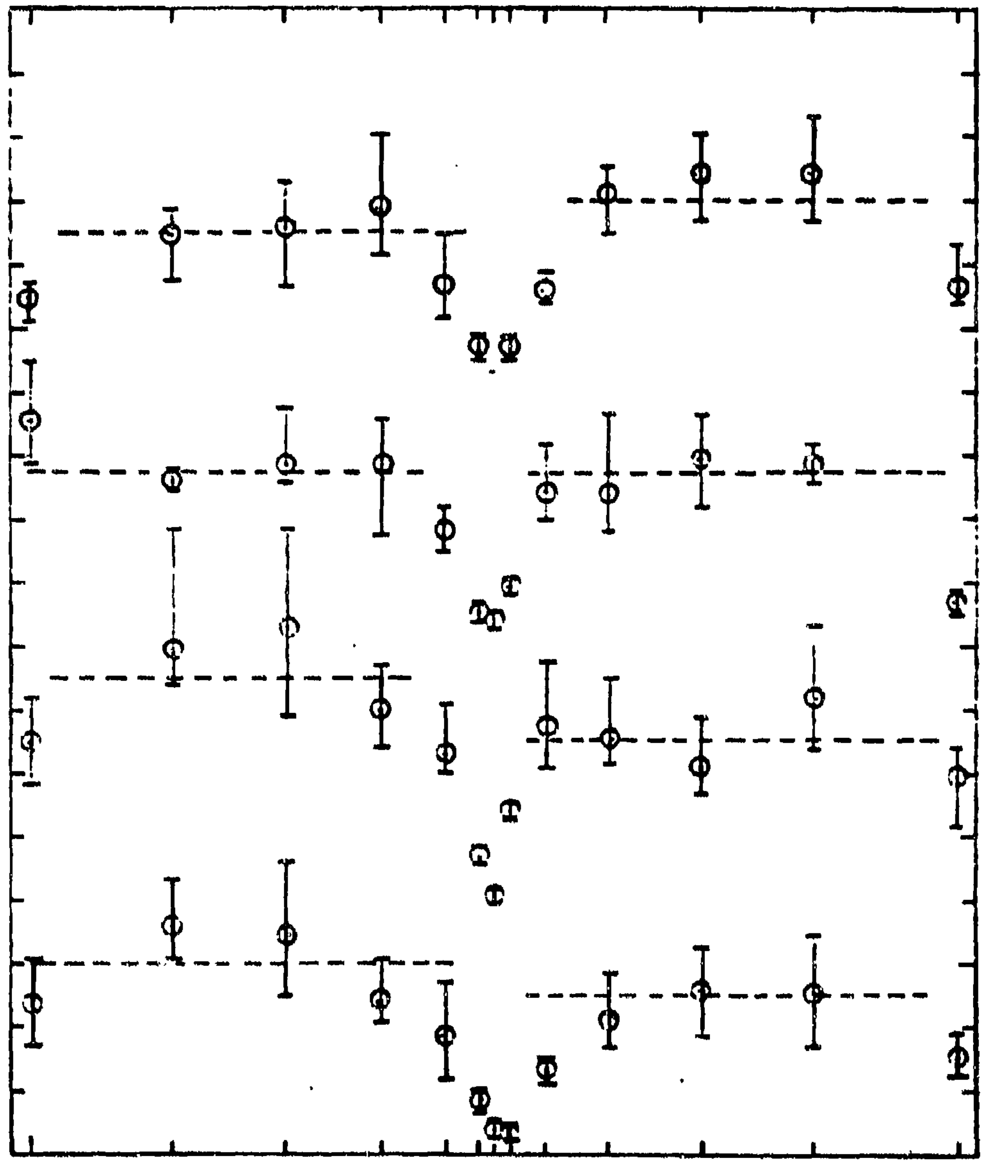
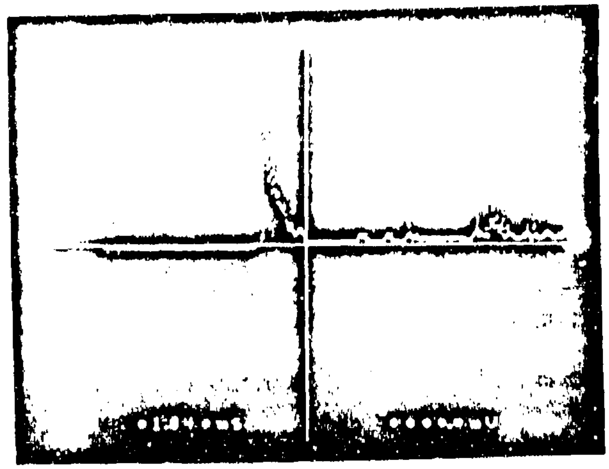
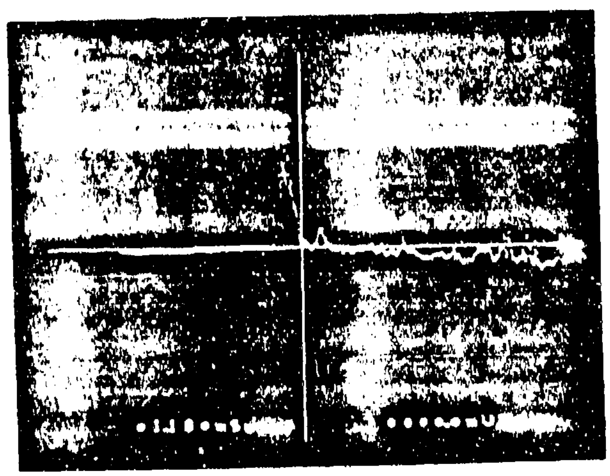


Figure 30. Pressure distribution in terms of r^2; $\bar{p}$ = 25 psi; standoff distance = 15"



P_{max} = 53 psi

Rise Time = 0.24 ms



P_{max} = 61.5 psi

Rise Time = 0.14 ms

P_{max} = 92 psi

Rise Time = 0.28 ms

Figure 31. Typical local impact signal as measured by a force transducer with a 2 in.^{2} target area

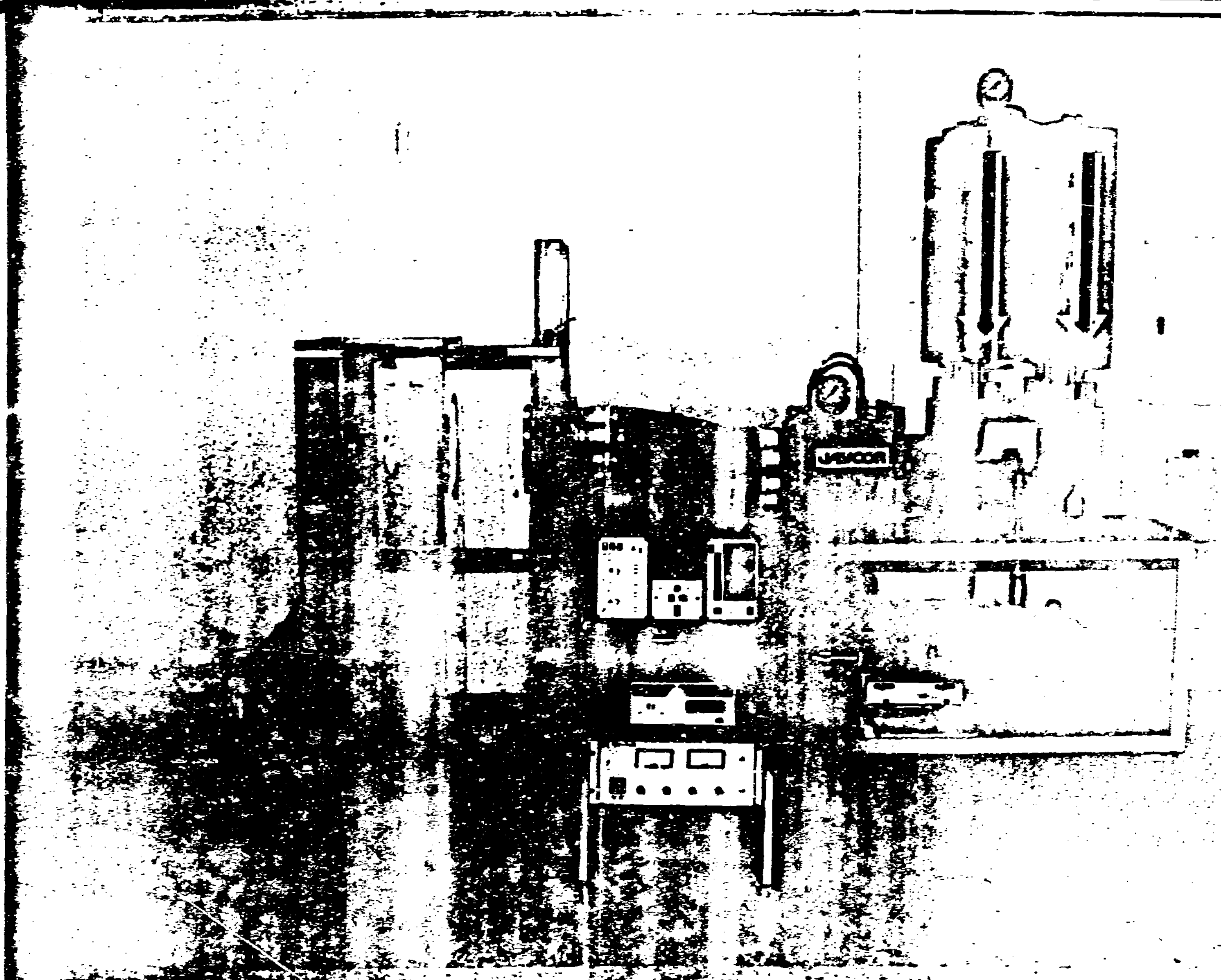


Figure 22. The prototype jet impactor

As in any new product development, there are always hurdles and stumbling blocks during the process, which are also exactly what makes the experience challenging and rewarding. Such was the case in the jet impactor development.

APPENDIX I

LIST OF PARTS AND VENDORS

Cole-Palmer
7425 North Oak Park Ave.
Chicago, IL 60648
800-323-4340 or 312-647-7600

Rectangular tank Cat #C-6323-43, 30 gal, 24" x 18" x 18".

Hoskel
8869 Balboa Ave.
San Diego, CA 92123

714-292-6667

Hydrodyne Industries, Inc.
35 Gilpin Ave.
Hauppauge
Long Island, NY 11787

516-234-0800

Hydrodyne water accumulator AX30-5W-B32.

Kistler Instrument Corp.
75 John Glenn Drive
Amherst, NY 14120

716-691-5100 Mr. Mike Murphy

1. Low impedance piezotron Type 211B4 pressure transducer (0-200 psi).
   Low impedance piezotron Type 211B3 pressure transducer (0-500 psi).

2. Transducer cable 1514A2.

3. Piezotron coupler Type 5116.

4. Model 223A flush mounting adapter for pressure transducer.

5. Force transducer Model 922F3 (0-500#).

McMaster-Carr
P. O. Box 54960
Los Angeles, CA 90054
213-945-2811

Water Supply Tank

1. Polypropylene float No. 9775K12.

2. Brass float rod No. 2754K3.

3. Brass float valve No. 4652K22 (1/2").

4. Suction screen No. 9877K63 (1-1/4" pipe size).

Orifice Plate

5. 1" union No. 4725K16 (to hold orifice plate in place).

6. Brass locknut No. 4557K28.

Motor

7. Cast iron pulley No. 6209K117, bore size 1-11/16".

8. B section V-belt No. 6187K142.

Other

9. Bronze check valve (1") No. 9770K35.

10. Stainless steel nipples, elbows, tees, unions, bushings.

Nelson-Dunn, Inc.
7818 Wilkerson Court
San Diego, CA 92111

714-268-4140

1. Flexonics series 401M stainless steel hose, 1-1/2" diameter, 24" long, male pipe fittings on both ends.

2. Internal swivel/external pipe No. 2045-24-24S.

3. Hydraulic hose #2781-16-36W/4722-16-16S, 1" diameter, 36" long, male pipe fittings on both ends.

PCB Piezotronics
3425 Walden Avenue
Depew, NY 14043

716-684-0001

1. Quartz force transducer Type 208A05 (5,000#).

2. Quartz force ring Model #202A (10,000#).

3. Coaxial cable #002C10.

Valvata Associates
13925 Minnesota Ave.
Paramount, CA 90723

714-761-3644

Automatic Switch Co.
6 Watsessing Ave.
Bloomfield, NJ 07003

201-743-2804

1. ASCO 2-way solenoid valve, 1-1/2", N.C., 24 VDC #8210B56.

2. Spare part kit #168-503.

3. Coil #74-073-5-D.

Xanadu Controls
45 Fadem Road
Springfield, NJ 07081

201-467-8100

1. Up-timer No. UPT100-10-10.

2. Option "C" surface mounted bracket interface.

3. Teledyne part #603-2 solid state relay.

Zemarc
5946 E. Washington Blvd.
Los Angeles, CA 90040

213-721-5598

Pump

1. CAT pump Model 2520.

2. Pulley assembly No. 30269.

3. Shaft protector No. 26516.

4. Mounting rail No. 30268.

5. CAT oil, 21 oz bottle.

Other

6. Baldor TEFC 3 phase motor MT333T-9T (15 HP).

7. WIKA pressure gauge Type 213, 4" glycerine filled, 0-400 psi.

8. Spring systems pressure regulator #6815-1/2-HSS-700.

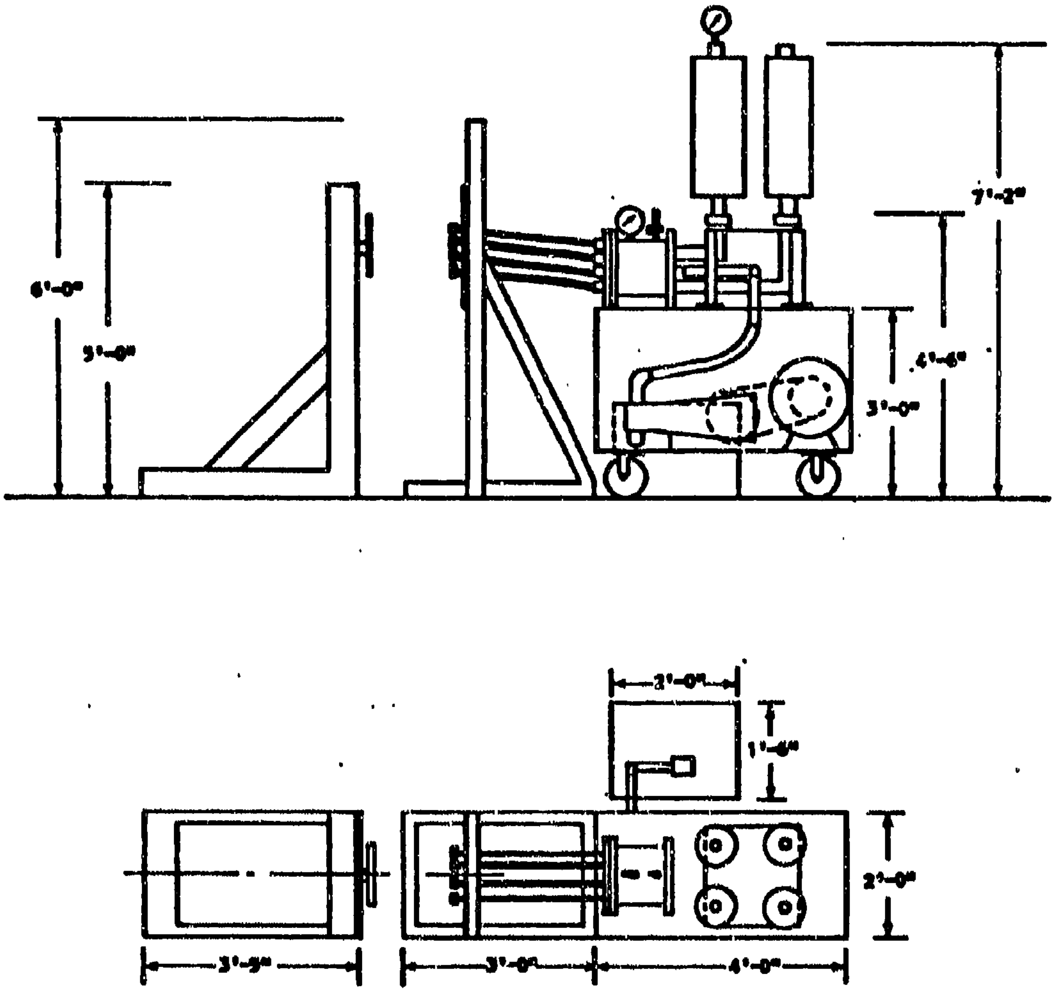
Accumulator Charging System

9. Gauge head assembly #A768-236.

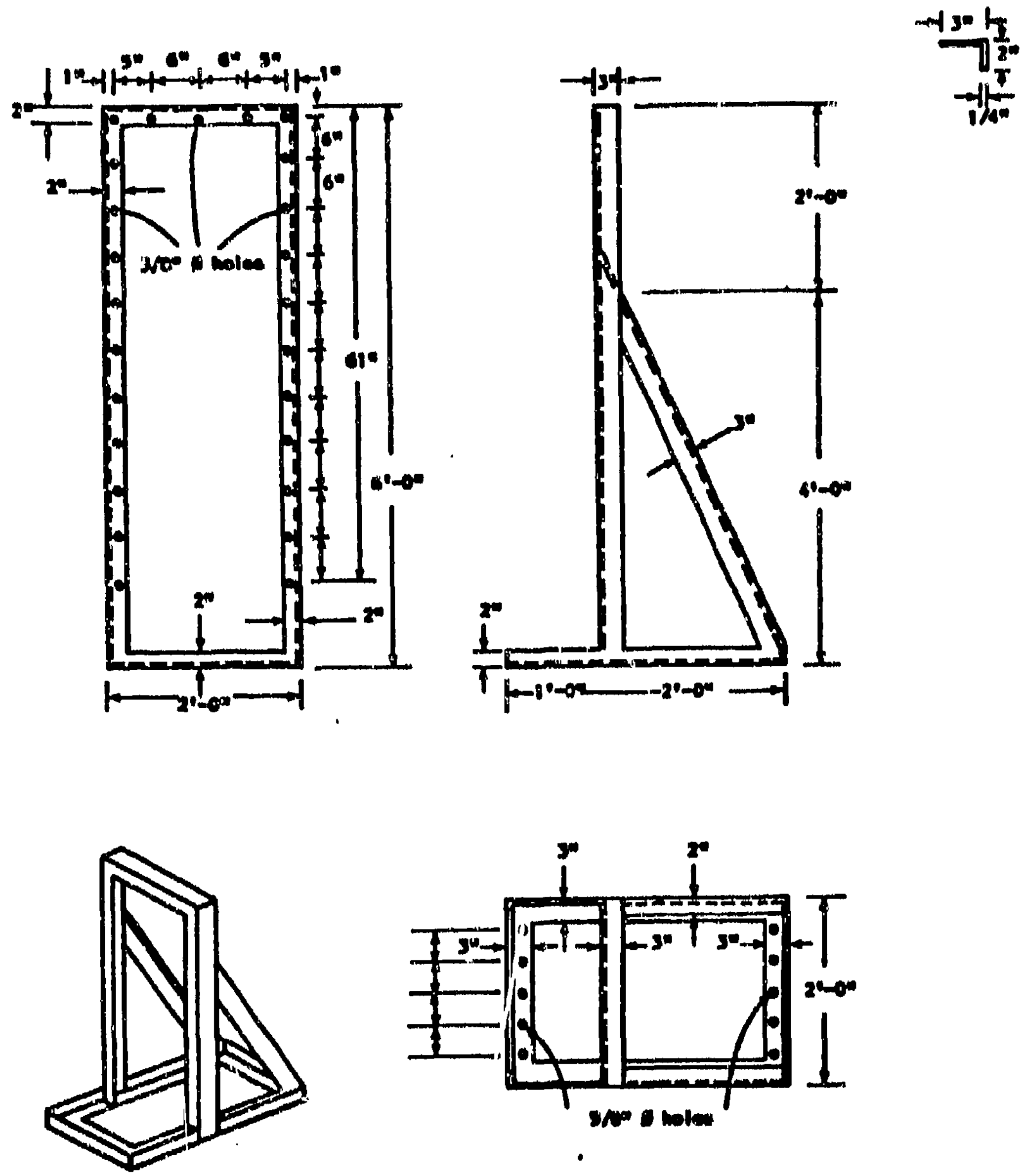
10. Charging hose (2 × 1/8" NPT) 2' long, #768-214-2.

APPENDIX II

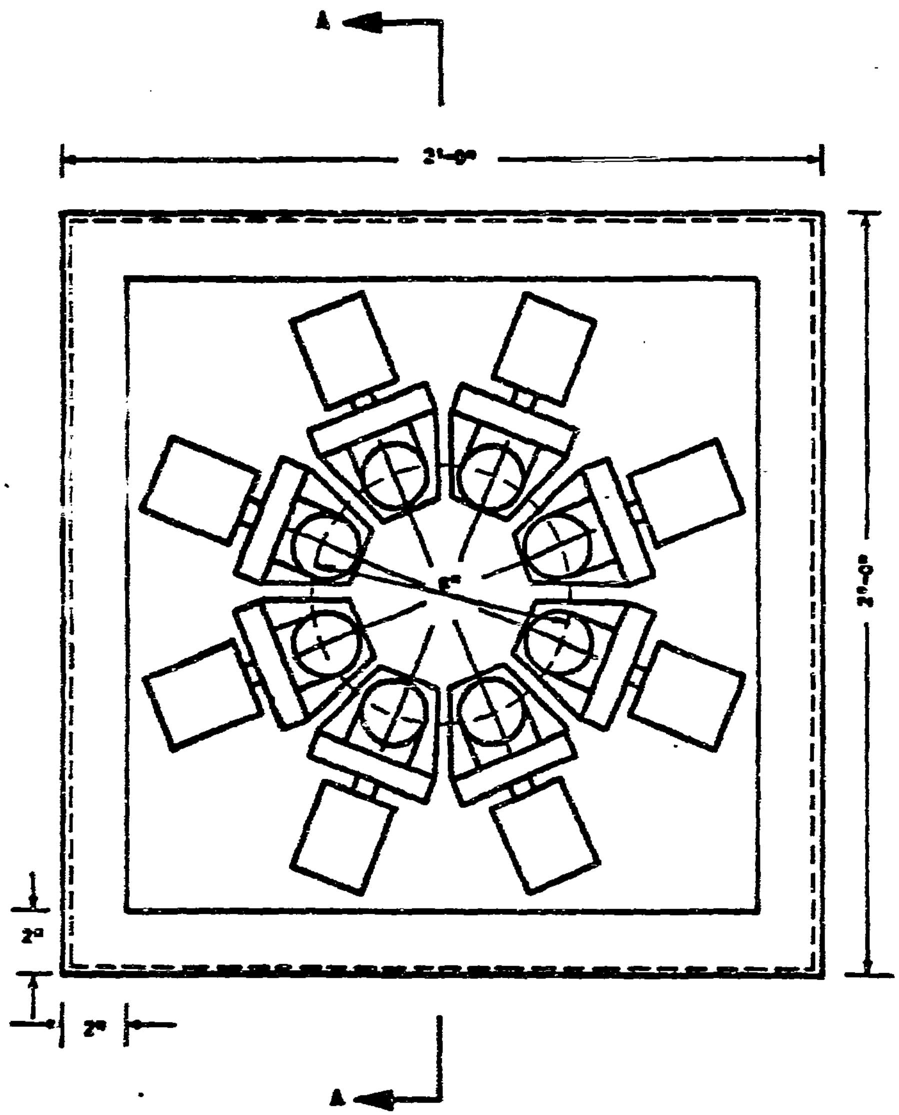
ENGINEERING DRAWINGS

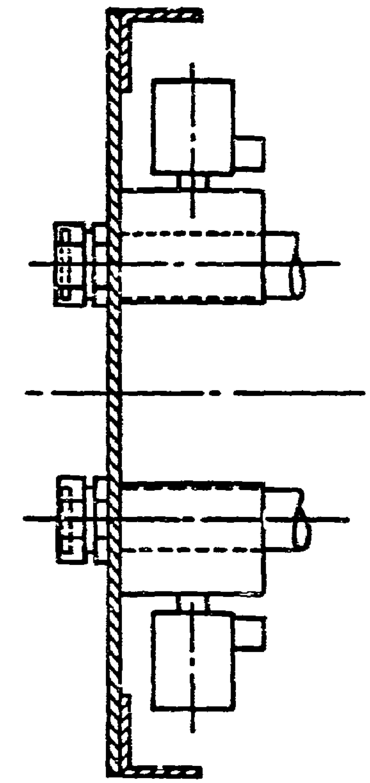


Schematic of jet impactor setup



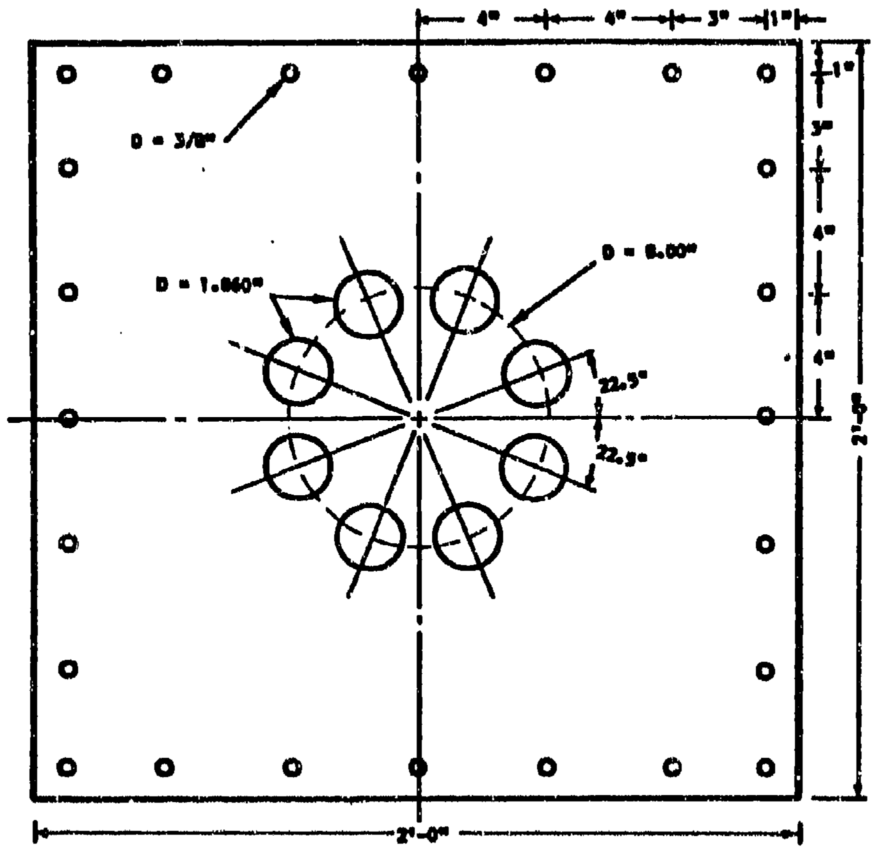
Nozzle & valve support frame



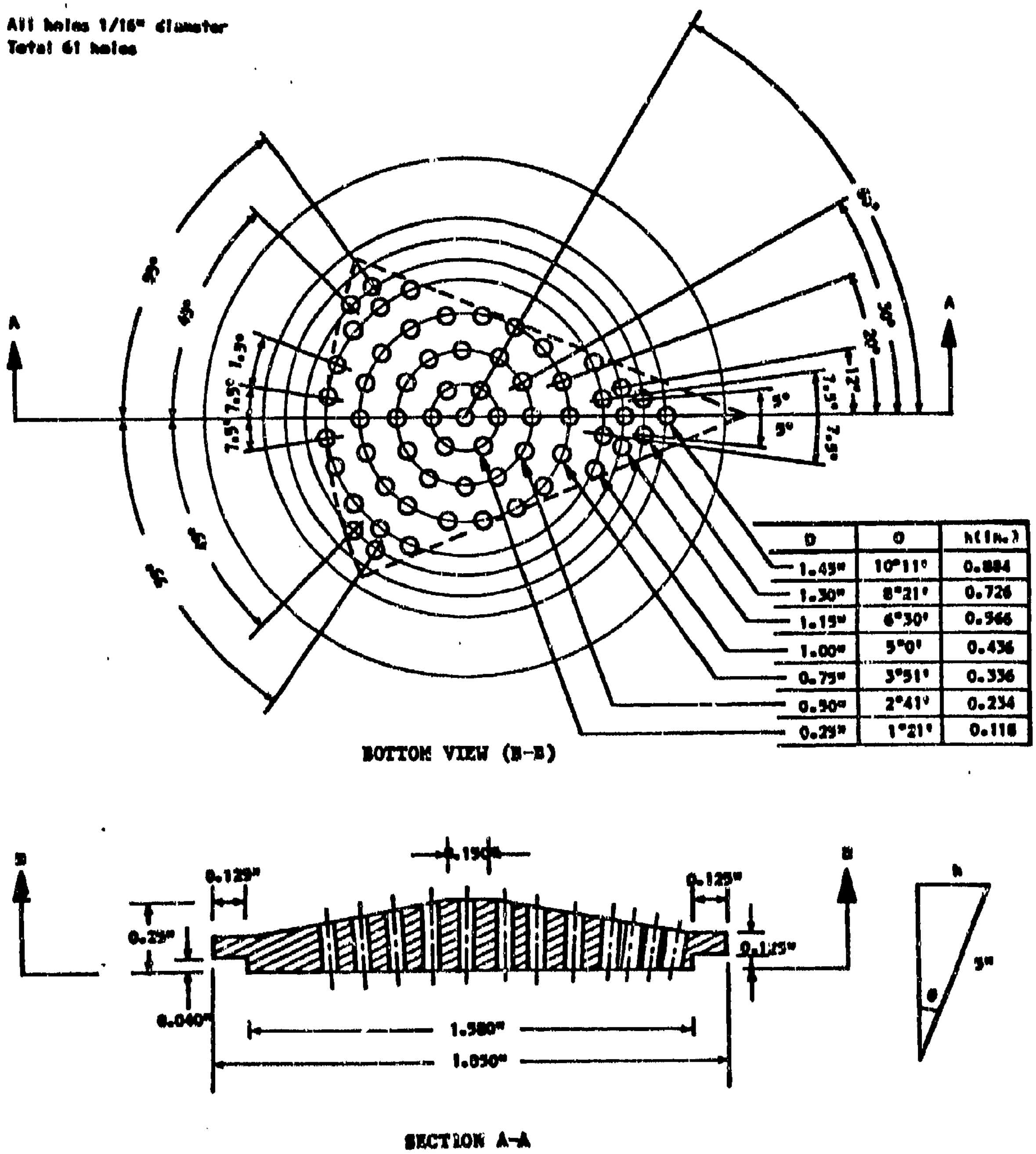


Section A-A

Nozzle head configuration

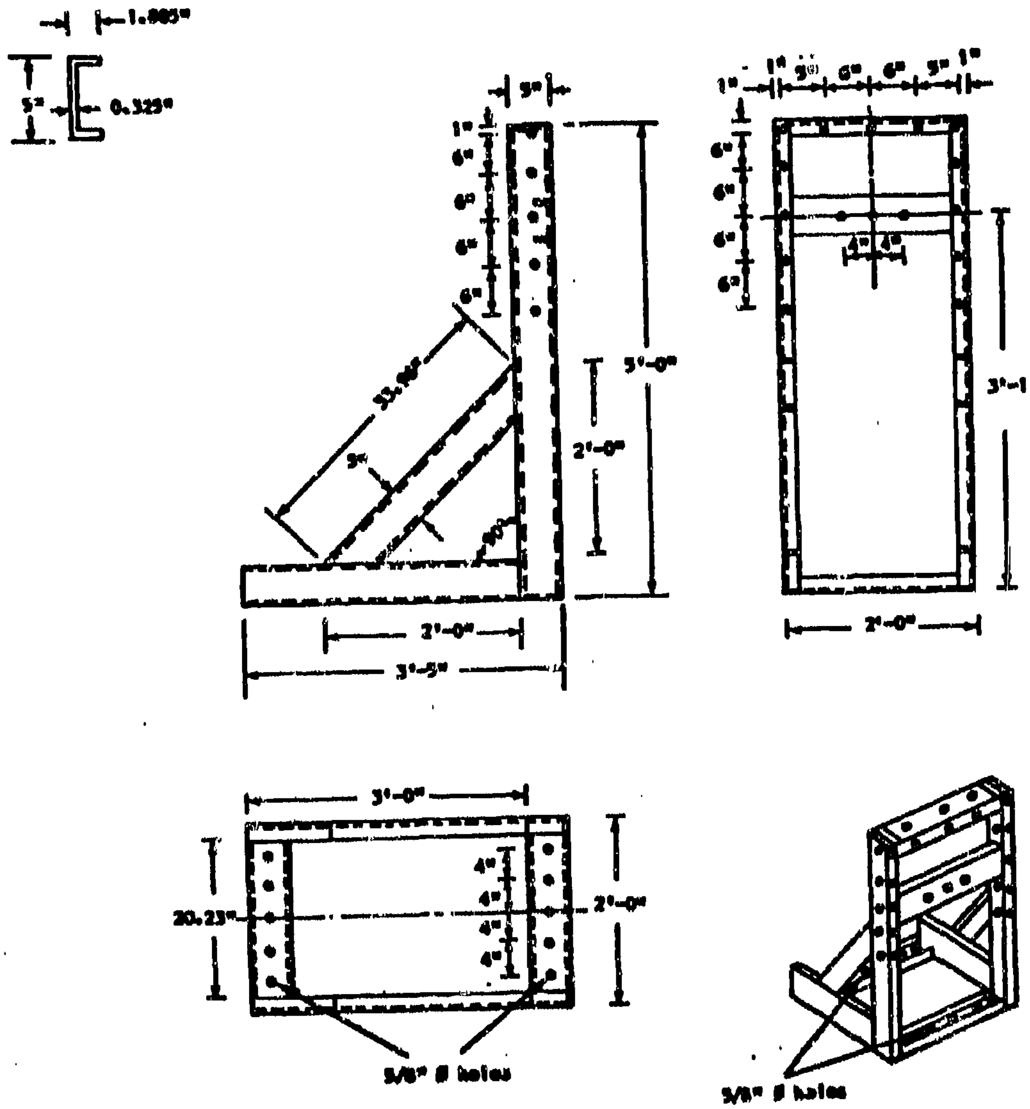


Valve mounting plate



D	θ	h(in.)
1.45"	10°11'	0.884
1.30"	8°21'	0.726
1.15"	6°30'	0.566
1.00"	5°0'	0.436
0.75"	3°51'	0.336
0.50"	2°41'	0.234
0.25"	1°21'	0.118

Orifice plate configuration and hole pattern



All holes 3/8" diameter
except as noted

Target support frame

APPENDIX III

INSTALLATION AND OPERATION MANUAL

FOR THE JET IMPACTOR

JAYCOR

INSTALLATION AND OPERATION MANUAL
FOR THE
JET IMPACTOR

5 March 1982

Prepared for

U. S. Army Division of Medicine
Walter Reed Army Institute of Research
Washington, DC 20012

under

Contract No. WRAIR DAMD17-81-1059

Prepared by

J. M.-Y. Yu
E. Vasel

Fluid Dynamics Division
JAYCOR

11011 Torreyana Road - Post Office Box 85154 • San Diego, California 92138 • (714) 453-6580

CONTENTS

1. GENERAL INFORMATION

1.1 This manual contains information for the installation, start-up, operation, and troubleshooting of the jet impactor develped by JAYCOR under Contract WRAIR-DAMD17-81-1059 for the U. S. Army Division of Medicine, Walter Reed Army Institute of Research.

1.2 The jet impactor was developed to simulate blast overpressure signals between 3 psi and 25 psi on target areas approximately 100 $in.^2$

1.3 The jet impactor was designed to be semi-mobile and has a flexible head assembly which can be targeted at various heights off the floor to accommodate different size test subjects. Specific principles of operation and performance characteristics will be contained in the final report.

2. INSTALLATION

2.1 Initial Inspection

Before shipment, this assembly was operational and found to be free of mechanical and electrical defects. As each crate is unpacked, inspect for any damage that may have occurred in transit. Save all packing materials until inspection is completed. If damage is found, file a claim with the carrier immediately. JAYCOR should be notified as soon as possible.

2.2 Mechanical Check

This check should confirm that there are no broken knobs or connectors, that all finished surfaces are free of dents and scratches and that meters and gauges are not scratched or cracked.

2.3 Electrical Check

All electrical components should be checked according to their respective check-out procedures in the appropriate operating and service manuals found in the appendix of this document.

2.4 Assembly and Installation

The jet impactor is shipped ready for permanent field operation. After assembly it is necessary only to connect the motor to a 230 volt 3-phase power source, the power supply and timer to a 115 volt AC source and the water tank to a water supply. The assembly procedure is done in six stages: impactor core assembly, accumulator, impactor nozzle head support structure, nozzle head assembly, water tank and calibration target support structure assembly. The final assembled unit is shown in Figure 1.

2.5 Assembly of the impactor should begin with the unpacking of Crate #1 which contains all the small components, gauges, transducers, target plates, O-rings, and bolts necessary for assembly and calibration.

2.6 Crate #4 which contains the impactor core assembly should be positioned near the final installation site and uncrated. This assembly contains the pump, motor and pressure chamber of the impactor. These are mounted on a cart which has wheels for relative easy movement of the jet impactor. Inspect the core assembly for damage. Remove the tape covering or holding the four accumulator O-rings on the top of the assembly. Clean the O-rings of all dirt or grit and apply an even coat of silicon grease. Reinstall the O-rings in the O-ring seats.

2.7 Open Crates #2 and #3 containing the four Hydrodyne Accumulators. Remove all protective tape from the accumulator openings and clean each mating surface with a mild solvent to remove any adhesive residue. Each accumulator is marked near the edge of the mating surface with a series of dots corresponding to similar dot patterns on the core assembly unit. Matching each dot pattern will insure proper installation of each accumulator and perfect hole alignment of mounting bolts. (Note: An overhead hoist using nylon straps is very useful for accumulator installation. Each accumulator weighs approximately 250 lbs.) Start all four machine bolts in each accumulator before final torquing is accomplished. Be sure two washers are used for each bolt

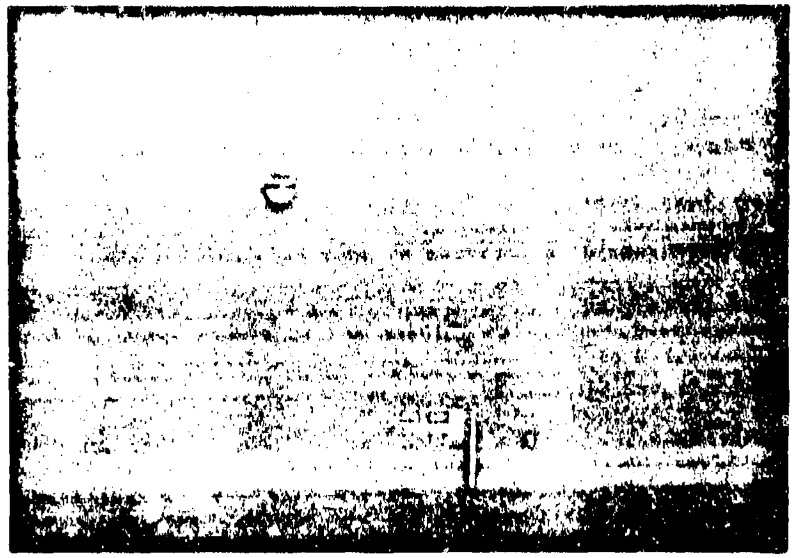


Figure 1

and all are fully tightened. After all accumulators are installed, the impactor can still be moved, but should be accelerated and decelerated slowly and smoothly to prevent rocking of the accumulators which could result in damage to the core assembly structure.

2.8 Crate #1 contains the pressure gauge/charging assembly, and charging hose for the accumulators. This 3 hose/1 gauge assembly is installed on the top of the four accumulators after removing the protective screw caps (silver and yellow). No teflon tape is needed for installation. The 2 ft cable sections should be coiled towards the center of the four accumulators as shown in Figure 2. The 10 ft charging hose is used to charge the accumulators from a bottled N_2 source.

2.9 A pressure gauge from Crate #1 should be installed using teflon tape to one of the ports on top of the pressure chamber. A petcock with tygon tubing for pressure relief should be installed in the remaining pressure chamber port. Move the core unit to the final installation position. The unit is designed to shoot from right to left from the operator's viewpoint.

2.10 Crate #6 contains the DC power supply, the valve timer, inlet pipe assemblies, calibration stand-off distance struts and the nozzle head support frame. Remove the nozzle head support frame and place approximately 3 ft in front of the pressure chamber.

2.11 Locate the large pressure chamber O-ring in Crate #1. Clean, grease, and install it in the pressure chamber O-ring groove.

2.12 Carefully unpack the nozzle head assembly from Crate #5. (Note: When lifting the assembly be sure it is evenly supported along all the flexible hose section so as not to induce undue stresses which could result in potential leaks.) Use six 5/16" hex bolts from Crate #1 to attach the head assembly to the frame while resting the pressure chamber mounting plate on the cart edge. Be sure the "TOP" of the nozzle support plate is in an upright position.

2.13 Mate the pressure chamber plate to the pressure chamber and install the proper bolts from Crate #1. Be sure to fully tighten all bolts and compress lock rings to prevent hammering of bolts during pressurization of system. After initial test run, re-tighten all bolts.

2.14 Connect the prewired relay panel assembly to the back of the programmable UP-TIMER from Crate #6 as shown in Figure 3. First connect the relay bracket screws. Next plug in relay connector plug. Finally, plug red and black pins into respective receptors. Connect power cord to UP-TIMER and connect to 115 volt source. Notice that the relay panel has 10 relays. The first eight relays are currently wired to valves #1-#8 respectively. Relays #9 and #10 are not currently being used. These are open channels for spares or future growth. Each valve relay has a channel color assigned according to the color code attached to the wiring harness. Color coded "pigtails" have been attached to each positive (red) wire going to each valve to help identify the relay number and TIMER channel assigned to that valve. For example, Channel 3 is red and valve number 3 is attached to the red "pigtailed" relay. Channel identification is essential for valve synchronization. The black wire going to each valve is a common negative ground (-). Therefore any

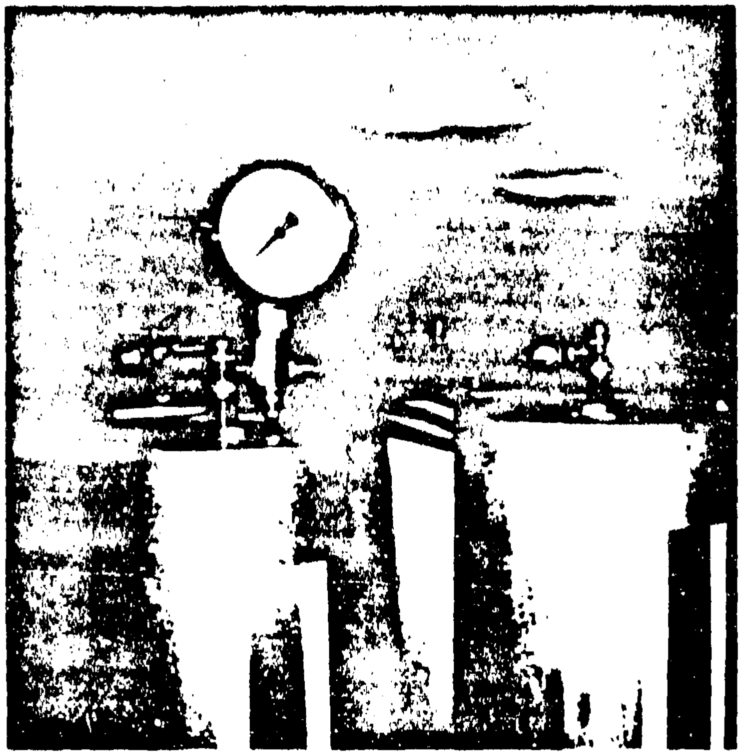


Figure 2.

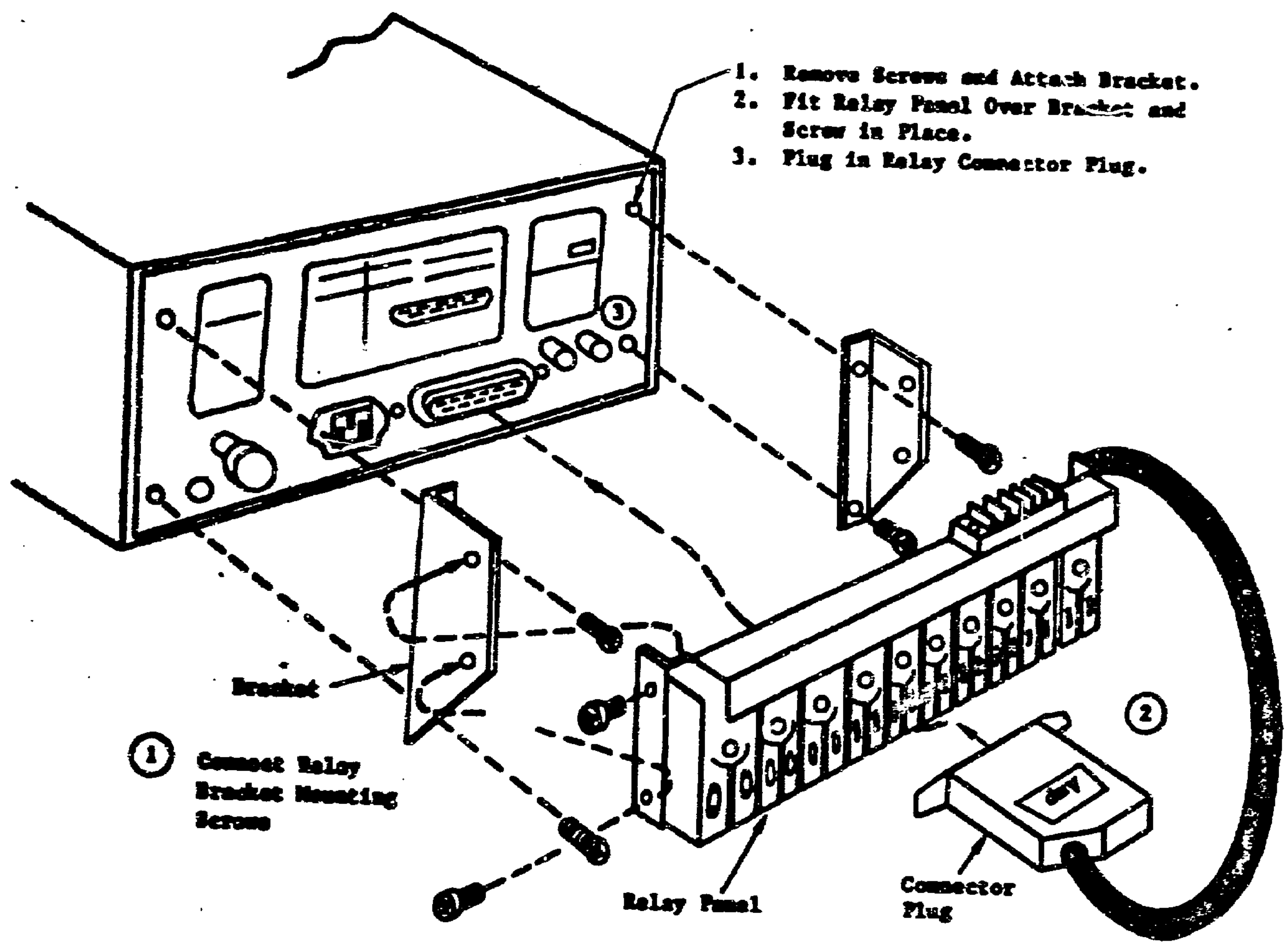


Figure 3. Option "C" Mounting Instructions.

black wire can be attached to any valve. However, only each valve's assigned positive (+) "pigtail" colored wire can be attached to each specific valve.

2.15 Unpack the DC power supply from Crate #6. (Note: This power supply has been converted to operate on 115 volts input current.) Refer to Section III of the Hewlett Packard Operating and Service Manual for the Turn-On Checkout Procedure. This must be done before any load is connected to the power supply. Section 3-8, 3-12 of the HP manual must be accomplished for proper operation of all eight valves. Set the current limit according to Section 3-8 at 12.0 AMPS. Set the "Overvoltage Trip" point in section 3-12 at 26.2 volts. Turn off power switch.

2.16 Connect the red power wires from the UP-TIMER relays to the DC Power Supply positive (+) output bar using two terminals to each free screw on the (+) power bus bar. Now connect the two terminals each of the black ground-wires to each free screw of the negative (-) power bus bar. See Figure 4 for proper installation.

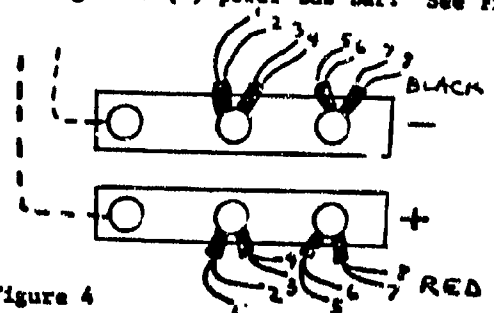


Figure 4

Proper installation requires that the black terminals come off towards the top of the bar and the red terminals come off towards the bottom of the bus bar to eliminate the possibility of shorting between bus bars.

The UP-TIMER and DC Power Supply may be stacked. Since both units are fan-cooled they must be installed with sufficient space for cooling air to reach their sides. These units should be used in an area where the ambient temperature does not exceed 55°C.

2.17 Attach the stainless steel inlet water pipe to the pump using teflon tape for sealant. Slide the water tank from Crate #7 into position and attach the fill shut-off float to the fill valve. Connect the water supply hose. Screw the plastic feed pipe filter section into the stainless steel inlet pipe assembly as shown in Figure 5.

2.18 Attach the pressure regulator with the by-pass port pointing aft as shown in Figure 6.

2.19 Install the by-pass stainless pipe section and support as shown in Figure 7. Attach the clear plastic by-pass section.

2.20 Before hooking power to the pump motor, loosen the brass belt tension adjustment screws on the pump and slacken the belts enough to remove them. Once the belts are removed, the motor can be wired and tested for proper rotation direction to prevent damage to the pump.

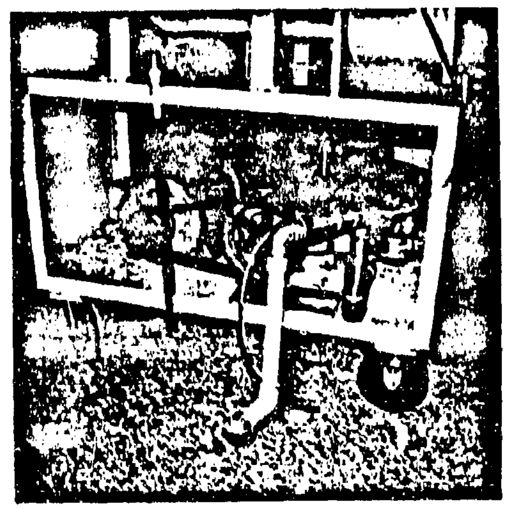


Figure 5

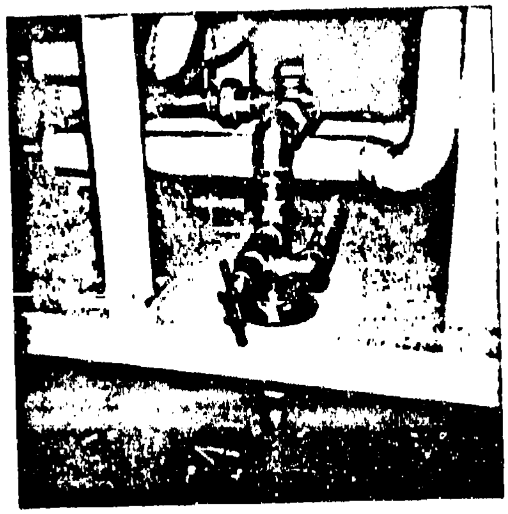


Figure 6

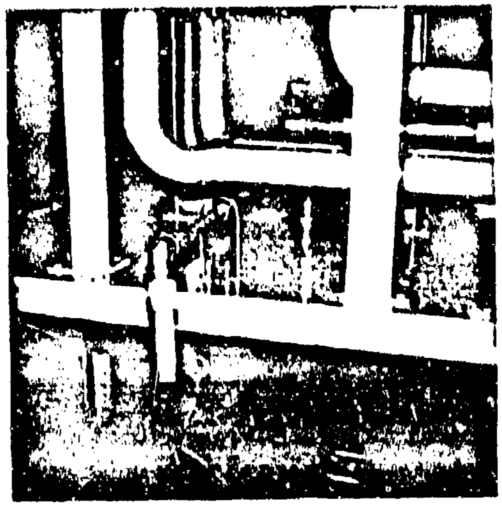


Figure 7

2.21 Wire the motor to the 230 Volts, 3-phase input as described on the motor for "Low Voltage" hookup. Make connections as to local code and install any necessary wire brackets or hold downs. Check for proper rotation of the motor. If motor turns in wrong direction, switch any pair of wires and test it again.

2.22 Once proper connection and rotation is established, reinstall and adjust belts. A properly adjusted belt should have less than 1/2" depression distance.

2.23 Unpack the target support frame from Crate #7. Attach the plexiglass splash shield to the target support frame. Attach the four stand-off distance calibration struts between the target support frame and the nozzle head support frame as shown in Figure 1. Set stand-off distance according to the calibration curve for different impact pressures.

2.24 Install a calibration transducer* or transducer array.* Attach transducer cable(s) to Piezotron Coupler input connector and attach black piezatron output cable to an oscilloscope. Turn on Piezotron coupler. Bias voltage should read 12 volts.

2.25 The jet impactor assembly is now complete.

*A single force ring and target plates of 2 in.^{2}, 5 in.^{2} and 113 in.^{2} are provided. A pressure transducer is also provided. User may elect to use an array of transducers.

3. INITIAL START-UP

3.1 Refer to the pump section in the Service Manual Appendix for proper adjustment of the automatic oilers on the pump.

3.2 Refer to the UP-TIMER section for the procedure involved in programming the timer. Although the valves should be resynchronized before each calibration test, the timing card supplied in the pack can be used for the initial start-up test. Set the timer on 020+100 sec* cycle duration. Turn on timer power. Pull out TIMER drawer. Push in control knob and rotate to "PROGRAM." Push "RESET." Place timing card in drawer. Be careful of proper corner orientation key. Carefully slide drawer in smoothly. Watch channel lights glow and turn off as push is complete. Rotate control knob to "SINGLE."

3.3 Charge accumulators to 80% of the desired line pressure. (Note: accumulator valves are open when rotated clockwise down into stem and are closed by backing valve stems counterclockwise out of stems.)

3.4 Turn on pump motor, loosen lock nut on regulator and rotate regulator adjustment control until chamber pressure gauge holds at the desired pressure.** Lock adjustment nut. Bleed any compressed air from chamber using petcock relief valve.

3.5 Turn power supply power on. Be sure 24 volts is indicated output.

3.6 To fire impactor, quickly depress and release "START" switch on the UP-TIMER. If switch is depressed too long, multiple valve firings will result and also may cause the valves to stick open. Note that the first firing may contain some compressed air. Bleed air from pressure chamber again and recharge system to the desired line pressure. Blow orifice plates clean of entrained water with compressed air supply. This insures similar chamber conditions for all valves. A series of 5 or 6 shots may be needed before system "WARMS" up and begins repeatable operation.

*020+100 sec = 200 msec cycle duration or 2 msec/unit. 60 units = 120 msec valve shot time. Note: When ÷100 sec are used no lights in elapsed time are visible.

**Note: Never pressurize system beyond 250 psi. Valves are not rated above 250 psi.

4. TROUBLESHOOTING

4.1 Problem: System Leaks

Remedy: The impactor is designed for relatively easy disassembly at various points in the system. Swivel connections are provided at the valve/flexible hose interfaces and at the pump flexible hose/pressure regulator interface. Also a union is provided between the pressure chamber and check valve. Loosen leaking section, retape with teflon tape and reassemble section.

4.2 Problem: Leaks at Orifice Plate

Remedy: A large leak at an orifice plate may reduce that specific valve's performance. Hold valve secure and loosen stainless "mason jar" retaining ring. Remove ring and orifice plate. Replace or reseat O-ring onto brass nipple. Retape teflon onto brass nipple. Reinstall orifice plate and retaining ring. Align orifice plate properly while tightening. It is important to tighten the orifice plate securely against the brass nipple O-ring seat for proper seal. If retaining ring begins to tighten but the orifice plate appears loose, slightly loosen retaining ring and begin to tighten again until proper seating is attained. IMPORTANT NOTE: If retaining ring is not tightened and fully seated, it may cause the orifice plate and the retaining ring to be "shot off" the brass nipple causing damage to calibration plate or injury to test subject.

4.3 Problem: Oil in Water Supply

Remedy: Oil slick in the water supply is caused by improper adjustment of the automatic oilers on the pump bearings section. Refer to the pump section of the service manuals for proper adjustment procedures.

4.4 Problem: Valve sticks open. System cannot be pressurized.

Remedy: This usually occurs if a valve has malfunctioned or it may occur if the operator has cycled the valves when the system pressure is zero. One solution to this problem can be attained by cycling the charging system on and off a few times in quick succession. The pressure pulses may close the valve. If this does not solve the problem, then the solenoid section of the malfunctioning valve must be removed and reinstalled.

Valve Removal Procedure:

1. Bleed system pressure
2. Remove solenoid retaining bolts from valve housing.