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NEW CONCEPT FIREFIGHTING AGENT DELIVERY SYSTEM

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13. ABSTRACT (Maximum 200 words) The objectives of this project were to develop conceptual designs for a long-range, fire suppressant delivery system and to construct, test, and demonstrate a prototype unit. Two basic long-range delivery system concepts were considered: streaming and catapulting. Design considerations were throw range, effect of winds, accuracy of delivery, and mass of agent delivered to the target. Streaming concepts were investigated initially, but were abandoned because the desired delivery range could not be achieved. Catapulting concepts became the focus of the remainder of the project. The first catapulting prototype device demonstrated in field testing that a 35-pound sphere filled with firefighting agent could be delivered a distance of 600 feet with a reasonable accuracy. JP-4 pool fires of 40 ft ² and 80 ft ² were extinguished in testing from a distance of 600 feet and 400 feet, respectively. This led to the development of a more advanced, computer-controlled, rapid-fire prototype. Field testing of the second prototype demonstrated the capability to deliver 6-shot barrages of 35-pound agent canisters to a distance of over 1400 feet.				
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EXECUTIVE SUMMARY

A. OBJECTIVES

The overall objectives of this effort were to develop conceptual designs for a long range fire suppressant delivery system and to construct, test, and demonstrate a prototype unit.

B. BACKGROUND

The importance of the effective delivery of fire suppressants to a distant target in a complex, multidimensional fire environment has long been recognized. There is a recognized need for the development of a long-range delivery system to combat effectively the hazardous environments encountered in postattack and postcrash firefighting situations, where munitions, volatiles, and surface obstructions multiply the challenges of safety and accessibility.

There are presently two basic long-range fire suppressant delivery system concepts: streaming and catapulting. Streaming delivery systems are the more common and have been used in numerous capacities (riot water cannons, field irrigation sprinklers, and standard firefighting vehicles). Catapulting delivery systems deliver specific amounts of agent in pulses and are thought to possess superior range and accuracy characteristics. These systems include grenade launchers, longitudinal flow delivery, and impulse mass transfer systems such as toroidal vortex flow. However, the parameters governing the performance of catapulting systems are not well known.

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C. SCOPE

The scope of this effort considered delivery system compatibilities with candidate fire suppression agents, and the determination of phenomena controlling aerodynamic characteristics. Design considerations were throw range, ability to overcome high winds, accuracy of delivery, and volume or mass transfer rates. Also, the system should be compatible with existing USAF firefighting equipment and concepts.

D. METHODOLOGY

The methodology used included the following:

1. An extensive literature and user survey was conducted to research the current status of delivery systems in use today. Developers and users of firefighting equipment were contacted to assist in the development of performance parameters for a new concept long-range delivery system.
2. Some advanced streaming concepts were initially investigated, but these initiatives were terminated when the USAF delivery distance requirement of 1200 feet was made known. At this time, the literature search focused on catapulting and the investigation of several viable catapulting concepts. Basic aerodynamic and dispersion studies were carried out with balloons.
3. During concept development, a prototype device built for the US Navy in 1984 was located and acquired. This prototype was designed to propel light loads of fire suppressant powder entrained in a toroidal vortex. This launcher was tested and modified to the point where it could deliver a 35-pound sphere of agent a distance of 600 feet. This load and distance represented the limits of the launcher system, and major modifications were undertaken to replace the firing valve, fit the launcher with a rapid-load cylinder, and computerize the entire aiming and launching operation.

4. A ballistics program was written and refined, laboratory tests were conducted on candidate canister materials, and bench tests were conducted on subsystems. After system integration, field tests were used to verify distance, circular error probable, and extinguishing characteristics of agent canisters.

E. TEST DESCRIPTION

Several types of spherical canisters were bench-tested to assess the characteristics of tensile strength, ductility, expansion coefficient, and compatability with candidate agents. Launcher testing included subsystem evaluations and field testing of the complete system. Field testing provided the assessment basis for distance, accuracy, system integrated operation, and agent dispersal from the canister. Four field tests involved extinguishment of remote fires. Two 80-ft² JP-4 fires were extinguished with single 35-pound canisters of agent from a distance of 400 feet. Similarly, two 40-ft² fires were extinguished from 600 feet.

F. RESULTS

Canister tests indicated that the polyurethane material best fit the requirements for this specific purpose. Subsystem and launcher system testing confirmed the operability of the system through the integrated computer controls. Field testing further supported the concepts of delivery distance, accuracy, and extinguishment capabilities of the assembled prototype.

G. CONCLUSIONS

The launcher prototype, at its present state of development, validates the concept of long-range fire suppression agent delivery via catapulting. The computer control system of the prototype effectively integrates the launcher's subfunctions and provides

required status and feedback advisories. The agent sphere and sabot fulfill the preliminary approaches to proof-of-concept extinguishing capabilities.

H. RECOMMENDATIONS

Before transitioning into Full-Scale Engineering Development (FSED), the prototype should be taken through an additional and extensive series of field tests to verify the ability of the system to withstand rugged field conditions, and to establish a firing history at chamber pressures of 150 lb/in.² and possibly higher.

While the sabot is improved through further testing, additional design studies should be undertaken regarding the advanced canister concept.

PREFACE

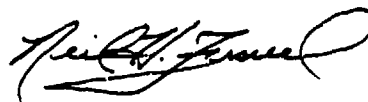
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This report summarizes work accomplished at NMERI between February 1986 and September 1990. HQ AFCESA/RACF Project Officers were Joseph L. Walker and Douglas B. Schwartz. The authors are indebted to the project technicians Jimmy D Watson, Jesse M. Parra, Brenda M. Wiuff, and Monica L. Rodriguez for their efforts during the testing portions of this work. This work also relied on communications, discussions, and support of Jack McLoughlin and Neocles Athanasiades of the Fire Research Corporation, and Bran Ferren and Ken Wisner of Associates and Ferren.

This report has been reviewed by the Public Affairs Officer (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.



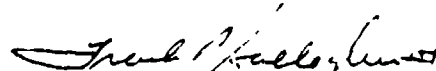
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SECTION I

INTRODUCTION

A. OBJECTIVE

The objectives of this effort were to develop conceptual designs for a long-range, fire-suppressant delivery system and to construct, test, and demonstrate a prototype unit.

B. BACKGROUND

The importance of the effective delivery of fire suppressants to a distant target in a complex, multidimensional fire environment has long been recognized. A long-range delivery system is needed to combat effectively the hazardous environments encountered in postattack and postcrash firefighting situations where munitions, volatiles, and surface obstructions multiply the challenges of safety and accessibility.

There are two basic long-range fire suppressant delivery system concepts: streaming and catapulting. Streaming delivery systems are more common and have been used in numerous capacities (riot water cannons, field irrigation sprinklers, and standard firefighting vehicles) for many years. Continuous streams are generated by expelling agent from pressurized vessels or expulsion of agent through engine-driven pumps. The catapulting delivery systems deliver specific amounts of agent in pulses. The agent is encapsulated in some type of fragile or dispensing device and released upon, or prior to, impact. This approach is relatively new and attractive because of its longer range potential. Although a catapulting system is thought to possess superior range and accuracy characteristics, the parameters which govern the performance of the system are not well known. A number of catapulting systems have been investigated and tested. These systems include grenade launchers, longitudinal flow delivery, and impulse mass transfer systems such as toroidal vortex flow.

C. SCOPE/APPROACH

The scope of this task involved the consideration of a delivery system compatible with fire suppressing liquids, powders, gases, or combinations thereof. Also included was the determination of phenomena that control the aerodynamics of the trajectory, delivery system range, and cohesiveness of the matter during flight, and state of the matter at the target. The design considerations were throw range, ability to overcome high winds, accuracy of delivery and volume or mass delivery rate. The delivery system should be adaptable to existing USAF firefighting equipment.

The approach to this task involved a literature and user survey, a study of the streaming concept and a Request for Proposal to develop catapulting design concepts. The reasons for the literature and user survey were twofold. The state of the art in long-range delivery systems was first examined, and the performance of the systems in actual working conditions by the people who use them was also studied. A streaming concept study evaluated the newest innovations as well as the existing systems. The Request for Proposal produced competing ideas on catapulting concepts.

SECTION II

PHASE I - NEW FIREFIGHTING AGENT DISPENSING CONCEPT DEVELOPMENT

Research efforts described in this section of the report are contained with additional detail and background in Reference 1.

A. LITERATURE AND USER SURVEYS

State-of-the-art literature and user surveys were conducted to research the current status of the delivery systems in use today. The areas examined were those directly or indirectly related to long-range fire suppression systems that would combat the effects of a crosswind. Systems with streaming or propelling capabilities were investigated. A thorough search of books, articles, reports, and report summaries was completed.

In combating partially or totally inaccessible fires, common problems are caused by wind conditions, obstacles in and around the fire, and the danger of an explosion. An optimum system should be able to overcome these factors and deliver a fire suppressant agent over long ranges with a large percentage of the agent reaching the target.

1. Literature Search

The technique of using a nozzle or a turret is commonly called streaming. One of the problems with this method is that only a small amount of the agent actually reaches the fire. Tests conducted by the Fire Research Station of the United Kingdom have shown that in calm conditions, at an operating pressure of 90 lb/in.² and at a range of 106.6 feet, only 25.5 percent of the agent (in this case water) actually reached its target. The maximum range of agent delivery occurred when the nozzle elevation was between 30 and 40 degrees above the horizontal. In further studies of nozzles, the best design incorporated a sharp-edged orifice plate, positioned in the exiting flow, to produce

a minimal exiting turbulence and spray. However, large eddies continued to lead to a premature breakup of the flow (References 2 and 3).

One of the streaming techniques that appeared to be promising was a vortex flow. This technique imparted a fluid rotation that seemed to control the fluid as well as limit the dispersion of the flow. The internal forces generated by the rotational motion produced this effect. Personnel at the US Navy's White Oaks Laboratory have experimented with this technique (Reference 4).

Wind effects are one of the greatest hazards a firefighter can face. The fire can become uncontrollable when the wind restricts the firefighter's ability to reach the fire safely. For example, on an aircraft carrier, in normal operating conditions of launch and recovery, there is a wind of approximately 30 knots over the length of the ship. In tests conducted on the USS Independence (CVA-62) aircraft carrier in 1968, winds were found to be laminar up to 6 feet off the deck. These winds significantly affected the reach of the agent (Reference 5).

The crash rescue vehicles in use today by the Air Force and Navy are of the P-series and MB-series. The Technical Orders for the P-2, P-4, P-13, and P-19 and test reports on the P-4 and P-15 were examined (References 6 through 9). Comparisons of the Air Force P-4 and the Navy MB-1 and P-4A capabilities were also examined (References 1, 10, and 11).

The P-2, P-4, P-4A, P-15, and P-19 each have two turrets with non-air-aspirating capabilities whereas the MB-1 has air-aspirating capabilities. Non-air-aspirating systems have a range of 188 to 213 feet, whereas the air-aspirating systems have a range of 120 to 175 feet. In comparative tests of air- and non-air-aspirating nozzles, the non-air-aspirating nozzle also provided a greater stream range of Aqueous Film-Forming Foam (AFFF), 6 percent mixture (Reference 12).

Another delivery system concept with notable long-range potential is a catapulting system. Minimal testing has been conducted using a device that would propel an encapsulized agent into a fire. Past research appeared to indicate that it would neither be economically nor physically feasible to pursue this idea. However, recent developments have determined that this type of product could be advantageously produced.

The only catapulting-type device ever to be seriously tested for fire suppression purposes was a prototype called the Gren-Gun. This apparatus was designed to deliver specific amounts of dry powder (4 pounds) into an inaccessible fire. This Gatling-type gun can deliver an encapsulized plastic powder grenade 200 feet and operates from a source of high-pressure air. A standard 9-pound backpack breathing air bottle can propel more than 60 grenades. This device, developed by the American Research and Manufacturing Corporation, did not progress beyond the prototype, and the status and availability of the device are not known. The general concept was abandoned many years ago as a result of the lack of perceived applicability.

2. User Survey

The user survey was conducted to assess the actual performance of current crash rescue vehicles by the people who use them, and to incorporate their experiences in combating the most difficult fires.

The people contacted during the survey were fire chiefs and fire research personnel. The fire chiefs agreed that their crash rescue vehicles could meet or exceed present military performance requirements. The fire chiefs were generally not interested in any change involving the current dispensing systems. Research personnel thought that long-range delivery systems could and should be dramatically advanced.

The literature survey has shown little recent advancement in long-range fire suppression. Although some of the current systems in use today have some interesting prospects, none can combat the wind and deliver an agent effectively to a distant target.

The information contained in the literature and user surveys indicates a foundation for the criteria of a long-range fire-suppressant delivery system. The system should be able to deliver a fire-suppressant agent over a significant distance with a relatively high percentage of agent delivery. This system should be constructed so that it can be combined with an agent and agent containment system to deliver successfully an effective amount of agent through a 30-knot crosswind.

B. STREAMING VERSUS CATAPULTING

Several methods and concepts have been developed to improve the long-range capabilities of firefighting equipment. Two of these methods and concepts were studied in depth in Phase I of this project - catapulting and streaming. With catapulting, the extinguishing agent is encapsulized and propelled by a launch tube or some similar mechanism into the fire from a distant location. This method is in the conceptual stage and has been only preliminarily field-tested. Streaming is the method being used by the Air Force and Navy today. Standard firefighting equipment is used to project a constant, solid stream of agent into the fire.

Using the information from the literature search and user survey, NMERI compared catapulting versus streaming systems. It was found that minimal research had been conducted and documented on long-range fire suppression concepts. The little significant work accomplished had concentrated on the streaming, not the catapulting concept. In that work, methods were used to improve streaming capabilities by promoting turret development, nozzle design studies, and agent additives.

Fire research equipment manufacturers have developed turret systems that are adaptable to current firefighting vehicles and have effective delivery ranges between 85 and 200 feet. Nozzle manufacturers and other fire technology researchers have studied nozzle design and performance and could develop a nozzle or nozzle system that could increase the effective range of most agent dispensing systems. Agent additives have been developed to mix with liquid agents, such as water, that apparently will allow them to be thrown farther while still using standard firefighting equipment.

In the survey of Air Force fire chiefs and firefighters, most stated they would prefer that only modifications to the existing streaming systems be attempted. Development of a new dispensing system, which would use a totally new concept of agent delivery, was not desired. This is a conventional position against radical change and was certainly not unexpected. However, it was also noted that most of the firefighters now in the service are young and inexperienced. The veteran firefighters are retiring and taking their knowledge and experience of operating conventional firefighting equipment with them. There is also a growing concern in the firefighting community that the firefighter should no longer be required to approach a hazardous fire at close range. Firefighters want their equipment to be simple to operate and to provide long-range capabilities.

After considering this information, NMERI personnel determined that, to solve the long-range problem effectively, the streaming concept should be considered first. It appeared more economically feasible to adapt or modify current equipment to meet new long-range capability needs. Also, knowledgeable and experienced personnel with the Air Force advised that the streaming concept could contribute to the long-range requirement. The catapulting equipment had questionable adaptability to current Air Force equipment and could require operating pressures and create jolting forces that would overstress this equipment. Finally, time constraints dictated that it would be more cost- and time-efficient to concentrate on the streaming concept and contract another research company to study the catapulting method.

The initial design criteria for the long-range system were chosen after considering the actual delivery requirements of the system and the feasibility of adapting such a system to meet the Air Force needs as perceived by its operational personnel. Several streaming concept designs were evaluated, and a few were chosen for further consideration. The most promising of these designs, the concentric ejector, was designed and fabricated. The design of the ejector incorporated the use of a swirling, external sheath of air, propelled around the agent stream to protect it from the effects of wind, air drag, and other range-limiting factors. In this way, the agent stream could be kept at a low pressure while still increasing its effective range.

A formal design process of analytical calculations and technical drawings for this concept was initiated and completed. A prototype was fabricated, complete with interchangeable unit modifications that were to be field-tested to determine which modification worked the best. A safety and test plan for this series of tests was submitted and approved. All equipment was made ready for the testing, and preliminary testing was completed as described in Section II.C.

Other designs that showed promise were documented but were not fabricated because of testing time and funding limitations. These designs considered the concepts of a movable iris-type orifice plate, a raised spiraling vane modification, and a pulsing, piston-like device that could deliver short, concentrated bursts.

The movable iris concept could be constructed to operate similar to the shutter of a camera. The opening could be closed down, and the effect would be the same as an orifice plate, which is commonly used in industry. When the opening becomes smaller, the velocity of the flow through the opening increases, thus causing it to project the flow farther. The pressure also will drop as the agent travels across this opening. In this way, the agent pressure would be decreased while the range of the agent is increased. The iris could be retracted to its normal opening size during normal firefighting situations.

The concept of the interior raised spiraling vane modification would work similar to the rifling of a bullet in a rifle barrel. The rifling in a gun barrel is a recessed groove, which causes the solid slug to spin, and this spinning dramatically improves the accuracy of the projectile. This concept could be applied to liquids and gases; however, the rifling would have to be raised like a vane and not recessed as a groove. This spiraling effect could keep the agent stream together longer and increase the range of the agent.

The piston pulse concept is used in many applications in industry today. Rock drills in mines use pulses of high pressure water to bore through soil and stone. Some lawn/field sprinklers use this concept to project water long distances while conserving the amount that is applied. A piston-driven pump could also be used to propel concentrated slugs of agent into a fire. This could cut down on air drag, as less agent would be subject to the wind, and be less wasteful. More agent could be applied directly into the fire.

C. STREAMING CONCEPT TESTING

After a comparison of the streaming and catapulting concepts and initial input from military fire chiefs, NMERI elected to develop ideas dealing with streaming. The most promising idea, that of a concentric ejector, was developed and tested.

Technical working drawings were made of an ejector apparatus. A working model/prototype of this design was fabricated. The ejector was fabricated so that many pieces were interchangeable, allowing a maximum amount of testing to be completed with a single apparatus setup. This also minimized the material and machining costs required to produce the ejector.

The purpose of the testing was to determine several operating parameters. The effective range of the ejector was tested; the optimum operating fluid flows and pressures that produced the most effective range were found. The effect of the air sheath around

the liquid agent stream and the resulting pattern of the expelled fluid were studied. Finally, the size, handling, and ease of operation of the unit were tested.

A 10-gallon CB unit was filled with water and kept at a constant pressure for this test. A 10-foot section of standard 1-inch firehose connected the tank to the ejector. Safety pressure relief and check valves were put in-line to prevent safety hazards to the test personnel. A test grid was laid out on a cleared area on the ground, and distance markers were set up every 10 feet up to 80 feet in line with the ejector. Video and still photos of all testing were taken. Different ejector configurations were tested at various operating pressures. The results are presented in Table 1. The test results showed that a projection angle of 30 degrees produced the maximum range, no matter what operating pressure was used. The ejector configuration with the least amount of swirled vane obstructions worked the best. The results of these tests did not show significant improvement over standard nozzle designs. However, not all configurations were completely tested and further testing might change these results. At the direction of the project task officer, this testing was halted and any further testing relating to the streaming concept was canceled.

D. CATAPULTING CONCEPTUAL DESIGN

1. Requirements

The streaming work described above was terminated in July 1986 at the direction of the project task officer. Upon the task officer's direction, the emphasis of the project was shifted from a comparison of two potential concepts to the sole study of the catapulting system. A catapulting-type system that could propel a projectile containing firefighting agent 1200 feet in a 30-knot crosswind was desired and was pursued from this point in time.

TABLE 1. CONCENTRIC EJECTOR TEST DATA.

Test No.	Agent Press Reg (lb/in. ²)	Ejector Press Reg/Actual (lb/in. ²)	Range W&W/O Air (ft)	Agent Flow Rate (gal/sec)	Angle of Projection	Nozzle Type (vanes/in.)
Cal Test	150	100/50	42/40	1	16	0
1	150	100/80	50/45	1	16	2
2	150	100/50	60/58	1	16	2
3	Varied	None	78	Varied	16	N/A
	100-200		Max			
4	200	100/80	70/69	N/A	16	2
5	150	190/90	60/55	N/A	16	4
6	200	190/90	52/45	0.9	0	0
7	200	190/90	50/50	0.97	16	0
8	200	190/90	86/78	0.98	30	0
9	200	180/80	60/53*	0.97	30	0
10	200	190/120	50/60*	0.97	30	2
11	200	190/120	63/60*	0.96	16	2

*Crosswind during test.

To meet the revised project requirements in the remaining time of the project, a Request for Proposal (RFP) was sent to fire technology research companies. Three companies, of the 18 that were contacted, responded. One of these companies, Fire Research Corporation of Nesconset, NY, agreed to present a conceptual design of a catapulting system in the time remaining for completion of Phase I of the project.

This proposed concept incorporated a launch tube, similar to a mortar projectile launcher. The firefighting agent was encapsulated in a flexible membrane similar to a balloon. A prototype device was tested and, it consistently projected the balloon 230 feet into a 6-foot diameter circle.

In the second phase of this project, the work with Fire Research Corporation was continued, and a working prototype of a system capable of meeting the new criteria was designed.

2. Concept Design Considerations

The initial approach to concept development identified a number of critical investigative areas that were singled out as being crucial to the whole concept. These areas are discussed below.

a. Selection of Optimal Suppression Agent

While there will obviously be no one optimal suppression agent for all types of fires, there will be optimal suppression agents for specific types of fires. Most of the better agents in use today are not effectively interchangeable for different fire scenarios. NMERI is presently emphasizing a next-generation fire extinguishing agent, one that will possess strong securing and flexible three-dimensionality characteristics. The final design of the long-range delivery device must be such that it will be adaptable to this future agent.

Present emphasis was placed on halons, the group of chemicals composed of carbon, bromine, chlorine, and fluorine atoms that effectively interfere with the combustion process. This interference results in a breakdown of the combustion process and rapid flame extinguishment, provided that the chemicals are present in sufficient concentrations in the airspace (normally 5 to 10 percent by weight). The essential difference is that with traditional means flame extinguishment is effected through cooling and oxygen starvation, whereas with halons a breakdown of the combustion process occurs.

The advantages of extinguishing flames through the use of halons are rapid flame extinguishment, and minimal damage, if any, to equipment and property caused by the extinguishing agents.

Halons are formulated both in gaseous and liquid states at standard temperature and pressure. They have been used successfully in fixed stationary systems, protecting enclosed areas such as computer rooms and some hangar areas. In these applications the agent is pumped through a fixed piping network to rapidly flood the enclosed area to the correct concentration levels. Halons have also been used in fire extinguishers, but their limited range often forces the operator to work very close to the flames. Attempts have also been made to mix halons in the firefighting water streams with ambiguous results.

An optimum catapulting system would enable the fire chief to have empty agent canisters at the response site and to fill and deliver them as required. It would also permit flexible and consolidated response to a wide variety of situations. The fire chief could either use foaming agents, wet sand for certain types of radiation incidents, halons, or new types of fire extinguishing agents that are being developed by NMERI such as the magnesium and next-generation agents. Some agents are only stable for a short period of time after mixture with other agents; thus, the system should provide complete mixing prior to loading into the throwing device. The new

replacement agents for Halon 1211 under development would certainly be compatible with this kind of delivery concept.

b. Packaging of the Fire Suppression Agent

The suppression agent must be available in large quantities for delivery at a rapid rate to overcome fire conditions normally expected at an aircraft crash scene. The capability to deliver a few pounds of agent per minute is inadequate.

One packaging approach considered was some type of balloon. Such a balloon could be designed to be filled on the vehicle by a selectable loading system with several extinguishing agents. The agent could be carried on the vehicle in tanks and pumped into the balloon-type canister system. The balloon could then be delivered by a mechanical throwing system or fired by a compressed gas system. Before a balloon can be accelerated to high velocities without the possibility of breakage, it would require some kind of protective cup around the balloon to prevent breakage. This cup could also be used in flight to prevent the balloon from seriously deforming under the aerodynamic forces. A free-thrown balloon will assume a shape in flight that creates drag and limits the throw distance. A polyethylene-type container could be used to streamline the balloon and to accelerate it in the gun. This protector may have to be perforated to allow dispersion of the agent at the time of impact.

Mylar and various rubber-type balloons were considered. The mylar balloons are stronger but have no give at the acceleration forces required and are subject to breakage. A rubber balloon of good commercial grade would be compatible with the various firefighting agents including 1211, 2402, AFFF, dry powder, etc. The balloons would have a rubber stopper with a built-in valve installed at the opening. These balloons could be mounted uninflated in a magazine or belt-type device and inflated with the proper agent immediately preceding the throwing sequence. The end of the rubber stopper could be fitted with a cyalume-type marker that would be activated by

acceleration forces of the throw. This cyalume would illuminate the path of the projectile in night firefighting operations. The balloons would be inexpensive, take up very little space, and be charged with the proper agent immediately prior to launch.

Another type of package considered was a canister. The canister could be an aerodynamic shape with rear fins and a weighted front to minimize wind drag and to ensure accurate and repeatable deliveries. These canisters can be designed to shatter or open on impact, dispersing the firefighting agent evenly over an area that the volume of agent can extinguish. Present thinking favors a streamlined canister, based on the Stradford Recovery Criterion, to minimize both its length to diameter ratio and the overall drag. For a 3.5-inch diameter projectile launched from a 4-foot tube expected exit velocities would be in the region of 115 to 120 ft/s based on a 20 lb/in.² mean pressure. The maximum range with this set of parameters is 300 to 400 feet.

This canister could be made of common materials, such as plastics, glass, or aluminum. The dispersing gas capsule as well as the acceleration-activated detonating system would be located in the center of the canister surrounded by the extinguishing agent. Serrations along the outside surface allow the canister to open predictably after impact.

While in the magazine and launch tube, the canister would be held by a circular plastic cup, which is located at the rear of the canister and serves a number of functions. It seals the propelling gases from escaping around and past the canister while in the launch tube and transmits the force extended on it by the propelling gases to the canister. It also incorporates an anchor point through which it is held to the breach against the propelling gas pressure before launch. Once the canister has left the launch tube, aerodynamic drag will pull this cup off the canister and decelerate it to low velocities.

Canister size is determined by optimal delivery rate and fire-extinguishing capabilities versus packaging. It is harder to disperse a larger canister than a smaller one, but the dispersion system (CO₂ charge) is easier to package in a larger device. The economic and logistic aspects point to larger canisters because they would be less expensive and easier to handle due to the decreased delivery rate. However, the cost of the throwing mechanism would increase significantly as the canister size increases. The damage caused by larger projectiles at higher velocities is obviously much greater. If it becomes obvious that the balloon cannot achieve a throw distance over 1200 feet, a reinforcement balloon or canister is next in line for consideration.

c. Delivery System and Rate

Four different types of delivery and power systems were investigated: rockets, explosives, propane, and springs.

(1) Rockets

The possibility of using a miniature solid fuel rocket to propel the container was investigated. As expected, a number of problems are associated with rockets. The rockets have a constant force that would not be able to be computer-controlled for filling or targeting. They would have to be individually inserted behind the container and ignited, which adds undesired uncertainty to the system. If a misfire takes place with a rocket loaded in the device, the system must be disassembled and the rocket removed -- a dangerous and time-consuming task. The rocket would also produce a fair amount of smoke that could have toxic characteristics.

(2) Explosives

Explosive charges would produce a tremendous acceleration to reach the final desired velocity. Even a slow-burning explosive charge would initially over-accelerate the unit and could destroy the balloon or canister. Also, an explosive charge could not be varied if the force had to be changed during operations. In addition, there is a possibility of having a misfire, again requiring someone to disassemble the launcher and remove the unexploded shell.

(3) Propane

The third area investigated was a propane explosion device. The explosive range for propane is 7 to 17 percent fuel/air mixture. Propane would also impart a huge initial acceleration unless it were fed to the discharge cylinder during the entire time of travel down the tube, approximately 0.1 of a second. This would require the control of a propane supply mechanism with a tolerance of an order of magnitude better than the 0.1 of a second. This would be extremely difficult to achieve and to maintain consistently on a firefighting vehicle.

(4) Springs

The fourth area investigated was the use of springs, i.e., compressing the spring and letting the extension of the spring be the driving force for the balloon or canister. Coil springs could not develop the extension forces required over the distance necessary to achieve the required velocity.

The investigation led to the initial design of the use of a gas spring, i.e., compressed gas. The spring mechanism selected was a cylinder with a piston that would compress nitrogen. This is a closed system precharged with dry nitrogen with the cylinder being pushed down the compressor-type tube by a water or Power Takeoff

(PTO)-driven lead screw. The throwing cup has a clutch device that clamps on the lead screw, which is being turned by a turbine water motor or PTO. The water motor wastewater would be returned to the tank. As the lead screw continues to turn, the clutch mechanism would be threaded down the lead screw, causing the piston to compress the nitrogen. When the pressure has reached the computed pressure and the projectile has been installed in the cup mechanism, the trigger is pulled and the clutch mechanism disengages, forcing the cup mechanism to proceed to the end of the barrel. The projectile is then accelerated to the proper velocity. The water motor is driven from the water supplied by the main pump or a PTO can be employed. The power required to throw a 15-pound projectile 1223 feet at the rate of 1 ft/s is approximately 38 hp, including losses. This is well within the capability of a water pump or PTO. The system should be sized to supply approximately 50 hp as a safety margin, which is within the capabilities of the engine pump combination of any crash vehicle.

d. Dispersion of the Agent in the Fire Zone

If a balloon-type encapsulating system is feasible, the aspect of agent dispersion becomes extremely simple. The balloon breaks up on impact requiring no separate dispersion material or mechanism. The dispersion pattern for different agents, balloon materials, impact velocities, and trajectories can be modeled relatively easily. The models can be empirically verified with repeatable results. Balloon dispersion patterns and characteristics are further discussed in the following section.

Canisters, on the other hand, must be specifically designed to open at the time of impact and dispense their agent as required. The first step is the rapid canister deceleration caused by the impact, whether it is on a burning structure or into a pool of burning fuel. The second step is that a mechanism internal to the center of the canister must be accurately and consistently activated by this deceleration to instantly release a charge of highly compressed gas through designed channels in such a way that the extinguishing agent is both aerated and blown out rapidly with uniform distribution.

The dispersing gas may be air, nitrogen, CO₂, Halon 1301 or any other suitable gas. An explosive charge may be used in lieu of the compressed gas. The detonation mechanism for the gas or charge would be a device that is enabled after the container leaves the launch tube. The agent canisters would be held in a pressurized magazine tray, to eliminate the need for thick-skinned agent canisters if the ambient temperature is high. This would particularly be required if agents such as 1211 or 1301 halon are used, as they change to a gaseous state at ambient temperatures. The magazine could also be designed to facilitate the quick reloading of the delivery system.

A floating canister may be a possibility for fighting deep pool fires. This type of canister would be lobbed into an open tank fire to dispel the agent over the surface before the canister has a chance to sink. A penetrating canister could also be designed to be thrown with considerable force against the metal skin of an aircraft, other vehicles, wooden walls, concrete walls, etc. The design of the canister would be such that the penetrating tip could pierce the wall, but the canister itself would not. The projecting portion of the canister would have serrated edges to allow it to penetrate a wall, but to catch and lock if the unit tried to expel itself. As soon as the unit hits the wall, the agent is dispensed through a series of nozzles immediately behind the penetrating point. This unit would be made of nonsparking materials and could provide an excellent method for fighting internal aircraft or vehicle fires.

e. The Targeting System

The targeting device could consist of a microcomputer connected to a monitor with launch to be controlled by servo-motors. A TV camera could be aimed at the fire area, and the firefighter would observe the fire on the monitor. The firefighter would adjust the camera position to align the fire box or bullseye in the center of the screen presentation. The camera direction is tied to X & Y servo-devices that adjust the aiming tube so that the canister hits the desired impact point. The inputs to the computer would be wind velocity and direction, either estimated or determined by

optical ranging. Range is estimated or determined by instruments. The TV camera is fitted for parallel IR or UV visual presentations with the option of all three images superimposed on the one monitor. The computer will not only determine the angle of the aiming tube, but also the charge required for delivery dependent upon the agent selected.

An alternative to this device is a video mechanism mounted parallel to the aiming tube incorporating a combination of cameras, which will use any combination of IR, UV, or standard video. The operator end of the tube will contain a TV monitor that will display any combination of the three videos. This will give the operator a clear picture of the fire regardless of smoke, fog, etc. The camera will have adjustable settings to adjust the trajectory. The following data will be input to a computer/microprocessor combination: canister designation (canister parameters) based on parameters stored in the computer memory, wind velocities and direction, distance to the fire (range) and camera elevation relative to the fire. The computer will generate a display on the TV monitor and indicate the point of impact. The operator will move the aiming tube to adjust the point of impact. Using this system, the firefighter can consistently place the canisters at the desired point. The computer can also be programmed to hold a series of agent lay-down patterns developed from agent delivery data as it would apply to different fire scenarios. The operator could select a delivery pattern, target a starting point, set the delivery system in motion, and then visually monitor the system's performance and results, or perform other duties while the laydown takes place.

E. CONCEPT SELECTION AND PRELIMINARY TESTING

1. Concept Selection

Based on a complete review of the data, the most promising approach to long-range agent delivery was the compressed gas delivery system with the balloon

encapsulators. Primary agent consideration was given to the halon family or compatible replacement agents, but the system should be designed for delivery flexibility including agent selection. Throwing a 15-pound projectile 1200 feet in a 30 mph crosswind would require a 6-foot launching tube, 7.5 inches in diameter with a muzzle exit velocity of 210 feet per second with a mean gas pressure of 107 lb/in.². This was the largest projectile being considered; however, further study of dispersion characteristics and lay-down patterns will determine projectile size. In addition to the gas delivery system, various means of using an explosive charge to fire the canisters were studied. The tradeoffs of gas-driven versus explosive-driven projectiles were considered. The tradeoff considered the amount of gas required, availability of the gas, the possibility of running a water pump or PTO on a fire vehicle, the cost and reliability of both systems, the throwing distance of both systems, and the possible negative publicity in using explosive-type devices in a fire situation. There are other problems associated with explosive-throwing systems; one is that the distance can only be changed by changing the amount of explosive or the angle of the throwing device. Other potential explosive problems relate to the storage, handling, inventory, accountability, and inspection of explosives. These are all additional training and operational burdens for a fire department. The shelf life of the explosive could cause problems in replacement cost or dud/misfire encounters. The economics and costs of the systems have not been analyzed here, but it appears the nitrogen system with balloon encapsulators would be significantly more cost-effective than explosive-launched canisters.

2. Preliminary Testing

The Fire Research Corporation conducted several tests to determine throw range, aerodynamic performance, trajectory, and dispersion patterns of 5-ounce and 7-pound water-filled balloons. These tests were conducted at their factory in Nesconset, NY, and at a nearby airstrip on 8-10 September 1986.

A slingshot catapult device was developed and used to replicate nozzle exit velocities and launch elevations. This simple looking device worked with good accuracy; after three calibration shots, the device delivered six consecutive 5-ounce balloons a distance of 220 feet within a 6-foot diameter circle. For these deliveries the catapult was calibrated to impart an exit velocity of 118 ft/s to the balloon. The repeatable results of these tests closely match the corresponding computer-derived predicted distances. Predictions were made for a variety of different balloon weights, launch velocities, and elevations. The predictions included one wind deflection calculation for a 15-pound projectile launched 90 degrees to a 30 mph crosswind. Deflection at impact was calculated to be only 10.26 feet at the 1218-foot range.

The balloons were studied visually for aerodynamic qualities and deformation during their travel to the impact point. They maintained their round shape well, as further shown by the impact accuracy. One balloon was noticeably misshaped prior to launch, the balloon having an extended end. This balloon tumbled in flight and landed 8 feet beyond the established impact area. It is theorized that the balloon traveled further because it took on an elongated shape.

The dispersion of the water after the impact was consistent. With the 5-ounce balloons, the dispersal fan was 90 to 110 degrees, centered on the line of flight. Scatter across the fan was uniform with visible water droplets advancing in decreasing concentrations to a point 13 feet from the point of impact. A visible mist extended beyond the fan to a distance of 18 feet beyond the impact point and evaporated before contacting the ground. A heavy concentration of water was deposited at the impact point in an area approximately 3 feet long and 2 feet wide.

On 9 September 1986, seven balloons, each filled with 7 pounds of water and paint mixture, were dropped over a small airfield from a light aircraft to examine aerodynamic performance and dispersion patterns. The aircraft was flying at an altitude of 300 feet and a speed of 100 mph. When the balloons were thrown from the aircraft

they immediately took on an elongated shape. After a few seconds, they assumed a generally spherical shape and did not tumble.

The dispersion of the liquid after impact was again consistent. The dispersal fan was 120 to 140 degrees, centered on the line of flight. Scatter across the fan was uniform with visible water droplets advancing in decreasing concentrations to a point 30 feet from the point of impact. A visible mist extended past the fan to a point of 40 feet beyond the impact point. This mist evaporated before reaching the ground. A heavy concentration of liquid was deposited at the impact point in an area approximately 20 feet long and 15 feet wide.

The tests indicated favorable aerodynamic balloon properties, consistent dispersion patterns, and repeatable targeting abilities.

F. PHASE I - SUMMARY AND CONCLUSIONS

In Phase I of this effort, both streaming and catapulting were investigated to determine a single avenue for further conceptual development. The catapulting concept was selected for further development.

The bulk of the catapulting investigative effort in Phase I was conducted through a subcontract to the Fire Research Corporation of Nesconset, NY. These investigations singled out several areas as being crucial to the successful application of the catapulting concept: (1) selection of an optimal suppression agent, (2) packaging of the agent, (3) delivery system and rate, (4) agent dispersion at fire, (5) loading mechanism, and (6) targeting system. Each of these areas was examined in detail under Phase I of the effort and is summarized in the following paragraphs.

1. Selection of an Optimal Suppression Agent

While there will obviously be no one optimal suppression agent for all types of fires, there will be optimal suppression agents for specific types of fires. Present emphasis is on a next generation fire-extinguishing agent that will be clean, nontoxic, and will possess strong securing and flexible three-dimensional characteristics. A long-range delivery system must be adaptable to this future agent. An optimum system may be one that enables the on-scene fire chief to have a variety of deliverable agents at the response site to be able to adapt the response to the specific nature of the situation. Foaming agents, halons, magnesium agents, water, or even sand could be used for certain types of radiation incidents.

2. Agent Packaging

The suppression agent must be available and deliverable in large quantities for rapid-rate application to overcome fire conditions normally expected at an aircraft crash scene. To be able to only deliver a few pounds of agent per minute is inadequate. The packaging approach considered initially was the balloon, and FRC conducted a series of experiments on scaled delivery systems employing water-filled balloons. The balloons proved to be relatively stable aerodynamically and exhibited good agent dispersal characteristics upon impact. It was further theorized that balloons could be modified to withstand the gravitational launch forces and could even be fitted with an illuminating device so they could be used more effectively in night firefighting. Balloons provide good logistics and flexibility possibilities. If they could be filled at the response site via a small portable bottling plant, they could be filled with an appropriate agent immediately before launch. Filling balloons with raw agent at the response site would minimize storage and transportation difficulties with prepackaged agents.

Another encapsulation scheme investigated was aerodynamic canisters shaped to minimize drag and ensure accurate and repeatable deliveries. They could be

made of common materials and designed to burst upon impact or contain some type of internal detonator. Aerodynamic canisters would require reduced launch forces and could thus be designed to carry larger amounts of agent and result in savings through decreased launch rates. However, the cost of the canisters themselves would be higher.

3. Delivery System and Rate

Delivery systems considered included rockets, explosives, propane, and springs. Rockets and explosives presented numerous problems, chief among them being storage and handling. Hung rounds could delay delivery for unacceptable periods of time, and the lack of precise control of propellant amounts could prohibit repeatable delivery. Firefighters working near the launcher would be subject to hazards.

A 7 to 17 percent propane/air mixture could achieve the required acceleration forces in the launch tube. However, to achieve the required accuracy and repeatability, the propane supply mechanism would be required to function within extremely close tolerances involving many variables. Such a mechanism would be very difficult to fabricate, maintain, and operate on a firefighting vehicle.

An investigation of springs indicated that coil springs of reasonable size could not develop the extension forces necessary to achieve the required exit velocities. This investigation led to a more detailed look at the use of a gas spring, i.e., a compressed gas system. This is essentially a closed system cylinder precharged with gas with the cylinder being set for firing by a water- or power takeoff-driven lead screw. The compressed gas power required to throw a 15-pound projectile 1223 feet at the rate of one launch per second would be approximately 38 hp. Maximum acceleration forces through a 6-foot barrel would be about 111 g. It appeared that the device could be constructed in a relatively simple manner with the design incorporating a balloon-holding cup and gas vent tubes to negate the effects of suction. This device could be configured to deliver a wide variety of objects in addition to balloons and canisters.

The launch rate developed by the system should be variable with the type of agent, amount of agent encapsulized and available at the response site, distance to the fire, and nature of the fire scene considering fire size and nearness of personnel, weapons, and combustibles. To accommodate the majority of anticipated situations, the fastest launch rate capability should be at least two per second.

4. Agent Dispersion at Fire

If a balloon-type of encapsulating system were possible, the aspect of agent dispersion would become relatively simple. The impact-induced breakup of the balloon takes place in a natural manner, requiring no separate dispersion material or mechanism. The dispersion pattern for different agents, materials, impact velocities, and trajectories could be modeled relatively easily. The models could be verified empirically for accuracy and repeatability. Canisters, on the other hand, must be specifically designed to open at or before impact and to dispense their agent in a prescribed manner. Impact breakup designs would strive to match a balloon breakup. If compressed gas or an explosive charge were to be contained within the canister, the detonator could be a device that is enabled as the canister leaves the launch tube. With the canister approach, agent dispersion could be regulated to allow for the design of a floating canister or a penetrating canister. One would also want to be able to alter dispensing time of the canister to account for the dispersion characteristics of different agents and the requirements of different fire scenarios. It is expected that uniform dispersion would be desirable in all cases, whereas the extent of dispersion would be varied.

5. Loading Mechanism

When encapsulation investigations centered on the possible adaptation of a balloon containment system, the obvious loading mechanism also incorporated a bottling plant subsystem that would load the balloons with agent immediately prior to placement in the launch tube. Such a system would have the features and the advantages discussed

in Section II.E.2. However, upon further study of the loading system requirements and complexities, it was decided that use of this system would not be prudent, for several reasons. A loading device capable of meeting the firing rate requirements and having the flexibility of loading more than one agent in a sequence would be necessarily complex and expensive. Bottling plants, while always appearing to run smoothly when the public views their operation on the TV or movie screen, are normally plagued with mechanical problems. In an actual bottling plant, mechanical experts are constantly on standby to resolve problems and to keep production line downtime to a minimum. Such mechanical expertise would not normally be available at the fire response site. Furthermore, regardless of the effectiveness of the delivery system, the failure of such a loading system would render the entire operation useless. There would be no other effective means of loading the agent into the balloons unless a redundant loading system was in place and could be put into immediate operation. This was considered unreasonable.

6. Targeting System

A targeting device should ultimately consist of a microcomputer connected to a monitor and to launch control servo-motors. It should incorporate a TV camera which enables the firefighter to monitor both the fire and system effectiveness. Such a camera arrangement could also be fitted for parallel IR or UV presentations with the option of all three images or any combination thereof superimposed on one monitor. The camera could be further tied to azimuth and elevation angle servo-devices to serve as a direct aiming system. Input data to the microcomputer could be as follows: canister designation (canister performance parameters contained in memory), wind velocity, distance to the fire, and launch tube starting configuration. A computer could also hold a series of agent lay-down patterns developed from agent delivery data as it would apply to different fire scenarios. The operator could select a delivery pattern, target a starting point, and set the delivery system in motion. He would then monitor the system's performance and results, and possibly perform other duties while laydown is taking place.

SECTION III

PHASE II - INITIAL CATAPULTING PROTOTYPE DEVELOPMENT

Design work was initiated by the Fire Research Corporation (FRC) on a launcher that would use compressed gas to propel the agent canister out of a launch tube similar in principle to an air gun. Initial calculations were made on sizing and power requirements for such a device to meet the delivery weight and range requirements.

In conducting the research for other work on similar devices, a device was discovered of the approximate size that could possibly be adapted to this project. The device was built under contract to the US Navy to study the generation of gaseous vortex rings as a possible fire suppressant agent delivery mechanism. Reference 13 contains additional detail and illustrations describing the work performed in this section of the report.

A. PULSED-GAS VALVE LAUNCHER

The Pulsed-Gas Valve (PGV) launcher built for the US Navy consisted of a large, fast-acting gas valve, which operated to release pressurized gas from a chamber into a 10-inch diameter by 6-foot long launch tube. The general dimensions were close to those desired for the air gun concept for this project. The Navy made the PGV available for use on this project, and it was provided to FRC as government-furnished equipment (GFE).

A computer program was written to predict launch tube exit velocities of the PGV with various initial chamber pressures and canister weights. This program was merged to a ballistics program (Reference 13), which took into account surface wind and drag effects, elevation angle of the launch tube and target elevation relative to the launcher. With the resulting program it was possible to predict range for any combination of chamber pressure, canister diameter and weight, launch tube elevation

angle, target elevation, and pressurizing gas. Preliminary calculations showed it was likely that the PGV could meet or exceed the throw weight and range goals (20 pounds to 1200 feet) of this project. For example, for a chamber pressure of 140 lb/in.², a spherical canister of 9.875 inches in outside diameter, a throw weight of 27.9 pounds, and a launch tube elevation angle of 45 degrees, the range achieved is about 1250 feet.

B. AGENT ENCAPSULATION

1. Canister Selection

The container or canister encapsulating the fire-suppressant agent must hold the internal pressure required to contain the agent, withstand the acceleration loads from the launcher, have a shape which contributes to accuracy and repeatability of trajectory and dispense the agent on the target.

A tradeoff study was done between spherical and aerodynamic forms for the canister body. Range and accuracy calculations were completed for canister shape, drag coefficient, weight and launcher exit velocity. Other factors considered were simplicity, ease of manufacture, and influence on launcher design. The accuracy reduction for a spherical canister was not significantly less than for an aerodynamic canister. All the other factors were in favor of the simple spherical shape. A summary of the factors considered with a qualitative comparison is contained in Reference 13. Based on this comparison, the spherical canister was chosen.

The next major consideration was the selection of a suitable material from which to make the frangible spherical canister. The material had to be compatible with halon agents and have sufficient strength to hold the internal pressure necessary to contain the agent as well as the additional stresses resulting from the acceleration associated with the launch phase. A plastic material was considered to be the most likely candidate. Data were gathered from several manufacturers and analyzed for this

application (Reference 13). Calculations were made to determine the canister stresses due to internal pressure and acceleration loads. Polystyrene plastic was considered to be the best candidate because it has adequate strength but low impact ratings for frangibility.

Another consideration that influenced the direction of the canister selection at this time was the realization that launching a 20- to 30-pound canister of halon (specific gravity approximately equal to concrete) at a burning aircraft or other object would be not unlike hitting it with a cannonball. It was decided that a means of exploding the canister and dispensing the agent in the near vicinity of the target just before impact would be very desirable to minimize undesirable collateral damage. This approach, although a major technical challenge, may also prove to disperse the agent more effectively on the fire, although actual tests will be required to confirm this hypothesis.

Because of the cost and time required to have molds made, it was decided to search for an off-the-shelf spherical shell. High- and low-density polyethylene spherical shells were available, with nominal outside diameters of 10 inches and 8 inches made by rotational molding techniques. Some spheres of each size and density were purchased for testing. Frangibility was now not a major consideration since the canister was to be ruptured and the agent dispersed over the target area prior to normal impact.

A sabot was constructed to cradle and support the spheres for the acceleration phase and help provide a seal to keep the high-pressure propelling gas behind the canister in the launch tube (Figure 1). The sabot was made by expanding polyurethane foam into a mold and using a plywood backing disk. A nylon-reinforced plastic skirt was used around the plywood disk as a gas seal. After exiting the launch tube, the sabot will separate from the spherical canister due to differential drag forces and thus not interfere with the flight of the canister.

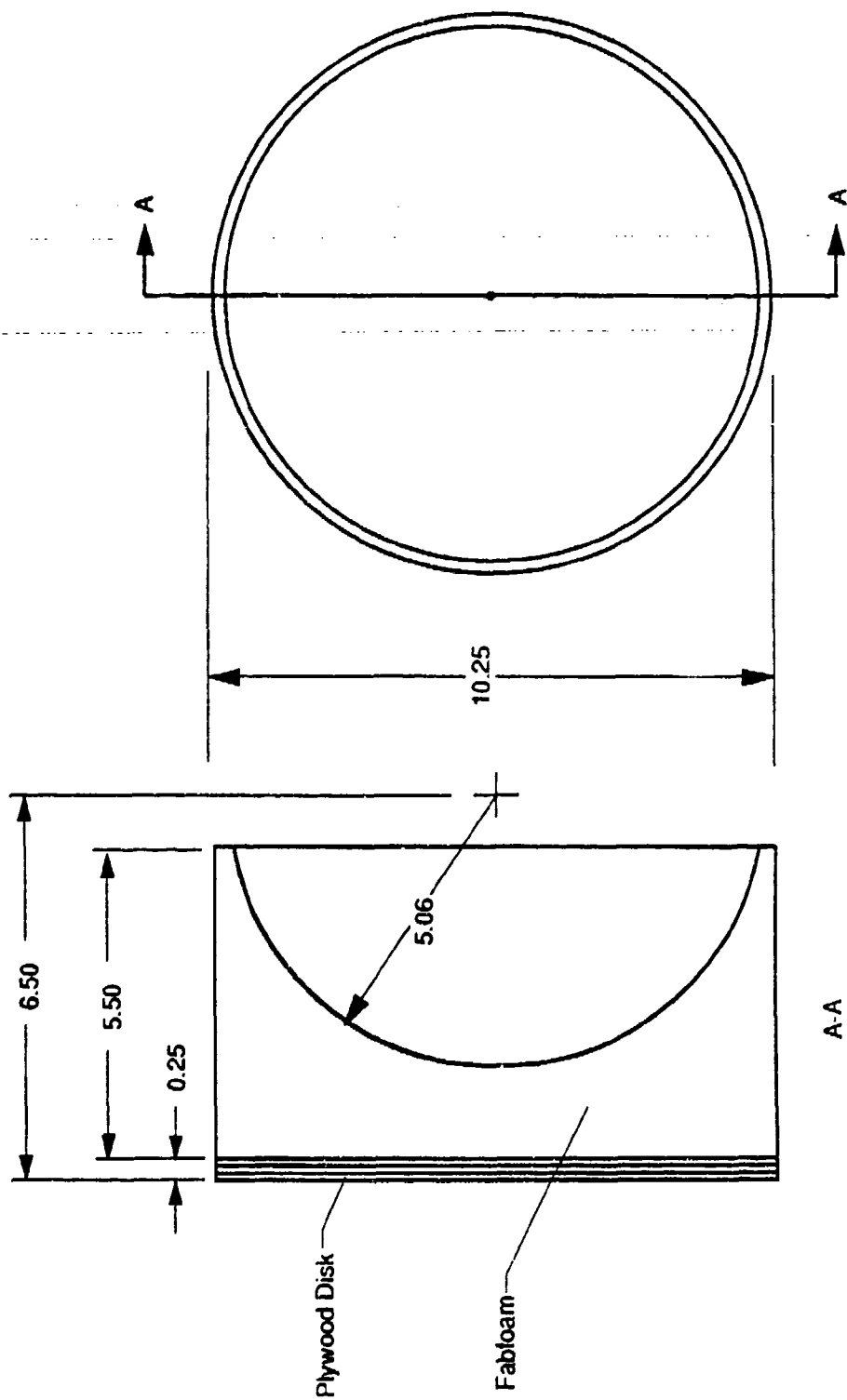


Figure 1. Sabot for PGV Launcher Canisters.

2. Agent Dispersal

The desirability to rupture the agent canister near the target prior to normal impact introduced additional complexity into the catapulting concept. The method considered was to use a squib or blasting cap-type device to provide a high-pressure pulse that would rupture the canister either by radio-frequency (RF) command or by a timer on board the canister. Using a command RF system would require an expendable receiver on each canister as well as human judgment to determine by sight the right time to send the command to rupture the canister. This approach was not considered to be very practical from a reliability and repeatability standpoint, nor affordable. An alternative is to provide the rupture command from an onboard timer. The timer could be started by a "g" switch from the launch acceleration, by an end of launch tube switch activation, or from separating the leads to the timer circuit. The time to rupture could be determined by the interactive computer associated with the launcher system based on range-to-target and windage effects.

The timer circuit considered was a simple resistance capacitance (RC) timing network with a set rate of discharge. The capacitor would be charged immediately prior to launch with the amount of precharge determining the time until the canister is ruptured. The leads from the precharging circuit to the canister timing circuit would be separated at launch and could initiate the timing sequence. A "g" switch could also be used to initiate timer start at launch to provide redundancy for safety reasons. The RC timing circuit could probably be built for about a dollar each in production quantities.

C. CATAPULTING CONCEPT PROTOTYPE TESTING

1. Launcher Testing

Several improvements were made to the PGV launcher received as GFE from the US Navy before initial testing began. A custom, roadworthy trailer was designed and built on which to mount the launcher to enable it to be easily towed to any test site. The trailer also had space to place high-pressure gas cylinders to provide the pressurizing gas for the PGV. For the tests performed in this task, CO₂ was used as the pressurizing gas. Diagnostic instrumentation was also installed to measure performance of the launcher. Five pressure transducers (four along the 6-foot launch tube and one at the high-pressure chamber) were installed with output data fed into an IBM PC compatible computer. Velocity information was measured by placing two light source/sensor devices 1 foot apart at the exit of the launch tube. At launch, the projectile exited the launch tube and interrupted the light beam of the two source/sensor devices, providing a time signal. The timer in the computer recorded the times; the velocity was calculated from the known distance and time measurements.

To become familiar with the operation of the PGV and do initial launch testing, it was decided to use something other than Halon 1211 to fill the canisters. The search for an inert material close to the 1.83 specific gravity of Halon 1211 revealed that concrete ranges roughly between 1.5 and 2.4, depending primarily on the aggregate used. It was decided to use concrete to fill the spherical canisters for the initial tests. Specific actual canister weights could be used for the ballistic trajectory calculations and then compared with actual measurements for each shot.

The initial tests were conducted at low elevation angles. The ranges achieved indicated that the range/weight goals could be achieved or exceeded with the PGV launcher. The sabot for the 8-inch diameter canister broke apart from the launch tube during the high acceleration phase, while the sabot for the 10-inch diameter canister

held. Since it appeared that the range of 1200 feet could be achieved with the 10-inch diameter canister (approximately 25 to 30 pounds weight), it was decided to discontinue testing of the 8-inch diameter canister and concentrate efforts only on the 10-inch diameter canister. Using the ballistic prediction program developed, the range for a 29-pound projectile at an elevation angle of 44 degrees, using 150 lb/in.² chamber pressure and launching into a 30 ft/s head wind, is 1476 feet. The chamber pressure limit recommended by the PGV designer for normal operations is 150 lb/in.². Table 2 compares the results of four tests with predicted ranges. Note that these launches were done with elevation angles from 31 to 35 degrees, chamber pressures from 138 to 147 lb/in.², canister weights about 28 to 31 pounds; the ranges achieved were around 1200 feet. Although tests were not done above 35 degrees elevation angle, one can conclude that the PGV should be able consistently to launch 30-pound canisters to a range of 1200 feet or better. This is significantly better than the 20 pounds to 1200 feet goal of the project.

Pressurized CO₂ cylinders were used to pressurize the chamber and thus power the PGV for this test series. Providing enough bottled gas to operate the system in an operational mode at the desired rate of two launches per second is not practical. Significant power would also be required to compress air at the response site to operate the PGV (Reference 13). The desired launch rate of two launches per second at 150 lb/in.² chamber pressure would require an air compressor with about 320 hp if 85 percent efficient. A large industrial compressor would be required to meet this requirement.

2. Canister Testing

As previously discussed, the final selection of a canister to contain the agent was a 10-inch outside diameter spherical shell made of polyethylene. The stresses due to launch and containment of the agent were calculated (Reference 13). The

TABLE 2. RANGE COMPARISONS.

Test No.	Canister Weight (lbs.)	Canister Diameter (in.)	Launcher Elevation Angle (deg)	Chamber Pressure (lb/in. ²)	Launcher Exit Velocity (ft/s)		Range (ft)	
					Predicted	Measured	Predicted	Measured
880112-1	27.98	9.875	31	138	214.72	214.1	1173	1140
880112-2	30.78	9.875	34	147	209.72	-----	1210	1190
880112-3	29.97	9.875	34	146	212.53	203	1233	1260
880112-4	29.77	9.875	35	144	211.34	208.1	1223	1200

calculated stresses due to acceleration were based on a launch table exit velocity of 210 ft/s, which corresponds to a maximum acceleration of 124 g. The peak meridional (σ_1) and parallel (σ_2) stresses were calculated for a shell thickness of 0.1 inch and are $\sigma_1 = 235 \text{ lb/in.}^2$ and $\sigma_2 = 1178 \text{ lb/in.}^2$. A plot of the acceleration induced stresses is shown in Reference 13. The stresses induced by the pressure from containing the agent must also be taken into account. Halon 1211, the most probable agent for this application, has a vapor pressure of 33 lb/in.² at 20 °C (68 °F) and 49 lb/in.² at 51 °C (124 °F). An internal pressure of 50 lb/in.² correlates to a stress in the shell of about 1060 lb/in.².

Since the canister must be pressurized to keep halon in a liquid state, the canister can be expected to expand in diameter. To determine how much swelling occurs an experiment was conducted by filling the sphere three-fourths full with water and pressurizing with compressed air to increasing pressure levels and measuring the outside diameter. The results are tabulated in Table 3.

TABLE 3. CANISTER DIAMETER VS PRESSURE.

Pressure (lb/in. ²)	Outside Diameter (in.)
0	9.900
20	9.900
30	9.925
46	9.925
60	9.953
75	9.995
85	not measured

At 85 lb/in.², the sphere began pulling out from between the bolted flanges of the pressurizing fitting. The fitting was redesigned and the test repeated with good results.

The creep characteristics of the canister must also be accounted for if the canister is going to be prefilled and stored until use. Since the canister will be continuously pressurized, it could swell to the point where it is too large for the launcher tube or eventually would fail. The creep characteristics of the canister material need further investigation and a long-term test program completed to characterize these properties fully.

Initial testing of the PGV launcher was done with the polyethylene spheres filled with concrete, which facilitated concentration on the PGV launcher range capabilities and verification of the ballistic prediction program. Concrete has about the same density as Halon 1211 so the canister weights were about the same as encapsulated Halon 1211. The fact that the spheres tested were rigid instead of an encapsulated liquid could influence the stresses introduced to the canister structure as well as the behavior of the sphere in flight. Launch testing of canisters containing Halon 1211 was not done in this phase of the project.

The findings of the initial investigation into agent encapsulation canisters point to the fact that the canisters may have to be filled at the response site, although this is not the most desirable alternative. Onsite filling would require a transportable system that would have to be operated under a variety of adverse environmental conditions. This approach should not be taken until all other possible avenues are fully explored.

Consideration of the complexities of the canister performance requirements and experience gained during this effort led to a reassessment of the design. The result was a new canister design that incorporates all of the needed features and may be easier to fabricate and use. This design uses a spherical shell made in two halves threaded at

the equator. The filling port is located in one half at the north pole, and the rupture system assembly is located in the opposite half at the south pole. The use of a bladder membrane or balloon liner eliminates sealing problems with the spherical shell and allows the shell to be perforated or prescored to optimize ballistic performance, rupture characteristics, and dispensing of the agent on the target. This design approach should be further evaluated in the next phase of this project.

D. PHASE II - SUMMARY AND CONCLUSIONS

Phase II covered the initial consideration of applicable concepts and the engineering, design, and operating characteristics of the Pulsed-Gas Valve (PGV) Launcher. Preliminary PGV operational test results are also presented. The following conclusions were reached in Phase II: (1) the PGV launcher can consistently deliver a 25- to 30-pound canister of agent to a range of 1200 feet or greater; (2) the ballistic prediction program developed in Phase I predicts the range of the PGV launcher to an acceptable accuracy based on specific canister size and weight, PGV chamber pressure, and wind effects; (3) the spherical canister appears to have advantages over the aerodynamically designed canister for this application; (4) polyethylene and polycarbonate spherical containers of the appropriate size and strength are commercially available and are feasible for use as agent containers; (5) due to the kinetic energy of the agent canister, and the danger to objects in the fire, it is desirable to rupture the canister and dispense the agent prior to impact; and (6) it is feasible to build a relatively inexpensive timing circuit and rupture device for each canister to dispense the agent in the target area.

The Phase II recommendations were that (1) a canister concept consisting of two spherical halves with an internal agent bladder be further explored; (2) the long-term creep characteristics of canister materials be explored to determine the necessity for filling the canisters at the response site; (3) the launch rate requirement be explored to determine the barrage length (number of launches per barrage) and time between

barrages (these two factors will dramatically influence the power requirements for the launcher and the complexity of the rapid-loading device); and (4) the concept of an onboard timing network and detonator to rupture the canister to dispense the agent be further investigated.

SECTION IV

PHASE III - PROOF OF CATAPULTING CONCEPT

A. PULSED-GAS VALVE LAUNCHER IMPROVEMENTS

The PGV Launcher was received at the New Mexico Engineering Research Institute (NMERI) from FRC at the beginning of Phase III of the project. Reference 14 contains additional details and illustrations describing the work performed in this section of the report. NMERI engineers discovered that the gas valve piston had been damaged during testing at FRC. Repairs had been attempted but did not meet the required specifications.

A visit was made to Associates and Ferren, Wainscott, NY (the designer and fabricator of the PGV under contract to the Naval Systems Warfare Center [NSWC]) to discuss design limitations and operation of the PGV. They emphasized that control of the piston valve between the 26-inch limits of travel after firing was essential. The factors that influence piston travel are firing chamber pressure, barrel size (diameter and length), projectile size and weight, and restrictor valve setting. The restrictor valve controls the gas bleed-off rate behind the piston and is the only mechanism for adjusting piston travel between the rear stop on recoil and the front stop on rebound.

Piston travel can best be determined experimentally because of the number of variables that influence it. Associates & Ferren had built and installed a Linear Variable Differential Transformer (LVDT) device to monitor piston travel, but FRC had not used it in their testing. It was also learned that a spare piston had been provided to NSWC.

The spare piston was requested and received from NSWC. The LVDT piston position sensing system was activated so that piston travel could safely be characterized for different loads and pressures. The resolution of the system is about + 0.25 inch.

More details on the LVDT are included in Reference 14. The results of the piston travel characterization testing will be discussed later in the System Testing Section.

The controller for the PGV is a microprocessor-based remote function controller. As received it was connected to the PGV by a 250-foot hard-wire cable bundle. The discrete functions of the PGV are controlled through 20 conductors in the cable. Some difficulty was experienced with the controller and was traced to bad solder connections in the cable connector pins. The connector was totally reworked. Documentation for the controller microprocessor, including calibration instructions, was obtained. The pressure set point was found to have a 7 lb/in.² offset, which was corrected by the calibration procedure.

The launch tube, or barrel, on the PGV was in three sections and had a 10-inch inside diameter and a total length of 6 feet if all three sections were used. It was necessary to replace this barrel with a 10.25-inch inside diameter barrel because of the size of the canisters chosen. To maintain desired range and accuracy, the length selected for the new barrel was 6 feet. Initial tests at low pressures showed a 15 percent increase in range over the 4-foot barrel.

The trailer fabricated by FRC on which the PGV launcher was delivered was not structurally sturdy enough for the conditions at the McCormick Ranch Test Site. The launcher system was mounted in the bed of a 3/4-ton, four-wheel drive pickup truck to improve terrain capability. The PGV launcher design was limited to about a 23-degree launch elevation angle for the barrel. A mounting fixture was designed and fabricated that provided another 22 degrees of elevation to achieve a total elevation angle of 45 degrees, the angle required to achieve maximum range for a given firing pressure.

B. AGENT ENCAPSULATION

1. Spherical Prototype Projectile

Initial canister testing to characterize and evaluate the PGV launcher was done with rigid spherical projectiles. The projectiles were made from 10-inch nominal outside diameter, polyethylene spheres filled with lightweight concrete. The lightweight concrete was made using pumice as the aggregate to achieve a specific gravity of about 1.8 to match the weight for a Halon 1211-filled canister of the same size.

The spherical plastic canisters chosen by FRC were believed to be the optimum at this point in the project. A listing of all the rotational molders was obtained from the Association of Rotational Molders. Many of the molders made plastic spheres as light fixture globes in the 10-inch diameter size; however, all of them had 3- to 4-inch openings, usually with a flange for mounting to the light fixture. Retooling for our special application was an expensive option. One vendor was found (Rotocast, Canine Castle of Brownwood, TX) that makes a 10-inch diameter polyethylene sphere with a 0.875-inch threaded hole. The sphere was made as a Canine Exercise Ball. Samples were procured in polyethylene (PE) and polycarbonate (PC) material for testing. Various thicknesses were tested and it was determined that the PE spheres needed to be cast with at least 0.75 pound of PE melt material to have sufficient strength to contain the 20 to 40 lb/in.² pressure of Halon 1211. The PC spheres could not be cast reliably with threads adequate to contain the pressure, although the PC sphere had superior rupture characteristics upon impact when filled with Halon 1211. The PC material is more brittle than PE and therefore breaks into smaller pieces.

The spherical canisters as received from Rotocast were slightly larger than 10 inches in outside diameter. Although the mold is 10 inches in diameter the spheres are not quite spherical due to expansion/shrinkage characteristics of the material as it cools. The sphere actually is almost 10.125 inches in diameter at the equator (the split line of

the mold) and slightly less at the poles, resulting in a slightly flattened shape. Since the barrel of the PGV launcher had a 10-inch inside diameter (I.D.), this difference posed a problem. It was solved by using a new barrel (10.25-inch I.D., 6 feet long) for the PGV launcher. The 10.25-inch I.D. barrel would allow for some variation in sphere size as fabricated and some stretching due to pressure from the Halon 1211. The gas seal needed for the launch of the canister would be provided by the sabot.

The sabots (Figure 1) were made from a 0.25-inch thick plywood disk with expanded rigid foam molded onto the disk. The mold for the outside diameter of the sabot was made from a piece of the same mechanical tubing (pipe) as the barrel. This assured a close fit for the sabot and minimized gas leakage during launch.

2. Advanced Projectile Concepts

In further advancing the canister or projectile concept, it was determined that the design should solve at least three problems: it should achieve reasonable areal distribution of the agent over the fire to permit the most efficient use of the agent; it must move the agent through the flames and turbulence to the base of the fire where the agent is most effective; and it must apply the agent as rapidly and evenly as possible to prevent flashback. A proposed dispensing projectile concept, shown in Figure 2 and described here, attempts to achieve all of these objectives. The proposed projectile consists of a lightweight housing (2) loaded with a large number of individual agent-filled spheres (1), balloons, or other frangible containers. The housing is equipped with a fin assembly (4), which is fitted with slanted fins (5) to provide rotation for stabilization during flight. Use of a smooth bore gun is assumed for this design; a future design incorporating a rifled bore could eliminate the need for the fin assembly. The housing is also equipped with a pusher plate (3), which is used to eject the spheres on command. The pusher plate is driven by an electrically activated gas generator (6), which vents into the gas chamber (9). When the gas generator is activated the bin assembly is pushed out of the way. The spheres are then expelled one layer at a time.

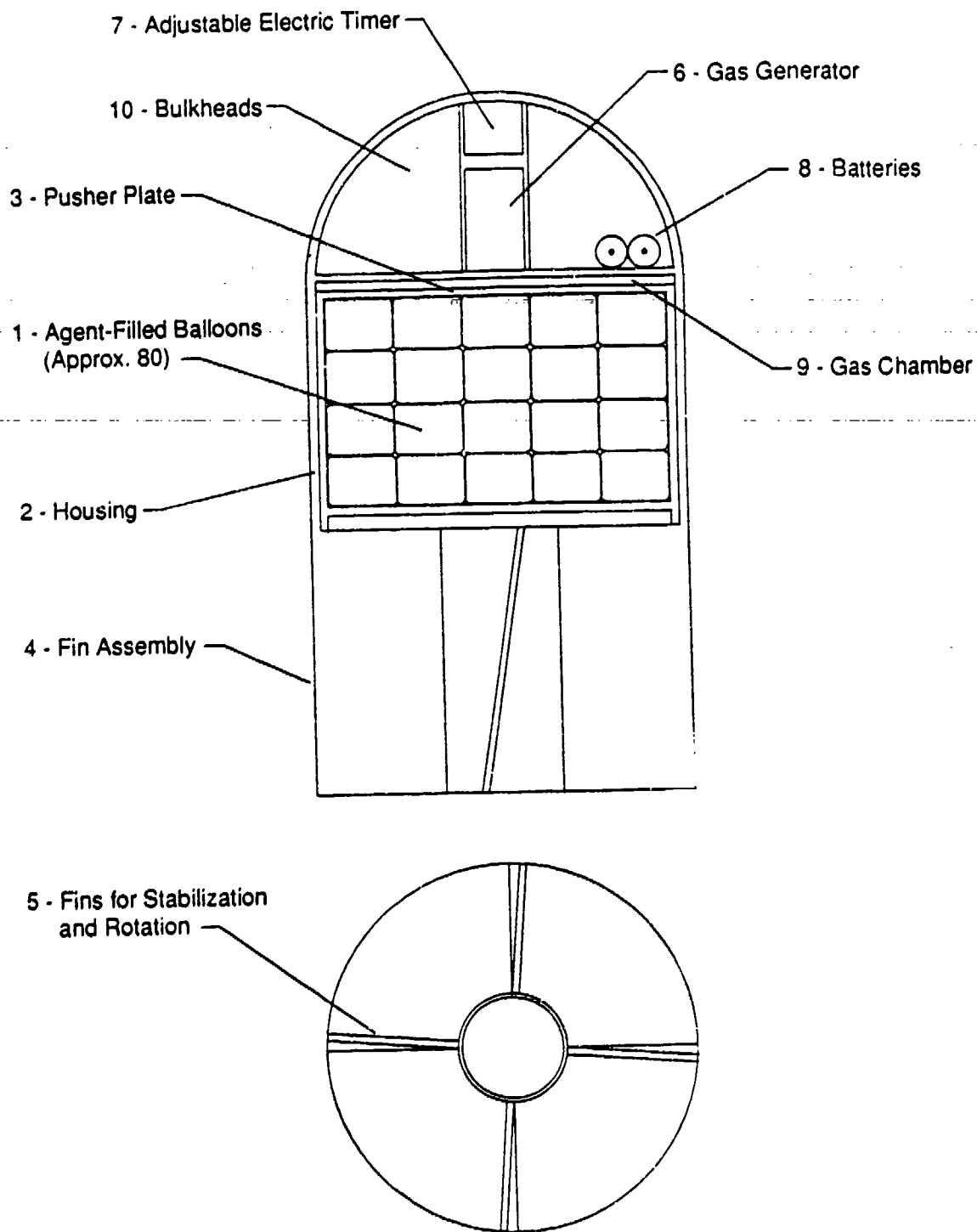


Figure 2. Firefighting Agent Canister Concept.

Ejection timing is controlled by an adjustable electrical timer (7), set according to the predicted flight time and the required agent dispersal height above the fire.

The use of multiple individual spheres should solve the problem of moving the agent through the flames and turbulence to the base of the fire. Although Figure 3 shows approximately 80 spheres, almost any number is possible. The spheres must survive the launch acceleration, but burst upon impact. Since the spheres are tightly packed within the housing, survival of the launch acceleration (as well as agent pressurization) should be provided primarily through the strength of the housing.

The spin distribution technique should achieve uniform area distribution. The size of the impact pattern can be controlled in three ways. (1) Packing pattern - since the radial velocity before ejection is dependent on the radial distance to each sphere, whatever pattern the spheres are packed into will grow in radial dimension upon release, while preserving the same basic radial geometry. Since each layer is released essentially independently (although rapidly), each layer will be rotated from the previous layer, depending upon the rate of expansion. (2) Projectile rotation speed - for higher rotation speeds, the radial velocities are greater and the patterns formed grow more rapidly; and dispersal height above the fire - the larger the height, the larger the pattern size at impact. (3) Rapid application, is automatically achieved with the projectile because of the impact speeds anticipated. At 200 ft/s impact velocity, the entire pattern should impact within a few tenths of a second, depending on pattern size. The ideal scenario would be to extinguish the entire fire with one projectile. Depending on the amount of agent required per unit area, this may be achievable with launchers and projectiles of reasonable size.

The amount of agent required to extinguish a given fire will have to be determined empirically. Theoretically, very thin layers of the appropriate agent can extinguish a fire. Intuitively, gaseous layers an inch or so thick are probably impractical, while a 1-foot thick gaseous layer could probably extinguish and secure the fire

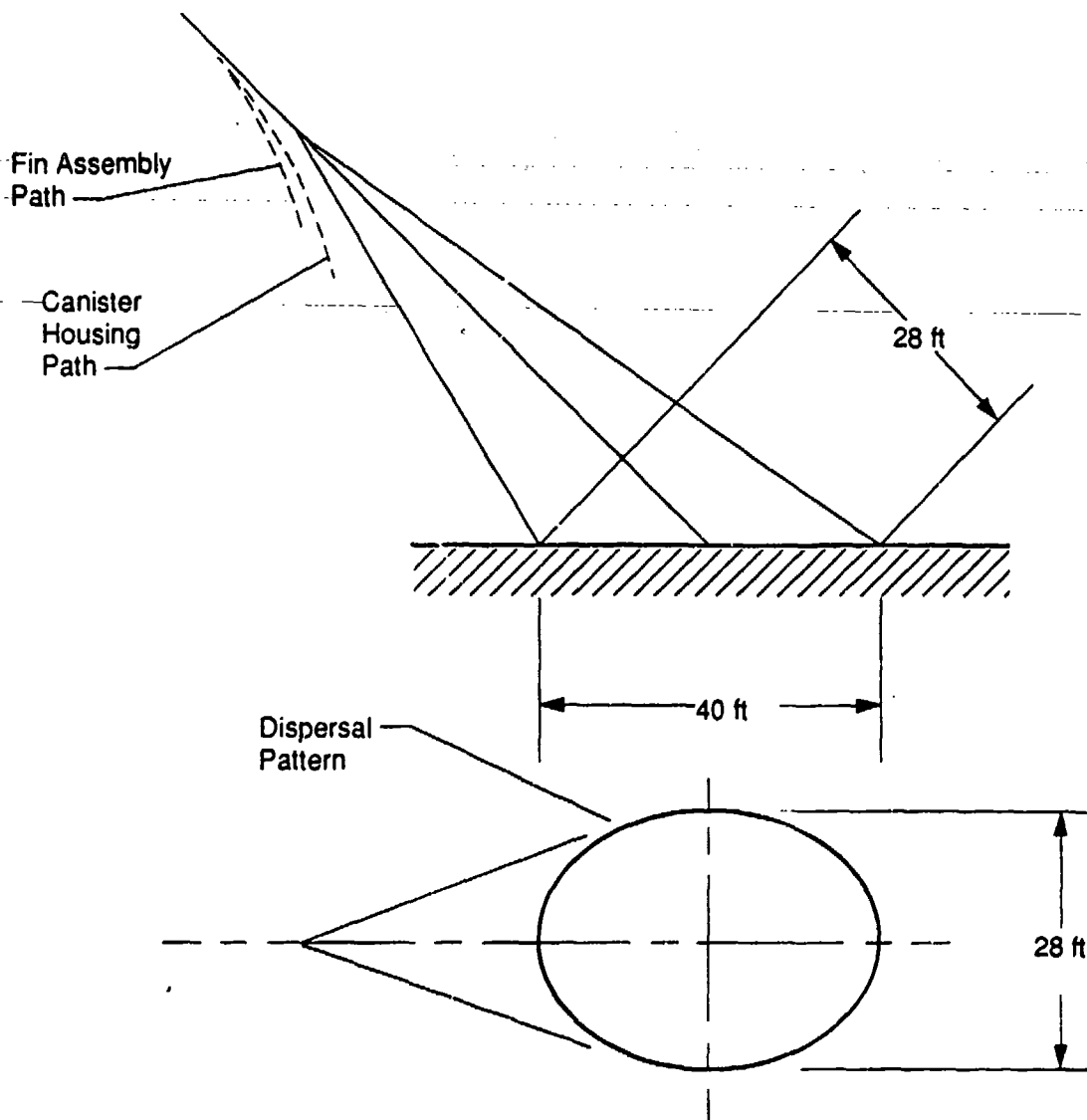


Figure 3. Dispersal Pattern for 10-inch Diameter Canister.

effectively in most scenarios. Assuming an agent concentration of 33 percent (by weight), 30 pounds of agent in a 10-inch sphere should develop a covered volume of 1200 cubic feet. For a 1-foot thick layer, the nominal areal coverage would be 1200 ft², or about 0.025 pound of agent per square foot. This type of distribution is shown in Figure 4. The balloon impact pattern here is idealized. Because of the anticipated impact angle, the actual pattern will always be egg-shaped. After the spheres have been ejected, the fin assembly and the canister housing will fall out of the ballistic path since the ballistic coefficient will drop dramatically. Consequently, a 10-inch projectile can probably be expected to cover an egg-shaped area roughly 30 by 40 feet. Following the same logic, a 20-inch projectile should carry about 240 pounds of agent and cover an area roughly 85 by 115 feet at a density of at least 0.025 pound per square foot.

A prototype external time-setting device for the agent dispersal canister has been designed and breadboarded (Figure 4). A 4 MHz crystal was divided down to 1 kHz and wired to a three-stage counter. The counter is capable of setting seconds, tenths, and hundredths. The device is configured to set only the first three digits for a maximum time delay of 9.99 seconds. Conceptual designs of the count initiating transducer are being finalized. Most likely, a g-sensitive preloaded flexure will be used to initiate the count by either making or breaking contact at a predetermined g level. When a computer is selected, calculations of both the time-to-target and automatic downloading of time to the projectile timer will be done by the computer. For prototype testing, time-to-target will be calculated externally and set manually with the master unit. An LED display shows the selected time from 0 to 9.99 seconds. An umbilical line will transfer the time from the master unit to the projectile timer. The line is then disconnected, and the projectile is placed in the launcher load magazine. The timer remains dormant with the preset selected time in memory. When the launcher is fired, an inertial switch will break the contact at a predetermined acceleration threshold, allowing an onboard clock to input a 100-Hz timing signal to the 1/100-second decade downcounter. A 12-input NOR gate receives all BCD outputs from the three-stage counter. The output of the NOR gate is positive only when all three input stages are

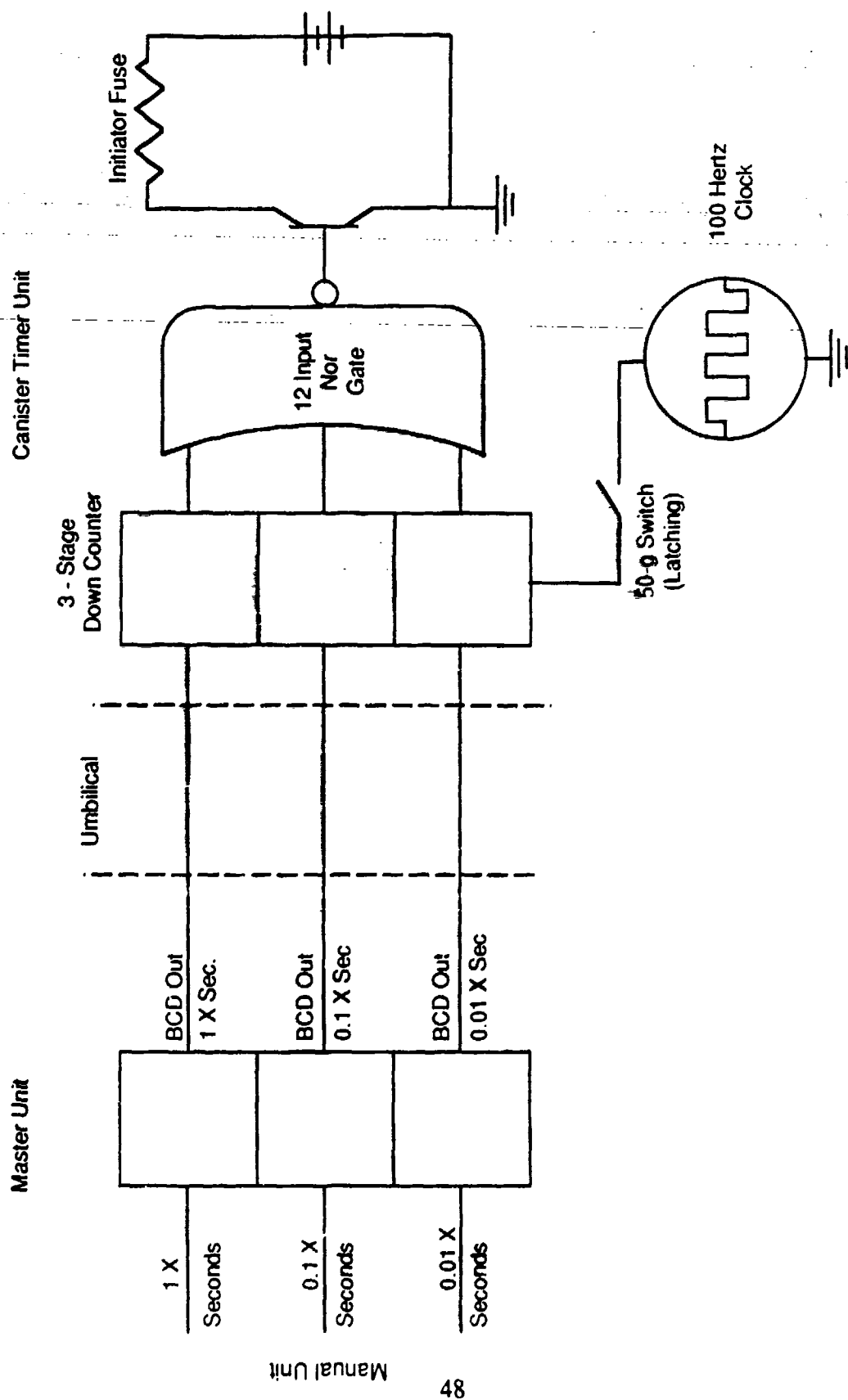


Figure 4. Master and Canister Timer Units for Agent Canister.

zero. This, of course, occurs after the preset count time has elapsed. At countdown completion, the NOR gate activates the final stage causing current to flow through the fuse device initiating the dispersal sequence. In addition to its function as a remote count-setting device, the master unit includes all electronics of the projectile unit with an LED and piezoalarm replacing the fuse. This substitution was made for experimental purposes and for stand-alone functional tests.

C. LAUNCHER SYSTEM TESTING

During this phase of the project, four series of tests for a total of 61 dry firings were completed to characterize performance of the PGV Launcher system, primarily related to piston valve travel. The original LVDT system coils, installed by Associates and Ferren to monitor piston travel, were still intact. Instrumentation required to excite the coils and read out data relevant to piston position was acquired from the available inventory. Initial calibrations were done on the disassembled piston and cylinder. The data recorded from these test series are contained in Reference 14. The highest chamber pressure that could be achieved was with the original refurbished piston installed, and that was 110 lb/in.². Although the PGV is designed to operate up to 150 lb/in.², any pressure higher than 110 lb/in.² caused the piston to hit at the rear or front, or both, resulting in damage. Further, this testing was accomplished without projectiles. With a projectile, the maximum allowable pressure would be further reduced because of the reaction forces produced by the projectile. This limitation will be pointed out later in the discussion of field testing. In the original development testing by Associates and Ferren, they were able to operate the PGV up to 150 lb/in.² before piston travel limits were achieved (Reference 4). The only plausible explanation for the difference in pressure is that the wear on the system reduced clearances resulting in less frictional drag on the piston and cylinder, thereby allowing greater piston travel.

The piston travel characterization continued in the field with projectile launches in combination with other testing. A remote test range was set up at the McCormick

Ranch Test Site to enable the safe launching of projectiles for distances greater than 1000 feet. A total of 62 projectiles were launched in 11 series of tests. The 62 launches included 49 rigid (concrete-filled) projectiles ranging in weight from 20.08 to 35.3 pounds, one canister filled with water weighing 17 pounds, and 12 canisters filled with Halon 1211 ranging in weight from 33.15 to 34.5 pounds. The data from the field tests are included in Reference 14.

The primary objectives for the early field testing were familiarization with the PGV Launcher, characterization of piston travel, development of sabots for the projectiles, and range and accuracy evaluation of the projectiles. The practical limit of the PGV Launcher on chamber pressure for projectiles of about 20 pounds each is currently 50 lb/in.² due to piston travel limitations. For projectiles of 33 to 35 pounds, it is 45 lb/in.². The range capability of the launcher is thus currently limited to about 700 feet for a 20-pound projectile and about 375 feet for a projectile of 33 to 35 pounds. The piston travel limitation problem will have to be solved to achieve the objective of 20 pounds to 1200 feet. The PGV Launcher has the potential of easily exceeding that goal. FRC testing achieved a range of 1140 to 1260 feet with 28- to 31-pound projectiles, elevation angles of 31 to 35 degrees, and chamber pressures from 138 to 147 lb/in.²; however, the piston was seriously damaged in the process.

Two approaches were considered for solving the piston travel problem. The first was the design and installation of a friction brake on the piston, and the second was the lengthening of the piston recoil cylinder to allow more room for piston recoil travel. It was decided to try the friction brake approach first. A brake system was designed that could be retrofitted on one of the existing pistons. It was a passive system in that the brake was applied by the firing pressure acting on the face of the piston during the recoil phase and by the vacuum behind the piston during the rebound phase. The brake system was fabricated, assembled, and installed on one of the pistons. After testing, it became apparent that this approach did not provide sufficient improvement to enhance significantly the launcher pressure/range capability. The second alternative, lengthening

the piston recoil cylinder, will have to be accomplished if the PGV Launcher is to achieve project requirements.

Along with the piston travel characterization, other data were gathered on the performance of the PGV Launcher. Projectile distance versus chamber pressure, projectile weight, and elevation angle were evaluated along with sabot configuration and size. Projectile impact point scatter is affected by variations in the influencing variables from one shot to the next and include, but are not limited to, projectile weight, firing pressure, sabot fit (gas leakage between the sabot and barrel), elevation and azimuth angle variation, and wind effects. Analysis of the data on five series of shots, for a total of 25 shots where direct comparisons can be made, shows that the average variation in range (projectile impact distance from launcher) thus far has been about 6 percent. It is believed that the two major contributions to that dispersion are variation in sabot fit and wind effects. An internally machined, honed, and polished barrel, along with better fitting sabots, should improve the dispersion considerably. Adjusting for wind speed and direction will be done later in the project with the automated aiming system.

The last two series of field tests in this phase of the project were done to evaluate the effectiveness of Halon 1211 canisters against JP-4 pool fires of 10-foot diameter (78 ft²). The canisters were 10-inch diameter polyethylene (PE) spheres filled to about 95 percent volume capacity (or about 33 pounds) with Halon 1211. Two canisters were launched with no fire to evaluate the frangibility of the canister and dispersal of the Halon 1211. The fires were ignited in a membrane-lined earth pit 10 feet in diameter, nearly filled with water and JP-4 floating on the water. The PGV Launcher was placed 375 feet from the center of the pool. The launcher was set at 42.5 degrees elevation angle and chamber pressures varied from 42 to 45 lb/in.². The objective was to launch the canister to the area immediately in front of the pool fire, rupture the canister upon impact, and thereby dispense the Halon 1211 on the fire. The ideal impact would be a few feet in front of the pool so that the momentum would cause the halon to sweep across the pool fire. Of the 10 attempts to extinguish the pool fire, two were successful.

Because of the dispersion inherent in the launch system at this time, the other canisters did not impact close enough to extinguish the fire. This test series did prove the basic concept of extinguishing fires using a Halon 1211-filled canister.

D. RAPID-FIRE CAPABILITY

The present PGV Launcher is a proof-of-concept prototype and launches a single round, which is hand-loaded into the barrel in a manner similar to early cannons. One objective of this project is to develop a rapid-fire capability so that successive launches could place more firefighting agent on the target fire if necessary. Rapid-fire capability could have multiple interpretations in this context. One practical interpretation in terms of launcher and support equipment design and logistics is that the system should be capable of rapid fire for a reasonable number of rounds, i.e., a barrage.

Several preliminary concepts were evaluated for providing a rapid-fire barrage capability. Many of these concepts are analogous to both military and civilian weapon system designs. The concept currently believed to be the most practical for adaptation to the PGV Launcher is the six-canister cylinder shown in Figure 5. The cylinder would be preloaded with six agent canisters and could be manually or automatically loaded into the launcher system. The overall weight of the cylinder would be on the order of 350 pounds. This would give the capability to launch and dispense about 200 pounds of Halon 1211 onto a fire area probably in a time frame of about 30 seconds.

E. PHASE III - SUMMARY AND CONCLUSIONS

The basic objectives of the Phase III effort were to restore the launcher to a safe, reliable operating condition, further refine the encapsulation concept, and construct a prototype projectile that incorporates an activation timing subsystem. The condition and documentation of the launcher, as received from FRC, were such that an inordinate

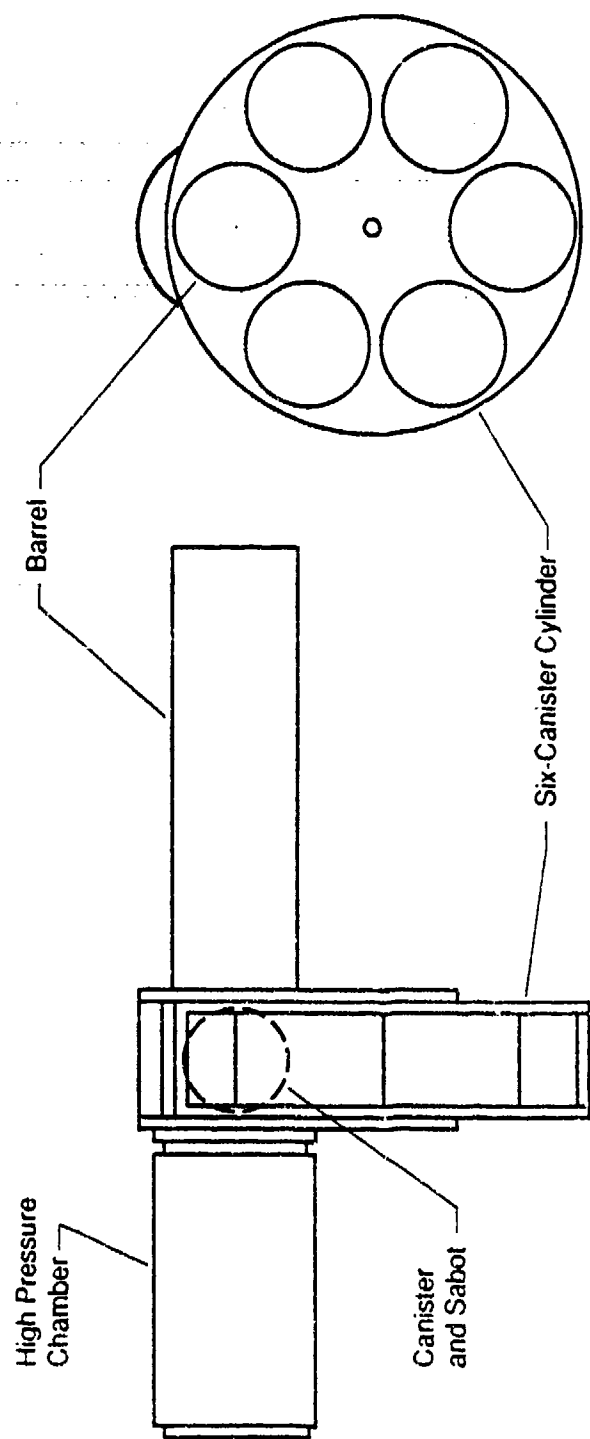


Figure 5. Rapid-Fire Barrage Concept.

amount of time was required to restore it and bring it to a reasonable level of operating performance. This part of the effort entailed damage repair, calibration, and reconstruction of the LVDT and the primary piston.

It was generally assumed that the launcher, as originally designed, was configured to launch heavy projectiles. This did not prove to be the case since the original launcher design was for light loads of powder only. Although most of the launcher subsystems could make this transition as designed, several pressure control valves had to be reconfigured, and the primary piston valve travel limitations prohibited reaching project requirements of launching 20-pound projectiles to a range of 1200 feet.

In order to achieve greater distance and improved impact repeatability, the original three-part barrel was replaced with a longer single-piece launch tube. This change resulted in some of the required improvement, but a better machined and honed tube will be required for the next phase of development.

The spherical canister design described earlier appears to satisfy the major requirements of repeatable delivery and dispersion, although some improvements in accuracy can be realized. The proposed canister designed to dispense the agent above the target fire will provide a more uniform agent application and therefore will be more efficient. In addition, it will eliminate the concern of a canister of 20 to 30 pounds of agent potentially impacting the burning object and the attendant damage that could occur.

Tests to date have further proved the potential of this system to deliver agent to extinguish a distant fire. However, many critical and difficult engineering challenges remain in the areas of agent dispersion, canister loading, and advanced aiming before the system will be able to realize the desired capability. Furthermore, the finalization of these design aspects is required before the system can be fitted into its ultimate configuration on a mobile vehicle with appropriately sized power units.

SECTION V

PHASE IV - COMPUTER-CONTROLLED, RAPID-FIRE PROTOTYPE LAUNCHER

As described in the Section IV, the original PGV design was intended to propel light loads of powder only. When heavy projectiles were launched, the piston contacted the ends of the cylinder at the higher launch pressures; this is essentially what caused FRC to damage the system during their testing. After discussing the problem with the original manufacturer of the launcher and exhausting the available combinations of valve adjustments, it was determined that a brake system or extension of the cylinder were the only options that would permit the valve to operate with heavy loads at the higher pressures necessary to achieve the required launch distance of 1200 feet. A mechanical brake system was designed and constructed but did not permit a significant increase in launch pressures. Before proceeding with a cylinder extension, the possibility of using a completely new valve was discussed, and a market survey was initiated. A fast-acting butterfly valve was located and became the basis of a totally new prototype design that would also incorporate a rapid-loader to give a 6-shot barrage capability. Work described in this portion of the report is described in additional detail in Reference 15.

A. APPROACH

The primary focus of this effort was to design a new prototype launcher incorporating an aiming and firing system that would provide for automated control of the variables influencing the launch of the agent canisters. This system would include elevation angle adjustment, azimuth angle adjustment, and advancement of the rapid-loader, chamber pressure control, and firing valve control. Other factors to be considered were projectile size and weight and wind effects.

The approach to the design of the aiming and firing system featured the use of a computer to control all the functions through electro-mechanical and pneumatic devices,

either in an automated logic sequence or through manual operator commands. Other redundant manual controls that do not depend on the computer were to be provided. In addition, the computer was to be programmed to make predictions based on trajectory equations and input of constants.

B. RAPID-LOADER DESIGN

1. Requirements

After the successful testing of the Pulsed-Gas Valve launcher, a multiple-shot prototype launcher was designed incorporating a rotating cylinder to enhance firefighting capabilities. The cylinder design contained loading chambers for six rounds of halon-filled canisters. The overall cylinder dimensions were 36 inches in diameter and 12 inches in width, and weighed approximately 400 pounds fully loaded. To meet the operating requirements of the rapid-fire system, this cylinder had to be rotated 60 degrees (distance from one chamber to another) in 1 second with minimal error or slippage. This relates to an angular velocity of 0.17 rev/sec. These operating requirements were later changed to an angular velocity between 0.06 to 0.03 rev/sec in order to maintain better testing control of the loading mechanism. A number of design calculations were completed to achieve these requirements.

2. Calculations

The torque required to rotate the cylinder from rest was calculated to determine the type of mechanism needed. Other factors used in this determination were size and space limitations, ease of incorporation with other system components, and the reliability/accuracy of the mechanism to establish and maintain a positioning point. A ring/pinion gear set, driven by a motor, was chosen as the most practical approach.

The launcher is loaded by rolling the fully-loaded cylinder into position in the loading frame of the launcher. The ring gear was mounted in the center of the back plate of the loading cylinder. The external ring gear meshed with the pinion gear as the cylinder reached its final position. Calculations were conducted to size an external ring/pinion drive-gear set and a drive motor.

The gear sizing was conducted using standard equations taken from American Gear Manufacturers Association (AGMA) standards (Reference 16) and physics laws of rotational motion (References 17-19). Using the AGMA equations and size limitations of the cylinder, it was determined that a 10-inch external ring gear, driven by a 1.5- to 2.5-inch pinion gear and a 0.5 hp motor, was sufficient. A gear ratio of 0.15 was also determined as optimal. These calculations were verified by using standard physics equations of torque, power, and angular velocity.

3. Component Selection

The results of the calculations provided guidelines for gear selection. After contacting several gear manufacturers, it was determined that, to be cost-effective, an existing gear set that could produce the required torque/velocities had to be found locally.

After much searching, an automotive flywheel gear set was located that could meet these requirements. Calculations showed that a 0.5 hp motor could produce a ring gear velocity of 0.39 rev/sec using this gear set. Most motors, however, must operate at a higher revolution rate to produce the torque necessary to rotate the cylinder. In order to achieve the required ring gear angular velocity with the required torque, a gear reducer was mounted between the motor and the pinion gear. The speed reducer selected was a Winsmith Model 133EU LR with a reduction ratio of 15:1. A total gear ratio of 255 to 1 was achieved.

During testing of this driving mechanism setup it was shown that this gear ratio was sufficient to maintain the required cylinder rotational speed. An angular velocity of 0.2 rev/sec was maintained when a 0.5-hp drive motor was used. Two drive-motor types were tested and their individual capabilities were compared.

The motors tested were an air motor (Dayton No. 4Z411) and an electric motor (Emerson No. 2635HA-4061) equipped with a magnetic brake (Dayton No. 6K233C). After extensive testing, the air motor was chosen as the best for this application. While both motors could maintain the rotating and positioning requirements, the air motor had more positive control and its speed could be varied, giving more control than with the electric motor/brake. This motor can also be used without significantly influencing the compressed air demands of the other launcher components.

C. ELEVATION ANGLE SUBSYSTEM

1. Requirements

A reliable, accurate, and reasonably fast mechanism was needed to rotate the cannon assembly vertically to achieve the desired elevation angles. Several design parameters were determined that governed the selection of this device.

This mechanism had to have the ability to position a combined assembly weight of 2000 pounds into elevation angles from 0 to 45 degrees and withstand the recoil loads experienced during launching. The anticipated center of gravity of the assembled launcher components was calculated; the amount of torque needed to rotate the launcher about a pivot point near this balance point was determined. The center of gravity of a fully-loaded launcher was located at the approximate center of the loading cylinder. A linear actuator with the required torque load rating was chosen as the best mechanism for these requirements.

To minimize the amount of lift for the actuator, the actuator mount was located on the back supporting plate of the loading cylinder, near the center of gravity. The mounting position was also determined to provide a range of elevation angles from 0 to 45 degrees. This positioning span proved to be the most efficient during the initial Pulsed-Gas Valve Launcher tests.

Finally, the mechanism was required to position the barrel accurately at a moderate speed and maintain that position. In this part of the aiming procedure it was decided that position accuracy and repeatability were more important than positioning speed.

2. Types of Actuators

Several types of linear actuators - screw jacks, pneumatic and air cylinders, and ball-screw actuators - were considered for this system. The screw jacks were considered too slow and required too much clearance to operate. Pneumatic and air cylinders would be unable to maintain their position if no pressure was applied to them. The only reasonable choice for this application was the ball-screw actuator.

Ball-screw actuators are highly accurate positioners that have minimal backlash. These actuators are also compact and space efficient, and can expand/contract from a small housing compartment. They were also the quickest responding heavy-duty actuators that were surveyed. The actuator selected used a static brake to maintain the position of the actuator after the power was turned off. Maintenance of the position is important because, due to the power and operating demands of the other components, the device would have to be held in position until further movement was needed. An Actionjac (TM) Electric Cylinder ball-screw actuator (Model No. RAD 2566) from Nook Industries met these specifications and was chosen.

The only significant disadvantage of the ball screw is that it cannot withstand a side thrust load. The mounts were designed so that the actuator would not be subject to any side loading.

D. RAPID-LOADER CHAMBER ALIGNMENT SUBSYSTEM

1. Requirements

To assure that the load is propelled out of the cannon on a straight trajectory, the loaded chamber must be properly aligned with the barrel. A dual-alignment pin mechanism was designed that could accurately position the chamber with the barrel of the launcher once the chamber was roughly in position. The alignment pin mechanism was designed to extend forward into positioning holes through the barrel flange, cylinder positioning flange, and other interconnecting pieces. The mechanism was also to retract to allow the loading cylinder to be rotated and then extended again to align the next chamber before the next shot. An actuator was needed to complete this function.

The requirements of the actuator used in this final positioning were positioning accuracy, feedback control, and sufficient power to position a fully loaded cylinder. Screw jacks, air/hydraulic cylinders and ball-screw actuators were considered; however, the ball-screw actuator was chosen as the best suited for this application. This actuator could position the mechanism with a backlash, or error, of 0.035 inch and could be controlled through a feedback system that was repeatable within ± 0.025 ohms/inch. Design calculations showed that a maximum load of 500 pounds would be necessary to position the pins in the cylinder, and this loading was well within the capabilities of such an actuator.

2. Component Selection

A Warner Electric Linear Actuator (Electrak 100 model) was chosen as the ball screw actuator for this function. This actuator had a stroke of 4 inches and a maximum load rating of 500 pounds. Feedback positioning of the actuator was accomplished by using an external actuator control, which could extend, retract, jog, or record the position of the actuator.

E. AZIMUTH ANGLE CONTROL SUBSYSTEM

1. Requirements

To provide azimuth control for the aiming system, the mounting base for the launcher needed to rotate. This base would be required to rotate 180 degrees (90 degrees in either direction) and have a loading capacity of 3000 pounds. The rotation had to be tightly controlled, allowing less than one degree of error during starting and stopping rotation. The base was also required to withstand a recoil loading of 300 to 500 pounds (the expected recoil loading from firing the launcher). An industrial turntable ordered from Tulsa Power Products was custom-designed to meet these requirements.

2. Construction

The launcher mounting design required that the turntable have a working diameter of 4 feet and a low structural profile. To meet these requirements and still provide enough structural support for static and dynamic loading, 0.5-inch thick steel plate with steel angle structural supports was used in the turntable construction. The turntable basic dimensions were a 4-ft² base, with a rotating top 4 feet in diameter, and an overall height of 7.75 inches.

A direct-drive bevel gear system driven by a geared electric motor was used to provide the control for the turntable rotation. The drive motor was a Dayton 1/4 horsepower split phase (reversible) gear motor, Mod. 5K933B, which had a reducing ratio of 288:1, produced 600 inch pounds of torque, and an output of 6 rpm. The gear ratio of the pinion gear to the ring gear was 1:2.21, producing a total ratio to 636:1, causing the turntable to rotate at about 2 rpm. Since rotational speed was not a critical factor and more accurate control could be achieved with slower speeds, the rotational speed of the platform was further reduced by the addition of a speed reducer between the geared drive motor and the platform shaft. The gear reducer selected was a Winsmith Model 133WU-LR with a 15:1 speed reducer. This final reduction of 9540:1 resulted in a platform rotational speed of about 48 degrees per minute or 0.133 rpm.

F. FIRING VALVE SUBSYSTEM

1. Design Considerations

The operating constraints of the original piston valve in the Pulsed-Gas Valve launcher would allow a charging pressure of only 45 to 50 lb/in.², producing a range of up to 650 feet, depending on projectile load. The design requirements of the launcher specified that a minimum operating range of 1200 feet was needed to combat hazardous munitions fires safely. To meet this requirement, the charging and firing systems were redesigned, and the piston valve system was removed. In the revised design, the original pressure chamber was used as a pressure reservoir; a conventional valve, mounted on the outlet of the chamber, was used to release the pressure and fire the launcher through use of a valve actuator. Several types of valves and valve actuators were considered.

Design parameters for the valve actuating system were derived from data obtained from operating the original Pulsed-Gas Valve system. The valve needed to be relatively lightweight, have an effective opening diameter comparable to the piston

system, and be fully opened in 50 ms or less. Several types of valves and actuators were surveyed, and three valve and four actuator types were considered in the final analysis.

2. Valve Types

A comprehensive study of different valve types revealed that only three types would be suited for use in the launcher. These types were the butterfly, ball, and pinch valve. A comparison of how well these three types met the design requirements was conducted and revealed the following information.

a. Effective Size of Valve Opening

When the piston was released in the PGV piston actuation system, the pressure relief opening that directed the air into the barrel exposed an effective diameter of 6.12 inches. The effective diameter is the diameter of a circle the area of which is equal to the area of the unobstructed opening of the valve. When compressed air flows through an opening, its speed and transfer efficiency are governed mostly by the effective diameter of the opening.

Three sizes of valves, 6-, 8-, and 10-inch, were considered for the valve types. It was found that the 8-inch valve size would be the maximum size that would adapt to the opening in the existing pressure chamber. When the effective diameters of fully opened 8-inch valves from each type were compared, the butterfly had an effective diameter of 5.44 inches, the ball valve was 8 inches, and the pinch valve was 8 inches.

The escape velocity/efficiency of compressed air is also governed by the Cv factor (Cv is the gallons per minute of air flow at 1 lb/in.² differential pressure through the valve at standard conditions). The higher the Cv, the better the flow

through a valve. The butterfly valve had a Cv of 2020, the ball valve 2970, and the pinch valve 2120.

b. Actuation Time

To maintain the same propulsion characteristics produced by the PGV piston valve firing system, the new valve had to be actuated (opened) in a comparable length of time. When the piston chamber was removed from the pressure chamber, there was an increase in the available pressure volume. The volume of air released from the chamber with the piston and recoil chamber in place was 2.6 ft³. With the piston and piston chamber removed, the chamber volume was increased to 4.1 ft³. The increase in volume allows a greater amount of compressed air to be released when firing the launcher. The increase in expelled air would improve the propulsion characteristics of the launcher and possibly increase the range of the projectile. An increase in range would be true even if the valve actuation time was somewhat less than the PGV piston actuation time of 30 ms. It was therefore estimated that the same propulsion characteristics could be achieved with a valve opening time of 50 ms with the increased chamber volume. The butterfly valve could be actuated in 50 ms or less, the ball valve in 15 ms, and the pinch valve actuation time could not be accurately estimated.

c. Size and Weight Considerations

The launcher components had to be as lightweight and as compact as possible to allow the aiming control system to position the launcher effectively in a reasonable amount of time. Of the three valves surveyed, the butterfly was the only one that was relatively compact and lightweight. Both the ball valve and the pinch valve weighed over 400 pounds (with actuators) and had lengths of 18 inches or more. The butterfly valve weighed only 54 pounds (without the actuator) and had a length of 2.5 to 5.5 inches.

d. Valve Seal Integrity

One of the problems with the piston system was the reliability of the pressure seal. The seal would regularly leak and cause operational problems. Of the three valves surveyed, only the butterfly could produce a leak-free seal that was reliable in any environment. This valve could produce a leak-free seal to 300 lb/in.², well above the operating pressure of the launcher.

After consulting valve manufacturers and valve experts, the butterfly valve was the only one that was recommended. The seal integrity and design were considered as the best for stresses that the rapid actuation of the valve would generate. The other valves were also too bulky and heavy and would cause design problems in the aiming system.

3. Valve Actuator Types

Four types of actuators were considered for the butterfly valve. These were the rack and pinion, helical coil, rotary vane, and scotch yoke actuators. The torque requirements and the associated stresses and forces that would be generated by such a fast valve actuation were calculated, and only the scotch yoke actuator could repeatedly actuate the valve at the required speed without failure of any components.

The scotch yoke actuator is designed to transfer a linear motion into a rotary motion without overstressing moving parts. A pressure cylinder with a piston can be used to close the valve. The piston pushes the yoke, which rotates the valve stem, and also compresses an opposing spring into its containment cylinder. The energy of the spring is released when the air is discharged from the air cylinder and the yoke is pushed the opposite direction, opening the valve. This type of actuator is routinely used in industry for rapid opening or closing of a valve.

4. Final Valve Selection and Testing

A high performance 8-inch butterfly valve (Durco Big Max BX series) was obtained from the Duriron Company; a scotch yoke actuator (Mod. 25006-SR, P2950-A1) was obtained from the Rotork Company. The actuation system was integrated and assembled by the Duriron Company. The system was tested before it was accepted to assure that the valve actuation time could be guaranteed.

The actuation system consisted of four parts. The primary components were the 8-inch high performance butterfly valve and the scotch yoke actuator. A limit switch/rotation position indicator unit, manufactured by Duriron, provided visible and microswitch electrical feedback to indicate valve position. The valve had to be fully closed in order for the firing system to operate properly. The actuator cylinder was controlled by a solenoid-operated spread bore poppet valve (Ross Mod. 2773B7001).

For acceptance testing at Duriron, a digital counter (Newport Mod. 6130) was wired to the solenoid and the rotation indicator terminal of the limit switch. This counter was used to measure the system time of the valve actuation unit. System time refers to the time necessary for all components of the unit to operate. The valve is only one component of the unit. After the system time was measured, the opening time of the valve was estimated by subtracting the known operating times of the other components. These times were obtained from the manufacturers of the components. The average opening time of the valve was estimated, after subtracting the component times from the system time, as an average of 20 ms, well within the required 50 ms opening time.

The actuation system was further tested after it was received at NMERI. A Nicolet Mod. 4090A digital oscilloscope was connected across Terminals 1 and 2 (Terminal 1 indicated the closed valve position, Terminal 2 the open valve position) of

the limit switch. An average valve-opening time of 29.24 ms was directly measured from 13 tests.

G. TRAJECTORY PROGRAM

1. Background

The original piston valve Pulsed-Gas Valve launcher system testing was done by Fire Research Corporation, which supplied a computer ranging program that could predict the expected range of a launcher delivery. The required inputs to this program included chamber pressure, elevation angle, wind speed and direction, and ambient pressure conditions. The program used trajectory physics, transient pressure change, and turbulence/drag equations. The content of the original program is explained along with the listing of the program in Reference 13.

This program was modified to run on GW Basic and was used to verify actual cannon shots in the field. The accuracy of the prediction was poor until changes for elevation, barometric pressure, and other constants were made. Predictions were then made that could estimate the range of many of the shots within about 2 to 3 percent; however, because of the nonideal conditions in the field, some predictions were inaccurate.

The program was proven as an approximation method of predicting the range of the cannon. The program could take inputs of wind speed and direction, elevation angle and charging pressure, projectile weight, and an initial range and then iterate until charging pressure was selected. This was only used as an initial positioning program. Final positioning could then be accomplished after test rounds were fired and adjustments made.

2. Program Modification

When the original piston valve chamber was removed from the pressure chamber, there were several parts of the prediction program that needed to be changed. The initial equations accounted for piston travel, pressure changes due to piston movement, and pressure vessel volume changes. Without the piston chamber, these equations could be modified to omit some transient characteristics. For instance, with the piston and recoil chamber removed, there was an increase in the available volume. The volume of air released from the chamber with the piston valve in place was 2.6 ft³. With the piston and piston chamber removed, the chamber volume was increased to 4.1 ft³. The volume also remained constant after valve opening.

As further testing is done in the field with the modified launcher system, changes to this program will be made to include information gained from test experience. A listing of this modified program is contained in Reference 15.

H. AIMING AND FIRING CONTROL SYSTEM

This section details the efforts to design, build, and test a system that will control the functions of an agent launcher used to extinguish fires from distances of up to 1200 feet. This launcher will have the capability of firing several canisters containing a fire-extinguishing agent in rapid succession.

1. System Requirements

The control system was designed giving safety top priority. The following control specifications were used. Azimuth of the platform on which the launcher rests will be required to move +/- 90 degrees from an established center reference. Elevation angle of the launcher will be required to rotate from 0 to 45 degrees above an established reference. Desired accuracy for these functions is 1 degree or better. The

control system would have to ensure that the controlled systems did not move beyond these limits.

The rapid-loader must be able to rotate as quickly as possible while being able to stop within ± 0.25 inch of an absolute reference on the circumference of a 36-inch diameter cylinder. It must be able to repeat this process six times.

Control of the actuator arm that aligns the chamber in the rapid-loader cylinder with the body of the launcher and also locks the rapid-loader in place must be automated, as well as the opening of the butterfly valve that causes the canister to be fired. The control system must also provide the ability to regulate air flow into and out of the pressure chamber that stores the compressed air necessary to fire a projectile. The system must be capable of monitoring pressure in the pressure chamber.

The correct firing position will be determined from a computer program that calculates elevation and azimuth, based on the range of the launcher from the fire, the weight of the projectiles, and possibly wind speed and direction. Currently, weight and range information will be entered manually. Further field testing of the launcher will help to determine the feasibility of automating the input of this information to a computer. The results of further field testing will also determine the need for input of wind speed/wind direction.

2. Control System Computer

To achieve control of the various functions of this mechanical system, several approaches were discussed. Figure 6 shows the basic control philosophy. In addition to meeting design criteria, other objectives were taken into consideration. One of the objectives was to use off-the-shelf components, in an effort to minimize procurement lag time and save money by avoiding the need for contracting with a vendor to build specialized control circuitry for the final model.

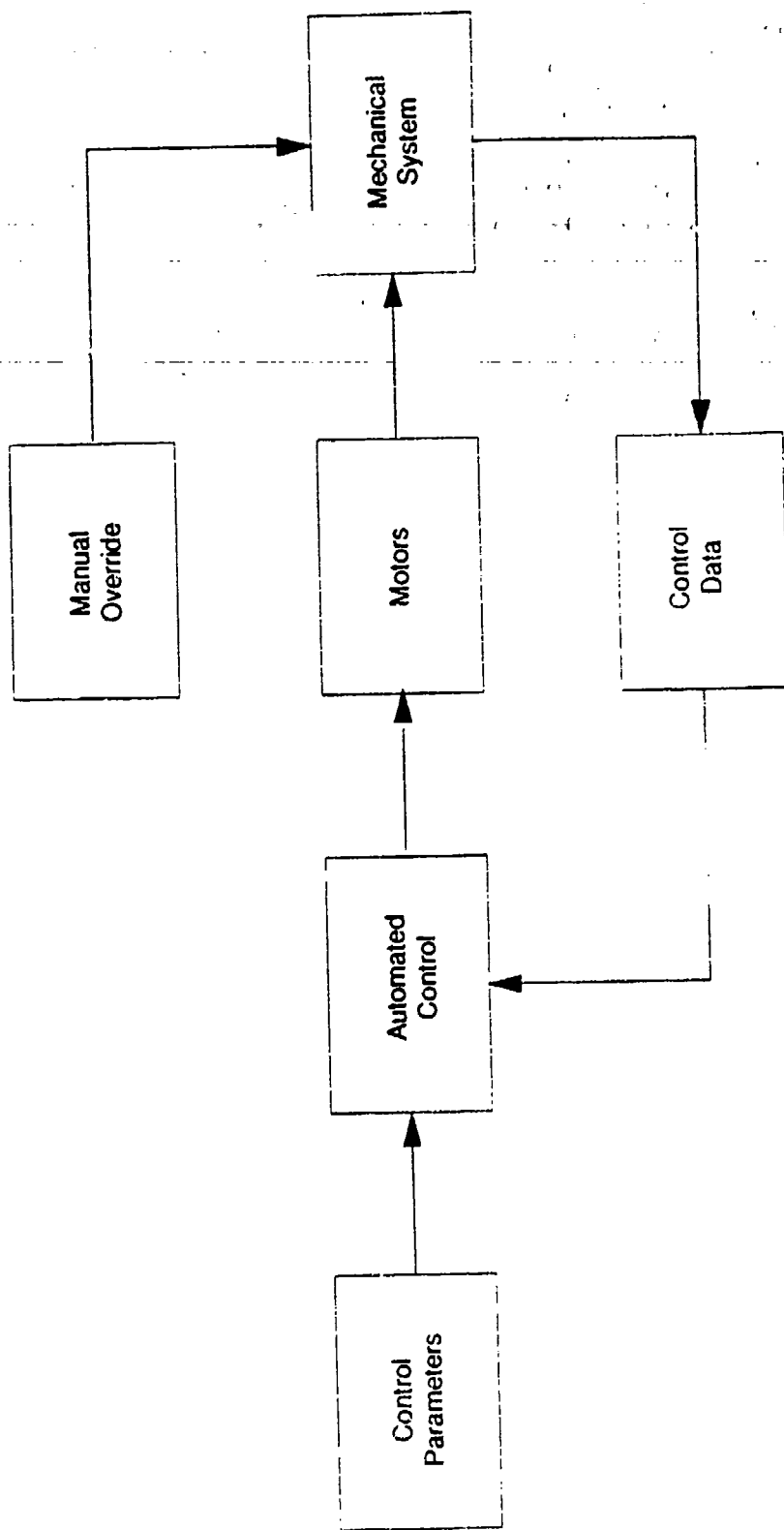


Figure 6. Control System Overview.

For development and testing of the control system and software, it was evident that the computer system would require more flexibility than the one used for later production cannons. This system should be able to interface readily with a wide variety of input/output devices such as voltmeters, computer-controlled relays, display devices, etc. It also should be compact for use in the field, although not necessarily battery-powered since 110 VAC would be required to operate other devices.

For the production version of the control system, a single-board computer running dedicated software (embedded system) is proposed. The main advantage of this type of system is reduced hardware cost. Since users would be unable to change the program, unforeseen hazards, such as rendering the system inoperable, would be avoided. Programs would be contained on an "erasable programmable read-only memory" (EPROM) chip on the computer board. Should operating changes become necessary, this chip would either have to be reprogrammed by removing it and sending it to some facility or simply replaced with another programmed chip.

Several computer systems were considered for this prototype, including an IBM PC (or clone) with control and data acquisition modules plugged into its backplane, individual servo-control systems connected to a computer through the RS-232 interface, and a system made by Hewlett-Packard. The Hewlett-Packard system fulfilled the objectives for both the developmental and operational modes. The device consists of a rack-mountable assembly, which accommodates several options including a voltmeter, computer-controlled switches (electronic and mechanical), and a stepper motor control card. This unit has a key pad on the front for manual entry of data and two display windows for giving prompts to the user, and displaying data. One of the reasons that this unit was chosen over similar units was the ability to download a BASIC program from a mass storage device (disk drive) then run it independently of a computer. Hence, using this system with a floppy disk drive will give the user a simple way to accommodate any program changes or refinements from the system developers by simply changing the disk instead of having to replace an EPROM chip. These make the unit similar in operation

to an embedded system since the user cannot modify the program. The unit can also be connected to a computer system using an IEEE488 interface providing the flexibility previously mentioned for development work.

One of the most difficult control problems was related to rotating the rapid-loader device the requirements for which alter during operation because of changes in the mass of the device as projectiles are fired. Normally, stepper or servo-motors would be used for this function. Use of these units, however, would increase the complexity of the overall control system and also increase cost significantly. Consequently, other methods were considered. In an effort to keep the system simple, a standard 1/2-hp electric motor operated with an electric brake or an air motor configured to run at different speeds was tested to determine suitability for rotating the rapid-loader.

Even though dedicated servo-systems are not being used, the control system will operate using servo-control techniques and principles; i.e., various sensors will be used in conjunction with the control of electric/air motors to feed back present status (position) data on the launcher. The computer will act on this information and cause the launcher to move to the calculated position.

The control system may also be required to perform other functions related to safety, such as actuating warning devices. The system design also includes manual electrical operation capability in the event of computer failure and manual mechanical parallel systems should a power loss occur. The system design has been completed to a point where the cannon will fire a six-round volley under computer control. Since the feedback signals are now completely wired with software written to accommodate them, all systems must function perfectly to fire the full volley. The computer has been programmed not to fire a projectile if the feedback signals indicate that a malfunction has occurred. The system will then advance the rapid loader, and if feedback signals indicate no errors, fire the projectile. The process repeats until the computer has fired

all six projectiles. This is achieved by running a program called "RAPIDF" on the HP 85 computer. The software also contains a user menu for operating individual subsystems for field testing.

3. Control System Description

A detailed description of the control system is now presented. Some of the devices being used have already been mentioned. Figure 7 shows the direction of control/data flow. As can be seen from the diagram, control of all functions is achieved from the Hewlett-Packard 3852A Data Acquisition/Control Unit. Currently this unit is being operated through a Hewlett-Packard 200 series computer. All operations discussed occur because of a software command or group of commands. A discussion of this software will be presented at the end of this section. It should be emphasized that this unit could be controlled by any computer equipped with the GPIB (IEEE488) interface. As indicated by the diagram, the computer will only be used in the development stages of this project. For the final application, the unit will be configured to download and run a basic program (stored on a floppy disk) when it is turned on. At present, we are only using approximately 40 percent of this unit's capabilities, making expansion relatively simple if other control functions, such as a stepper motor control, become necessary.

a. Rapid-Loader

To date, most of the control effort has been placed on optimizing the operating speed of the rapid-loader. The parts of the rapid-loader that require or are used for control are the yoke actuator, position feedback sensors, and the drive motor/brake. Two methods of rotating this device were investigated. Figures 7 and 8 show the flow of control and feedback signals.

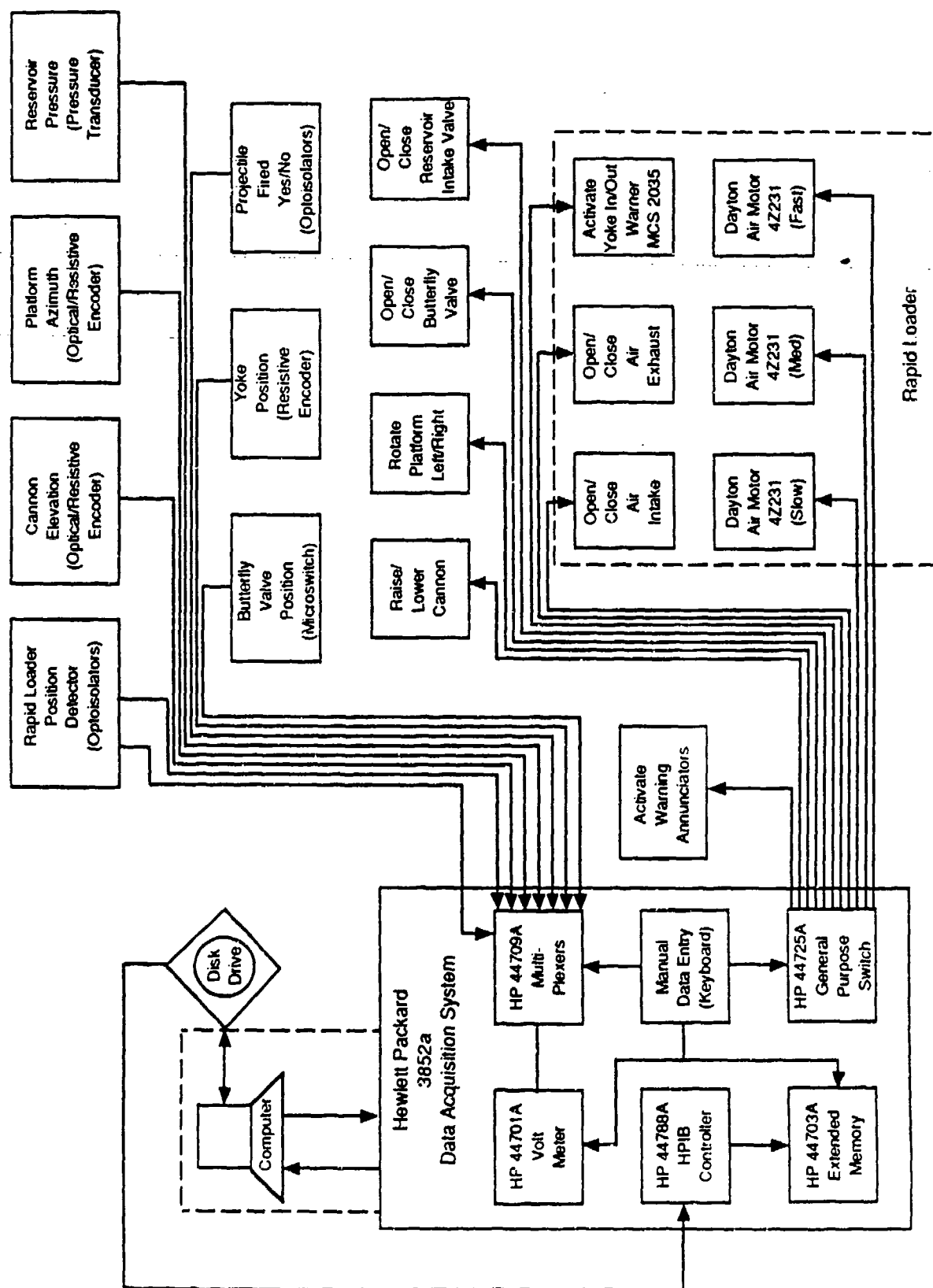


Figure 7. Control System Flow Diagram.

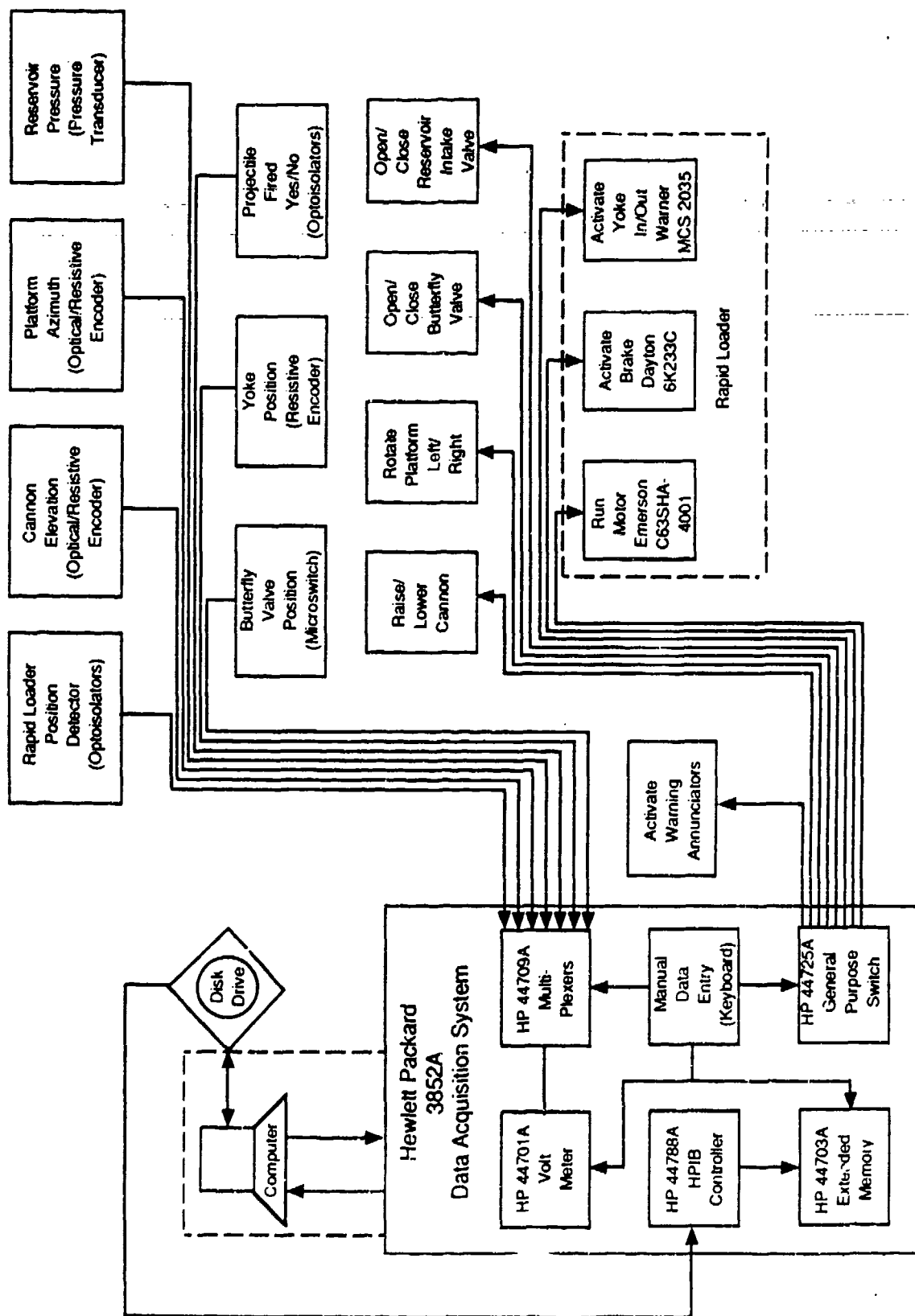


Figure 8. Alternate Control System Flow Diagram.

Since the operation of the position feedback circuit is common to both methods, its operation is discussed first. The signal that senses position is provided by an optical system consisting of a metal disk with slits cut in it every 60 degrees as shown in Figure 9. Depending on which method is used, one or two infrared optoisolator pairs, an infrared Light Emitting Diode (LED) and a infrared sensing phototransistor, are placed across the disk. When a slit allows light to shine from the LED to the phototransistor, the resistance of the latter decreases. This resistance change is converted to a voltage change by an electronic device called an op(erational) amp. The 0V or 5V output of this device is coupled into the HP 44701A voltmeter through an electronic (Field Effect Transistor [FET]) switch on the HP 44709A module. The use of this control signal(s) will depend on which method is being used to rotate the rapid-loader.

One method tested used an electric motor (Emerson C63SHA-4001) to rotate the cylinder through a gear reducer. This rotation is stopped by an electric brake (Dayton 6K233C) attached to the front of the motor's driveshaft. The motor is activated by closing a low voltage relay on the HP 44725A module, which applies a voltage to a solid state relay (Potter & Brumfield 3A968), which then switches 110 VAC to the motor and causes it to run. This type of control hardware (low-voltage relay, solid state relay) is used for virtually every control function that requires 110 VAC for operation. When the voltage change from the optoisolator is sensed, the relay that caused voltage to be applied to the motor is opened. The open relay would normally allow the motor to freewheel a certain amount, the extent of which depends on the amount of load in the rapid-loader and other factors. For this reason, simply removing voltage from the motor was not sufficient to guarantee a repetitive and accurate stopping position. Consequently, at the same time as the motor control relay is opened, the brake is also applied by using another low voltage relay in the module that also controls a solid state relay. This combination of an electric motor with a brake allows us to control the position of the rapid-loader within the ± 0.25 -inch tolerance.

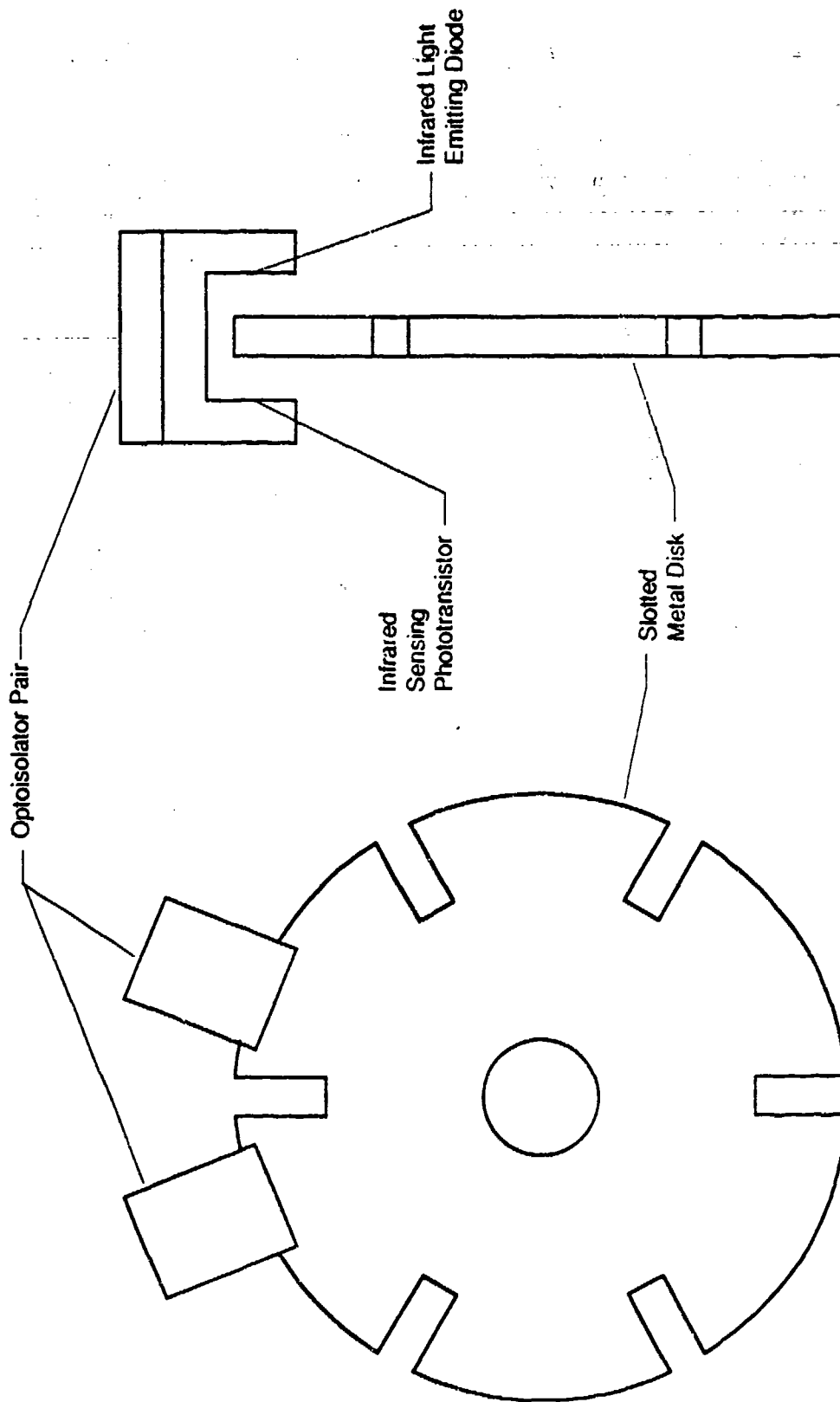


Figure 9. Optoisolator Feedback Sensing System.

Another method tested used an air motor (Dayton 4Z231) for cylinder rotation. The air motor was connected to drive the rapid-loader through the same gear reducer. Unlike the AC electrical motor, which can only operate at a single speed and requires a separate braking system, the air motor can be set up to operate at several different speeds. To achieve this capability requires five control parameters: one regulates the opening or closing of a valve that allows air to flow into the motor from a compressor; a second opens up the exhaust port of the motor into a parallel matrix of three automated valves, which are the remaining three control parameters, and a fixed, adjustable valve. The three automated valves also have a fixed valve in series with each one and the air motor exhaust port. These valves control the exhaust air flow rate allowing the motor to be operated at different speeds. Opening and closing of the three automated valves in the matrix requires the three remaining control parameters. These five valves are also controlled by closing five relays in the HP 44725A that applies voltages to five solid state relays. These solid state relays in turn control five solenoid operated valves (Automatic Switch Company [ASCO] 8210D2) that perform the functions previously listed.

One characteristic of air motors is that horsepower is directly proportional to the pressure of the air applied to it. Torque can easily be manually controlled and varied for development purposes using a standard air regulator connected between the air intake motor and the air source. This motor has been operated at pressures ranging from 60 lb/in.² to 100 lb/in.². Another characteristic of the air motor is that by closing the air intake and exhaust valves the air motor will function as a compressor. The energy derived from the inertia of the rotating system after the valves have been closed is then transferred back to the air motor via the gear reduction system. This pressure creates a braking action on the rapid-loader since the energy is being used to try to compress a very small volume of residual air in the motor causing the rapid-loader to stop almost instantaneously. By opening and closing various combinations of valves, several different operating speeds and braking can be accomplished.

The operating sequence for this method involves closing the proper combination of relays that will cause the air motor to operate in the high-speed mode. This mode requires a second optoisolator pair in front of the one required to stop the motor. The signal from this pair causes the motor speed to decrease until it is running at the lowest speed, minimizing the energy in the rapid-loader due to inertia. When the second signal is received, all control valves close causing the system to brake and allowing it to meet the ± 0.25 -inch specification.

One of the problems noted during the testing was the heating of the electric brake used with the electric motor. This heat accumulation could force a cooling time specification for the final version of the device, which may exceed the amount of time it takes to either reload or replace the rapid-loader assembly. Consequently, the amount of a fire retardant chemical that could be delivered to a fire during a specified time, would be further limited. The ability to operate the air motor at different speeds makes this system design closely mimic a true servo-system at a fraction of the cost. While electric motors normally have some protection to prevent a fire hazard if the motor is mechanically stalled, air motors do not have this problem. For these reasons, the air motor was chosen for the drive system. Some problems with the positioning of the rapid loader manifested themselves during the limited field testing of the prototype. The main problem was a shifting in the stopping position of the rapid loader assembly. A shift in the position of the metal disk used to sense the stopping position would cause this problem. In checking the disk position, there was no indication that the disk had slipped. The problem may have been caused by a change in the time that it took for some other associated operation to be completed. The problem was most severe at low ambient temperatures, and it was hypothesized that the solenoids controlling the air supply to the air motor may have been taking longer to function. It may also have been caused by a shift in the optoisolator sensor parameters because of the low temperatures (ca. $0^{\circ}\text{C}/32^{\circ}\text{F}$) evident in previous testing. This system had functioned well when ambient testing temperatures were between 20 and 27°C (68 and 81°F). Further investigation is required to isolate the cause or causes of this problem.

During field testing, it was noted that the drive gear would slip in its mount, increasing the play in the rapid loader due to loose-fitting gears and also affecting the stopping position of the rapid loader. The problem was exacerbated by the high starting torque provided by the air motor. To minimize these effects, and prolong the useful life of the mechanism, the software was changed to operate the rapid loader at reduced speed.

The actuator (Warner Electrak 100) that will be used to align and lock the rapid load chambers in place has its own basic built-in control system (Warner MCS 2035). The 24V power supply that is a part of the Warner system will be used to provide power for the rest of the launcher control system. The Warner system has an internal connection block for external control and external position monitoring. This device is activated using two low voltage relays located on the HP 44725A module. One causes the unit to retract, the other causes the unit to extend. The Warner control unit also provides connections to a potentiometer so that the position of the yoke can be monitored. This potentiometer will be monitored by connecting it to the HP 44701A voltmeter using an electronic switch in the HP 44709A module. The alignment pin controller was mounted inside a 12- by 12- by 4-inch weather-proof electrical box, and wiring exited the box through weatherproof connectors. The feedback wiring was connected to the computerized control system, which allowed it to monitor the status of the alignment pins when powered. Software was written to check the status of the alignment pins before trying to rotate the rapid loader. The software also monitors the progress of the pins as they align the rapid loader. If the pin assembly starts to jam, the computer stops the process.

Originally it was intended to tap the 24Vdc supply on the actuator assembly to provide control power, but, instead, a separate control power supply was built on the feedback/control power distribution board.

b. Firing Valve Control

To fire the launcher, air must be released quickly from a reservoir into the launcher itself. This action is accomplished using a butterfly valve (Durco Big Max series with actuator Rotork Model 25006-SR, P2950 H-1) that is also operated by air pressure. In addition, a 110 VAC solenoid valve is used to control air flow from a compressor into the reservoir. An electronic pressure gage is used to monitor the pressure in the reservoir. A mechanical pressure gage will also be connected to monitor reservoir pressure during manual operation or in the event that the computer system fails.

The butterfly valve actuator that allows compressed air from the reservoir to pass into the launcher to fire the projectile uses a 110 VAC solenoid for operation. A single low voltage relay in the HP 44725A along with a solid-state relay will control this device. Two microswitches physically attached to the valve shaft will provide the status of the valve, open or closed. These will be connected to the HP 44701A voltmeter using the electronic switch in the HP 44709A module or wired in series with the control circuitry.

Pressure inside the reservoir is monitored by connecting a pressure transducer to the reservoir providing feedback to the control system via the HP 44701A voltmeter using an electronic switch in the HP 44709A module for connection. The gage was calibrated while connected to this system to eliminate any errors that may be caused by the internal resistance of the electronic switch. A low voltage relay, solid-state relay combination will be used to control the 110 VAC solenoid that allows air into the reservoir from the compressor.

The butterfly valve that causes the projectile to be fired was connected to the computerized control system. Software was written to check the status of the two microswitches representing the valve "open" and "closed" status. Problems

with these switches caused the launcher not to fire a volley during a test series. The shaft that activates the microswitches has a set screw that connects it to the shaft that activates the butterfly valve. This screw had become loose while the launcher was being transported to the test range. Resetting the shaft corrected the problem.

c. Platform Azimuth and Elevation Angle Controls

To position the launcher for firing, it is mounted on a platform that rotates to provide azimuth angle control. A linear actuator is attached to the launcher to adjust elevation angle. The vertical motor associated with the linear actuator and the azimuth drive motors were connected to the computerized control system. Originally it was desired to use electronic switching relays exclusively for 110 Vac applications. Currently, one electric and one mechanical relay are used to control each motor. In addition, the elevation motor has an electric brake attached.

Feedback devices were installed. The elevation feedback employs a Bourn linear potentiometer mounted parallel to the linear actuator. The length of the wiper rod changes with changes in elevation. For azimuth, a 10-turn potentiometer was fitted with a 4-inch round wheel with foam. This device is mounted so that the foam-covered wheel pushes against the platform, and as the platform turns, the wheel also rotates.

The elevation system was calibrated and fitted to software to allow the user to specify the desired angle of elevation. The computer then causes the launcher to be elevated to this angle. Tests have shown the accuracy to be ± 10 minutes, including the error caused through the calibration device.

The software for the azimuth positioning was written, but because of problems with slippage of the feedback system, it was neither calibrated nor verified. Wiring from the motors to the limit switches was completed. Limit switches are not

physically mounted to the launcher and are currently being bypassed to allow for azimuth and elevation positioning.

d. Firing Verification

To assure that the projectile has exited the launcher, it is planned to mount a phototransistor with a light source to the end of the launcher barrel. The output of this device will be monitored through its connection to the voltmeter and an electronic switch. Originally it had been planned to place sensors at the front of the launcher to verify that the projectile had exited the barrel. This was given a low priority as there had never been an instance of jamming within the barrel. This system may be implemented in the future as a feature to provide redundancy.

e. Other Controls

For reasons of safety, the control system selected is capable of operating various types of annunciators and warning devices directly either by using a low voltage relay on the HP 44709A module or by adding a solid state-relay for control of high voltage (110 VAC) devices.

Manual operational and override controls will also be provided. All functions controlled by the computer will also be able to be operated manually. Intermittent pushbutton switches will be wired in parallel with the low voltage relays. Since position feedback circuits rely on computer operation, they will not be used in the manual operation.

To ensure that all mechanical devices do not travel beyond specified limits, switches will be placed in series with the controlling relays and activated for both manual and automated control. These limit switches will stop the motion of the device if it moves to its set range.

Provision has been made for a 110 VAC alarm or siren on channel number 208. To implement this, a device would be connected to the 208 terminals in the high voltage power distribution box, and software modified to activate the device at appropriate times. All other wiring is in place.

f. Manual Operation

A manual control box has been constructed that allows manual operation of the prototype functions. This box can be connected either directly to the launcher, or to connectors attached to the terminal strip board; the latter allows manual control in tandem with computer control. The box contains switches that are wired in parallel with the computer controlled switches. Light-Emitting Diode indicators are also provided, including two that indicate the status of the two optoisolators.

The box is equipped with a master power switch. If the power switch is turned off, most of the other controls will not function. The pin actuators will continue to operate from the remote control box because they do not rely on system control power to function. The box has switches that allow the operator to select the speed of operation of the air motor. If these switches are inadvertently left in the "on" position, they will also affect the speed of rotation of the rapid loader under computer control. This situation can be improved by using special optoisolator switches. For testing purposes, the box was used primarily to position the launcher or operate the alignment pins. It was possible, but very difficult, to align the rapid loader properly with the barrel. The LED indicator for the second optoisolator will not be lit when the rapid loader is in correct alignment. Another improvement to the manual control box would be to add a double-pole locking switch that could terminate power to all switches, including the pin actuator switch.

4. Computer Software

The software currently being used for development purposes is described in Reference 15. The software, written in HP BASIC, has been developed primarily as a series of increasingly complex subroutines and subprograms. Some of these routines and programs run in the host computer while others are run directly by the HP 3852A data acquisition system (DA/L). This approach was taken so that the desired control function could be easily incorporated in the final software version by including the correct subroutine or subprogram. It should be noted that in the description of this software, certain statements that appear in the listing are not discussed. These statements have an exclamation mark as the first character after the line number. This notation in BASIC means that it is a comment and not an executable statement, even though the form may otherwise appear identical to an execution statement. These statements, when not actually used for comments, represent ideas and methods that may be necessary for controlling the rapid-loader when it has been installed in the prototype as opposed to operating the rapid-loader in the laboratory test fixture.

a. Overview of Software Operation

A general overview of the software and how it interacts with the control system is presented by first describing the GPIB (IEEE488) bus interface, then examining the setup operations. The main menu and control subroutines are discussed next.

The GPIB interface is a standard operating configuration that was adopted by the Institute of Electrical and Electronic Engineers (IEEE) in 1974. It has 16 discrete interconnect lines between devices, 8 data lines (BYTE), and 8 control lines. Since it is a parallel system, 14 individual devices can be connected to it in any order and several busses can be operated with a single computer. The standard operating rate is 19.2K bytes per second; however, using special configuration techniques, baud rates of

190K bytes per second can be achieved. Each device on the bus interface has an address as well as the bus itself. One device connected to the bus, usually the host computer, must act as the system controller.

The first five lines of code (10 through 35) initialize and define operating parameters in the HP DA/L. The output statement is an I/O command. The number 709 is the address of the bus (7) and the HP DA/L (09). The first command, "RST", resets the HP DA/L. "MSI" defines the address of the disk drive and the bus to which it is connected. The latter is controlled by the HP DA/L. Since no disk drive is currently connected, no address is given. The comment statement in the coding shows the format of this statement "MSI:100,0" for a dual floppy disk drive connected to the DA's internal GPIB bus control card. (Note: This may be somewhat confusing for the DA itself is controlled through a different GPIB bus as shown in the flow diagrams in Figures 7 and 8.) Again the bus address (1) and the disk address (00) are given. The "0" after the comma is a secondary address that refers to the specific drive being used in the multiple drive unit. Since some functions require simultaneous operation (within the limits of software execution time), the "SERIAL" function must be turned off. Because software commands use electronic devices they execute much faster than do hardware functions based on mechanical devices. The "SERIAL OFF" statement removes the settling time built into software. This settling time would normally wait until the hardware had completed a command, i.e., open/close a relay, before the next command could be executed.

The next group of statements (40 through 186) defines the variables used in the program and their type. For example, "VOLTS" and "THRESH" are declared as real variables having decimal points and requiring the use of precision math functions. The variables "I", "J", "INP_ENA", "EXH_ENA", "SPD_MAX", "SPD_MED", "SPD_LOW", "PIN_EXT", "PIN_RET", "FET_C0", "FET_C1", "FET_ISO", "FET_BA", "BRAKE", "MOTOR", and "VALVE" are all integers and do not require precision logic for manipulation. In addition to being good programming practice, this group is required

to maximize operating execution time since integer numbers are processed more quickly than real numbers.

These variables are defined by the next series of statements (190 through 300). Since "THRESH" is a variable used in the subroutine that determines whether a slit has been detected, it is assigned an initial value of two (volts). The "200" series numbers refer to relays contained on the HP 44725A module since it has been physically installed in Slot 2 of the DA unit. The "500" series numbers identify electronic "switches" that are on the HP 709A module, installed in Slot 5. One important difference between these modules is that only two switches in the HP 709A may be closed at one time, whereas all 16 switches on the HP 725A module may be closed simultaneously. Consequently, operations involving the HP 709A must be done serially. Another difference is that the HP 44725A module provides for using either a direct connection to the voltmeter or the internal bus to connect these switches to the voltmeter. Since we are using the internal bus for connection to the voltmeter, software statements that close these switches will close two additional switches in addition to the switch being used for control. These two additional switches provide an internal path between the measurement quantity being monitored and the internal bus.

b. Main Program Operation

Statements 320 through 1210 send information defining subroutines to the HP DA/L unit. These subroutines will be discussed shortly. Program execution actually begins at line 1225, "CALL Help". This subroutine displays a menu of different tasks that the user can select, such as rotating the cylinder using either the air or electric motors, operating the linear actuator or the butterfly valve, etc. In some cases it is not desirable to have certain routines available to general users. Therefore, certain subroutines are made available, but their functions are not displayed. Only the system developer will normally be able to use them. One example is the "SUB Ramp" that will

be described later. Others, such as the "cat" function, are aids for system development and for general users.

The user selects the proper function by entering up to three letters, which are displayed as the first characters of the line containing the routine description. These data are entered into the string variable A\$. The computer then compares this value to fixed values by using IF...THEN logic. If a match is found, that subroutine is executed; if not, e.g., the user makes a typo or other error when entering data, the system continues to display the menu and "ENTER SELECTION ... ?". This loop is created using a WHILE statement and will continue as long as the letter "Q" ("WHILE A\$ < "Q" ") is not entered by the user. The loop and the program will terminate if the user enters the letter "Q" for quit.

c. Subroutine Functions

The subroutines providing control are now discussed. Some are very basic and control only a single function or relay. Extensive subroutines are then developed using the basic ones. Subroutines that operate in the HP DA/L are denoted by a "SUB ..." statement preceded by an OUTPUT statement as the first statement in the routine. The first 12 subroutines run in the DA unit. Subroutines that operate in the computer have a "SUB..." as the first statement in the subroutines. The SUBEND statement denotes the end of a subroutine.

The subroutine that starts at line 320 and ends at line 400 ("SET_DCV") defines the operating parameters for the HP 701A voltmeter. The USE statement defines the number of the slot (6) where the voltmeter has been installed. "CONF DCV" and "RANGE 10" configure the voltmeter for direct current voltage measurements with a range of up to 10 VDC. "TRIG AUTO" enables the internal trigger circuits of the voltmeter to take readings at a preset rate. The "NPLC .0005" defines the amount of integration time per measurement, which is voltage in this case.

Integration time affects measurement speed, accuracy, maximum number of digits of resolution, and normal mode rejection (ability to reject the influence of the power line frequency on the measurement). $\text{Time} = 20 \text{ msec} \times .0005 = 10 \text{ microsecs}$. For more information, see "Programming the Voltmeter", Sections 4 through 18 of the "HP 3852A Data Acquisition/Control Unit, Plug-in Accessories Configuration and Programming Manuals." The "AZERO OFF" command turns the auto zero option off in the voltmeter, which is done to decrease the throughput time for voltmeter operations. The last command in this subroutine resets (opens the switches) the HP 44709A module, which is installed in Slot 5.

The next subroutine ("DISP_DCV") (lines 420 through 480) displays 2000 readings of the voltmeter and is accomplished using a standard FOR-NEXT loop. The statement "CHREAD 600 INTO VOLTS" transfers the contents of the voltmeter buffer into the variable "VOLTS", which is then displayed on the front panel of the DA due to the "DISP VOLTS" command. The DA is then programmed to "BEEP" upon completion of this routine.

The subroutine "OP_WAIT" (lines 500 through 570) is a timing routine used to determine when an optoisolator pair detects a slit in the metal disk. It also provides a "time-out" counter, which will force this routine to complete in a specified amount of time if a slit is not detected because of an electrical or mechanical fault. A loop is created using the WHILE statement. The voltage in the voltmeter (from the optoisolator's operational amplifier) is read. A loop counter (I) is established and initialized to a value of 1. The value of the voltmeter is compared to the preset voltage level stored in the variable "THRESH"; the counter (I) is compared to the number 2000. If both of these values are less than the preset values, the loop will continue by reading the voltmeter and incrementing the counter. These values are again compared to the preset values. When either parameter is exceeded, the loop and the subroutine end.

"SUB ELECMR" (lines 720 through 910) rotates the rapid-loader through a 60-degree arc (one position) using an electric motor. Even though this is an alternate method, it is discussed first for purposes of simplicity. The voltmeter is first initialized ("CALL SET_DCV") and the second optoisolator pair connected to it ("CLOSE FET_C1,FET_BA,FET_ISO"). C1 is the actual switch used for control, while the BACKplane and ISOLation switches provide a connection to the voltmeter through the internal bus. The electric motor is then started ("CLOSE EMOTOR"). A time period of 250 ms is introduced ("WAIT .25") to allow the rapid-loader to move before monitoring the feedback system ("CALL OP_WAIT"), otherwise the feedback system would shut the motor off immediately since the sensors would be resting on a slit. When the next slit is detected, the electric motor is turned off ("OPEN EMOTOR") and the brake is applied ("CLOSE BRAKE"). Since the brake is not designed for continuous operation, it is only allowed to operate long enough to guarantee that the rapid-load has stopped moving, 10 ms ("WAIT .01"), before it is turned off ("OPEN BRAKE").

The subroutine "A_MOT" (lines 590 through 700) operates the rapid-loader in a similar fashion but using an air motor. This routine first sets up the voltmeter using the "SET_DCV" subroutine. The next command, "CLOSE FET_C0, FET_BA, FET_ISO" connects the first optoisolator position detector on the rapid-loader to the voltmeter using the electronic switches in the HP 44725A. Three valves connected to the exhaust port are opened by closing three relays in the HP 44709A ("CLOSE EXH_ENA, SPD_LOW, SPD_MED"). A small waiting period is introduced, 50-ms ("WAIT .05"), before air is allowed into the motor. This is done to eliminate a "jerky" start. After air flow is started ("CLOSE INP_ENA") and another 50-ms ("WAIT .05") waiting period ends, the last automated valve in the exhaust control system is opened ("CLOSE SPD_MAX") allowing the motor to run at full speed. The motor is only allowed to operate at maximum speed for 150 ms ("WAIT .150") before the speed is reduced ("OPEN SPD_MAX"). This reduction is necessary to obtain the fastest throughput time while allowing time for the feedback controls to operate. The "OP_WAIT" subroutine is now used to detect a slit in the metal disk. When a slit is

detected, the second optoisolator detector is connected to the voltmeter ("CLOSE FET_C1, FET_BA, FET_ISO" [closes control relay, C1, and the two relays that complete the connection to the DA's internal bus, BACKplane and ISolation]), and one of the automated exhaust valves is closed ("OPEN SPD_MED"). The computer then waits 3 ms ("WAIT .003) and closes the last automated exhaust valve ("OPEN SPD_LOW"). The air motor is now operating at its lowest speed. The "OP_WAIT" subroutine is again used to provide timing coordination from the second optoisolator detector. When this device detects a slit in the metal position disk, the exhaust port and air intake valves are closed ("OPEN EXH_ENA, INP_ENA"), which causes the air motor to brake and stop.

To position the rapid-loader manually using either the air or electric motor and the computer keyboard with no feedback, subroutines were developed that cause these devices to operate for a short period of time (toggle). "SUB ELETOG", lines 702 through 709, provides this capability for the electric motor. The motor is turned on ("CLOSE EMOTOR") for 100 ms ("WAIT .10"). The motor is then turned off ("OPEN EMOTOR") and the brake applied ("CLOSE BRAKE"). The brake is on for 10 ms ("WAIT .01") and then turned off ("OPEN BRAKE"). Similar operation for the air motor is provided in the subroutine "SUB AMTOG", lines 1010 through 1090. The exhaust port is first opened ("CLOSE EXH_ENA"). After a waiting period of 100 ms ("WAIT .1"), which allows the exhaust port to open, the air intake valve is cycled by first ensuring that it is closed ("OPEN INT_ENA") then waiting 100 ms for this operation to complete ("WAIT .1"). Finally, the motor is allowed to run by opening the air intake port ("CLOSE INP_ENA"). After 300 ms ("WAIT .3") the motor is stopped by closing the exhaust port ("open EXH_ENA").

Two subroutines are used to control the position of the linear actuator that will be used to operate the chamber alignment yoke. "SUB PIN_IN" (lines 1110 through 1150) causes the actuator arm to retract ("CLOSE PIN_RET"), waits 1.2 seconds for this operation to complete, then stops the retraction ("OPEN PIN_RET"). "SUB PIN_OUT", lines 1170 through 1210, does just the opposite by causing the actuator

arm to extend ("CLOSE PIN_EXT"), waits 1.2 seconds for this operation to complete, then stops ("OPEN PIN_EXT").

Three subroutines are used to control the butterfly valve firing, which causes a projectile to be fired. "SUB CVALVE" (lines 1158 through 1160) closes ("CLOSE VALVE") the butterfly valve. "SUB OVALVE" (lines 1162 through 1164) opens ("OPEN VALVE") this valve. "SUB VALVER" (lines 1152 through 1155) cycles the butterfly valve once by first closing it ("CLOSE VALVE"), waiting 2 seconds ("WAIT 2.0"), then opening the valve ("OPEN VALVE").

d. Host Computer Subroutines

The last topic is a discussion of subroutines specific to the host computer. The "Help" subroutine, which has been previously discussed in the explanation of the menu system, is an example of this type. "SUB Ramp" (lines 1550 through 1610) is a developmental subroutine that brings the air motor up to its maximum operating speed for the required air pressure in three steps and cycles it down to its slowest speed in four steps. The air motor will run at current speed until the user pushes the "enter" key. Then, the motor will increase or decrease speed, or the subroutine will end, depending on which part of the subroutine it is currently executing. To accomplish this, the air input valve is closed ("OPEN INP_ENA") and the exhaust enable valve and low speed valves are opened ("CLOSE EXH_ENA, SPD_LOW). The system waits 50 ms ("WAIT .05) for these commands to complete. The air input valve is now opened ("CLOSE INP_ENA") running the motor at its lowest speed. It continues to operate at this speed until the user presses the "enter" key ("INPUT A\$"), which forces the computer to wait for some kind of keyboard data entry followed by the "enter" key. The medium and high speed valves are opened in the same manner ("CLOSE SPD_MED," "INPUT A\$," "CLOSE SPD_MAX," "INPUT A\$"). The decrease speed cycle is now initiated when the user depresses the "enter" key by successively opening the speed valves. The time between speed changes is controlled by the user ("OPEN

SPD_MAX", "INPUT A\$", "OPEN SPD_MED", "INPUT A\$", "OPEN SPD_LOW", "INPUT A\$"). The air motor is now running at its slowest speed. When the user presses the "enter" key, the exhaust valve is closed ("OPEN EXH_ENA"), the air motor stops, and the subroutine is complete.

Subroutine "SUB catalog" (lines 1850 through 1920) provides a listing of the contents of a floppy disk controlled by the HP DA/C and allows the listing to be displayed on the host computer's monitor. The routine first sends the catalog command to the HP DA/C ("OUTPUT 709;"CAT"") which causes it to read the directory of the floppy disk controlled by it. A blank line is created ("PRINT"") on the host's monitor. The directory is read into the host computer ("ENTER 709;A\$") and displayed ("PRINT A\$") on a line by line basis. This is accomplished by another loop format, ("REPEAT", "UNTIL"), which repeats the process until no further data are detected ("UNTIL A\$ < >").

The next two subroutines cause the rapid-loader mechanisms to go through their operational sequence six times using either the air motor, "SUB Full_Cycle" (lines 1940 through 1978) or the electric motor, "SUB Full_Cycle" (lines 3000 through 3060). Both routines use FOR-NEXT loops to create six cycles ("FOR J=1 to 6 ... NEXT J"). These routines also use other subroutines that have been downloaded into the HP DA/C and have been explained in earlier sections of this report. The rapid-loader position lock actuator arm is first retracted ("OUTPUT 709;"CAL PIN_OUT") at the start of each cycle. The rapid-loader is then rotated 60 degrees using either the air motor ("OUTPUT 709;"CALL A_MOT") or the electric motor ("OUTPUT 709;"CALL ELECMR"). The position lock actuator arm is then engaged ("OUTPUT 709;"CALL VALVER"), which causes a projectile to be fired. This completes one cycle. The counter J is automatically incremented, and the process repeats until six cycles have been completed.

The final subroutine in the software listing moves the rapid-loader 60 degrees using the electric motor ("SUB Sing_eycle") by calling the "ELECMR" subroutine, which has been downloaded into the HP DA/C ("OUTPUT 709;"CALL ELECMR").

Additional software using these same programming methods and techniques were developed to automate the remaining control functions shown on Figure 7.

e. Wiring Methods

Reference 15 includes details of the initial wiring philosophy used to implement the control functions. Shielded 4-conductor (Belden 8723) and 6-conductor (Belden 8777) cables were used to connect control relays to the HP DA/C. For the connection of 110 VAC devices, standard #18 zip cord was used for solenoid valves and three-conductor #16 cables were used to wire the electric motors used to rotate the elevation angle and mounting platform.

For use in the field, a single 50-conductor cable similar to the type used for multiple telephone circuits connects control signals between the HP DA/C and the agent launcher. Thirty-seven-pin male and female DIP type connectors and 25-pin male and female DIP type connectors are attached to the 50-conductor cable to allow for the control system to be disconnected from the agent launcher device. The current cable is over 50 feet long and will allow the operation of the launcher from this distance if required for safety reasons during initial testing of the prototype. Eventually, the HP DA/C unit will be mounted to the agent launcher.

The original 110 VAC control switches were fabricated inhouse using a device called a TRIAC. This was done to facilitate testing as the supplier of the Potter Brumfield relays quoted a long delivery time.

For mounting of the Potter Brumfield control relays an 11- by 11- by 0.25-inch clear Lexan panel was used. Since most of the control functions involve the use of 110 VAC to operate the various electrical devices associated with the agent launcher, care has been taken to isolate the 24 control lines from the 110 VAC. The relays were mounted with the low voltage (24 VDC) connection terminals facing toward the outside of the panel. The 110 VAC connection terminals face the inside of the panel, which provides maximum separation of these voltages. Two terminal strips having provisions for 20 connections were mounted to the panel. Short jumper wires from the 110 VAC terminals of the Potter Brumfield relays to these terminal strips were fabricated using white, black, and green #16 wire. Standard wiring conventions were followed with black used as the "hot" connection, white was used for "neutral," and green for "ground" connections. Two standard 16-gage, 3-conductor power cables with a standard 110 VAC grounded plug on one end were used to provide power input. The bare wires on the other end were stripped and had spade lugs crimped to them to facilitate connection to the terminal strip. Spade lugs were also crimped onto the ends of the jumpers for the same reason. Each circuit will provide power for seven Potter Brumfield control relays. Power will be distributed so that the total current required by each circuit does not exceed 15 amps. The 110 VAC connections to the devices and power input wiring are not shown.

This panel was mounted in a 12- by 12- by 4-inch weather-proof electrical box with a hinged cover. Wires will exit this box from the bottom using connectors that form a seal around the control and 110 VAC cables. Another panel and box combination will house the circuitry primarily associated with the feedback signals. This box will be mounted next to the control circuit box. Twenty-two unused wires from the 50-conductor cable will be fed into the feedback box from the control box via conduit connecting the two boxes. These will be used to return feedback signals to the HP DA/C. The HP DA/C will have a metal terminal strip board mounted to the top of it for easy connection of control wires and monitoring of control and feedback signals during the development testing.

The Warner Electric linear actuator controller, model MCS-2035 has provisions for connection of the linear actuator, as well as for remote control capabilities using signals from the HP DA/C. The 24 VDC supply of this unit will be tapped to provide the 24 VDC control voltage required by the system, thereby eliminating the need for an additional power supply.

The circuit utilizing an op amp was built initially on a prototype board. This circuit was moved to a printed circuit board, which was mounted to the Lexan in the feedback control box.

5. Ballistic Software Modification

The purpose of the original ballistics program developed by the Fire Research Corporation was to use the angle of elevation of the barrel, the chamber firing pressure, and other variables to predict the distance a projectile would travel. This program based the exit velocity of the projectile on changes in pressure and volume as the projectile traveled along the length of the barrel, and as the firing piston moved in its track. Since the new launcher uses a butterfly valve rather than a piston, this software had to be rewritten. The rewriting of the program was done in the BASIC computer language with new exit velocity equations. The equations used to calculate total distance traveled by the projectile are the same ones as those in the original program, except for variable name changes.

The program was reworked to take advantage of the BASIC programming features of the Hewlett Packard 300 series computer and to provide a self-documenting program. Variable names were changed to make them descriptive of what they represent, and comment statements were used liberally throughout the program. They were also chosen to conform with the requirements of the 3852 DA/L so that the program could be transported as a subroutine into the launcher's control software. The equations that calculate exit velocity will have to be changed so that pressure and

elevation are calculated from a known range specification. Because of the iterative process of this software, we had hoped to develop our own equations based on field testing. Tables would be generated for different conditions greatly reducing the calculation time required to run the software. Similarly, because of time and fund limitations, the total reworking of the software could not be completed.

A first approach used in verifying the accuracy of this software was to ignore the change in volume as the butterfly opened, i.e., assume that it opened instantaneously. The second was to disregard the effects of friction between the sabot and the cylinder walls. This was to allow for comparison of experimental versus calculated distances for known pressures and elevations with a minimum number of effects caused by other variables such as wind shear, barometric pressure, etc. Print statements were added to the program, and the program was given a loop structure so that the effects of chamber pressure varying between 39 to 150 lb/in.² absolute could be determined. The printout reflects total chamber pressure, which is atmospheric pressure (12.2 lb/in.²) plus applied pressure. Other variables affecting range were fixed. The angle of elevation was 40 degrees, crosswind velocity was set at zero, projectile weight was 33.85 pounds, and projectile diameter was 10 inches.

Quick comparisons of predicted versus actual range as shown in Table 4 indicate that actual ranges fall short of predicted ranges with an error band of 19.4 to 22.6 percent. This is because frictional effects were not included in the calculations, and the experimental data had a wind shear factor estimated to be between 20 and 25 mph. There was insufficient time to run this program with other variable changes. Taking the worst case error figure into account, the launcher should be capable of delivering a projectile a distance of 1789 feet with a firing pressure of 150 lb/in.². If the angle of elevation were increased to 45 degrees, this distance would increase.

TABLE 4. PREDICTED VERSUS ACTUAL.

Lb/in. ²	Predicted Range	Actual Range	Percent Error
50	755.44	609.0	-19.39
50	755.44	585.0	-22.56
93	1453.36	1153.0	-20.66
100	1586.39	1236.0	-22.09
100	1586.39	1254.0	-20.95

Another factor indicated by the computer printout is that small changes in pressure such as 1 lb/in.² will cause a distance change of 30 feet. One of the problems encountered during the testing phase was the failure of the pressure transducer from the original launcher. A Kulite transducer was calibrated and substituted for this device. Testing the device in NMERI's calibration laboratory showed an accuracy to a tenth of 1 lb/in.² when compared to the Druck DPI 500 laboratory standard. In the field, however, performance deteriorated to +/- 1 lb/in.² when compared to the Heise gage. The bulk of this error was most likely caused by the noise of the field generators. Since the Kulite gage generates a small signal, 1 to 100 mv, amplifying the signal at the launcher may correct this problem, and is recommended in the continuation of this project. Increasing the system accuracy will help minimize dispersion effects in the x-axis direction.

6. Ballistic Software Program Description

The "Ballistic" program listing is provided in Reference 15. The program uses comment statements, and the reader is asked to refer to the listing for specific definitions.

The program starts by declaring real and integer variables (20 through 420). Variables and constants are next defined and initialized using values adjusted for local elevation (5200 feet msl) where necessary (440 through 820).

The following section calculates exit velocity. A header is printed before actual calculation starts (850 through 940). A "while-end while" loop is constructed to determine when the projectile has exited the barrel (960 through 1080). Various parameters are printed while the loop is executing. Since certain variables of interest are only printed for every tenth iteration, the final values of these variables are printed using statement 1090.

Actual range calculation starts with line 1091 and concludes with line 1540. This routine prints a header (1091 through 1200), calculates initial velocities in the x and y directions based on exit velocity (1210 through 1230), and uses the "while-end while" loop structure to determine the distance the projectile travels in the x direction (1240 through 1540). The loop checks for the y distance to be zero. Since the projectile will travel in an arc, its height will increase from the height of the launcher barrel as it exits, to the maximum height where velocity in the y direction is zero, and eventually falls back to earth at a zero foot elevation. Variables of interest are also printed on either every one hundred or one thousand iterations depending on the total number of iterations. Statement number 1550 prints the final values of these variables, which is why some printouts show a small negative y displacement.

A master loop using a "for-next" structure causes the whole process to repeat in 1 lb/in.² increments (line 571 and line 1560). The program terminates with an end statement.

I. RAPID-FIRE LAUNCHER SYSTEM TESTING

1. Function Testing

Initial testing of the launcher system involved testing of individual subsystems after initial assembly. This was followed by testing of the entire system through a firing sequence with manual control of the functions. Finally, the automatic control computer and software were used to run all functions through six complete cycles to simulate firing a full barrage.

Following the successful completion of the above tests, the launcher was moved outside and a launch test sequence was completed using sabots and empty agent canisters. This test provided a realistic verification of the chamber-to-barrel alignment without serious damage in the event of a malfunction. This test sequence was successfully completed on the first attempt.

2. Field Testing

After successful completion of the function testing, the launcher system was mounted to a mobile vehicle for field testing. The vehicle used was a one and one-half ton flatbed truck. The full weight of the launcher is about one ton. Because of transportation to and from the test site, and the recoil loads from firing the launcher, the launcher platform was bolted directly to the frame of the truck.

a. Support Equipment

Compressed air is required for the operation of the firing valve actuator and the cylinder positioning drive motor, as well as for pressurization of the chamber for firing the canister. The compressor used for field testing was a Sullair Model 185DP02WJD diesel-powered portable rated at 185CFM at 120 lb/in.². Air was supplied from the compressor to the launcher by a 1.5-inch hose.

Electrical power for operating the remaining functions of the launcher was provided by a 6 KW Onan generator driven by a gasoline engine.

The majority of field testing was done with test projectiles made from the normal 10-inch diameter polyethylene canisters filled with lightweight concrete to simulate the weight of Halon 1211. The fill weight of Halon 1211 was between 33 and 35 pounds. The six concrete-filled canisters made for test projectiles weighed 33.85 pounds each. Their weight was closely matched to minimize dispersion due to weight differences.

b. Test Operations

The approach for field test operations was to begin with manually controlled, single-shot firing at lower pressure and progress to fully-loaded, automatic computer-controlled firings at higher pressures. The procedure permitted a systematic check of system operation in a step-by-step manner, beginning with the less complex, and progressing to the more complex, as confidence was gained in system functions.

There were six series of field tests completed from a low of five shots to a high of 24 shots per series for a total of 72 shots in the test series. This was only the beginning of the field tests planned, but project resources were not available to complete all the planned testing.

c. Test Series Descriptions

The launcher was designed to operate in the range of 0-150 lb/in.² chamber pressure. The project requirement for range was a 1200-foot capability. The first test series, 900125, was a series of seven single shots using manual controls. The objective of this series was to perform basic checks of subsystems performance and measure range. The average range of the seven shots, using 50 lb/in.² nominal chamber pressure, and 44 degrees elevation angle, was 624 feet, with a range variation from short to long of 22 feet. Cross range dispersion was 29 feet. This test series demonstrated basic operation of launcher subsystems and indicated that the required range of 1200 feet would be achievable. In this and subsequent test series, the projectiles used were one or more of the six test projectiles fabricated with a matched weight of 33.85 pounds, unless otherwise noted.

The second test series, 900130, consisted of five single shots, again using manual controls for operation. The first shot was inadvertently fired at between 100 and 110 lb/in.² chamber pressure and 44 degrees elevation angle and achieved a range of 1387 feet. This shot clearly demonstrated the capability to reach and exceed the 1200-foot range requirement. The other four shots in this series were fired at 50 lb/in.² nominal chamber pressure, 44 degrees elevation angle and reached an average range of 700 feet with a variation of 40 feet. Cross range dispersion was 24 feet.

Test series 900131 consisted of seven single shots fired with 50 lb/in.² chamber pressure and 44 degrees elevation angle. The average range was 667 feet with a variation of 50 feet. Cross range dispersion was 26 feet.

The next test series, 900206, consisted of 24 shots made up of three sequences. Shots 1-18 were single shots while 19-24 were the first 6-shot barrage. Shots 1-12 were at 50 lb/in.² chamber pressure and 44 degrees elevation angle. The average range over the 12 shots was 672 feet with a variation of 95 feet and a cross range

dispersion of 44 feet. Shots 13-18 were a sequence of single shots at 100 lb/in.² chamber pressure and 44 degrees elevation angle. The average range was 1363 feet with a variation of 79 feet and a cross range dispersion of 112 feet. Shots 19-24 were the first automatically controlled six-shot barrage attempted. The chamber pressure was 100 lb/in.²; the elevation angle was 44 degrees. The average range was 1363 feet with a variation of 166 feet and a cross range dispersion of 92 feet.

Test series 900207 was a total of 21 shots. These were made up of three single shots, and two 6-shot and two 3-shot auto-fire sequences. The two 6-shot sequences were at 100 lb/in.² chamber pressure and 44 degrees elevation angle. The single shot and three-shot sequences were at 50 lb/in.² chamber pressure and 44 degrees elevation angle. This test series demonstrated the capability of the general launcher in the auto-fire mode, and time constraints did not permit making range and dispersion measurements. Two of the shots were fired using 35-pound, Halon 1211-filled canisters to demonstrate agent dispersal at impact.

The final test series, 900215, was another launcher demonstration consisting of seven shots. Shots 1-3 were at 50 lb/in.² chamber pressure and 40 degrees elevation angle. The average range was 609 feet with a variation of 66 feet. Cross range was not measured. Shot 4 was at 93 lb/in.² chamber pressure achieving a range of 1153 feet. Shots 5-6 were at 100 lb/in.² chamber pressure with an average range of 1245 feet. The final shot was with a Halon 1211-filled canister weighing 35 pounds fired at 50 lb/in.² chamber pressure. The range was 609 feet.

d. Discussion

As stated above, these test series were only part of what had been planned for complete evaluation of the launcher system. Sufficient resources were not available to complete the planned testing. However, the tests completed demonstrated basic operational capabilities of the launcher system. Fully automatic, computer-

controlled firing of six-shot barrages was demonstrated. The launcher system exceeded the 1200-foot range requirement at only two thirds of the design chamber pressure capability.

An area that needs further work is that of reducing the dispersion of impact points of successive shots with equivalent firing parameters. A number of factors influence the dispersion. Some of these are accuracy and repeatability of chamber pressure, azimuth angle, and elevation angle settings between successive shots. These are determined by the accuracy of the actuators, drives, and instrumentation that controls these functions as well as the shifting of the launch platform between shots due to the recoil loads. Installation of stabilization jacks on the launch platform will significantly reduce this contribution to dispersion. The variation between sabots, which push the canisters down the barrel, influences the range and cross-range dispersion. Some difference in the fit of the sabots was noted during testing. There are some fairly simple process modifications in fabrication that will solve the sabot fit differences. Of course, winds have a strong influence on dispersion. The winds cannot be controlled but accurate measurement of the wind speed and direction at the launcher and use as an input to the ballistic prediction program will help reduce the wind contribution to dispersion. These improvements were originally planned in the final stages of the test program, but were not accomplished because of lack of project resources.

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Tests to date have verified the potential of this prototype system to deliver agent to and to extinguish a distant fire. However, many critical and difficult challenges remain in the areas of agent dispersal, canister loading, and advanced aiming before the system will be able to realize its full potential. Finalization of these design aspects is required before the system can be fitted to its ultimate configuration on a mobile vehicle with appropriately sized power units.

The spherical canister design appears to satisfy the major requirements of repeatable delivery and dispersion, although some improvements in accuracy can still be realized. The basic concept for dispensing the agent relies on the canister bursting upon impact in front of the burning object and the agent then sweeping across the fire. A canister that is launched too far could impact the burning object and cause additional damage. The proposed canister designed to disperse the agent above the target fire will provide a more uniform agent application and will be more efficient. In addition, it will eliminate the concern of a canister weighing more than 30 pounds potentially impacting the burning object and multiplying the damage.

The control system has been automated by a computer, and manual operation capability has been retained. Software has been written and incorporated into an integrated system that handles the control functions. Other software provides the capability to determine the interrelationships of trajectory and launcher parameters for prediction purposes. Status and feedback advisories are incorporated into most of the software.

Electro-mechanical and pneumatic systems have been designed to perform the various functions necessary for integrated launcher operation. The simplest approach that would perform the desired function completely and reliably was always used. All of the functional subsystems have been successfully tested at the subsystem level. The majority of the integrated full-up system tests have also been successfully completed.

The control system computer operation is technically more detailed and complex on this prototype than it will be on a production model. The design was approached in this manner in order to maintain flexibility in the development process for ease of making changes as experience is gained and results are achieved. Once the final configuration evolves, the software can be employed in an "embedded" system, with a set of user friendly commands and help files incorporated to make the system simple to operate.

B. RECOMMENDATIONS

The barrel and sabot systems must be further refined to reduce the circular error probable and achieve maximum distance. This will entail further honing and precision alignment of the barrel, and development of a more consistent and controllable process for the manufacturing of the sabots.

The continual feeding of the rapid-fire cylinder must be developed to surpass the operational limitations of a six-shot barrage. The existing cylinder can be belt-fed, or it can be alternated with a second cylinder in a slide-in/slide-out type of operation. A magazine feed approach should also be investigated. The exact extent of barrage capability required should be arrived at empirically after agent dispersal requirements and characteristics are defined along with operational procedures expected to be employed.

The capabilities of the automated aiming and launching system should be expanded. An advanced system should include laser-based or optical ranging, which would be mated to canister weight and windage data to compute and set azimuth, elevation, and launch pressure. The program should also be developed to accommodate a variety of pre-determined agent lay-down patterns.

In conjunction with further field testing and operational concept definition by the user, an in-depth study of mobility concepts should support the mounting configurations and movement parameters of the launcher, including the parallel movement of all launcher logistical requirements.

Prior to conversion to Full Scale Engineering Development (FSED), the prototype should be taken through an additional and extensive series of field testing to verify the ability of the system to stand up to rugged field conditions, and to establish a firing history through the full range of chamber pressures.

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