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The design, development and testing of a test prototype hydraulic servo recoil system that reduces the recoil forces of the 20mm M197 gatling gun to ~~to~~ near-constant levels is described. The system concept, system implementation and engineering, preflight and flight test on board an AH-1G helicopter are summarized. Preliminary conclusions are that the vibrations in the helicopter resulting from gun firing are virtually elimintated.

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SECTION I
INTRODUCTION

This is the final report of Contract DAAA09-74-C-2077 awarded to Honeywell by the U.S. Army Armament Command (ARMCOM) for the design and development of a flightworthy test model of a hydraulic constant recoil system. The hydraulic constant recoil system reduces the recoil forces of the 20mm M197 gatling gun to a near constant level. The flightworthy test model was used to conduct firing tests aboard the AH-1G Multiweapon Helicopter to evaluate the benefits of low-level, near-constant recoil forces of helicopter-mounted weapons. The successful firing tests, from the helicopter in flight, were completed in February 1977. The contract was directed by Rodman Laboratory personnel, and the flight tests were conducted by Frankford Arsenal personnel with assistance of personnel from the Naval Air Station, Aberdeen Proving Grounds, and Honeywell. Preliminary conclusions are that the vibrations in the helicopter resulting from gun firing are virtually eliminated. Frankford Arsenal is reducing the data and will report the quantitative results.

This contract is part of the ARMCOM research and development programs directed toward improving the effectiveness of helicopter weapons for the helicopter's role in the mid-intensity conflict. ARMCOM has identified that greater firepower is needed to improve attack helicopters' effectiveness and that the large recoil forces from the weapons with greater firepower precluded their use on helicopters when conventional recoil adapters are used. Further investigations by ARMCOM demonstrated that the high, cyclic recoil forces could be reduced to a near constant level by the use of servo recoil systems rather than the simple spring/damper recoil adapters. In the previous contract, DAAF03-73-C-0083, Honeywell had investigated the use of a hydraulic positional servo to reduce the recoil forces of the 20mm M197 weapon as part of ARMCOM's program.

That contract culminated in the firing of the M197 weapon mounted on a laboratory breadboard model of the hydraulic positional servo in Honeywell's Hopkins firing range. The peak to peak recoil forces were reduced from 4000 pounds to 1000 pounds. That contract effort is reported in Honeywell's "Final Report on Recoil Force Reduction Weapon Mount Feasibility Study" dated 1 November 1974.

In this contract Honeywell advanced the design of the breadboard model to a flyable test prototype that could be used for the evaluation of low-level recoil forces. It should be noted that this prototype is not representative of a production model nor was there effort to advance the design beyond the functioning, test-feasibility model stage.

The recoil system is a total system consisting of a hydraulic positional servo that continually commands the weapon to follow a prescribed recoil displacement movement during firing and subsystems that:

- Synchronize recoil system operation with gun firing
- Compensate for changes in gun elevation
- Control the gun motion in the event of misfires
- Provide a backup safety system that will prevent damage to the helicopter in the event of hydraulic failure

SECTION II
SUMMARY AND CONCLUSIONS

The Army's overall objective is to maximize the mission effectiveness of the attack helicopter in mid-intensity conflict environments. Previous studies have established that effectiveness can be improved if automatic gun weapons with greater firepower are mounted on attack helicopters. However, automatic cannon using conventional recoil adapters produce highly peaked cyclic recoil force loads which limit the choice to relatively low-fire-power weapons with recoil loads that will not overstress the helicopter structure nor produce vibrational loads that will fatigue the structure or degrade the functional life of the helicopter avionics or control functions. If these recoil force loads can be reduced, greater firepower is available to attack helicopters.

The objectives of this contract were (1) to design, build and proof test a prototype recoil system that could be used by ARMCOM to evaluate the benefits of low-level, near-constant recoil forces, and (2) support ARMCOM's flight test program to evaluate the benefits of low recoil forces on a helicopter. The weapon used is the 20mm M197 gatling gun which is presently mounted in AH-1J helicopters. It was selected for its availability and the fact that data was available on its use with standard recoil adapters for comparison with the recoil servo system. The recoil forces, using standard recoil adapters, are close to the upper level that can be tolerated by the Cobra helicopters and therefore provide a good basis for comparison. Figure 1 shows the high-peak, cyclic recoil forces produced by the 20mm M197 when mounted on standard recoil adapters.

The objective of the contract was met. A test prototype recoil servo system was designed, built and tested at Honeywell that greatly reduced the peak recoil force (see Figure 2). ARMCOM mounted the system on the AH-1G

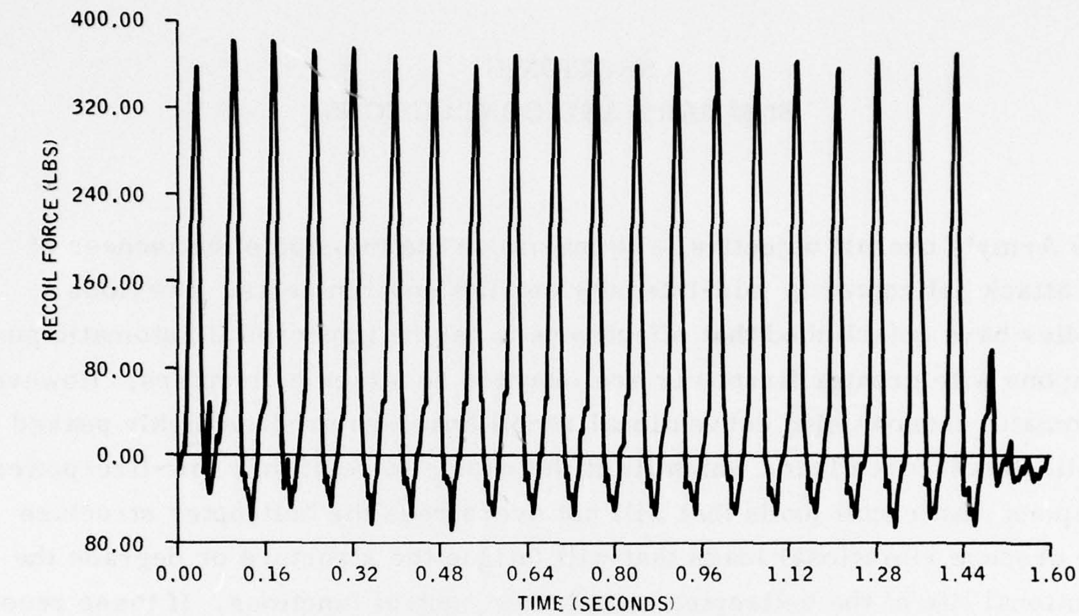


Figure 1. Recoil Force for the 20mm XM197 Gun (From "The Investigation of Dynamic Gun Pointing Errors for Helicopter Mounted Automatic Cannon Systems, Final Report" by T.O. Hutchings and A.R. Zak, Rock Island Arsenal)

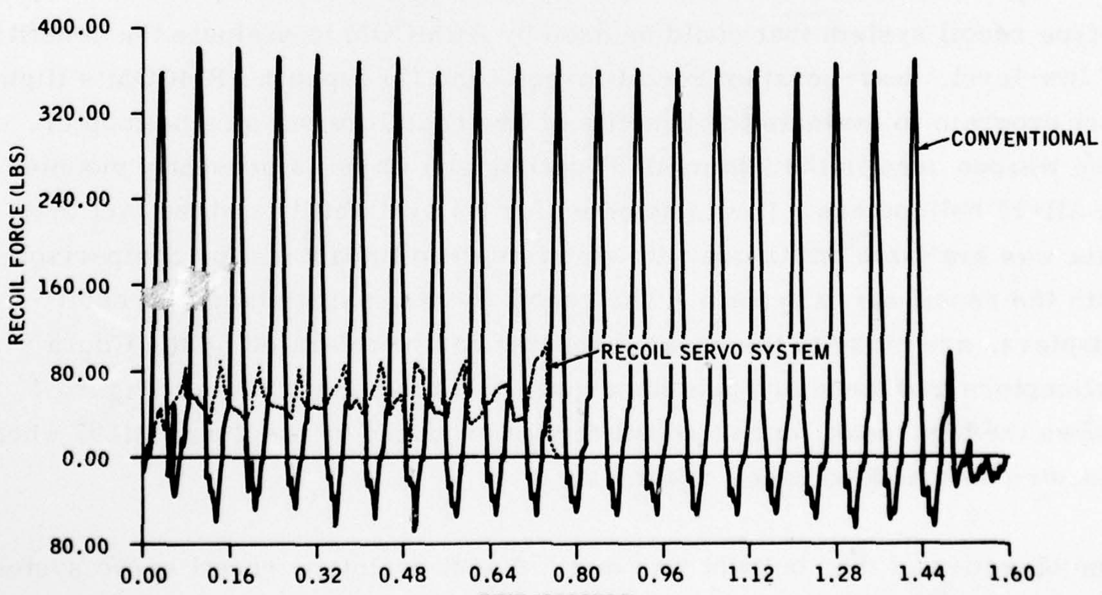


Figure 2. Comparison of Recoil Forces - Conventional Recoil Adapter Versus Recoil Servo System

Multiweapon Helicopter and conducted evaluation firing tests. The weapon and recoil system installed in the M97 turret on the AH-1G Multiweapon Helicopter are shown in Figure 3. Approximately 2000 20mm rounds were fired from the M197 gun/hydraulic constant recoil system on the Multiweapon Helicopter. Qualitative results (pilot and gunner observations) are that the vibration in the helicopter generated by firing the gun is barely noticeable with the gun mounted on the hydraulic recoil system. This is not the case with the conventional recoil adapters; the vibrations generated by the gun firings shorten the time between failure of the avionics, cause structural fatigue and prevent the pilot from accurately controlling the aircraft during firing. Frankford Arsenal directed the test program for ARMCOM and will report the quantitative results.

PROGRAM SUMMARY

The program was conducted in six phases of which the first phase was performed under a previous contract in which a hydraulic servo concept was synthesized and analyzed and a simple laboratory model was fabricated and tested under laboratory conditions. Phases II through VI were conducted under the present contract as follows:

- Phase II - The hydraulic servo concept of Phase I was redesigned into flyable hardware. A state-of-the-art rotary servo valve is the heart of the recoil servo system. Subsystems that synchronize the gun firing and recoil system operation, that compensate for weapon elevation and misfires and that serve as a failsafe backup were designed and analyzed. Preliminary reliability and hazard analyses were made.

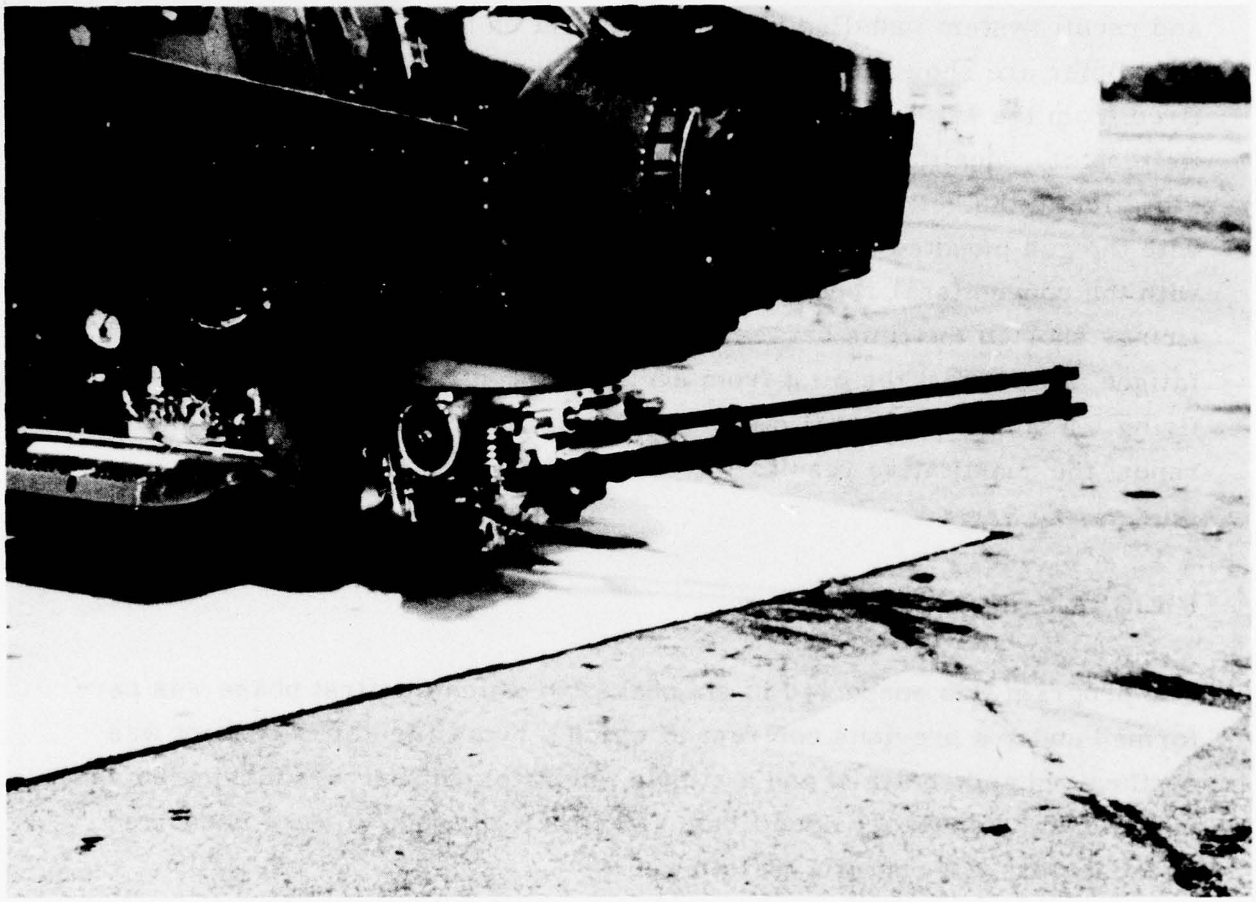


Figure 3. M197 Gun and Recoil System Installed in the M97 Turret of the AH-1G Helicopter

- Phase III - The design of Phase II was fabricated and subjected to engineering development tests. Five hundred and five rounds were fired that verified most of the design analysis. The forces were much smoother than recoil adapters, but not as smooth as predicted. Control of weapon movement was positive throughout the entire range of firing conditions including successive misfires and the design is mountable in the M97 turret.

- Phase IV - Tests were conducted on a recoil system design by ARMCOM for the 20mm M39 gun. These results were reported separately.

- Phase V - Flightworthiness tests were performed consisting of firing over 1900 rounds from the gun mounted on the hydraulic recoil servo system which in turn was mounted in a M97 turret on a test stand on the firing range. Firings were conducted at 15 combinations of azimuth and elevation of the weapon relative to the turret.

  A continuous 250-round burst was fired as part of these tests. Also, the recoil system, weapon and turret assembly were subjected to simulated helicopter vibrations in accordance with Mil-Std 810C.

- Phase VI - An Army flight test program was supported by ensuring that the recoil system functioned properly when mounted on the AH-1G Multiweapon Helicopter in flight tests at the Patuxent River Naval Air Station, Maryland. Over 200 rounds were fired in ground tests and 1700 in flight from the helicopter.

The reduction in the recoil forces is significant as can be seen in Figure 2. These lower forces produce a vibration only slightly above the ambient vibration level in the helicopter. The qualitative reaction of the pilot affirms the low vibration in that he can now control the helicopter during firing when previously he was buffeted about by the vibration of the airframe.

Over 4500 rounds were fired from the gun mounted on the recoil system without signs of wear to the weapon or the recoil system.

There are deficiencies in the present design; however, in view of its uniqueness and its being the first complete system model, these are relatively minor. The specific deficiencies are:

- System weight is much too great.
- A slow shutdown sequence produces unnecessary, large recoil forces at the end of a burst.
- The compensation for gun elevation does not function properly.
- Recoil forces can be further reduced.

CONCLUSIONS

The hydraulic servo recoil system substantially reduces the recoil forces of the 20mm M197 weapon and maintains positional control of the weapon during firing. The benefits of this system can be in either or both the reduction of recoil forces or the upgunning of the weapon system. It is estimated that a 30mm weapon firing GAU-8 type ammunition when mounted on a hydraulic recoil system could fire at 750 shots per minute (the same rate as the 20mm M197 weapon on standard recoil adapters) with lower peak forces, although the average force would be almost 3.5 times greater.

SECTION III
CONCEPT DESCRIPTION

The test prototype recoil system developed on this contract is the first complete hydraulic constant force recoil system for automatic weapons. The system consists of five subsystems:

- Constant Force Recoil Servo
- Start and Stop
- Misfire Control
- Elevation Compensation
- Failsafe Backup

CONSTANT FORCE RECOIL SERVO

The constant-force recoil servo is the heart of the system; it controls the recoil motion of the weapon during normal gun firing with near constant forces. The design and operation of the constant-force recoil servo is best explained in three steps:

- Theory of constant force recoil concept
- Hydraulic implementation
- Error control

Concept Theory

Conservation of momentum requires that when a gun is fired the net change in momentum be zero. If the gun is at rest when fired, the momentum of the gun is equal and opposite to the momentum of the propellant gas and projectile. Also the impulse, the integral of the force on the gun, is equal to the momentum.

In the design a recoil system, it is necessary to know the recoil momentum of the gun or the firing impulse. In this contract we estimated the firing impulse by integrating a measured pressure time curve from the firing of 20mm M56 rounds and multiplying the integral by the bore area. This measurement gives a slightly higher value of impulse because gas and projectile friction were not deducted. The impulse used is 34.56 pound-seconds. The peak force applied by the propellant gas pressure to the gun during firing is 25,000 pounds. The total pulse lasts about 2.7 milliseconds.

The purpose of the recoil system is to:

- Reduce the forces applied to the gun over the short time period of 2.7 milliseconds firing pulse by the propellant gases to a much lower force applied to the helicopter over the entire time interval between firings.

- Maintain positional control of the gun while it moves (recoils) due to the forces of firing and those applied by the recoil system, while maintaining those of the recoil system to a near-constant level.

The lowest possible value of the recoil force is determined by the firing rate and ammunition impulse. For the 20mm M197 weapon firing at 750 shots per minute, the longest time interval for the recoil force is 0.08 second. Since the product of the recoil force and this time interval must equal the ammunition impulse, the minimum recoil force is 432 pounds $\left(\frac{34.56}{0.08}\right)$. This force must be constant over the firing interval.

The objective of this contract effort was to reduce the forces transmitted to the support structure to as close to the constant force as possible.

The requirement to maintain control of the gun's position during firing has several implications since the M197 gun is an automatic weapon that fires large numbers of rounds in rapid fire:

- The gun must return to its start position after each round is fired.
- When the gun returns to its start position its recoil velocity must be zero.

The only way that the constant force can be applied to a rapid-fire weapon and meet the positional control guidelines is by applying the force to the gun before it fires such that the gun fires exactly halfway through one operating cycle. This type of gun firing operation is known as "out of battery" or "sear off" firings. Figure 4 shows the movement of the gun forward, firing at its peak position and returning to its start position. Figure 4 also illustrates the recoil velocity of the gun for this sequence of events. As shown, the gun is back to its start position and zero velocity at the end of the cycle.

For the 20mm M197 firing at 750 shots per minute with an ammunition impulse of 34.56 pound-seconds and recoiling weight of 187.6 pounds (gun plus feeder plus moving recoil system components), the recoil distance, velocity and constant force can be computed with the following results:

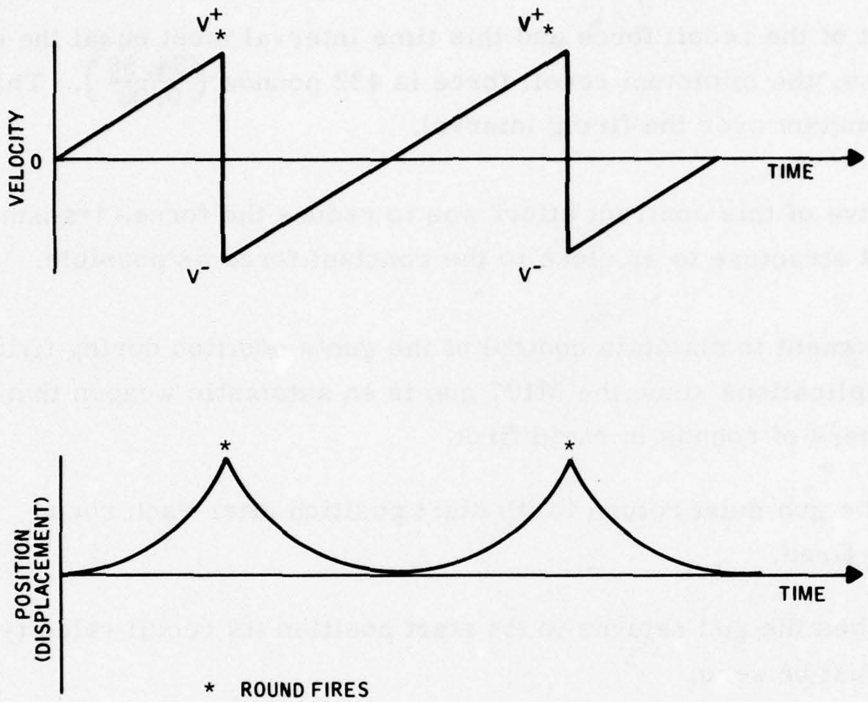


Figure 4. Nominal Position and Velocity Profiles for Weapon Recoil in Out-of-Battery Firing

Constant force:	432 pounds
Maximum forward velocity:	2.96 ft/sec
Maximum rearward velocity:	2.96 ft/sec
Maximum forward recoil movement:	0.71 inch

Hydraulic Implementation

Figure 5 illustrates the initial concept visualized for employing hydraulic components to provide constant force. It consists of a piston connected to the gun. The hydraulic pressure on the piston is applied by compressed nitrogen gas pressure in the accumulator being transmitted through the rubber diaphragm to the hydraulic fluid to the piston. The pressurized nitrogen gas and trapped hydraulic fluid in the accumulator are effectively a preloaded spring.

The cylinder is attached to the support structure, with the only forces transmitted to the structure by the cylinder being the pressure on the back end and friction of piston motion regardless of the piston motion. These forces can be accurately estimated — the hydraulic pressure, which is equal to the nitrogen pressure that varies with piston movement and the friction force, is viscous friction proportional to gun recoil velocity. However, the sum of these two forces is not constant.

This is corrected by adding another piston. The second, smaller piston is added as shown in Figure 6. By appropriately controlling the hydraulic pressure on the small piston, the net force can be kept constant at 432 pounds over the total recoil cycle.

In the previous contract this pressure was controlled by adjusting the position of the spool in a three-way hydraulic spool valve (Figure 7). The spool is lap fitted into the cylinder, and the ports to the pressure and return lines are thin slots. The position of the lands of the spools controls the relative sizes of the opening to the pressure and return lines. By moving the spool, the range of pressure on the piston varies from zero to full supply pressure (1500 psi). Also the pressure on the piston depends on piston velocity, piston area, and the ratio of that area to the openings in the servo valve.

In the previous contract a mechanical cam was used to adjust the position of the spool to control the pressure on the small piston. The cam was attached to the gun and rotated with the receiver. Since the gun fired at a fixed rate, the rotation of the gun provided the time base for the cam. While this cam

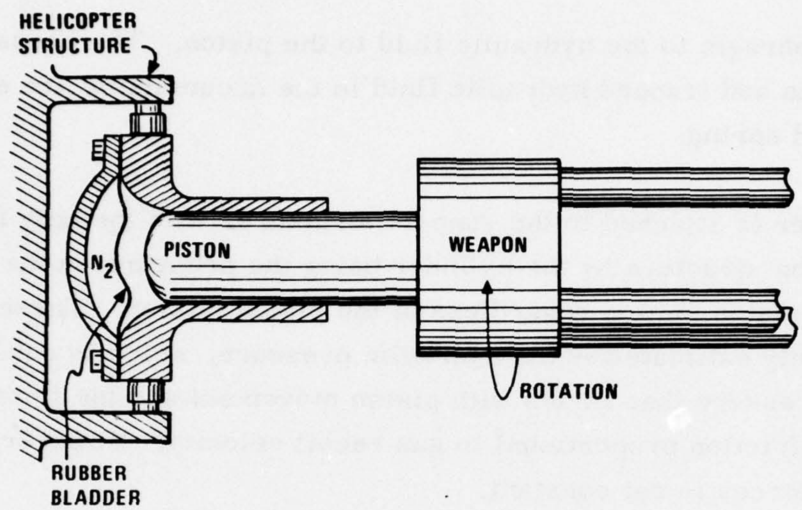


Figure 5. Initial Rotary Valve Concept

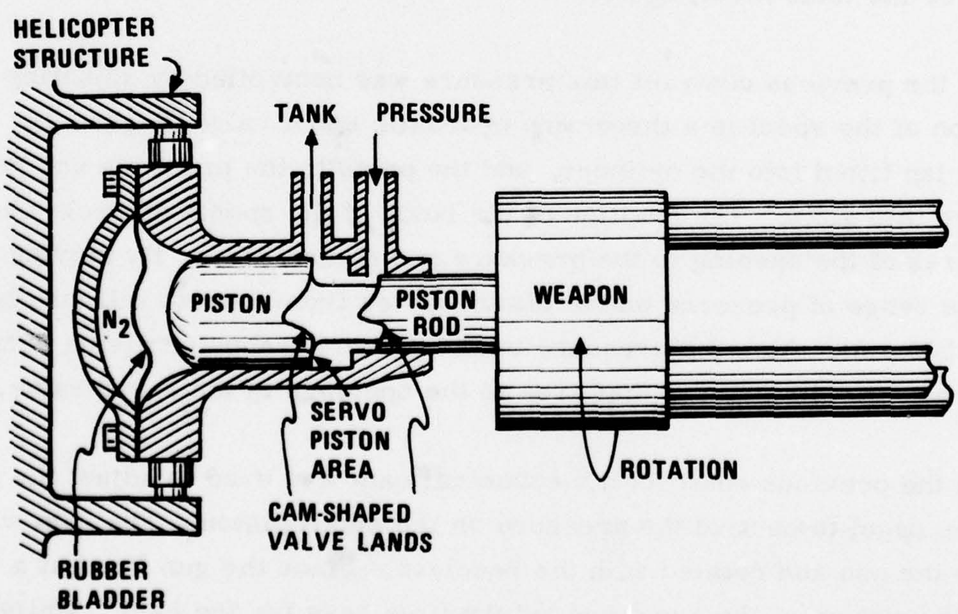


Figure 6. Improved Rotary Valve Conecpt

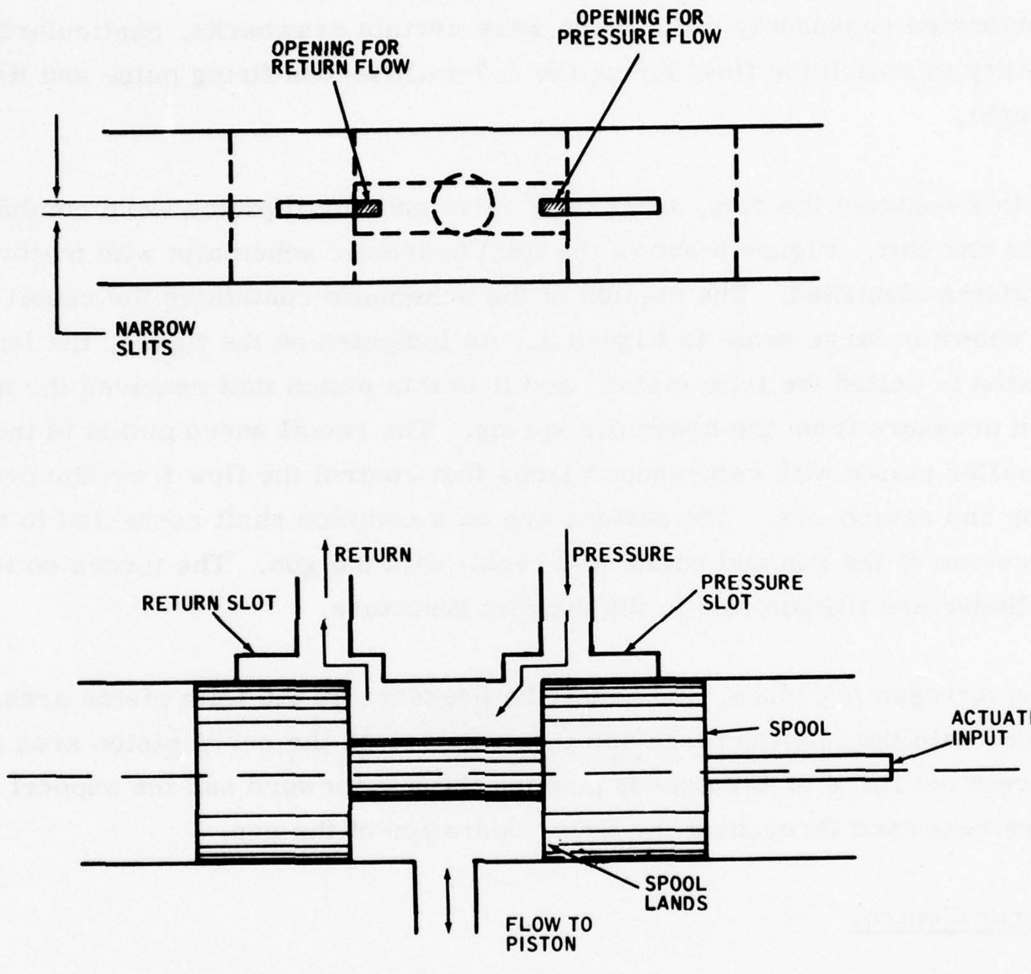


Figure 7. Three-Way Hydraulic Spool Valve

performed reasonably well, there were certain drawbacks, particularly in its ability to switch the flow during the 2.7-millisecond firing pulse and its large weight.

In this contract the cam, three-way valve and small piston were combined into one unit. Figure 8 shows the total hydraulic schematic with major subsystems identified. The portion of the schematic containing the recoil servo is shown in large scale in Figure 9. As indicated on the figure, the large piston is called the trim piston, and it is this piston that receives the nitrogen pressure from the hydraulic spring. The recoil servo piston is the smaller piston with cam-shaped lands that control the flow from the pressure line and return line. The pistons are on a common shaft connected to the receiver of the gun and rotate and recoil with the gun. The forces on the cylinder are transmitted to the support structure.

The nitrogen pressure, and hence the pressure on the trim piston area, combined with the friction force and the pressure on the servo piston area produce a net force of 432 pounds pushing the gun forward and the support structure rearward throughout the firing operation of the gun.

Error Control

If the impulse of the rounds is greater than the 34.56 pound-second value used in the design, the higher impulse would cause the gun to move more rapidly rearward after firing, and, if the force applied to the gun remained at 432 pounds, the displacement velocity curves would be as shown in Figure 10. The position and velocity errors — differences between the design curves and the actual — have the following effects:

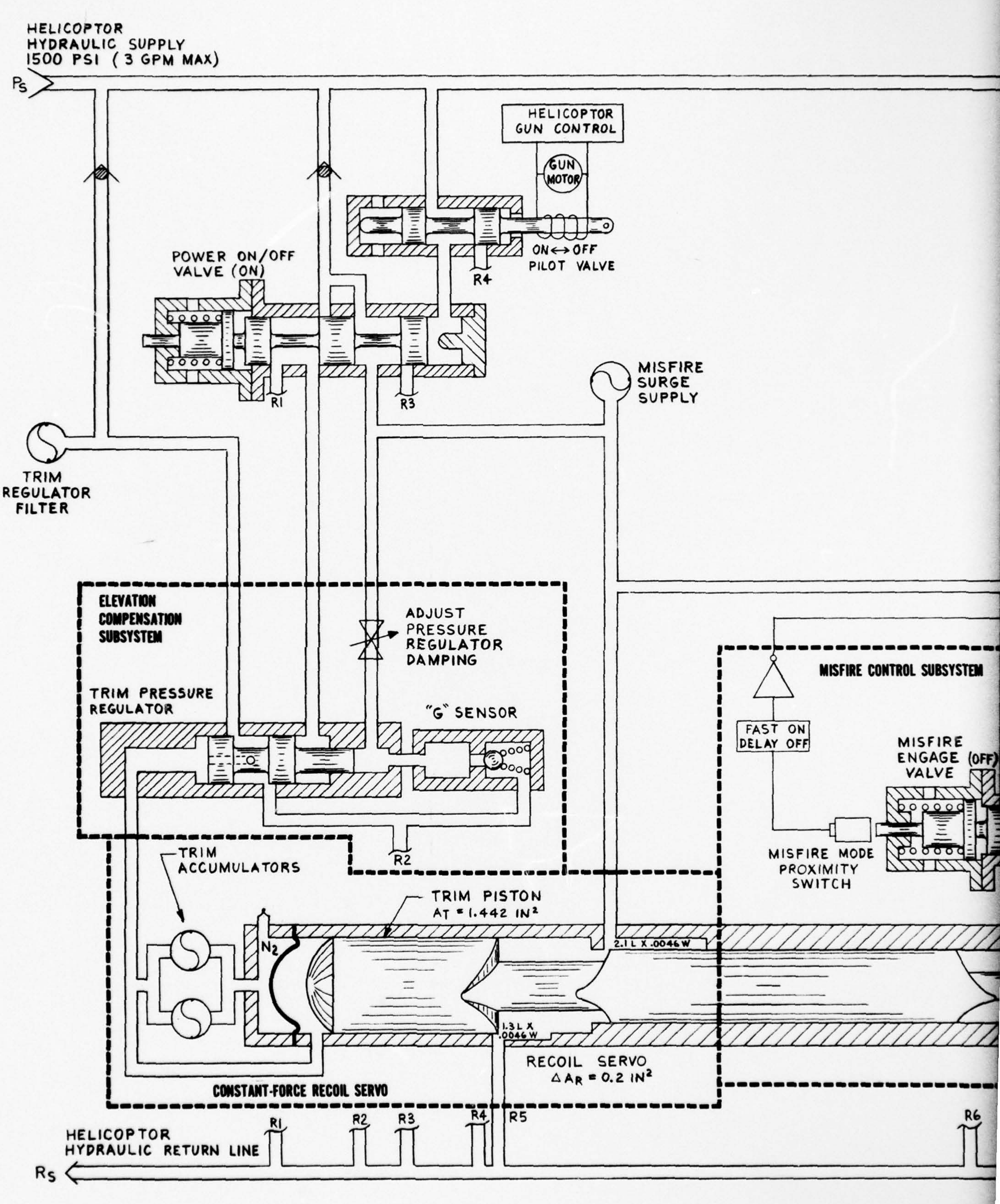
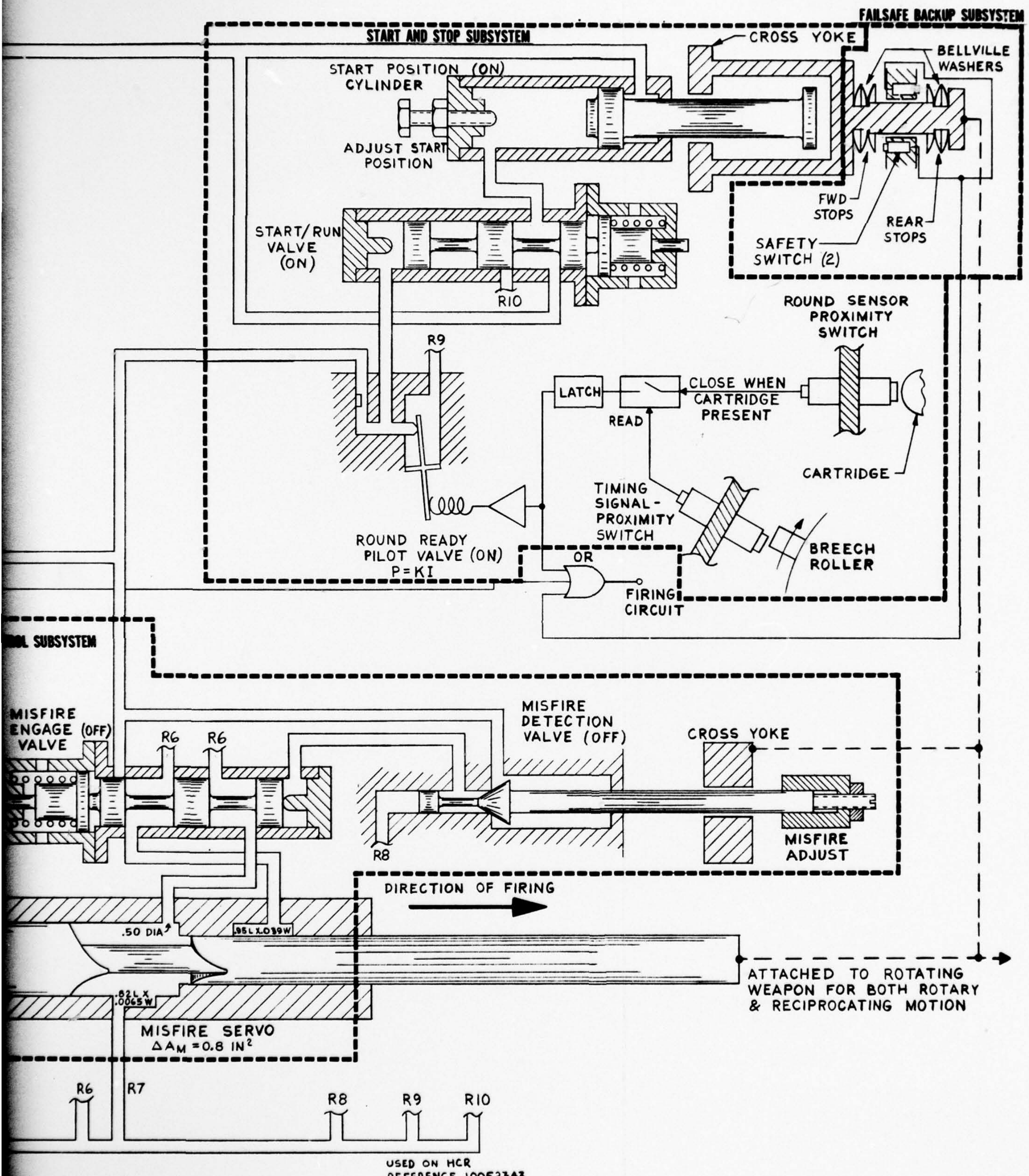


Figure 8. Hydraulic Constant-For



tant-Force Recoil System Schematic

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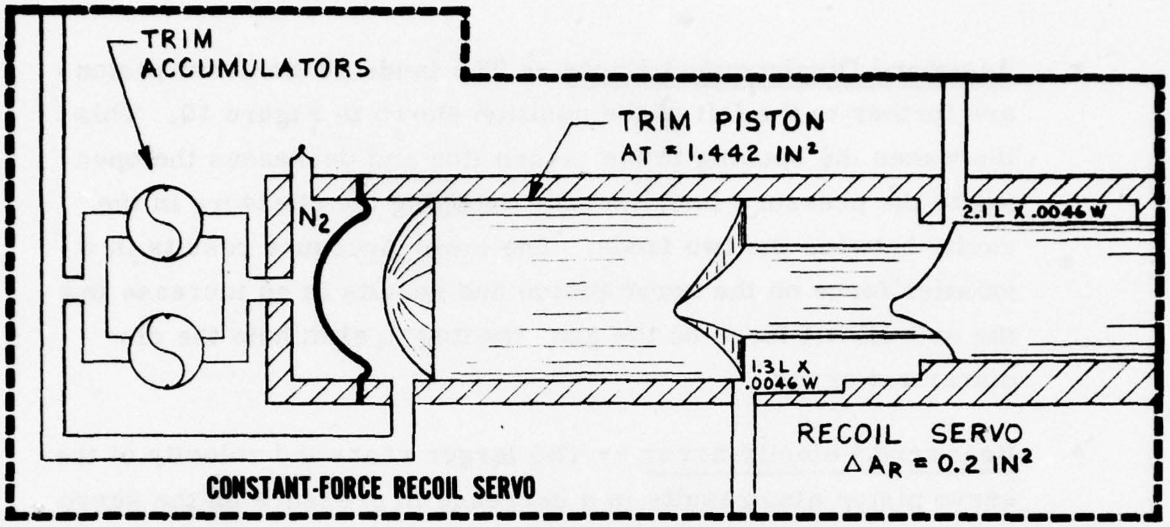


Figure 9. Constant-Force Recoil Servo Schematic

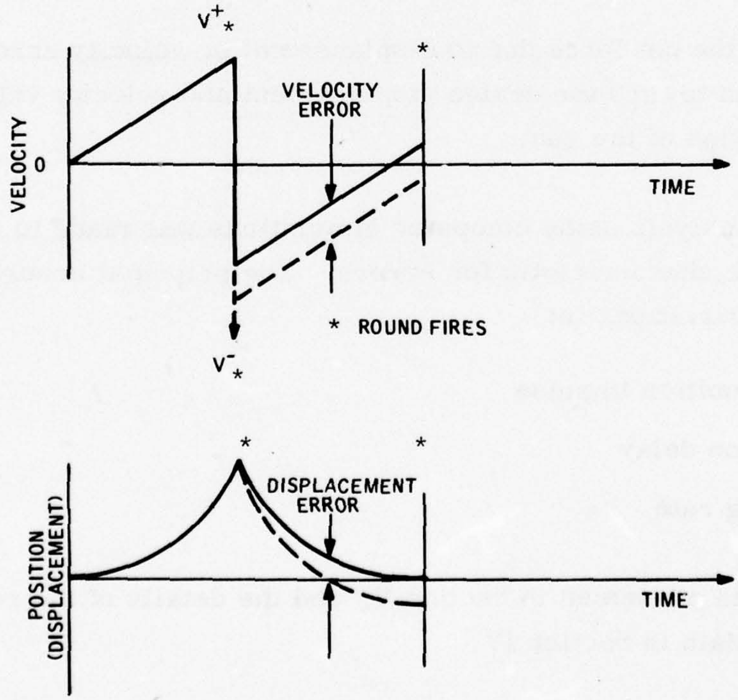


Figure 10. Nominal Position and Velocity Profiles for Weapon Recoil With Errors for High-Impulse Round

- Rearward Displacement Error -- The lands of the servo piston are further to the left of the position shown in Figure 10. This increases the opening to the return line and decreases the opening to the pressure line, thereby dropping the pressure in the cavity between the two lands. The lower pressure results in a smaller force on the servo piston and results in an increase in the overall net force on the gun, tending to eliminate the displacement error.

- Rearward Velocity Error -- The larger rearward velocity of the servo piston also results in a decrease in pressure on the servo piston even if the openings to the return line remain the same. The effect of the velocity error in Figure 10 is to increase the net force on the gun, tending to correct for the velocity error.

The change in the net force due to displacement or velocity errors is such as to drive the gun toward the design displacement and velocity values at each instant of rotation of the gun.

An extensive analysis using computer simulations was made to establish the servo response characteristic for errors. The principal errors were considered to be variations in:

- Ammunition impulse
- Ignition delay
- Firing rate

This analysis is presented in Section V, and the details of the rotary valve design are contain in Section IV.

START AND STOP SUBSYSTEM

An essential part of the concept is the start of the recoil motion before the shot is fired. The start, if position and velocity errors are not to be introduced, must be precisely 39 milliseconds before the 2.7-millisecond firing impulse occurs. The start and stop subsystem consists of two proximity sensors, a logic switching circuit, a rapid-response electrohydraulic valve, a switching valve and a two-sided piston. The subsystem was identified in Figure 8 and is shown in detail in Figure 11.

The need for this complex a subsystem is partly dictated by the operation of the M197 gun. The M197 is a gatling with three rotating barrels. When a bolt carrying a live round sweeps by a fixed firing pin, the round is fired. To preclude live rounds in a hot chamber, feeding of the ammunition is controlled by an interruptible feeder. When the gunner pulls the trigger the gun starts to rotate and live ammunition starts moving through the feeder into the gun. The arrangement is such that three empty bolts pass the firing pin before the first live round reaches the firing pin. When the gunner releases the trigger, the feeder is declutched, preventing any more rounds from passing through the feeder into the gun. The gun meanwhile continues to fire until all the live rounds downstream of the clutch have been fired and the weapon has been cleared of live rounds and empty cases. Therefore, the gunner's pull and release of the trigger could not be used to start the out-of-battery motion.

In the two-sensor concept adopted to solve this problem, one sensor is used to monitor the presence of a roller attached to a bolt. When a roller, indicating the presence of a bolt, is sensed the round sensor is turned on. If this sensor senses a round, the fast acting electrohydraulic valve is turned on. While this valve comes up to full output in 2 milliseconds, its flow is small. This small flow is used to move the spool of the start/run valve which in turn allows a large flow or oil into the start piston. The start piston up to this

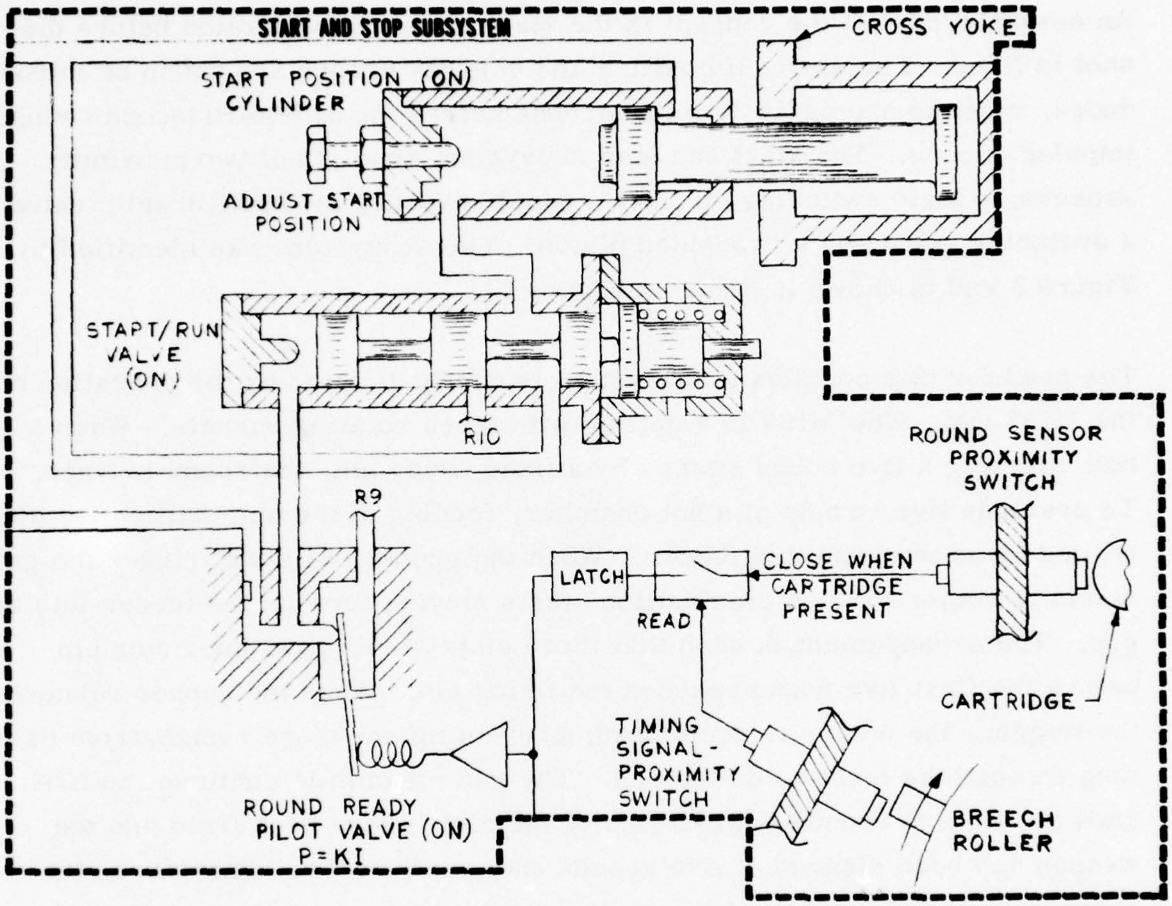


Figure 11. Start and Stop Subsystem Schematic

time has opposed the trim piston and held the gun at the start position. When the other side of the piston receives oil from the start/run valve, the piston is moved forward as shown in Figure 11, releasing control of the gun motion to the servo system. By adjusting the position of the sensors, the start of the recoil motion 39 milliseconds before firing is obtained.

Each time a bolt comes by the bolt sensor, the logic sensor is updated. If a round is present, the system remains in the run mode. When a bolt comes by the sensor and the round sensor does not sense a round, the system is shut down by retracting the start piston (and the weapon with it) to the start position.

To preclude the chance of an error in the output of the logic circuit resulting in the gun firing in the start position, the output of the logic circuit is also connected to a relay in the firing line to the gun. The firing line is interrupted by the relay until the round sensor signals there is a round in the gun.

MISFIRE CONTROL SUBSYSTEM

The basic scheme of the recoil system requires the gun to be moving forward at 2.96 ft/sec when the round is fired. The firing of the round drives the gun backward. In the event of a misfire, the gun would continue forward and impact the front of the turret unless restrained in some fashion. The misfire control subsystem must provide the controlled force to prevent the gun from impacting the turret. The problem is further complicated in that the recoil motion is synchronized with the firing of the gun, and a misfire disrupts the synchronization. The regaining of synchronized recoil motion and gun firing could not be obtained by stopping and restarting the gun without considerable gun redesign. Since the objective was to design a recoil system requiring minimum gun modification, other means were considered.

An analysis was made into the dynamics of stopping the forward motion and returning the gun to the start position at the end of the cycle. This motion is shown in Figure 12. The two forces F1 and F2 are needed to bring the weapon back to the start position for the next round. The magnitude of each force depends on the time needed and is inversely proportional to the radius of curvature shown in Figure 12. The sharper the curve the greater the force. The tradeoffs in forces F1 and F2 are shown in Figure 13. To accomplish this type of motion either or both F1 or F2 must be much larger than the 432-pound value of constant force. A second misfire operational mode was considered and selected. The recoil path and force is shown in Figure 14. In this scheme the gun is returned to the next firing position with the appropriate rearward velocity, as if a round had been fired by the hydraulic system. However, the round after the misfire cannot be fired as the additional impulse is more than the recoil system could tolerate. In this system the round after the misfire is ejected as a dud. Firing commences again on the second round after the misfire.

The misfire subsystem portion of the hydraulic schematic is shown in large scale in Figure 15.

The misfire control subsystem consists of a misfire detect valve, misfire engage valve and rotary misfire servo valve and piston, and a sensor connected to the logic circuit that detects the misfire engage valve in the "on" position.

When a misfire occurs, the gun moves forward of its normal furthermost recoil position. This movement opens the misfire detect valve (shown closed in Figure 15) which turns on the misfire engage valve. The misfire engage valve shuts off the large return line to the misfire servo piston/valve and opens the pressure line and return line to this piston/valve. The misfire

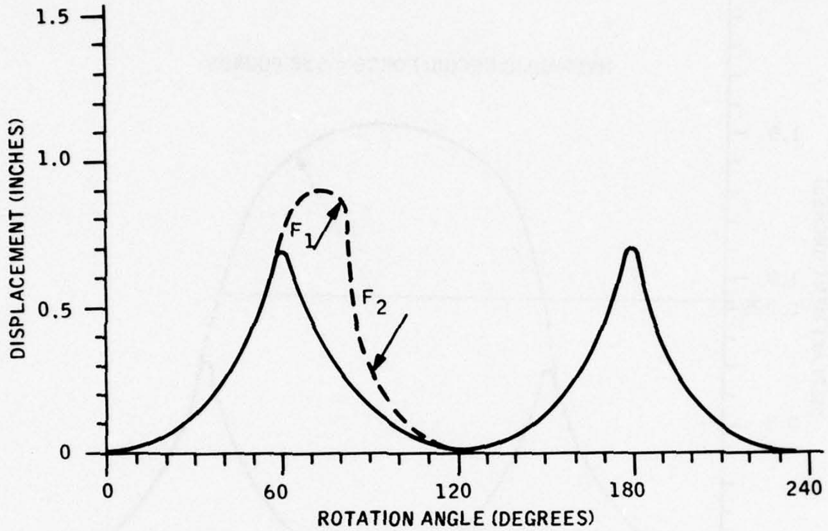


Figure 12. Misfire Recoil Control Technique - Initial Concept

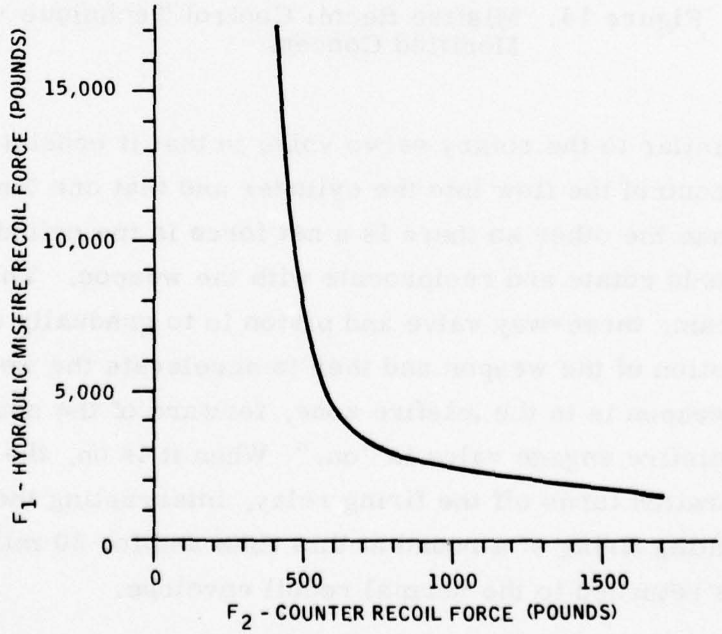


Figure 13. Counter Recoil Force Requirement - Initial Concept

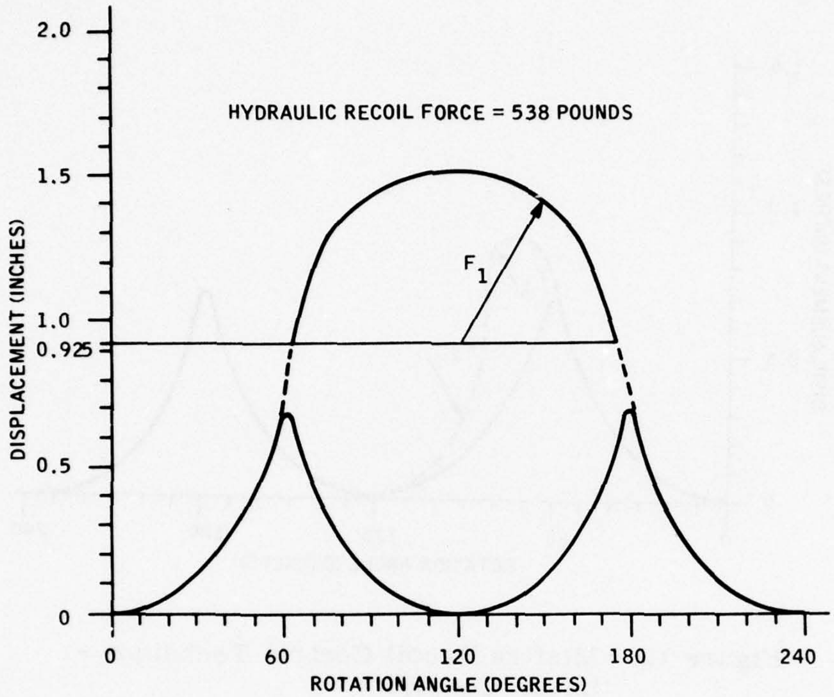


Figure 14. Misfire Recoil Control Technique - Modified Concept

servo is similar to the rotary servo valve in that it consists of cam-shaped lands that control the flow into the cylinder and that one land is larger in diameter than the other so there is a net force in the cylinder on the gun. The cam lands rotate and reciprocate with the weapon. The action of this combined cam, three-way valve and piston is to gradually decelerate the forward motion of the weapon and then to accelerate the weapon rearward. While the weapon is in the misfire zone, forward of the normal recoil envelope, the misfire engage valve is "on." When it is on, the misfire mode proximity switch turns off the firing relay, interrupting the firing line and thus preventing firing of a round at this time and for 30 milliseconds after the gun has returned to the normal recoil envelope.

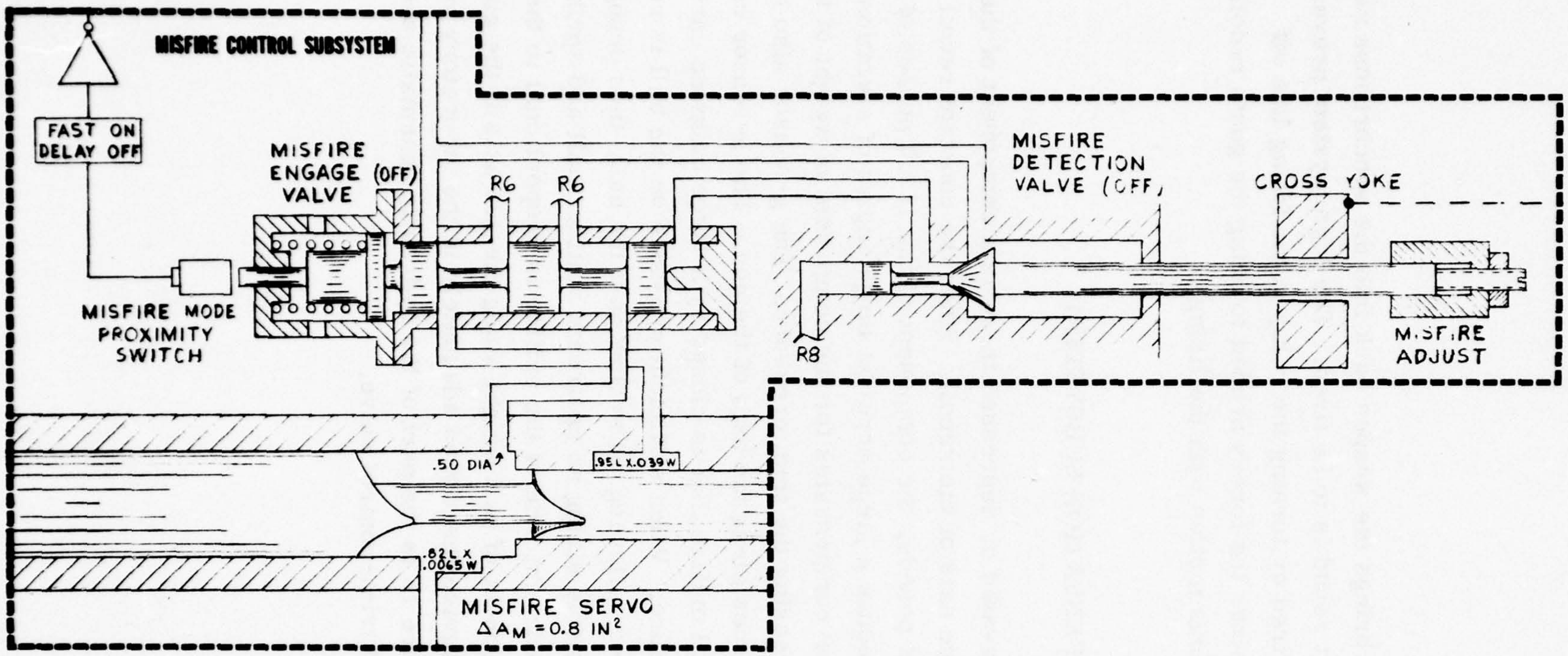


Figure 15. Misfire Control Subsystem Schematic

The misfire servo brings the weapon back into the synchronous recoil motion at the time the next round is to be fired. The logic system prevents this round from being fired by turning the relay in the firing line off. This mode of operation minimizes the forces needed to bring the gun's recoil motion back into synchronous motion with the firing.

ELEVATION COMPENSATION SUBSYSTEM

When the gun is elevated or depressed there is a component of the weight of the weapon along the axis of the recoil. Since the constant recoil force is estimated to be 432 pounds, the component of the 187.6 pounds of the recoiling parts would produce a large error at large angles of elevation or depression. The g-sensor compensates for the component of weight of the gun by increasing or decreasing the trim pressure. The g-sensor also compensates for helicopter g forces along the axis of the gun. The g-sensor consists of a valve with a small orifice that is closed by a large tungsten carbide ball under spring pressure. When sufficient pressure on the ball is reached, the orifice is opened, allowing oil to flow past the ball, thus dropping the pressure. By properly sizing an upstream orifice, ball and spring, the pressure on the upstream side of the orifice is proportional to the spring force and the component of ball weight along the gun axis if the gun is not horizontal. This device functioned adequately in the laboratory but not during practice. Figure 16 is the part of the hydraulic schematic showing the g-sensor valve and trim-control valve.

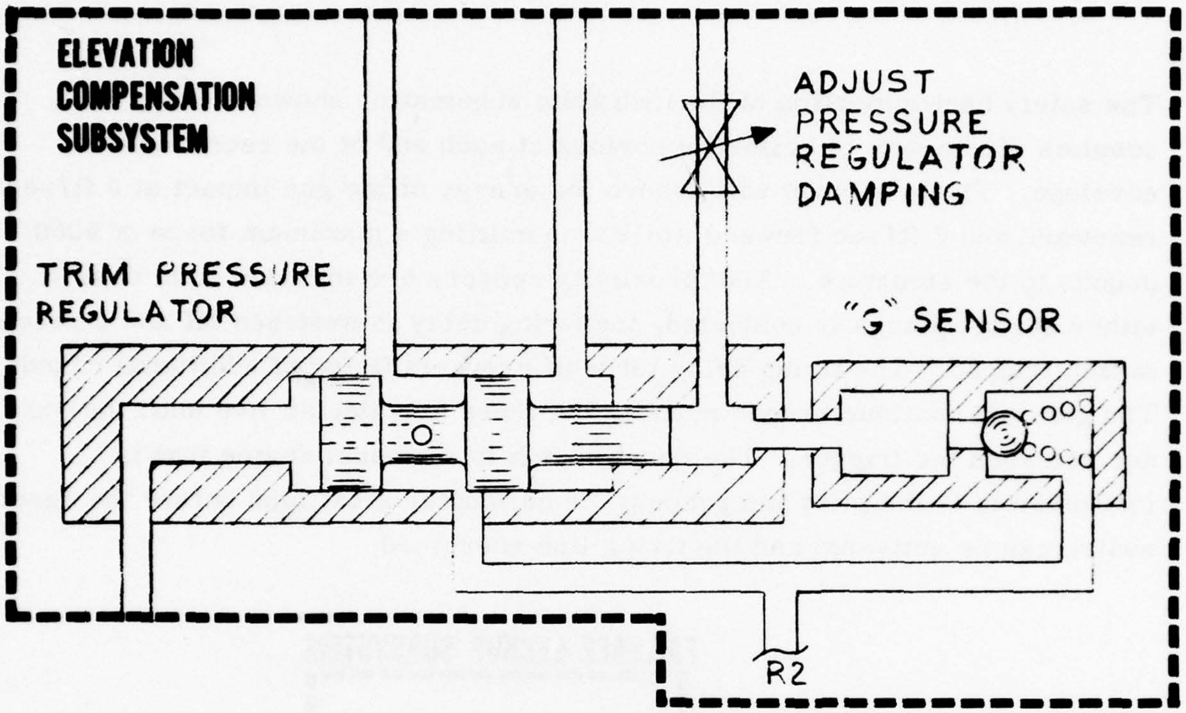


Figure 16. Elevation Compensation Subsystem Schematic

FAILSAFE BACKUP SUBSYSTEM

The principal hazardous failure of the recoil system is failure to reduce the recoil force. A hard-mounted 20mm gun firing an M56 round generates a peak recoil force of 25,000 pounds. If the weapon is against the helicopter frame without some energy absorber in between, the helicopter could be severely damaged. Also it is possible that, should the misfire control subsystem fail, the impact of a 187.6-pound gun traveling at over 3 ft/sec would also severely damage the airframe. Therefore, two actions are required to preclude damage in the event of system failure:

- Stop the gun from firing.
- Provide backup energy absorbers at each extreme of the gun recoil motion envelope to reduce the impact load to a suitable level.

The safety backup portion of the hydraulic schematic, shown in Figure 17, consists of two sets of belleville springs at each end of the recoil motion envelope. These springs will absorb the energy of the gun impact at 9 ft/sec rearward and 6 ft/sec forward while transmitting a maximum force of 9000 pounds to the structure. Also proximity sensors are included such that, if either set of springs is contacted, the firing delay is switched off and a reset switch tripped. The firing delay turn-off prevents firing of additional rounds. The gun will continue to feed rounds, but these are ejected live until the gunner releases the trigger. The reset switch is a manual device that is inaccessible to the pilot and gunner; the helicopter must land before the reset switch can be activated and the firing line energized.

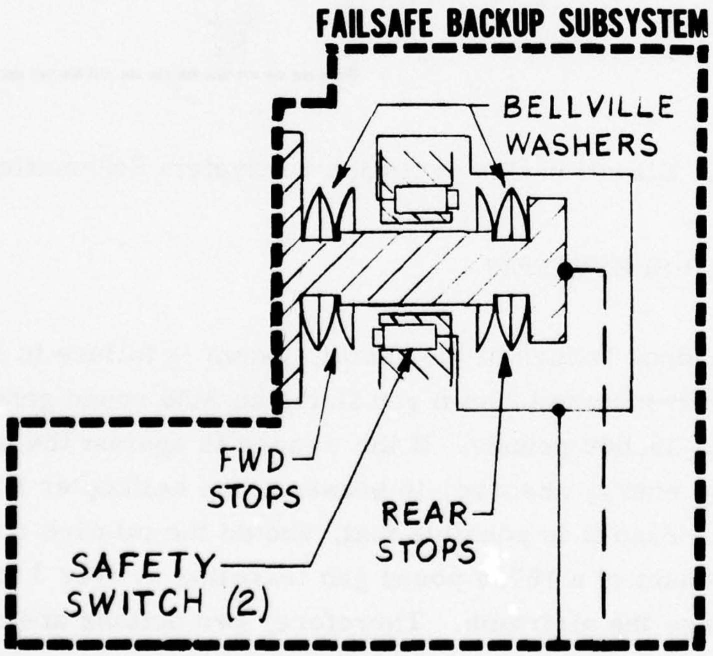


Figure 17. Failsafe Backup Subsystem Schematic

SYSTEM OPERATING MODES

The hydraulic constant recoil system has four operating modes:

- Hold Mode -- In this mode the weapon is held rigidly in a fixed position by the trim piston forcing the gun against the retracted start piston. The hydraulic power consumption in this mode is negligible. This mode is maintained until there is a round in the weapon to be fired.

- Firing Mode -- When the first live round is 39 milliseconds before firing, the recoil system is switched to the firing mode; it remains in this mode until the last round is fired. The switch to the firing mode is initiated by a sensor that signals the presence of a round to the electronic control box. In the firing mode the start piston that has held the weapon in the start position is extended and no longer restrains gun recoil motion. This enables the weapon to move forward for "out-of-battery" firing under the control of the trim piston and rotary servo valve. Rearward motion occurs when the weapon fires. The rearward motion is brought to a stop and the weapon is accelerated forward for firing the next round by the trim piston and rotary servo valve. When the last round is fired, the recoil system returns to the hold mode.

- Misfire Mode -- If a round does not fire (misfire) the forward motion continues until the weapon enters the misfire displacement zone. A detect valve then switches on a large misfire control hydraulic piston that decelerates the forward motion and then accelerates the weapon rearward into the normal firing displacement zone. During this excursion the firing line is interrupted by the electronic control which duds the first round after the misfire. Firing resumes on the second round after the misfire.

- Safety Backup Mode -- In the event of hydraulic failure, two sets of belleville springs will stop the forward or rearward motion of the weapon without damage to the aircraft. Should this occur, the firing line is interrupted, and all subsequent rounds are dudded.

  During the initial evaluation firings the system was slightly out of adjustment resulting in the recoil system creeping into the misfire zone. Once this proper adjustment was made the recoil system operated in the firing mode. At no time was the safety backup mode used in the flight tests.

SECTION IV
HARDWARE DESCRIPTION

This section describes the physical implementation of the constant force recoil system test prototype, both as originally built and as modified before and during field and flightworthiness testing. Assembly of the recoil system to the 20mm M197 gun and total system installation in the test helicopter turret are also discussed.

RECOIL SYSTEM/WEAPON ASSEMBLY

The constant recoil design assembly before testing is shown in Figure 18. The recoil assembly is mounted on the elevation saddle of the M97 turret, and the M197 weapon is mounted on the recoil assembly. The recoil assembly had to be adapted to both the existing turret and weapon with minimum modifications to each.

Turret modifications involved slight changes to the elevation saddle - removal by machining of the two projections that hold the existing recoil adapter in the front of the saddle and disassembly of the mount and its supporting structure from the rear of the saddle. A large aluminum plate was attached to the top of the saddle, and two support blocks were bolted to the underside of the plate, each block containing ball bushings in which the weapon support rods ride. The front of the weapon is rigidly attached to the support rods by the weapon supports. The intent of this part of the design is to support the front end of the weapon by firmly attaching it to the support rods which are free to translate along the recoil direction with minimum friction.

The weapon is also supported at the rear end of the outside of the rotary valve assembly. This support is shown in Figure 19. The modification to the weapon consisted of removing the back plate and needle bearings and replacing these with a modified plate and roller bearings and a ball bushing as shown in Figure 19. Also the connector to the firing pin of the weapon was replaced with one of smaller height.

The rotary valve assembly fits inside the receiver of the weapon, and the rotary valve spool that contains the trim, servo and misfire pistons is keyed to the front of the M197 receiver by a plate. The purpose of this assembly is to minimize translational sliding friction by supporting the weapon weight with the support rods sliding in ball bushings and the rear of the weapon receiver sliding on the rotary valve assembly. The force on the weapon to control recoil is applied by the rotary valve spool along the centerline of the weapon. As the test program proceeded several changes were made in this arrangement because of the larger than computed recoil forces that occurred immediately upon firing. These forces are believed to result from increased friction caused by the pitch-up motion of the gun as it fires. The gun barrel that fires is above the center of gravity of the weapon, thus producing a large angular "pitch-up" impulse. To minimize this angular deflection during firing, the support rods were lengthened, and an additional set of ball bushings were added (Figure 20). This modification helped slightly; however, the peaks, approximately 900 pounds, were still considered undesirable. Analysis of test results still indicated abnormal friction. This was believed still a result of the pitch-up torque bending the end of the rotary valve shaft. An additional modification was made (Figure 21) in which two universal joints were added along with a stand-off support to provide a length between the U joints. It was hoped that this would prevent the pitch-up movement from transmitting large bending moments to the lap-fitted rotary valve shaft. Tests of this configuration indicate slight improvements, and they are analyzed in detail in the Test Results Section.

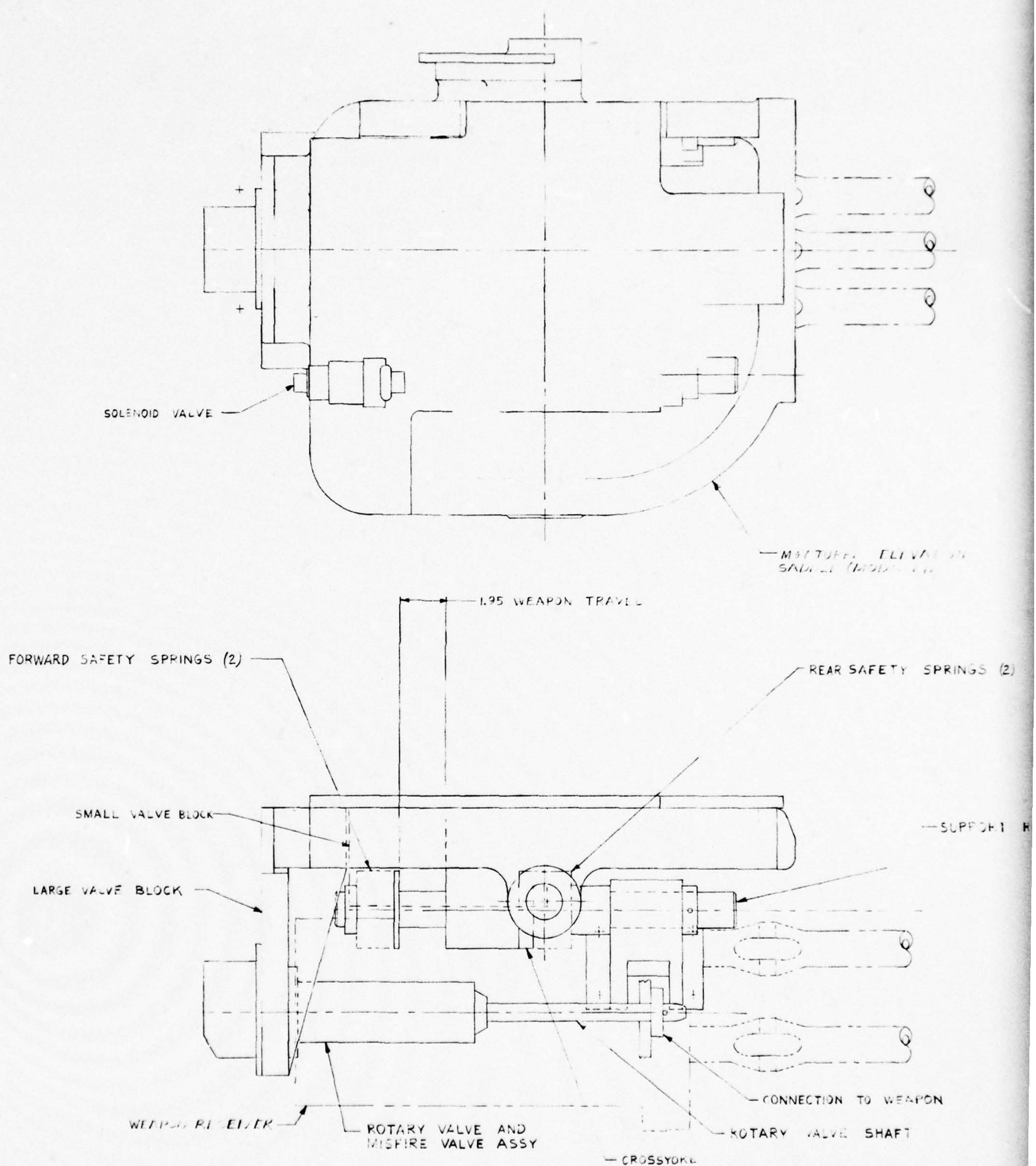
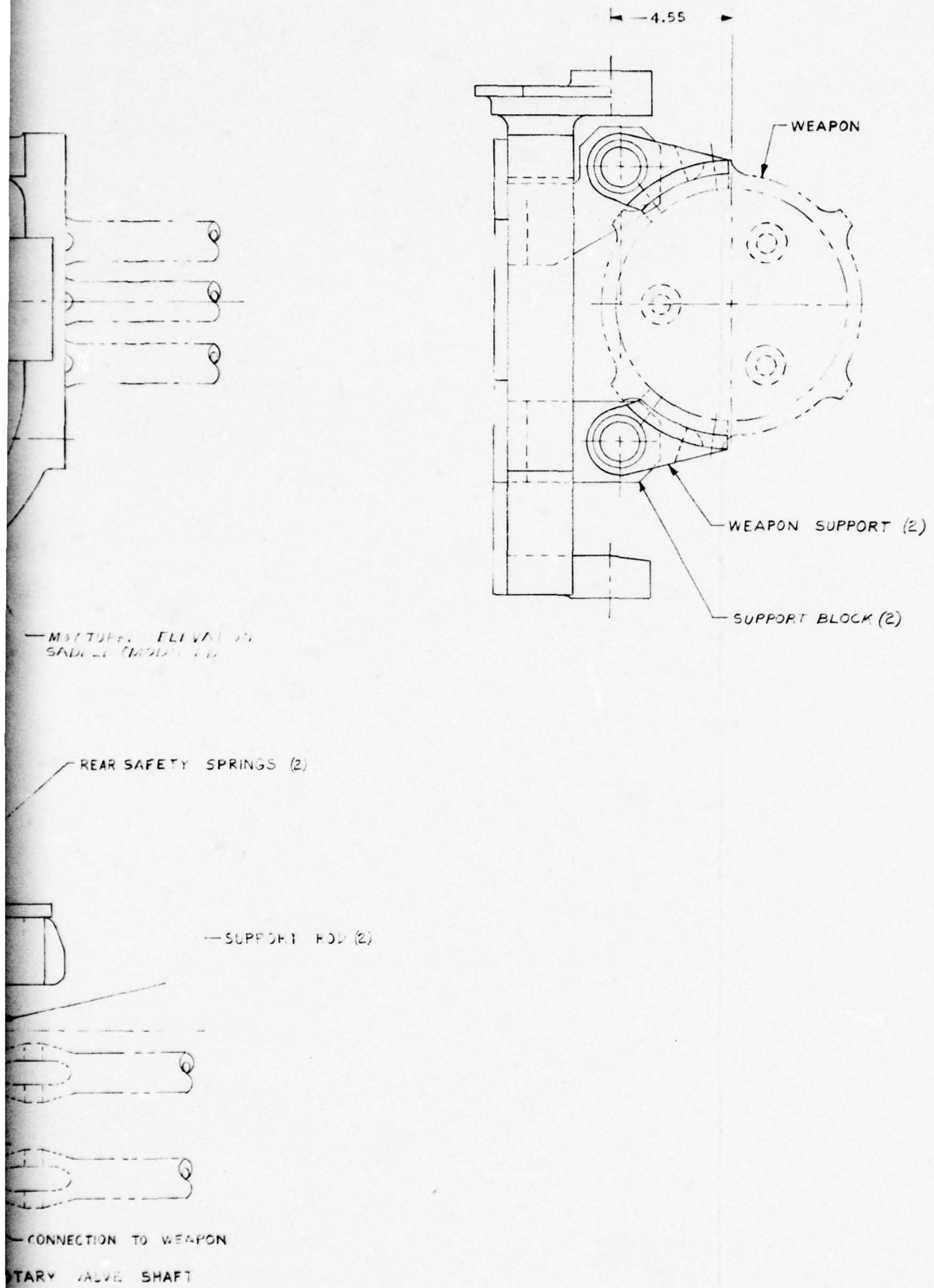


Figure 18. Constant-Force Recoil Design Assembly



Recoil Design Assembly Before Testing

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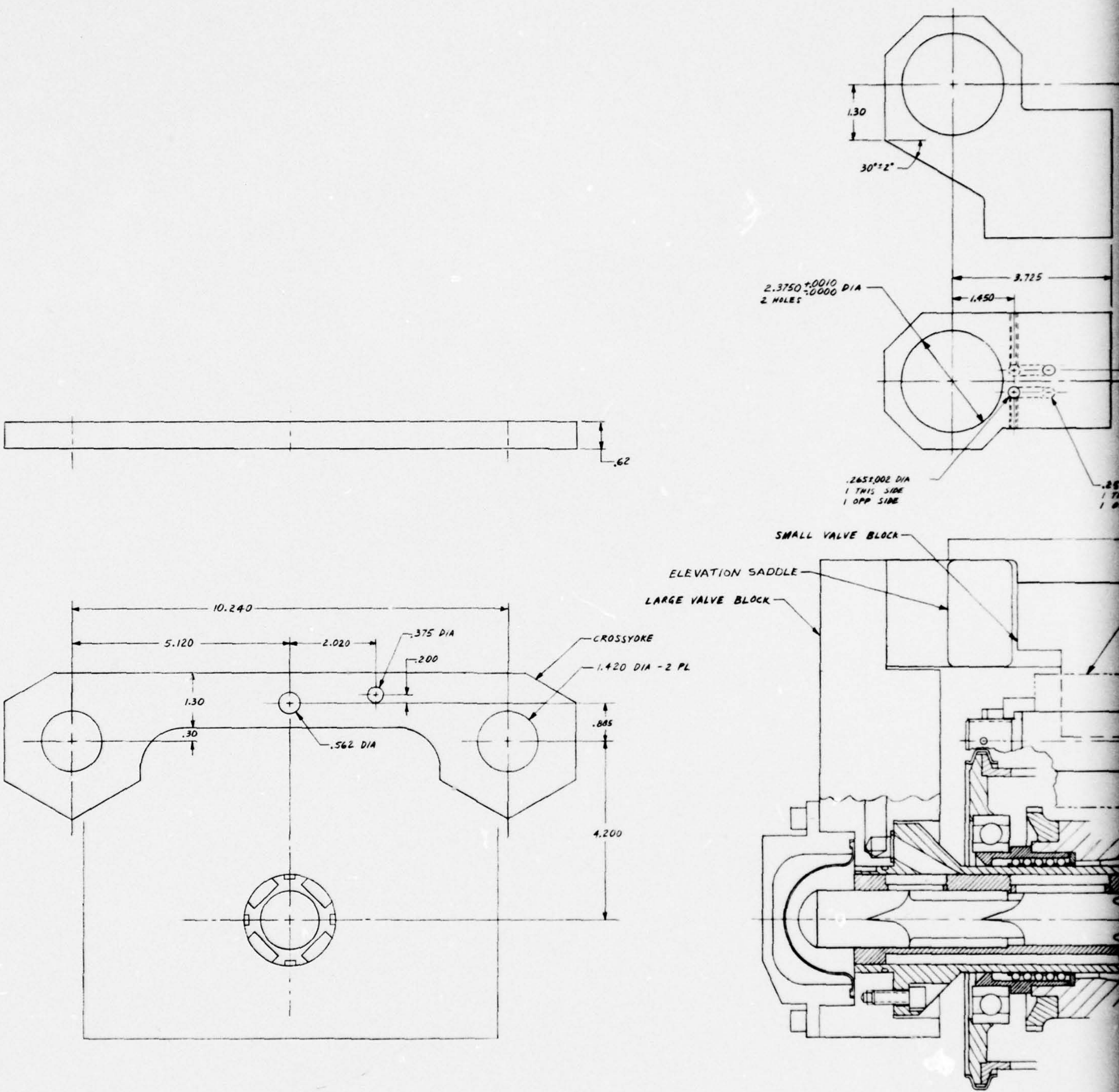
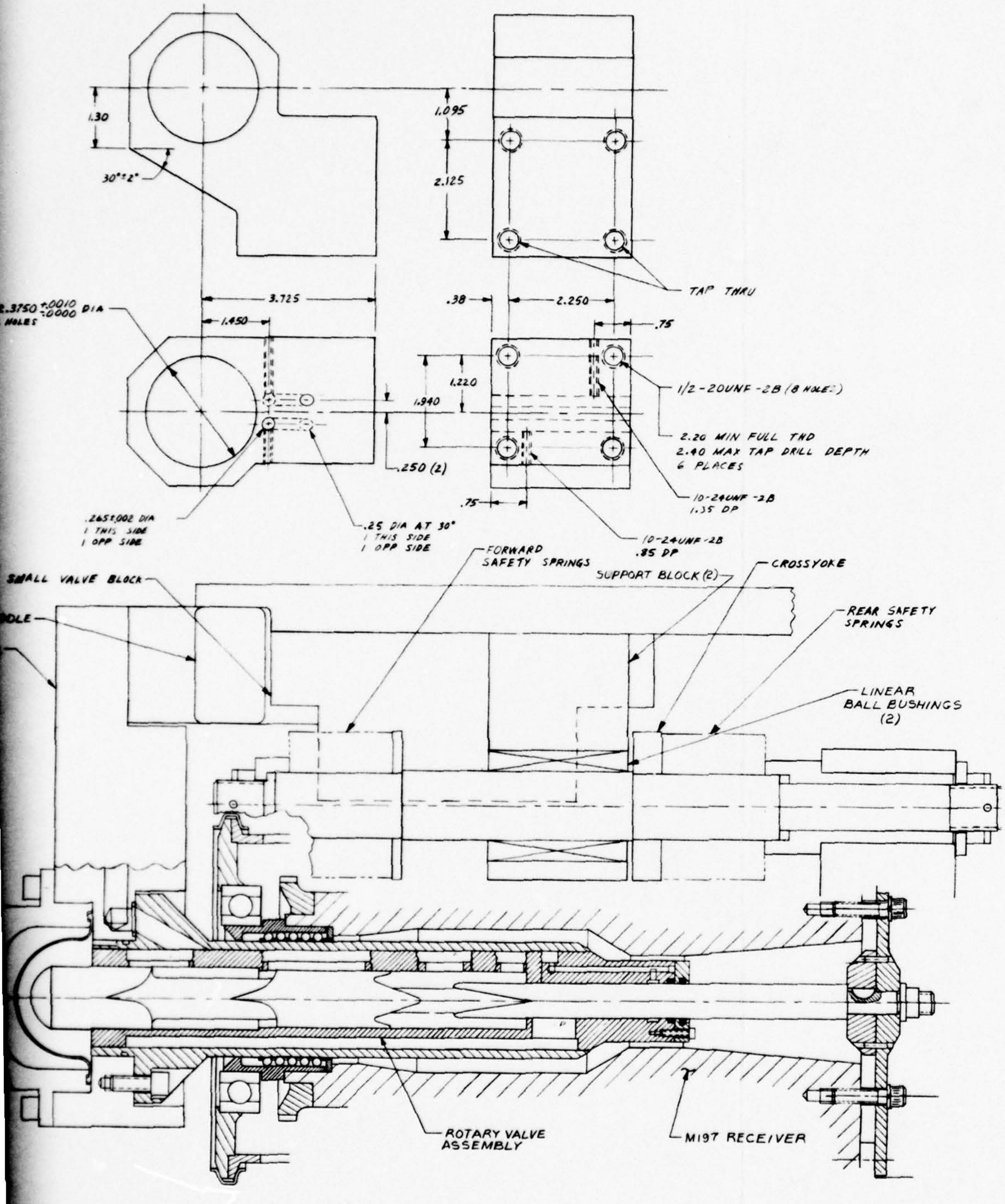


Figure 19. Rotary Valve and Misfire Valve Lay



Valve and Misfire Valve Layout

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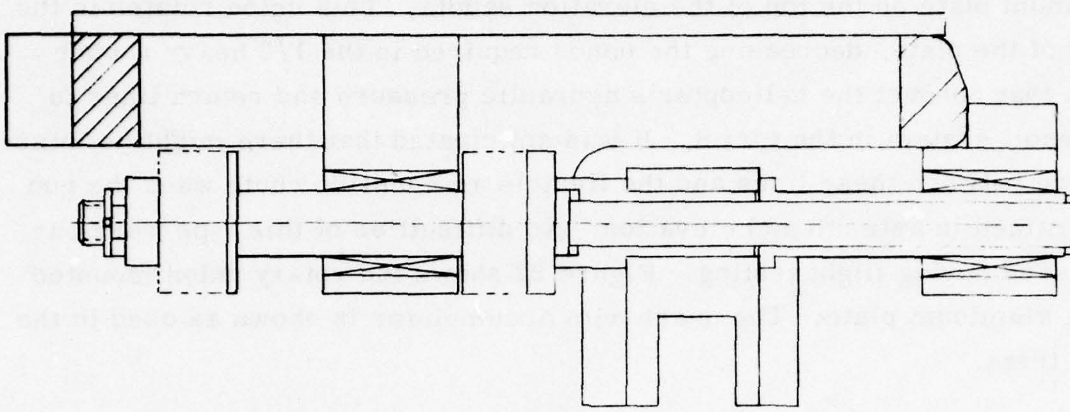


Figure 20. Gun Barrel with Lengthened Support Rods and Additional Ball Bushings

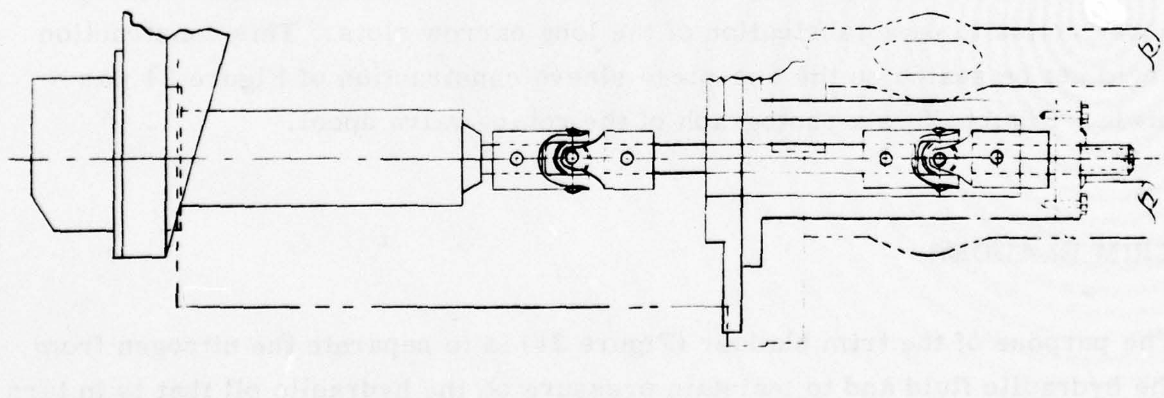


Figure 21. Gun Barrel Showing Addition of Two Universal Joints

After field testing but prior to flight testing, a rotary union was added to the aluminum plate on the top of the elevation saddle. This union rotates in the plane of the plate, decreasing the bends required in the 1/2 heavy rubber hoses that connect the helicopter's hydraulic pressure and return lines to the recoil system in the turret. It was anticipated that there might be interference between these lines and the flexible ammunition chute when the gun was trained in azimuth and elevation. No difficulties of this type were encountered during flight testing. Figure 22 shows the rotary union mounted to the aluminum plate. The quart trim accumulator is shown as used in the flight tests.

ROTARY VALVE ASSEMBLY

Figures 23 and 24 are detail drawings of the rotary valve spool and sleeve. These drawings illustrate the servo valve lands for both the recoil and misfire servo. The first attempt to make the sleeve consisted of a two-piece construction to ease fabrication of the long narrow slots. This construction could not be sealed so the one-piece sleeve construction of Figure 24 was made. Figure 25 is a photograph of the rotary valve spool.

TRIM BLADDER

The purpose of the trim bladder (Figure 26) is to separate the nitrogen from the hydraulic fluid and to maintain pressure on the hydraulic oil that is in turn transmitted to the trim position. The reason for its location and the rounded end on the trim position is to mitigate pressure spikes upon firing. In the previous contract, the connection of oil on the trim piston to the nitrogen in the accumulator was through a small oil line to the oil side of the accumulator. Just before the firing the oil in this line would be moving rapidly toward the

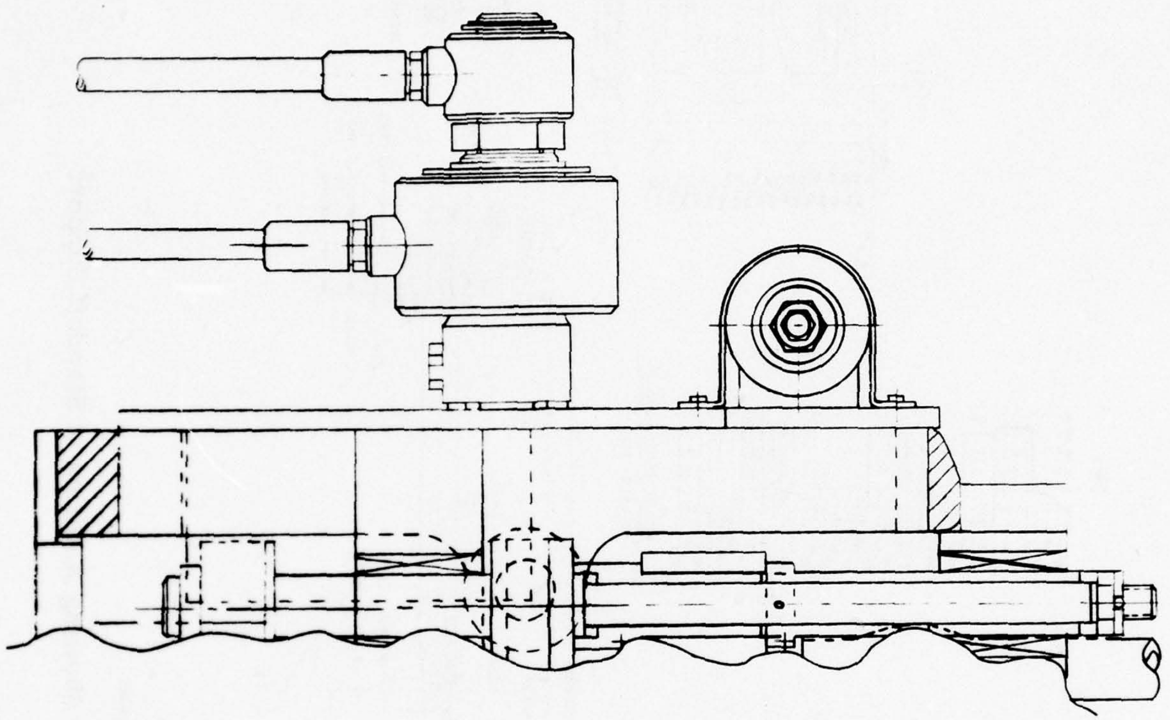
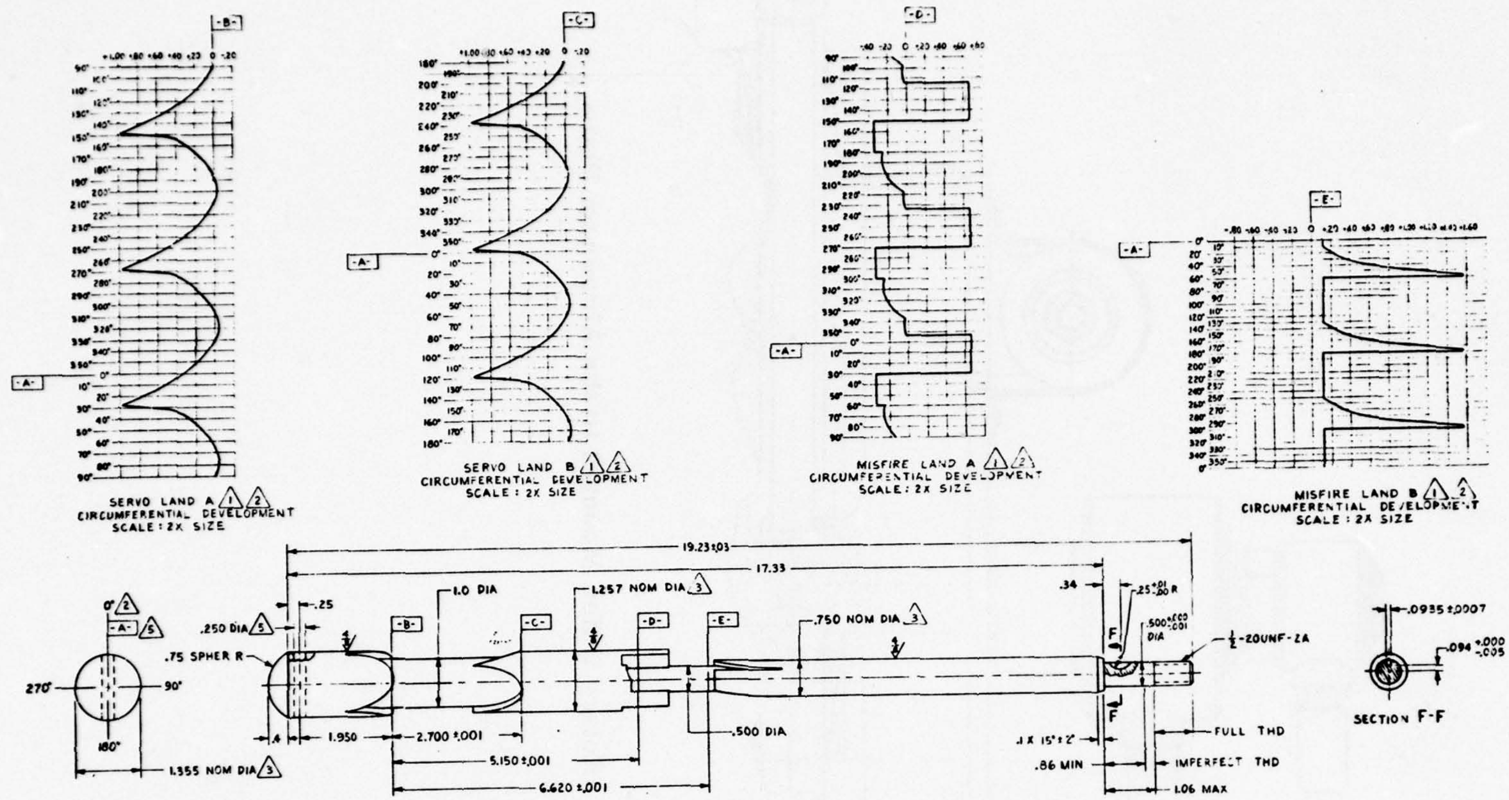


Figure 22. Rotary Union Mounted to the Aluminum Plate



5 -A- IS DEFINED BY .250 DIA HOLE

4-EXCEPT AS NOTED, ALL SURFACES

3-INDICATED DIAMETERS TO HAVE .0001 TO .0003 TOTAL DIAMETRAL CLEARANCE WITH CORESPONDING DIAMETERS ON PART 10052535-101

2-THE ANGLE COORDINATE OF THE LANDS OF THE CAM SURFACES IS MEASURED CLOCKWISE POSITIVE IN THE END VIEW AS SHOWN

1-ACTUAL LAND DIMENSIONS MUST BE DETERMINED WITH N/C MACHINE READING COMPUTER MEMORY

Figure 23. Rotary Valve Spool Showing Addition of Standoff Support

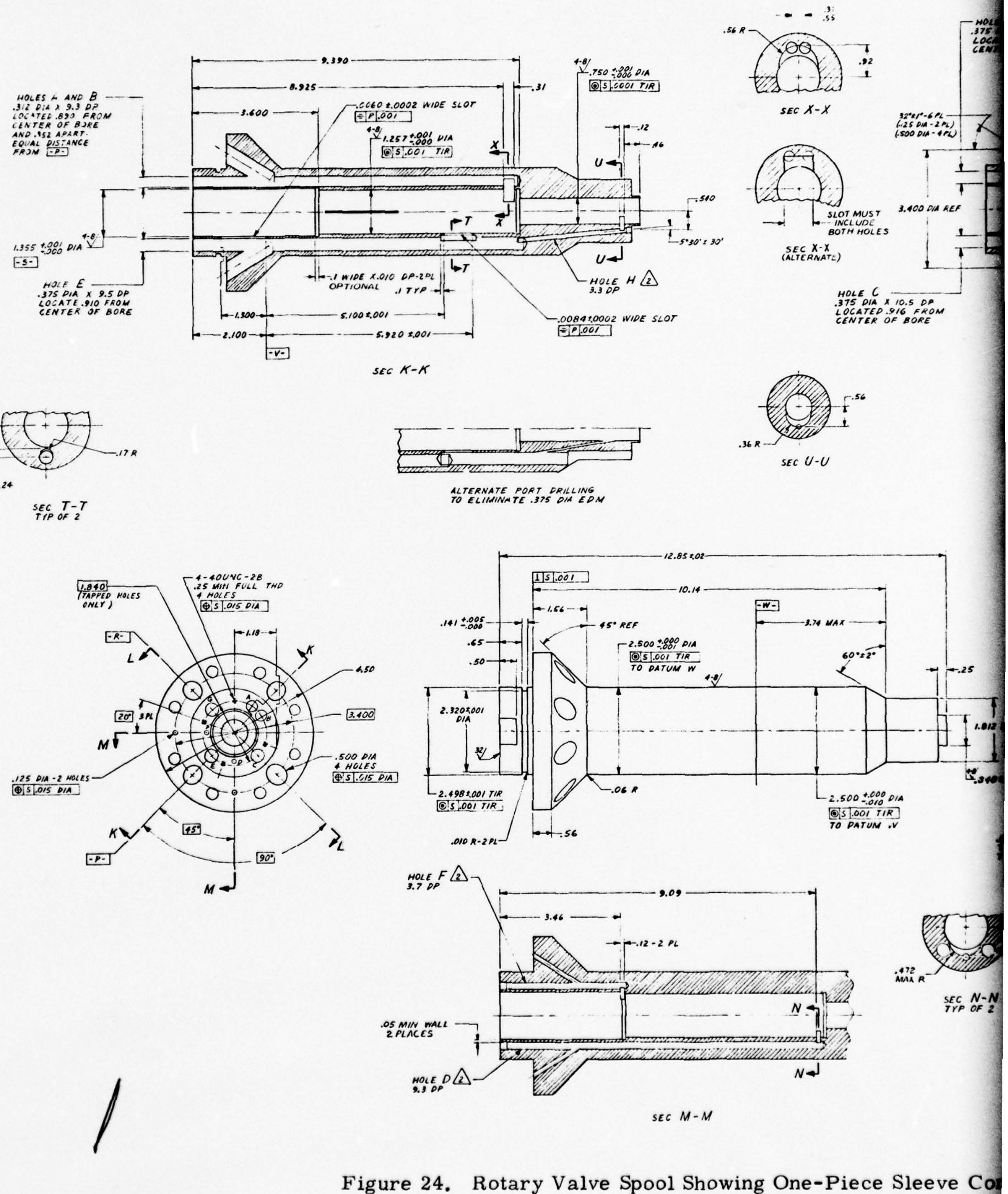
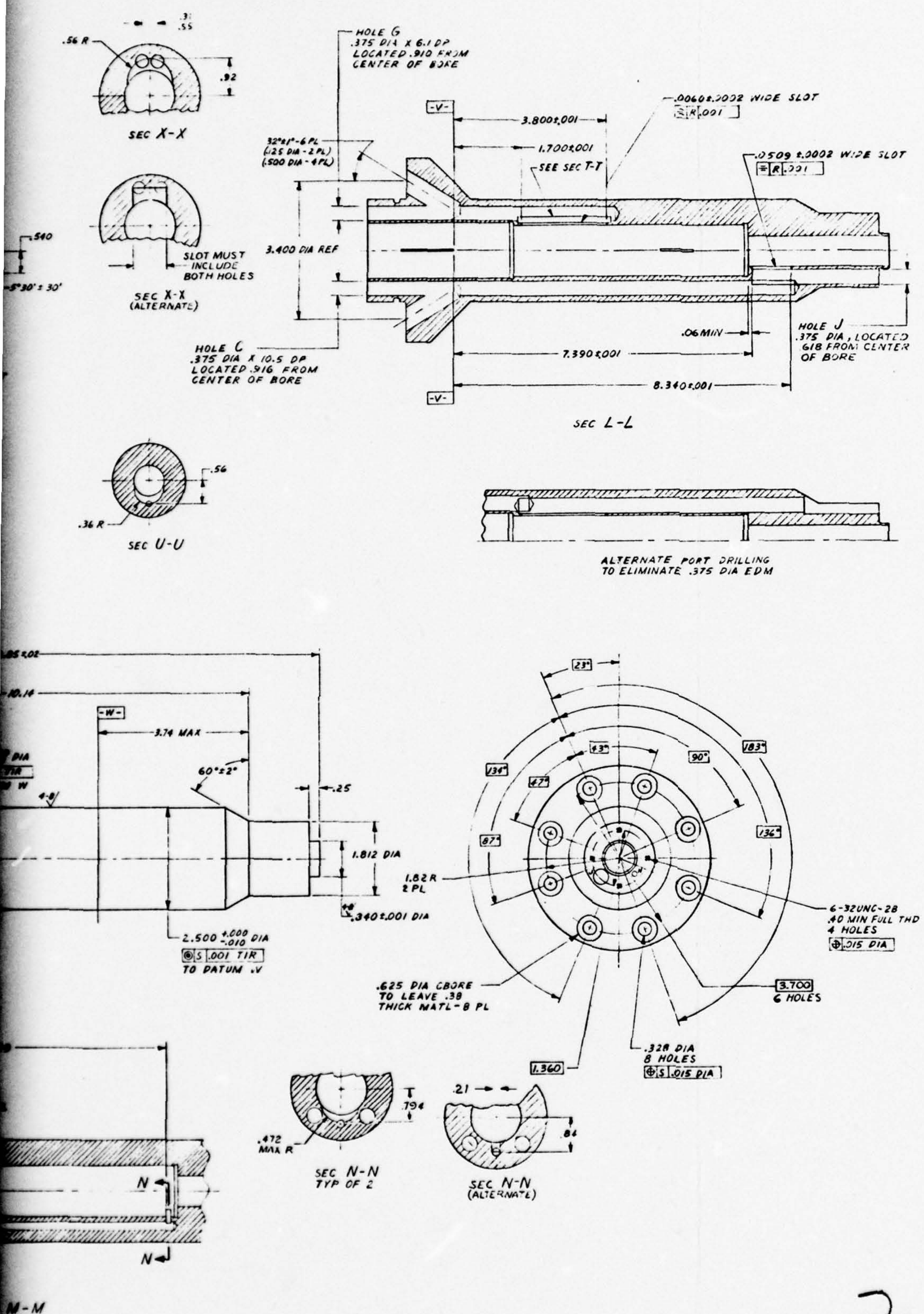


Figure 24. Rotary Valve Spool Showing One-Piece Sleeve Co



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Showing One-Piece Sleeve Construction

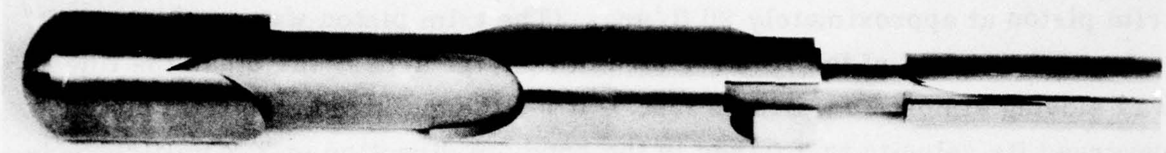

Figure 25. Rotary Valve Spool Configuration

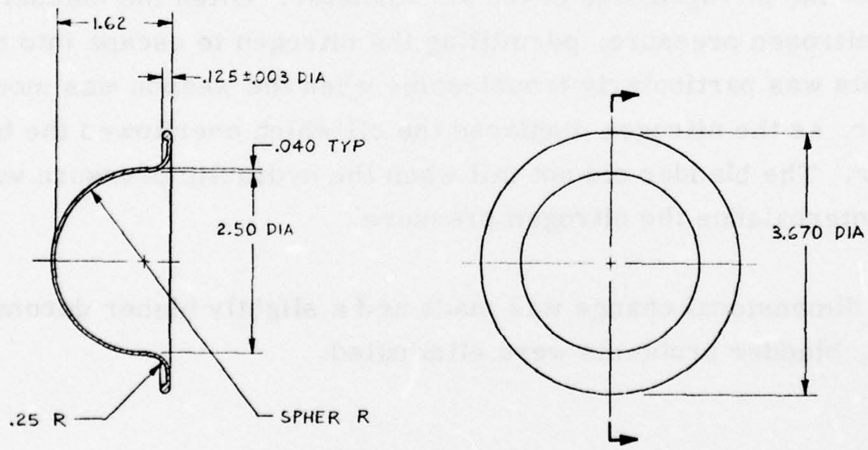

Figure 26. Trim Bladder Layout

trim piston at approximately 90 ft/sec. (The trim piston was moving at 3 ft/sec, and, because of the relative size of the pipe areas, the oil in the lines was moving almost 30 times as fast.) When the gun fired, the trim piston reversed its velocity to 3 ft/sec in the opposite direction in 2.7 milliseconds. This required the oil in the lines to be accelerated to a net 180 ft/sec velocity change in the same time period. The resulting pressure spikes required to accelerate the oil also produced force spikes of over 2500 pounds on the trim piston.

In the present design, the rearward acceleration of the trim piston is transferred to the oil and to the nitrogen over the large area of the bladder, completely eliminating the pressure spikes of the previous design.

However, a slight dimensional error in the size of the bladder that went undetected until very late in the program made this component the most troublesome item in the entire design. The preparation-for-firing procedure was to pressurize the nitrogen side of the accumulator. Often the bladder failed to hold the nitrogen pressure, permitting the nitrogen to escape into the hydraulic side. This was particularly troublesome when the weapon was mounted on the helicopter, as the nitrogen displaced the oil which overflowed the helicopter's reservoir. The bladder did not fail when the hydraulic pressure was brought up to counterbalance the nitrogen pressure.

Once the dimensional change was made and a slightly higher durometer material was used, bladder problems were eliminated.

LARGE VALVE BLOCK

The large valve block is bolted to the back end of the elevation saddle. In addition to supporting the rotary valve assembly, it contains the elevation g-valve and trim pressure regulator valve assembly, the misfire engage valve, and power on/off valve. It is a large hydraulic manifold in which most of the connection between the valves is made by holes drilled in the block. The only difficulty encountered with this block is that the pressure passage to the g-sensor was too small, resulting in a pressure drop in the supply line to the g-sensor. The g-sensor was unable to maintain the proper pressure level during recoil operation and was replaced with a pressure regulator. Figure 27 shows a large valve block with the pressure regulator attached as assembled on the AH-1G helicopter. Figure 28 is a drawing of the large valve block, and Figure 29 shows the four operational valves. The misfire, power on/off and start run valves are surplus spool valves modified for the hydraulic circuit.

The purpose of the trim pressure regulator valve is to maintain the trim pressure at the nominal value of 584 psi while the helicopter is flying and not firing. This conserves oil because the g-sensor is not in the circuit at this time. When the gunner pulls the trigger, the solenoid valve initiates the power on/off valve which switches control to the g-sensor valve to adjust the trim pressure for the elevation at the time of firing. Due to the failure of the g-sensor valve to maintain pressure in tests, both it and the trim pressure regulator valve were eliminated from the hydraulic circuit by the pressure regulator. Time did not permit investigating the g-sensor failure. It is our opinion that a regulated flow to the g-sensor would eliminate the deficiency; however, since the helicopter firings took place at a fixed predictable gun elevation the pressure regulator was adequate for the flight tests.

Figure 30 is a schematic of the modified hydraulic circuit used in the test program.

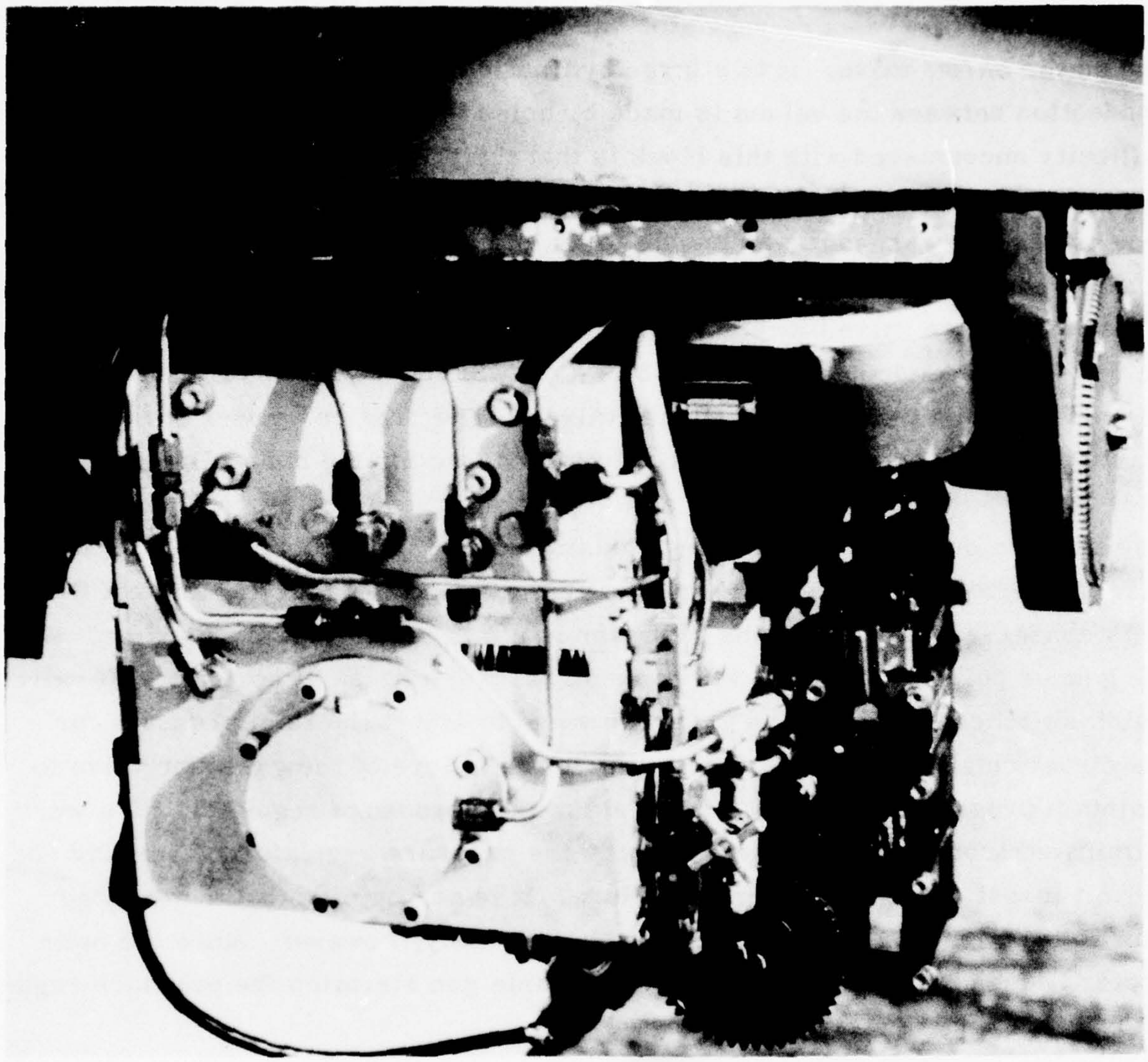

Figure 27. Large Valve Block with Attached Pressure Regulator as Assembled on the AH-1G Helicopter

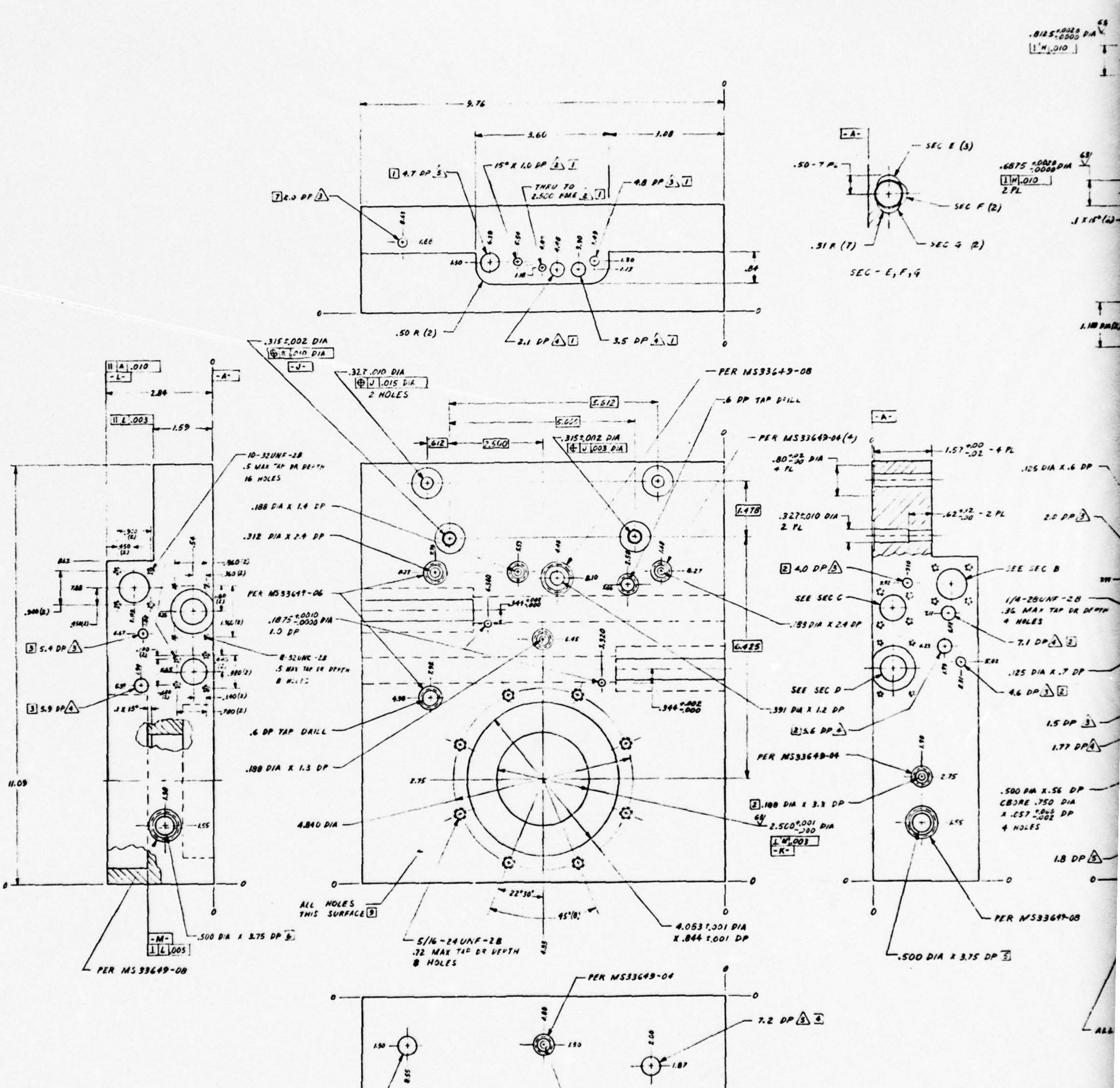

Figure 28. Large Valve Block without Three Valves

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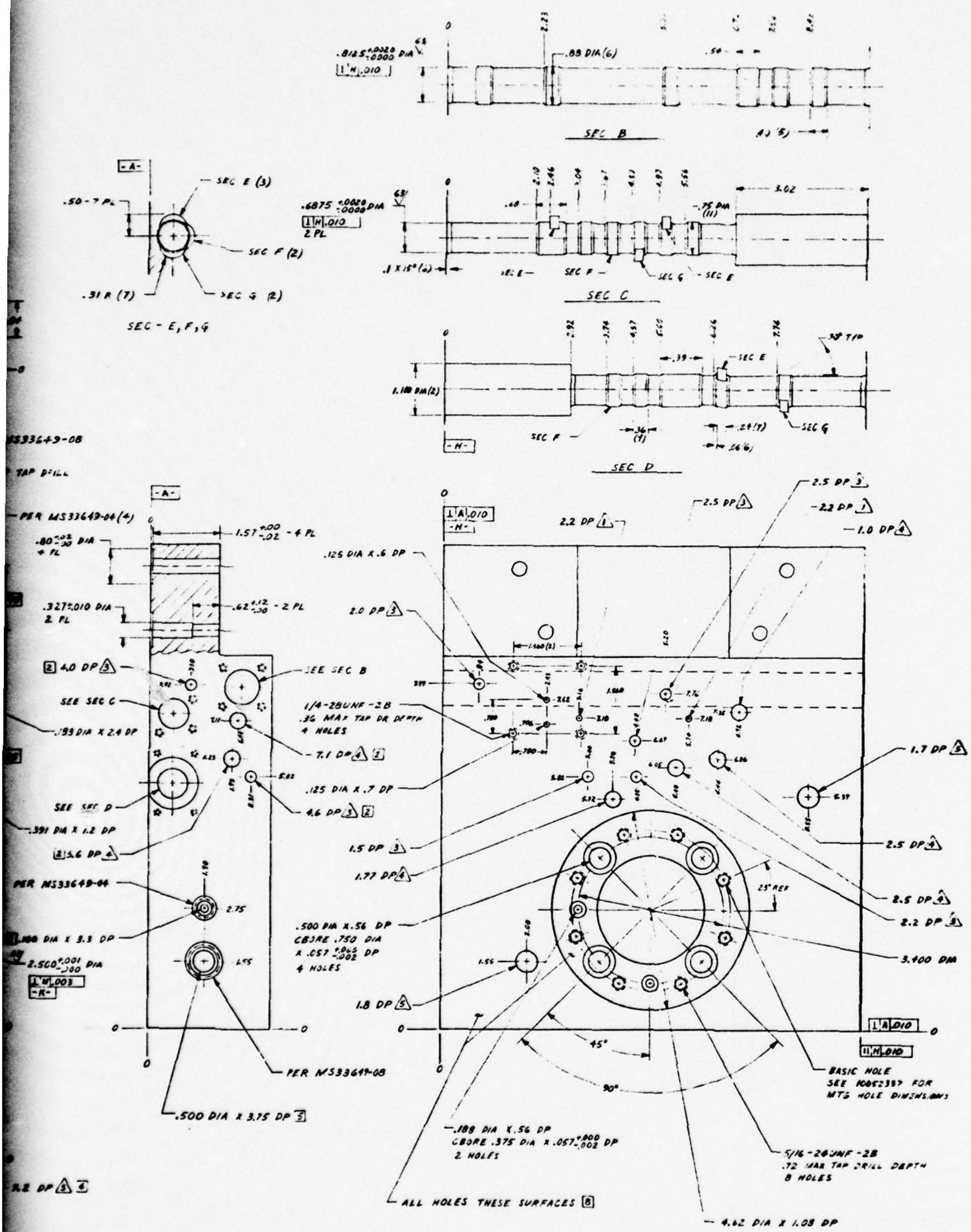

ve Block without Three Valves

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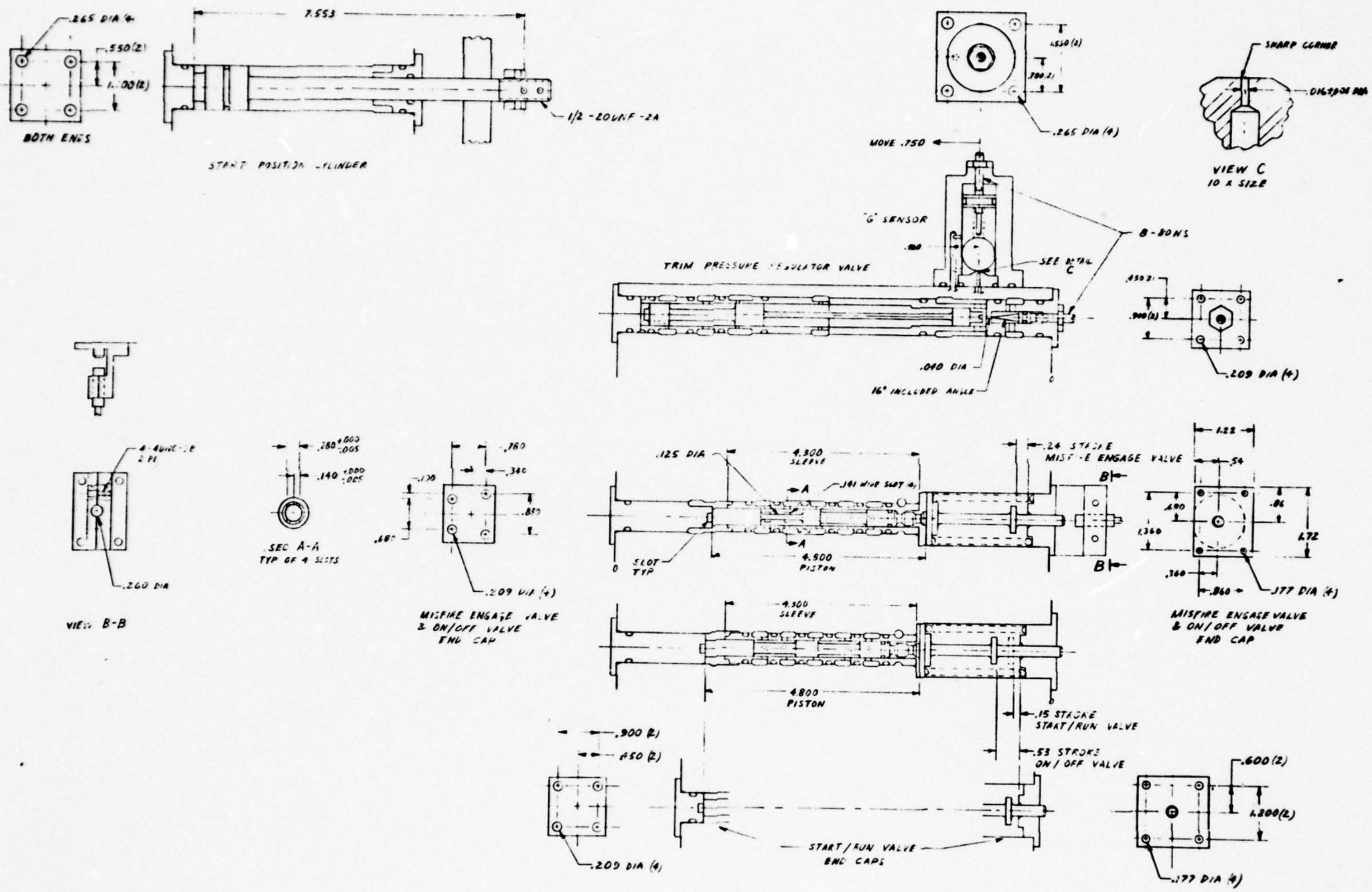


Figure 29. Four-Valve Layout

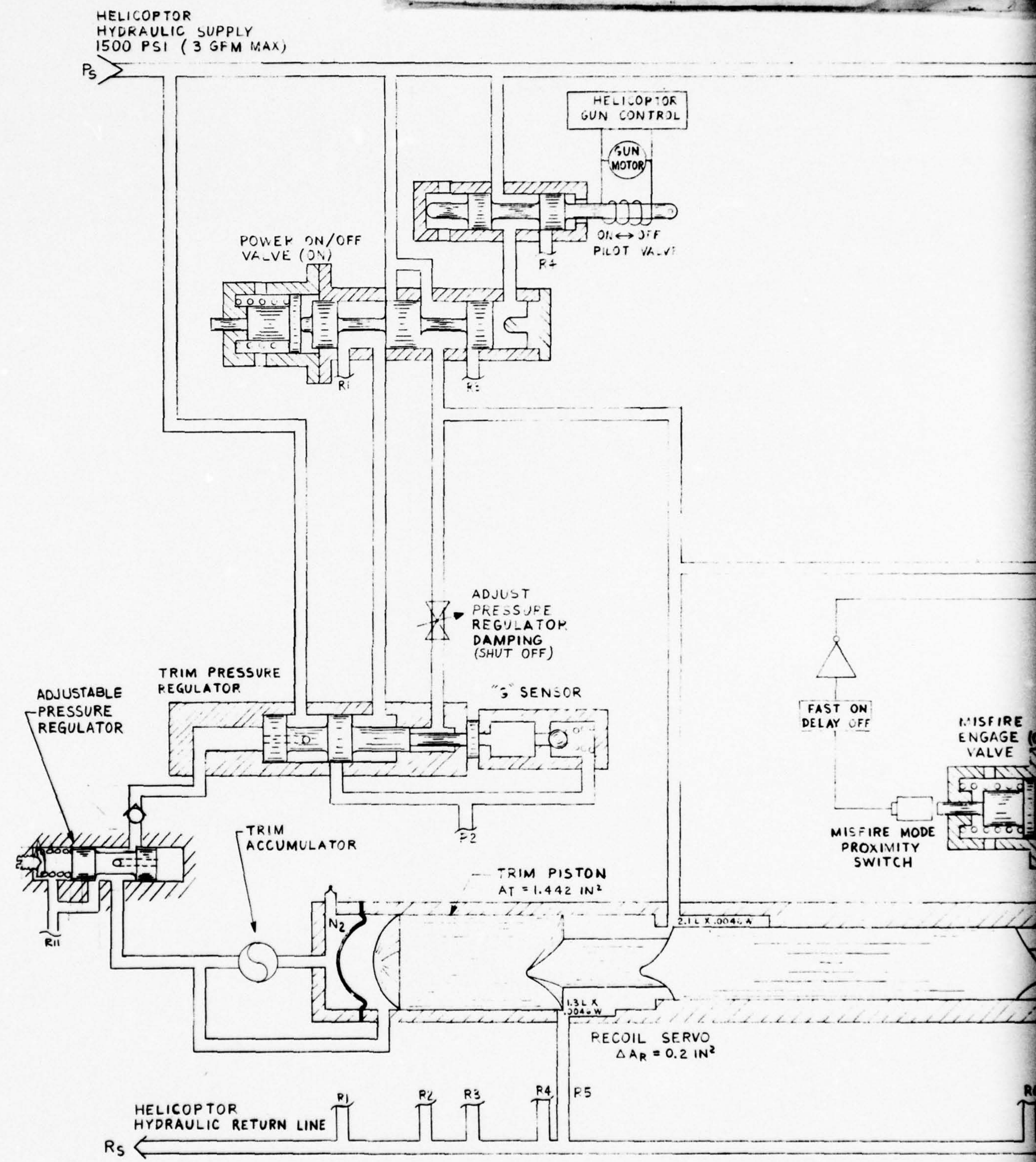
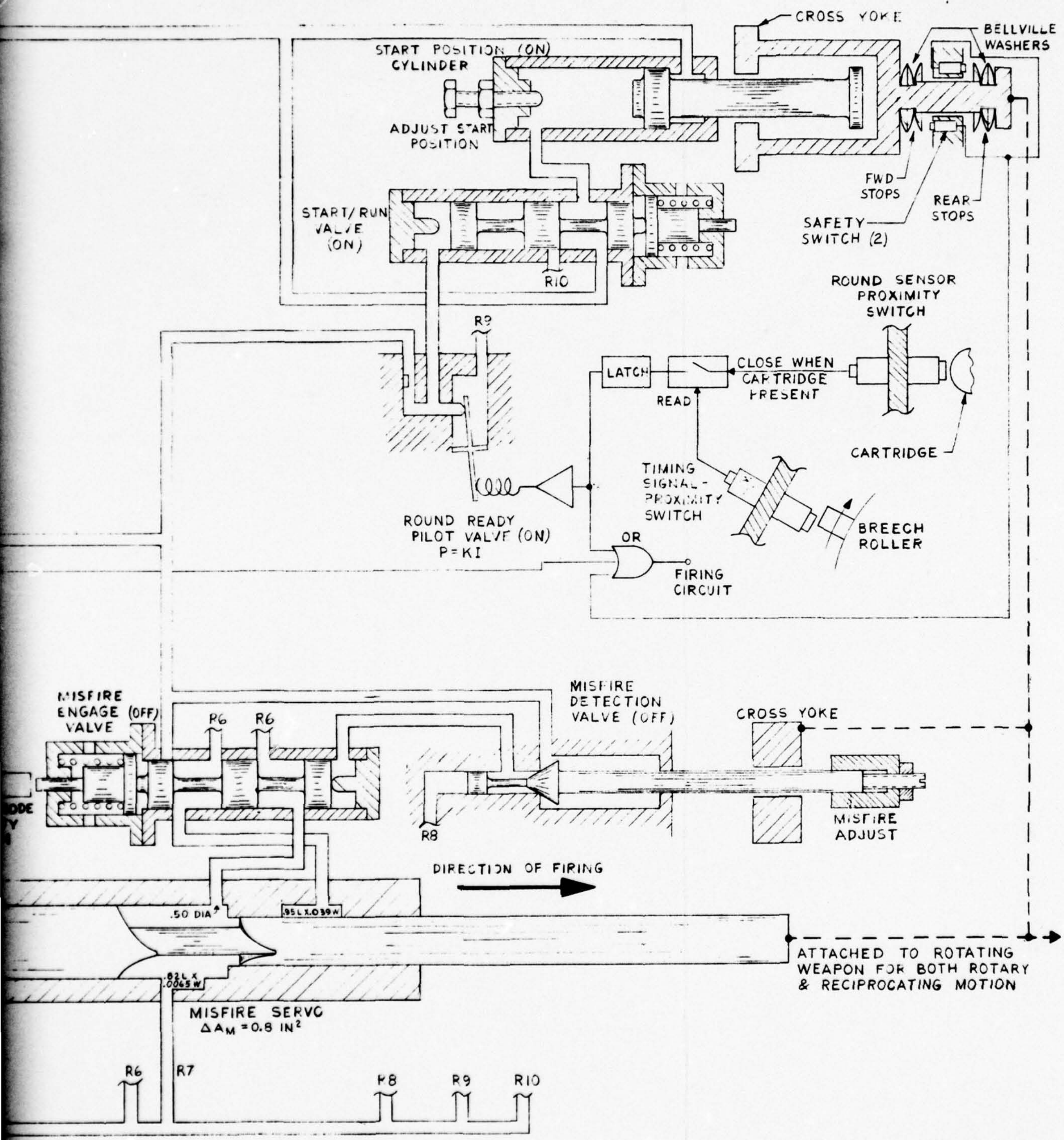


Figure 30. Modified Hydraulic Constant-



c Constant-Force Recoil System Schematic

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SMALL VALVE BLOCK

The small valve block (Figure 31) contains the start/run valve, the fast acting electrohydraulic valve, the misfire detect valve and the start piston. This set of valves is located on the underside of the aluminum plate attached to the saddle.

ELECTRONIC CONTROL UNIT

The gun control logic controls the round-ready pilot valve and the fire control enable relay. The circuit is initially reset (no round-ready and no fire control relay closure) when power is applied.

At the time the breech roller comes into position, the logic starts looking for a round to be sensed. After the breech roller leaves the position, the round-ready and fire control are set if a round is present or reset if a round is not present. The condition is retained until the breech roller again comes into position at which time the state is updated. The fire control relay is reset if the cross yoke is sensed and remains reset until 30 milliseconds after the cross yoke clears. The next breech roller into the detection position updates the fire control condition.

The main logic power relay is dumped (causing the round-ready and fire control relay to drop) if either the forward stop sensor or rear stop sensor is activated. A manual reset must be performed to reactivate the circuit.

The logic system is fabricated from standard CMOS integrated circuits and is very noise-immune. With proper packaging, the circuits easily withstood aircraft vibration.

The electronic control main timing diagram is shown in Figure 32 and the electronic latch timing diagram in Figure 33. Figure 34 is a schematic of the gun control logic electronics, and Figure 35 shows the electronic control unit mounted in the ammunition bay of the test helicopter.

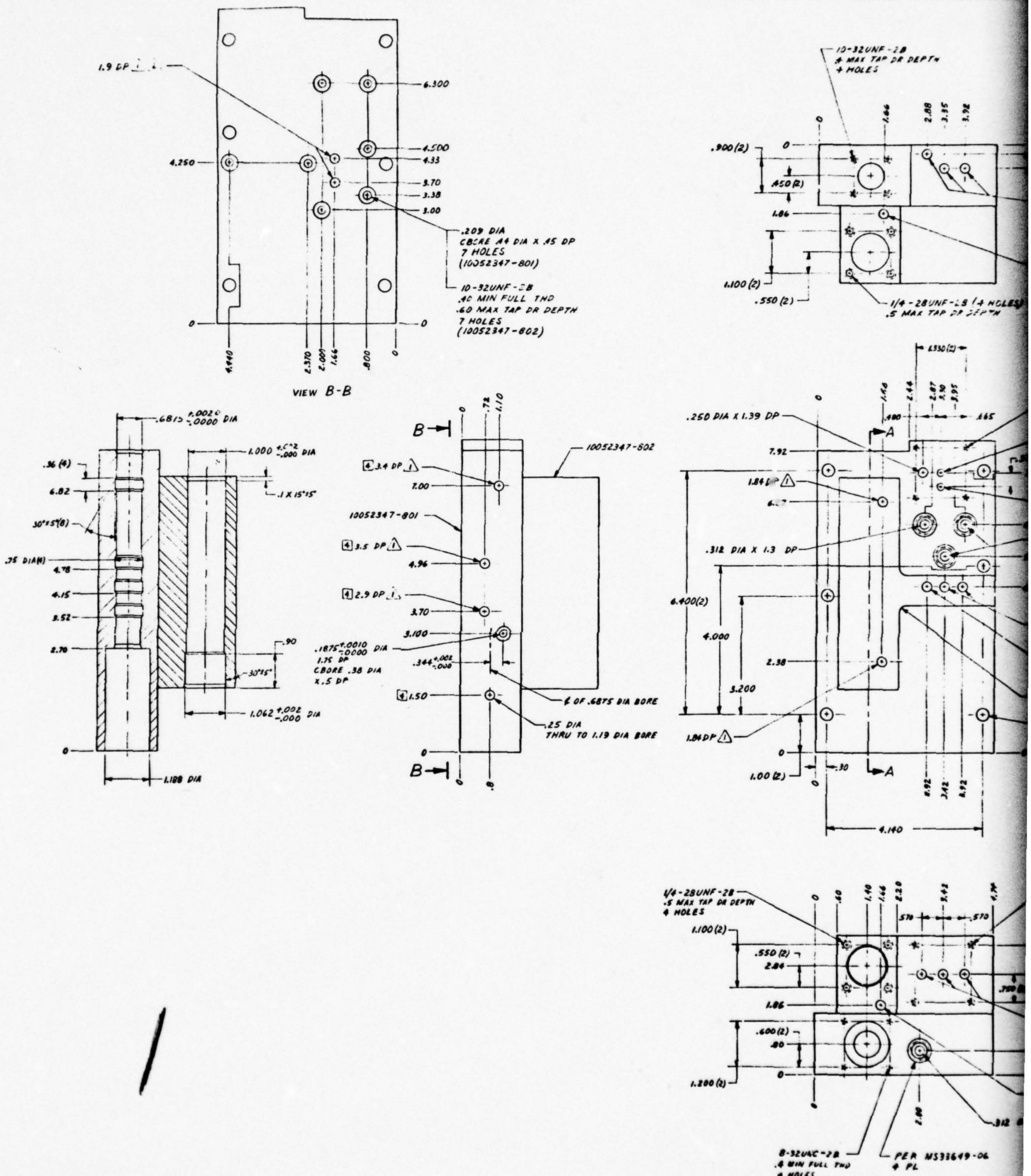
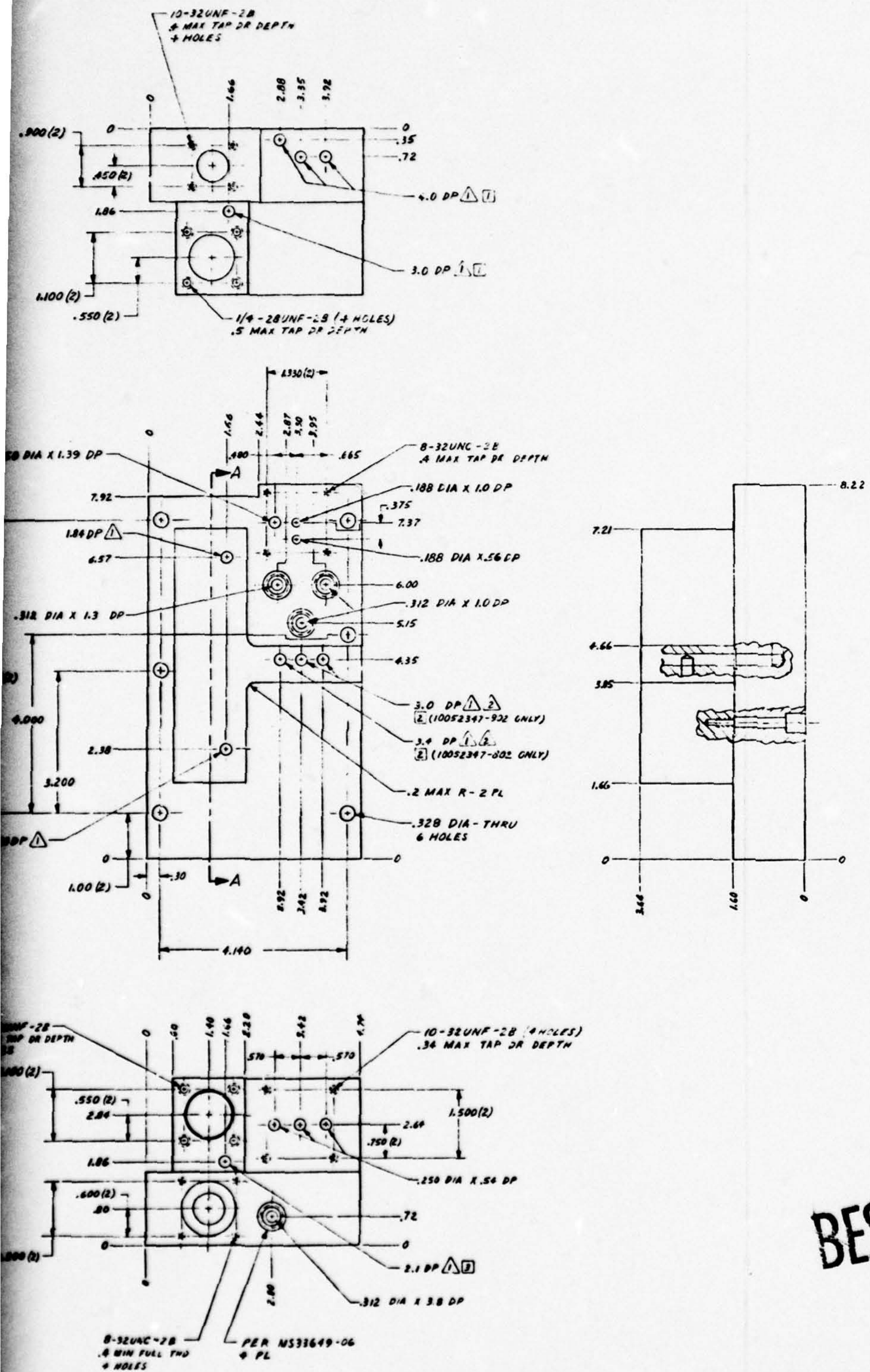


Figure 31. Small Valve Block Schematic



Valve Block Schematic

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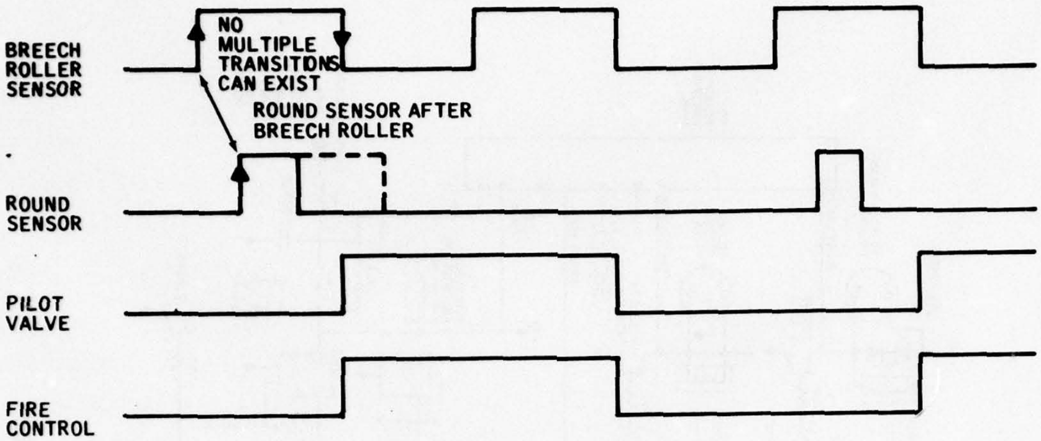
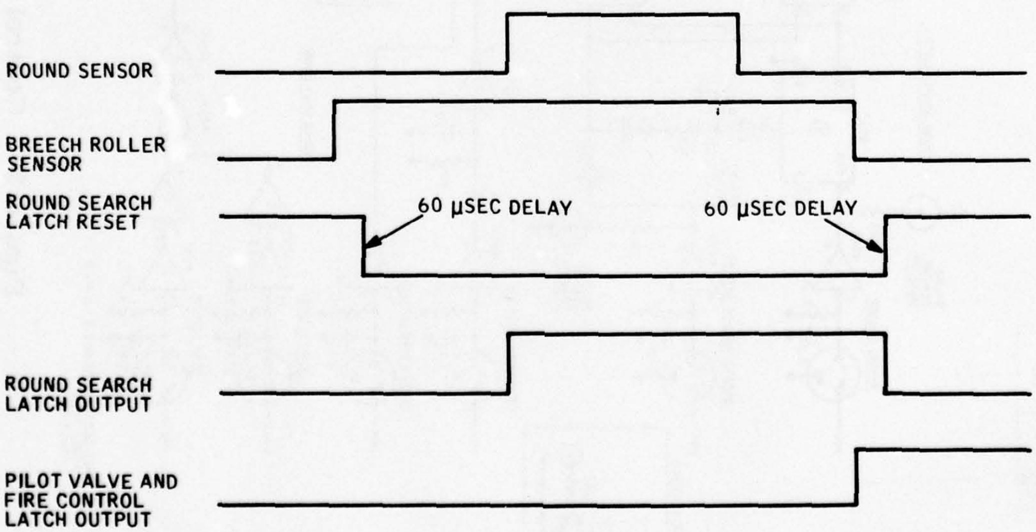


NOTES:

1. THE POSITIVE TRANSITION OF THE BREECH ROLLER STARTS THE SEARCH FOR A ROUND. THE NEGATIVE TRANSITION STOPS THE SEARCH AND UPDATES THE PILOT VALVE LATCH AND THE FIRE CONTROL LATCH. NO JITTER CAN BE TOLERATED ON THIS LINE.

2. THE POSITIVE TRANSITION OF THE ROUND SENSOR INDICATES A ROUND IS PRESENT. THE NEGATIVE EDGE IS UNIMPORTANT. THE POSITIVE TRANSITION MUST OCCUR AFTER THE POSITIVE TRANSITION OF THE BREECH ROLLER. MORE THAN ONE TRANSITION OR JITTER CAN BE TOLERATED.

Figure 32. Electronic Control Main Timing Diagram



NOTE: 60 μSEC DELAY IS NOT CRITICAL, CAN BE ± 50%

Figure 33. Electronic Latch Detailed Timing Diagram

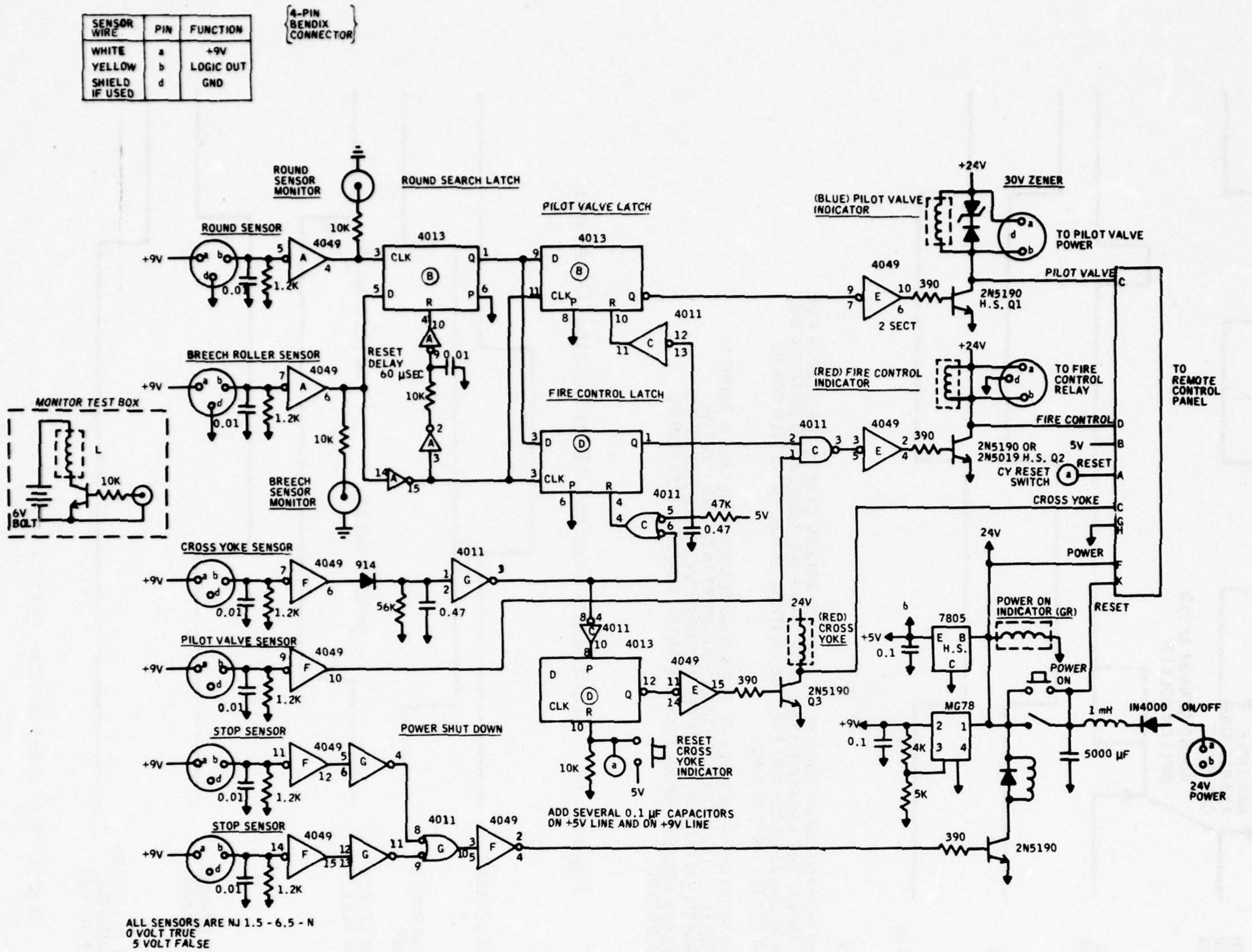


Figure 34. Control Logic Electronic Schematic

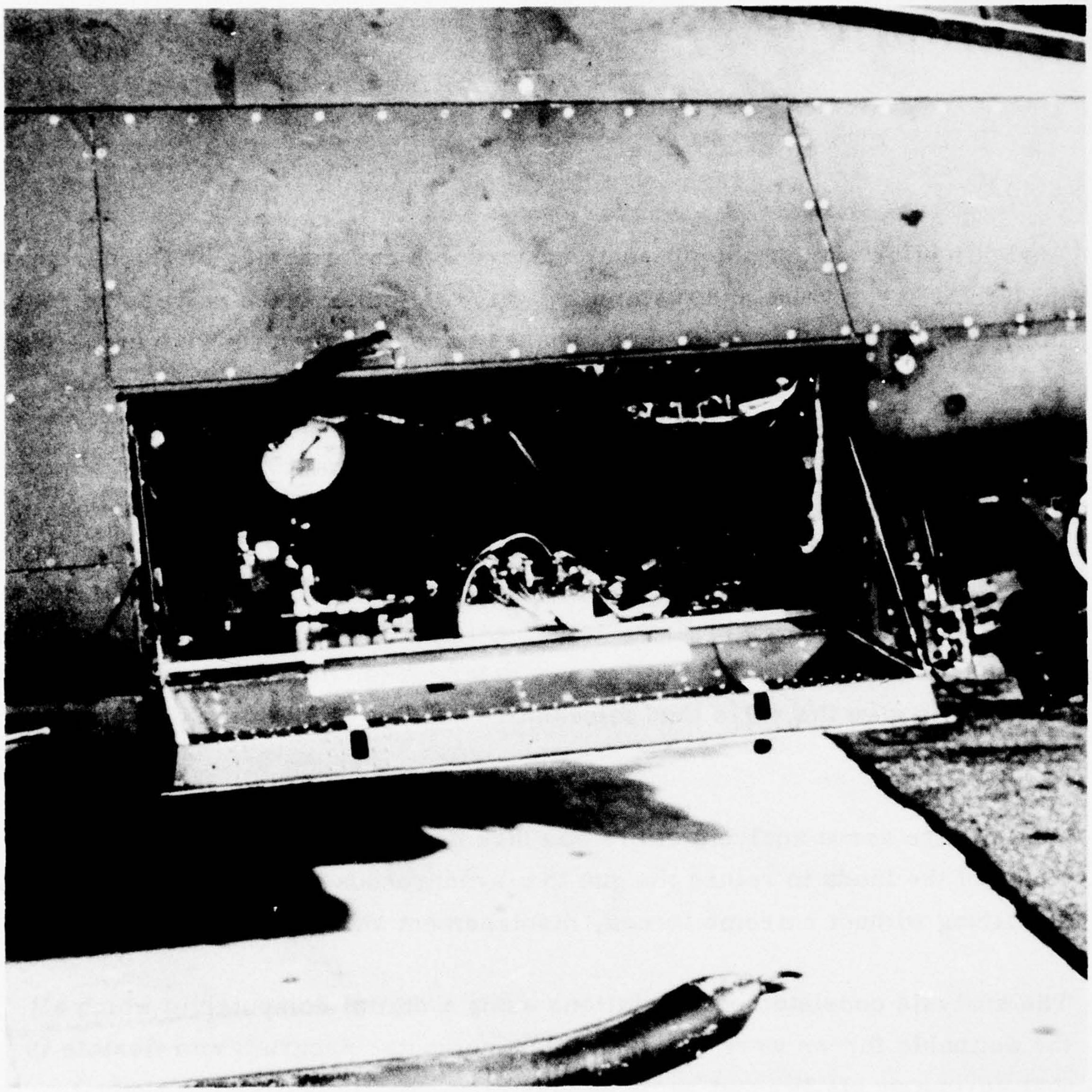


Figure 35. Electronic Control Unit Located in Helicopter Ammunition Bay

SECTION V
DESIGN ANALYSIS

Analysis effort during the present contract was concentrated on the design of the recoil servo valve and the misfire valve. Both of these valves are rotary three-way servo valves with lands shaped to control the pressure in the recoil servo and misfire servo. Emphasis in the recoil servo rotary valve analysis was to define the characteristics that would maintain positional control of the gun over the full range of operating conditions without requiring large control forces or an excessive flow of hydraulic oil. This was accomplished by selecting valve conditions and then using the computer program to compute the recoil motion, control force and hydraulic power consumed for a wide range of firing rates, ammunition impulse and ignition delays. Once a satisfactory valve was determined, the computer output was modified to give the valve land dimensions and the width of the oil passage slots.

The misfire servo analysis effort was directed to determining the proper shape of the lands to return the gun to a synchronous position of recoil motion and firing without extreme forces, displacement and oil consumption.

The analysis consisted of simulations using a digital computer in which all the definable forces were included. The computer program was flexible in that anyone or all 35 input variables could be readily changed to evaluate their effect on the system performance. Also the output could be printed and/or plotted at the user's selection. The Honeywell Time Share computer was used directly by the design engineer, enabling fast turn around in the iterative design process.

The intent of the computer simulation was to simulate the recoil system in actual operation of a burst firing. The simulation operated as follows:

1. A theoretically perfect rotary valve for both recoil and misfire was designed in the program for a specified value of firing rate, ammunition impulse, and ignition delay valve characteristics, weapon weight, friction, piston sizes, hydraulic oil supply pressure characteristics and start conditions of position and velocity.

2. A second set of input data determined the actual conditions. Primary variables were:

   - Firing rate
   - Ammunition impulse
   - Ignition delay
   - Friction
   - Weight
   - Misfires
   - Number of rounds fired

3. The output was the forces transmitted to the structure as a function of time and the velocity and displacement of the gun, the pressures in the recoil and misfire servo valves and the average and peak hydraulic flow rates.

4. The integration routines assume constant force for 0.0001 second and equilibrum conditions at the time of integration. The nominal period for one cycle is 0.08 second (750 shots per minute); 800 iterations were made for the simulation of the firing of one round.

The first portion of this section is devoted to a general description of the program. It is not the intent of this description to go over the program instruction by instruction, as each engineer and programmer uses techniques best suited to the computer available to him, which may be different than the Honeywell Time Share system.

A complete listing of the main program and all subroutines except the plotting subroutine is provided in Appendix A. The plotting subroutine is not listed because it requires a large, general-purpose plotting program that is uniquely programmed for the Honeywell Time Share Computer and is of little value in other computer facilities.

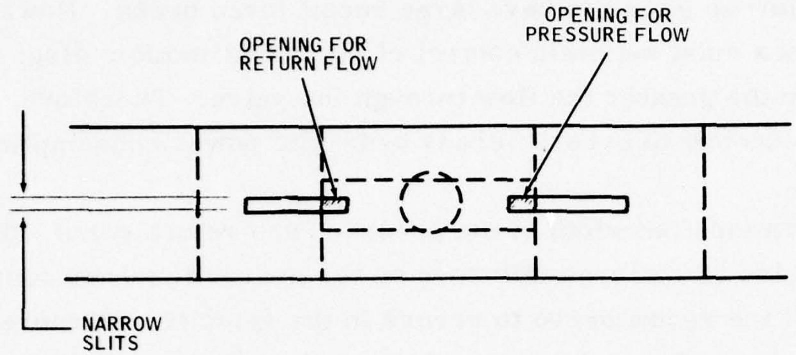
The balance of the section discusses the simulation results and tradeoffs and reliability and fault tree analyses.

SIMULATION PROGRAM

Three-Way Servo Valve Analysis

Three-way servo valve performance can be widely varied by changes in two parameters. One parameter, the pressure gain, is a measure of the change in the output pressure (pressure on the piston) for an inch of movement of the spool. The second parameter, flow gain, is a measure of the change in output flow of the valve per inch of spool movement.

Physically the pressure gain value determines the size of the opening in the pressure port and return line ports when the spool is centered (see Figure 36). With the spool at the centered position the output pressure is 750 psi, half the supply pressure. If the pressure gain is large, the openings in this position, called underlap, are small. A small movement of the spool changes the relative flow areas, causing a large change in recoil force for a small error in gun position. In a constant-force system the intent is to keep the



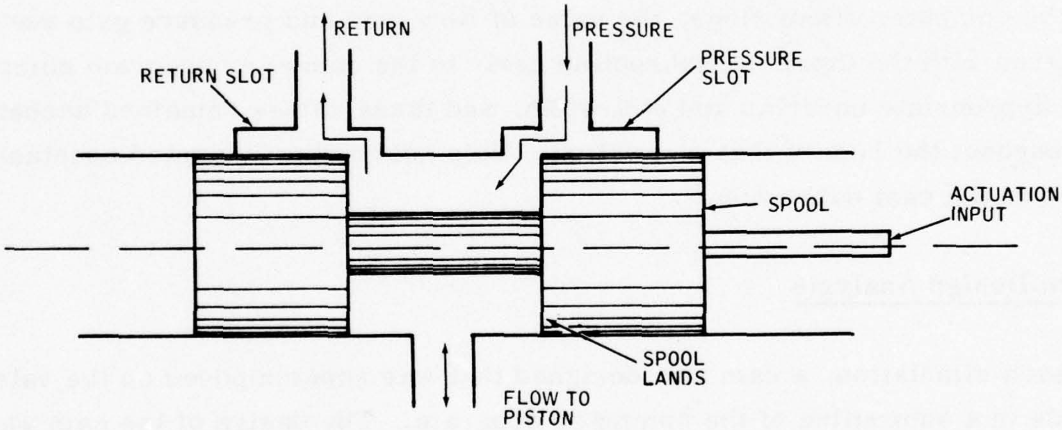


Figure 36. Three-Way Servo Valve

corrective forces low so as not to have large recoil force peaks. However, the corrective forces must maintain control of the recoil motion; also, the larger the underlap the greater the flow through the valve. Therefore, the tradeoff is force response to errors versus hydraulic power consumption.

The flow gain determines the width of the pressure and return ports. The width of the ports also has a large influence on the hydraulic power consumed and the response of the recoil servo to errors in the velocity. In conventional three-way servo valves, flow gains above 200 cubic inches per inch of spool travel usually result in vibration of the power cylinder. Therefore, the value was limited to 200.

In the computer simulations, the value of flow gain and pressure gain were entered with the input. A subroutine early in the computer program computed the appropriate underlap and slot width, and these values remained unchanged throughout the rest of that simulation. This subroutine computed constants used in the cam subroutine.

Cam Design Analysis

In each simulation, a cam was designed that was superimposed on the valve lands in a subroutine of the computer program. The design of the cam was based on the theoretical constant-force system described in Section III. The principal function of this subroutine is to determine the height of the lands of the recoil servo valve for later use in the program. The procedure in the cam subroutine is as follows:

1. A complete displacement and velocity cycle was computed for the theoretical cycle of the gun using special input data employed only in this subroutine.

2. The pressure in the servo cylinder necessary to product the net 432 pounds was computed.

3. The valve flow equations were solved to determine the opening in the pressure slot and return slot.

4. Using the valve characteristics computed in the valve subroutine and the movement of the gun from step 1 the height of the cam lands were computed.

5. This value was transmitted to the main program.

In the main computer program the height of the cam lands is combined with the displacement of the gun computed in the main program (not the displacement in the cam subroutine) to give the opening of the pressure slot and return slot (not the ideal opening in the cam subroutine). This process is done as a function of receiver angle. The force time profile of the ammunition was simulated initially by a triangular gun chamber pressure spike and later replaced with a quadrilateral pressure spike. These two representative pressure curves are shown in Figure 37 with a measured pressure time history. The force curves were obtained by multiplying by the bore area of the gun.

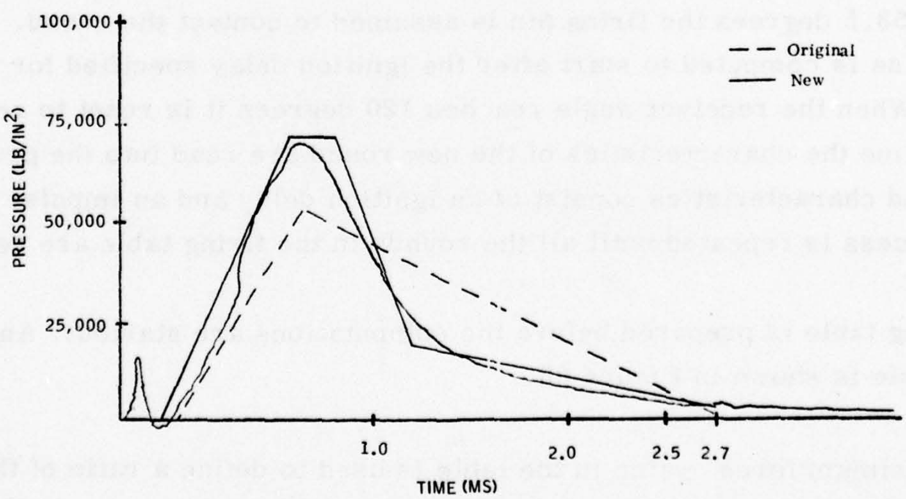


Figure 37. Servo Cam Simulation Comparison, Normal Firing Conditions

Constant force was assumed throughout the cycle, and the firing force spike was defined. The theoretical displacement and velocity of the theoretical gun as a function of time was known. The gun was assumed to be firing at the fixed rate of 750 shots per minute (in the cam subroutine only). The theoretical displacement and velocity were known functions of gun receiver rotational angle. These were computed in closed-form constants for the force spike in Figure 37 with 34.56 pound-seconds impulse and 187.6 pounds recoiling weight. The closed-form constants are computed in the valve program as they are only needed once in the computer.

The cam subroutine is also used to generate the land heights of the rotary valve spool which has three identical sets of lands, to match each of the three barrels of the M197 gun.

Main Program

The gun dynamics are computed in the main program. The firing rate is input as a constant as is the initial receiver angle. The angular position of the receiver is computed for each time iteration. When the receiver angle reaches 58.5 degrees the firing pin is assumed to contact the round. The force pulse is computed to start after the ignition delay specified for that round. When the receiver angle reaches 120 degrees it is reset to zero. At this time the characteristics of the new round are read into the program. The round characteristics consist of an ignition delay and an impulse value. This process is repeated until all the rounds in the firing table are read.

The firing table is prepared before the computations are started. An example firing table is shown in Figure 38.

The "maximum force" value in the table is used to define a ratio of the impulse of the round compared to 432 pound-seconds. The force pulse (quadrilateral in Figure 37) is computed to be proportionally higher than the one

Figure 38. Example Firing Table

FIRING TABLE G$10 (TEN HOT ROUNDS)		
ROUND NO.	IGNITION DELAY (SECOND)	MAXIMUM FORCE (POUNDS)
1	+0.0001	27,648
2	+0.0002	27,904
3	+0.001	28,160
4	0	27,392
5	+0.0001	27,904
6	+0.001	28,160
7	+0.002	27,392
8	0	27,904
9	+0.001	28,160
10	+0.002	27,904

used in the cam program by the ratio for each round. The purpose of the firing table is to enable the input into the simulation of any number of rounds with arbitrary variations in ignition delay and impulse such as might be encountered in lot-to-lot variations in ammunition or from non-standard round temperature from firing on hot or cold days. Misfires are included in the firing table as rounds with zero impulse ratios.

The translational recoil motion is computed by summing the forces. These are:

- Viscous friction - constant coefficient not necessarily the same as used in cam program
- Trim pressure force
- Servo piston force
- Firing force if the cycle is within the 27-millisecond time pulse (roughly if the receiver is between 58.5 and 62.55 degrees in rotational angle)
- Misfire piston force if the gun is far enough forward to initiate this system (0.94 inch forward of the start point)

The sum of the forces is assumed constant over the 0.0001-second time interval. The sum is then used to compute the gun acceleration, velocity and displacement.

Recoil Servo and Misfire Servo Pressure Computations

The pressures in the misfire and servo valve are computed in separate subroutines in the following manner:

The flow in the cylinder is determined by the velocity of the piston, the valve port openings and the compressibility of the hydraulic oil. The equations cannot be solved uniquely and require iterative solutions. A solution is considered acceptable if the two flows, the flow due to piston movement and the flow due to valve openings and compressibility, are within 0.0005 cubic inch per second. The two equations are:

$$\text{Piston flow} = A_1 X_D + \frac{Vol}{BM} \times \frac{dp}{dt}$$

$$\text{Valve flow} = (X_{ulp} + Z_V) A_F \sqrt{(P_s - P)} - (X_{ulp} - Z_V) A_F \sqrt{P}$$

where

A_1 = piston area

X_D = piston velocity

X_{ulp} = valve underlap

Z_V = valve opening due to cam height and movement

A_F = valve flow characteristics

P_s = supply pressure

P = servo pressure

Vol = oil volume in servo cylinder

BM	= oil bulk modules
dp/dt	= time rate of pressure change

SIMULATION RESULTS

Recoil Servo

The requirements are that the recoil system function properly for firing rates of 675 shots per minute to 825 shots per minute and for ammunition impulse variations of ± 10%.

The design selected has the following features:

- Trim Piston

Area (in^2)	1
Pressure (psi)	582
Nitrogen volume (in^3)	27.6

- Servo Piston - Rotary Valve

Area (in^2)	0.2
Flow gain (in^3/in/sec)	200
Pressure gain (psi/inch)	3000

The piston area for the rotary servo of 0.2 square inch gives a range of servo force of 0 to 300 pounds. The midrange value of 150 pounds combines with the trim force of 582 pounds to yield the 432-pound force. This combination gives the range of recoil servo force from a minimum of 282 to 732 pounds. Computer simulation results show that this range of servo force is adequate to control the recoil motion over the extreme ranges of 825 shots per minute

(10% high) and ammunition impulse of 38.01 pound-seconds (10% high) to 675 shots per minute (10% low) and an impulse of 31.10 pound-seconds (10% low). The average hydraulic flow rate over these conditions is less than the required 3 gallons per minute although there are short-lived peaks as high as 7 gallons per minute.

Figure 39 contains the computed recoil force and displacement of the weapon firing 10 rounds at the standard conditions of 750 shots per minute, 34.56 pound-seconds impulse and no ignition delay. Figure 40 is a copy of the computer heading listing showing the input and firing table. Figure 41 contains the computed-recoil force and displacement at a firing rate of 825 shots per minute (10% high) and 38.01 pound-seconds impulse (peak force value 28, 160, +10% high). Figure 42 contains the computed recoil force and displacement at a firing rate of 675 shots per minute (10% low) and 31.10 pound seconds impulse (peak force value 23, 040, -10% low). Figure 43 illustrates the computed recoil force and displacement for the firing table in Figure 38.

Misfire Servo

Considerable more difficulty was encountered in designing the misfire servo. The requirements for the system are to tolerate two consecutive misfires and to continue firing additional rounds. The basic scheme for the misfire control is shown in Figure 44. The major problem is to smooth the forces used to control the recoil motion during misfire and bring the weapon back into synchronous motion for firing subsequent rounds. Figures 45 and 46 illustrate the simulated performance for two consecutive misfires at the two extreme conditions. In these simulations the first round is fired, the second round misfires, the third round is dudded by the system, the fourth round misfires, the fifth round is dudded by the system and the sixth through twelfth rounds are fired normally. The top curve on each figure is the gun displacement. Note that after the second dudded round the system controls the movement in normal fashion. However, the force profile (the lower curves) is

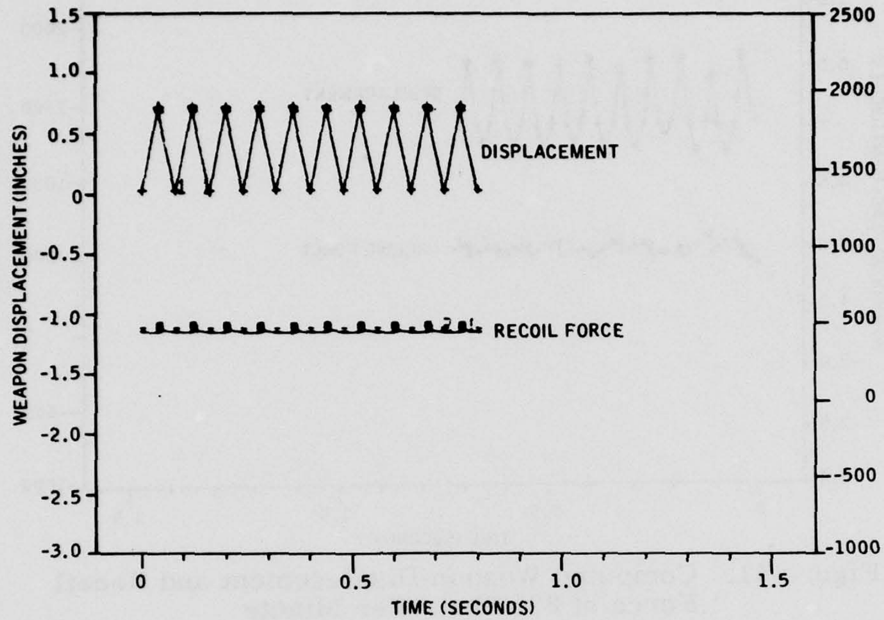


Figure 39. Computed Recoil Force and Displacement for Standard Rounds at 750 Shots per Minute

```
          C O N S T A N T . F O R C E   R E C O I L   S I M U L A T I O N
                       (VERSION: ROTARY JUNE 74/RFG)

RUN NUMBER 002.

DATE:  10-17-74
TIME:   5:30 PM


DATA LOAD STATUS:

WMNT     186.00    TPRES      0.00    TRISE      0.00    TINT0      0.10
PS      1500.00    PM       750.00    A1         0.20    KEG        1.00
ATRIM      1.44    BM       300.00    CFR       20.00    RHOG      79.56
PG      3000.00    PTRIM    403.66    QG       200.00    SPM      675.00
VOL1       1.60    CFRD      20.00    ROTAF      0.00    TMN        0.00
TMX        1.20    XMN       -3.00    XMX        1.50    FMN    -1000.00
FMX     2500.00    SPCOM      0.00    VOLTR     27.60    PLOT       1.00
PRINT      1.00    X0         0.00    ROSTRT     0.00    OLDRUN   002.00
A2         0.80    THETA      6.00    QG2       50.00    XNUL3   1000.00

FIRING TABLE IS GGML2
AF,SLWA,XULPAF2,SLW2= 0.73030 0.00461 0.50000 1.03280 0.00651
```

Figure 40. Example Computer Program Recording of Input Data

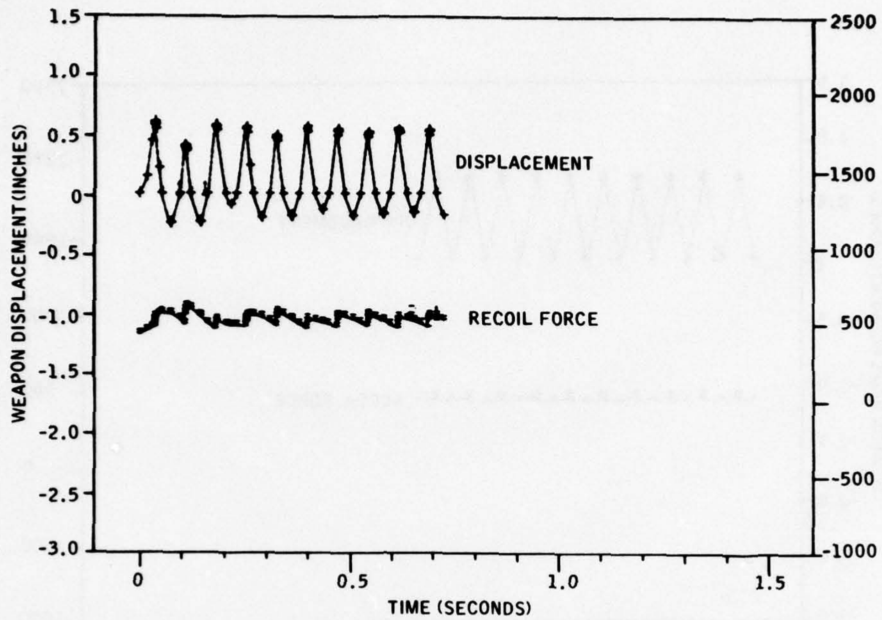


Figure 41. Computed Weapon Displacement and Recoil Force at 825 Shots Per Minute

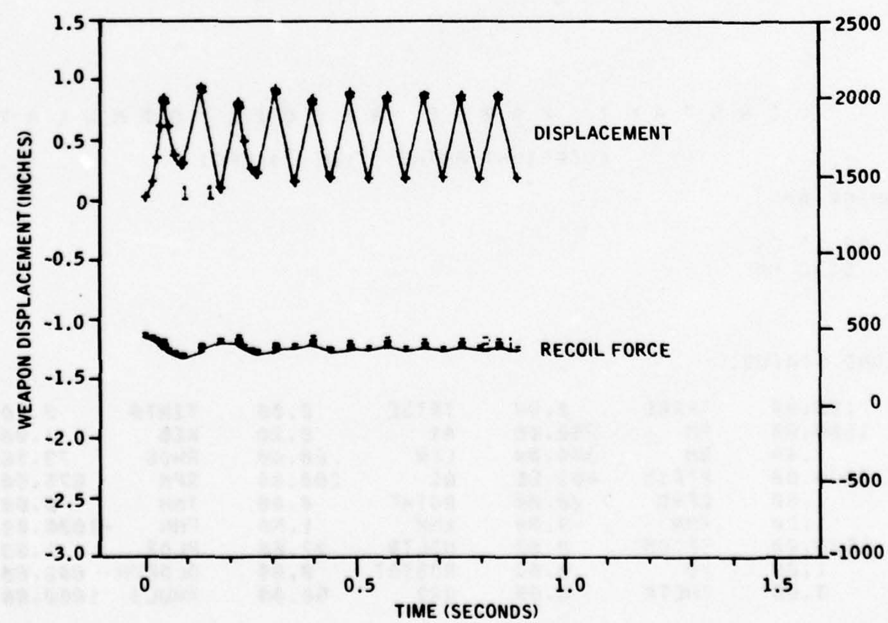


Figure 42. Computed Weapon Displacement and Recoil Force at 675 Shots Per Minute

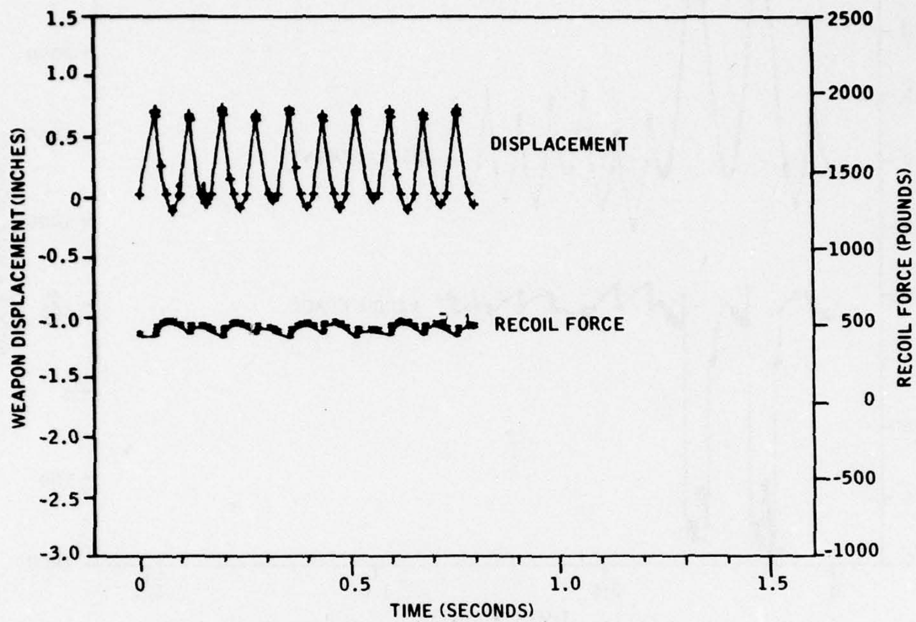


Figure 43. Computed Weapon Displacement and Recoil Force at 750 Shots per Minute for Firing Table in Figure 38

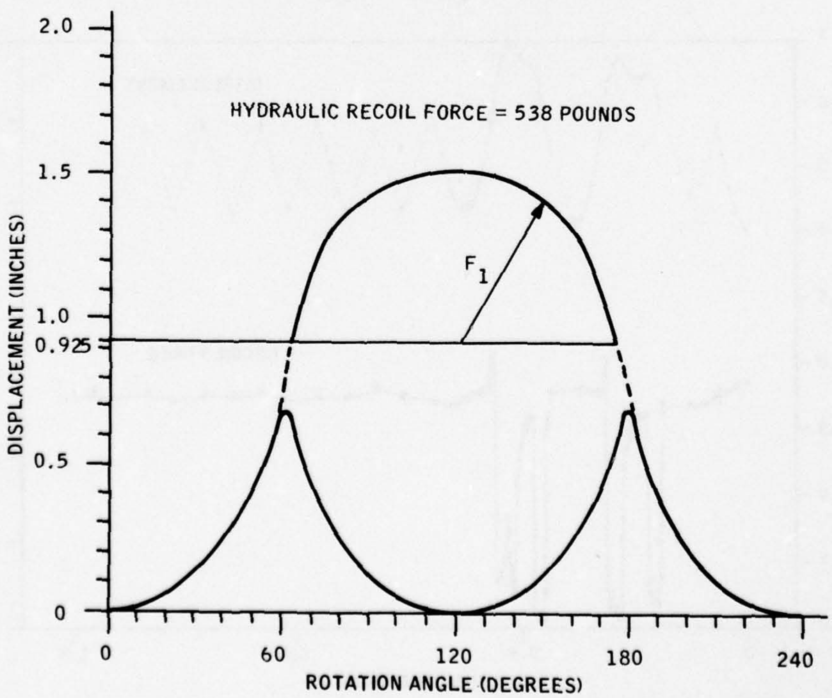


Figure 44. Basic Misfire Control Scheme

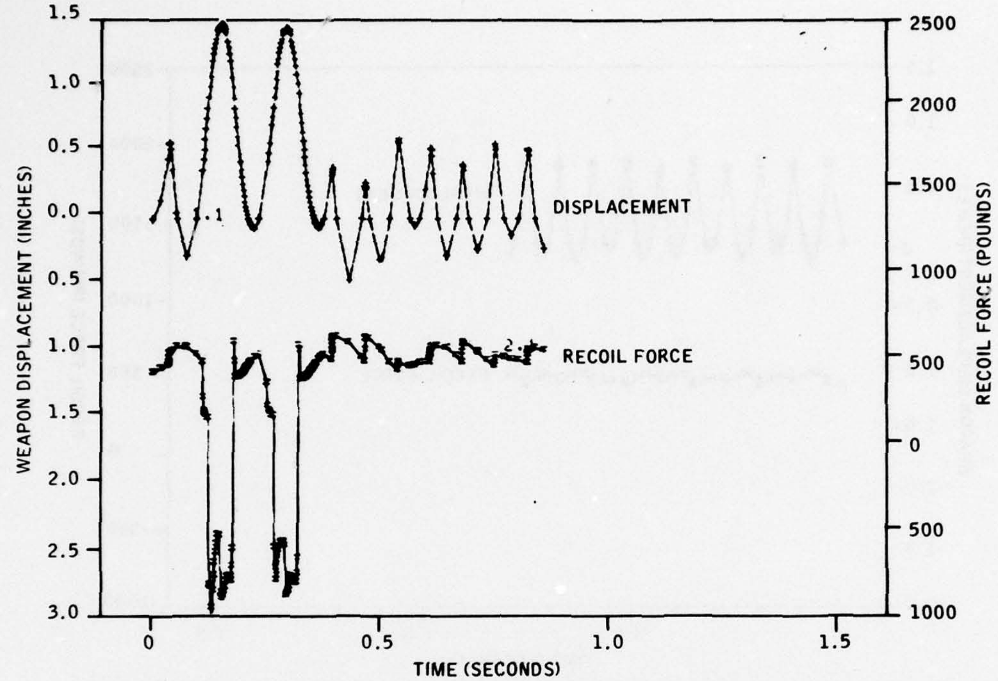


Figure 45. Consecutive Misfires at 825 Shots per Minute, High Impulse

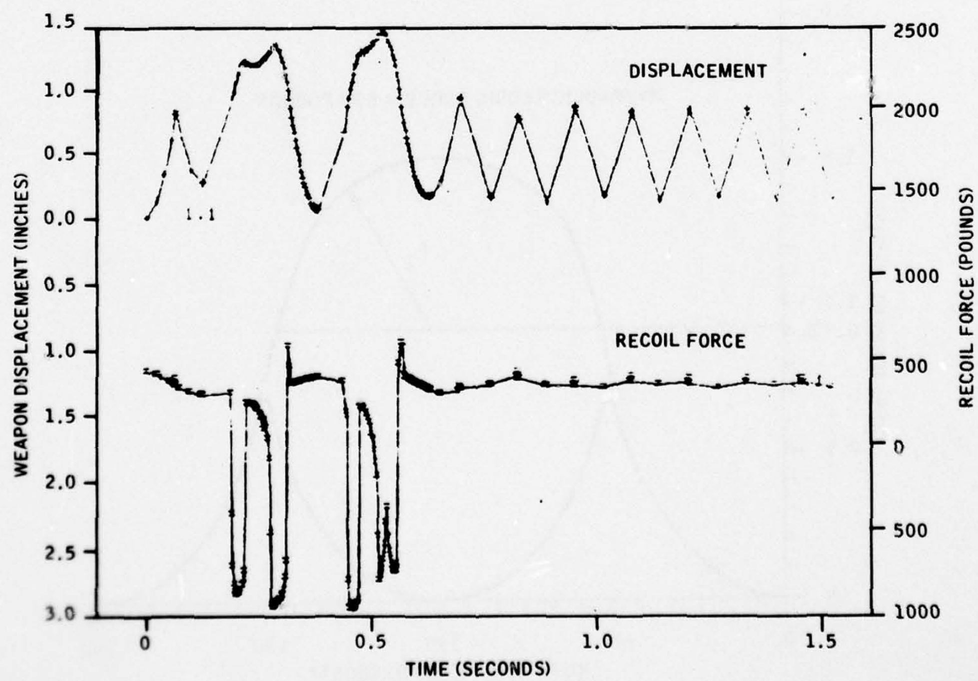


Figure 46. Consecutive Misfires at 675 Shots per Minute, Low Impulse

not smooth during the misfire stroke. We were not able to reduce the two spikes for each misfire to the average of the two. This misfire valve was considered acceptable although not optimum.

During the peak misfire stroke the gun travels 1.52 inches forward of the start position, generates a recoil force in the opposite direction of close to 1000 pounds and requires a peak flow rate of 8 gallons per minute although only 0.5 cubic inch of oil is required during this period. The misfire piston area is 0.8 square inch.

Safety Springs

Two recoil system failure modes might damage the weapon and helicopter. The first and most probable mode is a hydraulic failure shortly before a round is fired resulting in the recoil system not providing a retarding force on the gun and thus resulting in the weapon impacting the support structure. In the worst case the gun would not be moving forward when fired. To preclude damage to the helicopter a set of Schnoor belleville springs is arranged on each of the two support shafts to absorb the load of firing. The kinetic energy from firing is 102 foot-pounds. Two parallel stacks of Schnoor springs, ten in each, have the capability of absorbing 128-foot pounds with a maximum transmitted force of 9560 pounds, slightly less than the 9600-pound maximum limitation of the turret. A stack of 10 Schnoor springs was added to each support shaft for the lessening of the rearward impact load.

The second failure mode is a failure of the misfire control system to function. In this case the weapon would move to the front end of travel. The impact energy for this condition is estimated at 73 foot-pounds. A stack of 8 springs on each shaft will absorb 102 foot-pounds without exceeding the 9600-pound force limit on the turret. These were added to protect the system for forward impact.

In addition two sensors are positioned such that, if either the front or rear set of stacked springs is compressed, the firing line relay switches the firing line off.

RELIABILITY AND FAULT TREE ANALYSES

Reliability and fault tree analyses were made to predict the reliability, principally the number of rounds fired between recoil system failures, and to assess the likelihood of a failure in the recoil system producing catastrophic damage to the helicopter. Failure rate data of existing, fully qualified, developed components used in the flight control systems of military aircraft were used. Since the recoil system designed for this contract is a test prototype these estimates are not directly applicable, but are indicative of the potential performance of a fully developed system. The predicted Mean Time Between Failure is 1619 firing hours. With a firing rate of 750 shots per minute, the Mean Rounds Between Failure is in excess of 72, 500, 000. This exceeds the contractual requirement of 30, 000 Mean Rounds Between Failure by over 2300 times. At first glance these estimates appear to be extremely high, but when considered in the light of aircraft flight control hydraulic components that often function at many times a minute and their long life, the estimate appears more meaningful and realistic.

The large excess in the mean rounds between failure and the requirement of 30, 000 would indicate:

- The 30, 000 Mean Rounds Between Failure contractual requirement will be readily obtainable in a fully developed system.
- Aircraft-quality components may not be necessary, permitting tradeoffs in cost versus reliability in production.

The fault tree analysis was made as part of the reliability study. Again failure predictions were based on fully qualified components. The hazard considered was structural damage to the helicopter due to failure of the recoil system to reduce the recoil forces to a nondamaging level. The significant conclusion is that no single component failure will result in damage to the weapon or the helicopter due to the fail-safe features of the firing circuit interlocks and safety springs. These design features effectively eliminate the possibility of catastrophic failure in the hardware being tested.

SECTION VI
ENGINEERING TESTS

The engineering testing program at Honeywell primarily concentrated on debugging and calibrating the recoil system by small-burst firings. A total of 505 rounds was fired in these tests. Initially the firing test program was based on 20-round bursts.

Preliminary laboratory tests were conducted. In these tests the two-piece rotary valve sleeve assembly was shown to be unsatisfactory due to the failure of an epoxy bond between the two pieces. Also, the servo pressure and return ports in the inner sleeve were found to be inadequate and were increased from 0.046 to 0.060 inch wide in the new one-piece sleeve to produce the flow computed in the computer analysis.

The g-sensor valve was calibrated with the results listed in Table 1.

Table 1. *A Comparison of Theoretical and Actual* G-Sensor Trim Pressures at Three Temperatures

Angle (deg)	Theoretical Pressure (psig)	Actual Pressure (psig) Oil Temperature (°F) 81	120	160
0	398.75	400	400	400
+45	490.74	500	508	540
+90	528.80	545	555	590
-45	306.76	285	285	308
-90	268.60	243	242	260

The principal findings from the firing tests are:

- The recoil system maintained positional control when firing rounds at:
    - 750 shots per minute
    - 675 shots per minute
    - 825 shots per minute
    - Ammunition conditioned at +165°F
    - Ammunition conditioned at -65°F
    - Two consecutive misfires at 825, 750, and 675 shots per minute
    - 30 degrees up elevation
    - 74.8 degrees depression
- The average oil flow was 2.8 gallons per minute.
- Recoil forces were much lower than conventional recoil adapters, although greater than predicted.
- The failsafe backup system prevented damage to the recoil system, gun and feeder.
- The major deficiencies are:
    - Recoil forces were greater than predicted, both in recoil and misfire modes.
    - The g-sensor valve did not maintain pressure.
    - Trim bladders would not consistantly seal the nitrogen precharge pressure.
    - The shutdown sequence was slow.

It was concluded that the recoil forces, although larger than predicted were low and smooth enough to warrant continuing the program through flight tests and that the other two major deficiencies were correctable by remedial action and were not serious enough to warrant significant redesign or program stoppage.

The remedial action for the g-sensor was to shut it off and to use a purchased pressure regulator in its place.

In the case of the trim bladder, the failures were sporadic and only occurred during the initial preparation of the system for test, not during the operation of the system. Once hydraulic pressure was applied, the bladder functioned without failure. These failures were mostly an annoyance; the system had to be disassembled, a new bladder inserted, the system reassembled and the hydraulic lines purged before the system could be operated. However, there did not appear to be a hazard from this type of failure.

The shutdown sequence is slow, not stopping the weapon at the proper position after the last round is fired. The stop sequence allows the weapon to continue forward into the misfire zone, resulting in a misfire-like counter-recoil force at the end of each firing. Remedial action would require investigation and rework. Since the burst is completed at this time there is no effect on accuracy from the large counter-recoil force. Therefore, it was decided to continue the program and accept this deficiency.

TEST RESULTS

Figure 47 is a record of the force and displacement data for event number 86, a 10-round burst fired at 720 shots per minute. The forces were measured by strain gages on two beams that supported the saddle. The displacement was measured by a rotary potentiometer. The data was recorded on

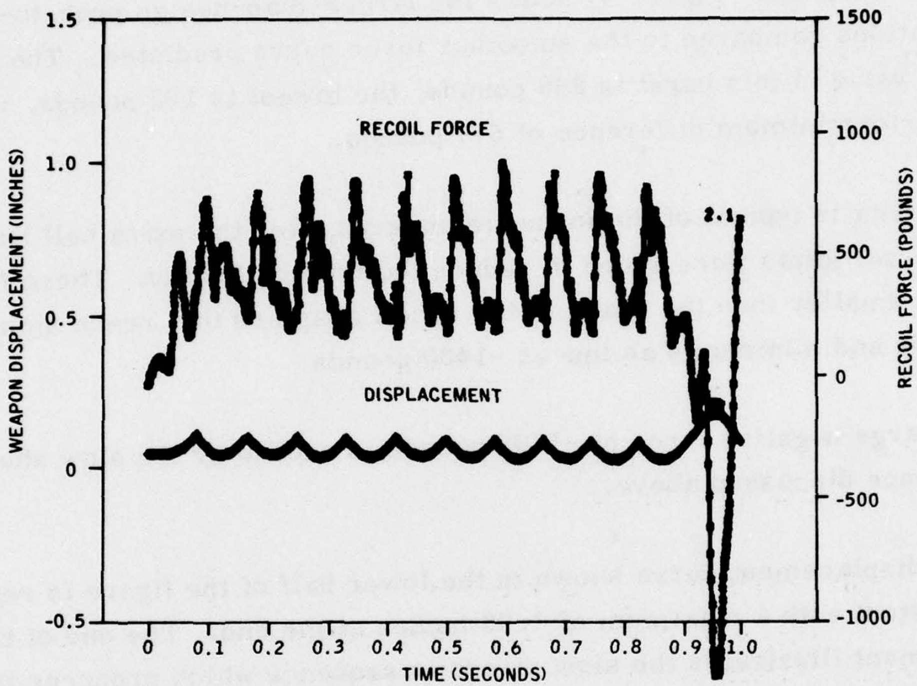


Figure 47. Recoil Force and Displacement Versus Time for Event 84, 720 Shots per Minute

magnetic tape and digitized. The calibration values were then used to convert the signal to force measurements. The force values from each beam were added, and the data was presented on a CRT tube and listed on a computer terminal. Figure 47 shows the larger-than-design peak-to-peak force variations compared to the smoother force curve predicted. The greatest peak value in this burst is 869 pounds, the lowest is 162 pounds, with a maximum-to-minimum difference of 677 pounds.

This data is typical of the force traces even after the extra ball bushings and universal joints were added to reduce the friction forces. These forces are much smaller than the peaks of the recoil adapters that reach highs of 3100 pounds and minimums as low as -1400 pounds.

The large negative force of -1239 pounds is caused by the slow shutdown sequence discussed above.

This displacement curve shown in the lower half of the figure is regular and consistent with a maximum of 1.08 inches at the end. The end of the displacement illustrates the slow shutdown sequence which produces the large excursion and counter-recoil force of -1239 pounds. The slow shutdown data is typical of that recorded on each run.

The forces and displacements of a 10-round burst, event 85 fired at 818 shots per minute, are shown in Figure 48. This data was prepared in the same manner as event 86. As expected, the forces are higher and the displacements smaller at the higher rate of fire. The maximum force is 1001 pounds and the minimum is 51 pounds during the burst. The displacement curve is repetitious and stable showing no evidence of a forward or rearward trend.

Figure 49 is a force and displacement trace of 10-round burst fired at 675 shots per minute. During this burst the strain gage legs were preloaded to evaluate their response characteristics, resulting in the loss of the force

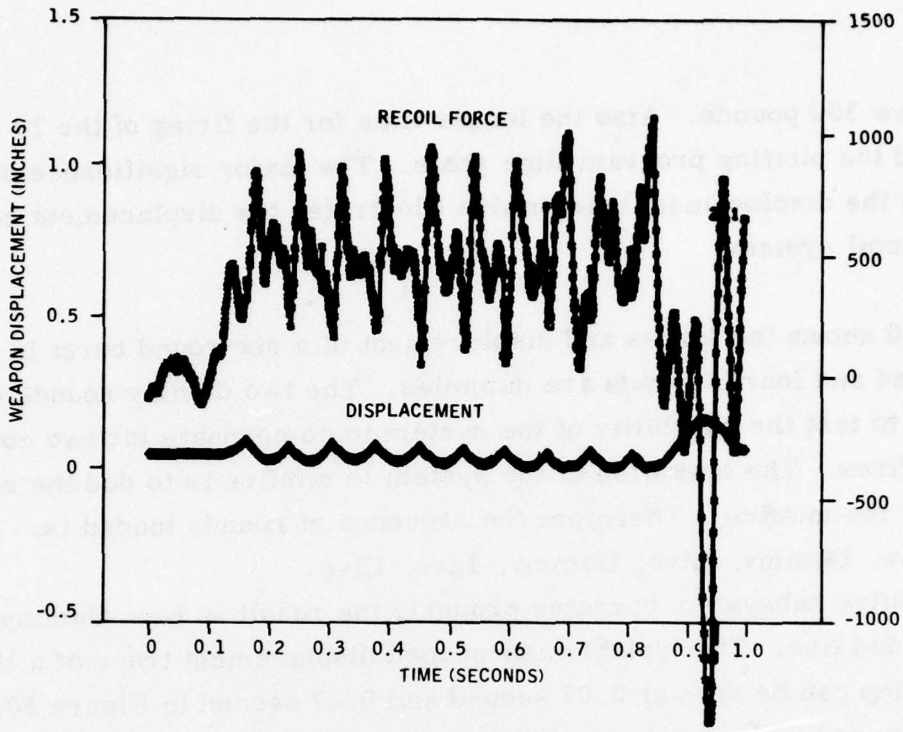


Figure 48. Recoil Force and Displacement Versus Time for Event 84, 818 Shots per Minute

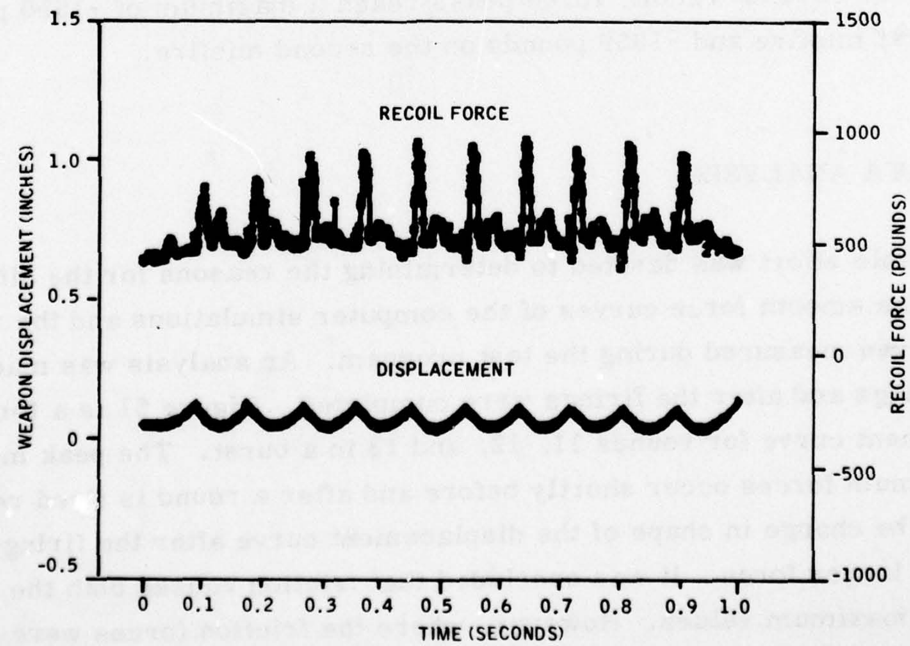


Figure 49. Recoil Force and Displacement Versus Time for Event 89, 675 Shots per Minute

data below 390 pounds. Also the longer time for the firing of the 10 rounds exceeded the plotting program time scale. The major significance of this figure is the displacement trace which illustrates the displacement control of the recoil system.

Figure 50 shows the forces and displacement of a six-round burst in which the second and fourth rounds are dummies. The two dummy rounds were included to test the capability of the system to compensate for two consecutive misfires. The operation of the system in misfire is to dud the round following the misfire. Therefore the sequence of rounds loaded is:

Live, Dummy, Live, Dummy, Live, Live.

If the misfire subsystem operates properly the result is live, dummy, dud, dummy, dud live. The typical cusp-shaped displacement trace of a live-round firing can be seen at 0.07 second and 0.47 second in Figure 50. In between these two live firings are two forward traces indicating the movement of the gun into the misfire zone and retraction into the fire zone. The negative, or counter-recoil, force peaks reach a maximum of -1550 pounds on the first misfire and -1259 pounds on the second misfire.

TEST DATA ANALYSIS

Considerable effort was devoted to determining the reasons for the difference between the smooth force curves of the computer simulations and the rougher force curves measured during the test program. An analysis was made early in the firings and after the firings were completed. Figure 51 is a force and displacement curve for rounds 11, 12, and 13 in a burst. The peak minimum and maximum forces occur shortly before and after a round is fired respectively. The change in shape of the displacement curve after the firing confirms the larger force. It was concluded that friction caused both the minimum and maximum values. However, where the friction forces were acting could not be located. Additional ball bushings were added to reduce the

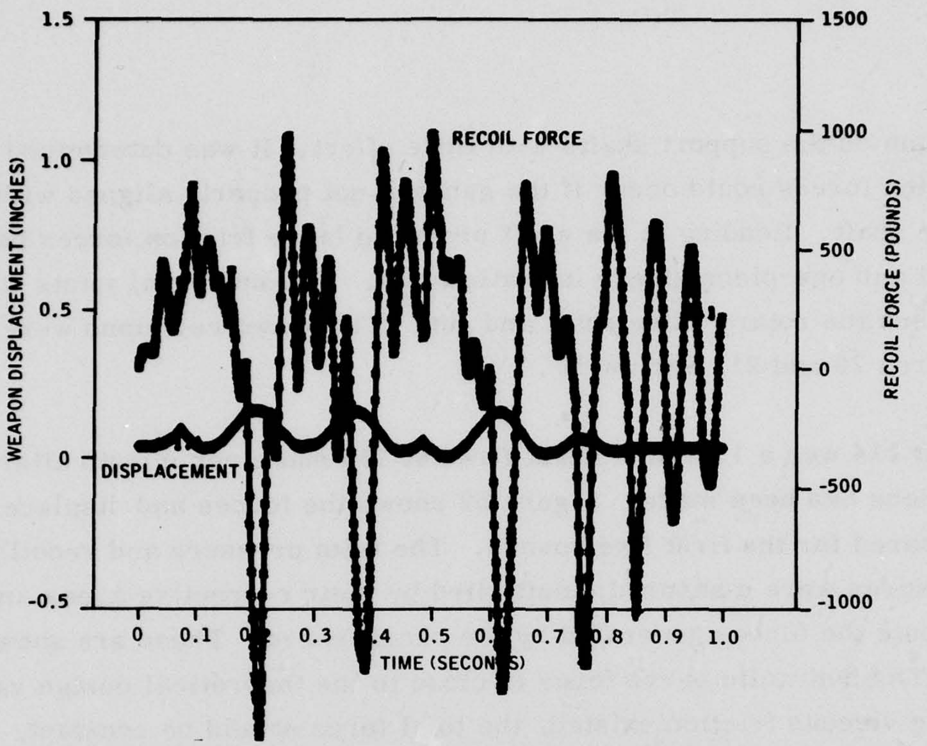


Figure 50. Recoil Force and Displacement Versus Time for Event 94, 740 Shots per Minute, Two Misfires

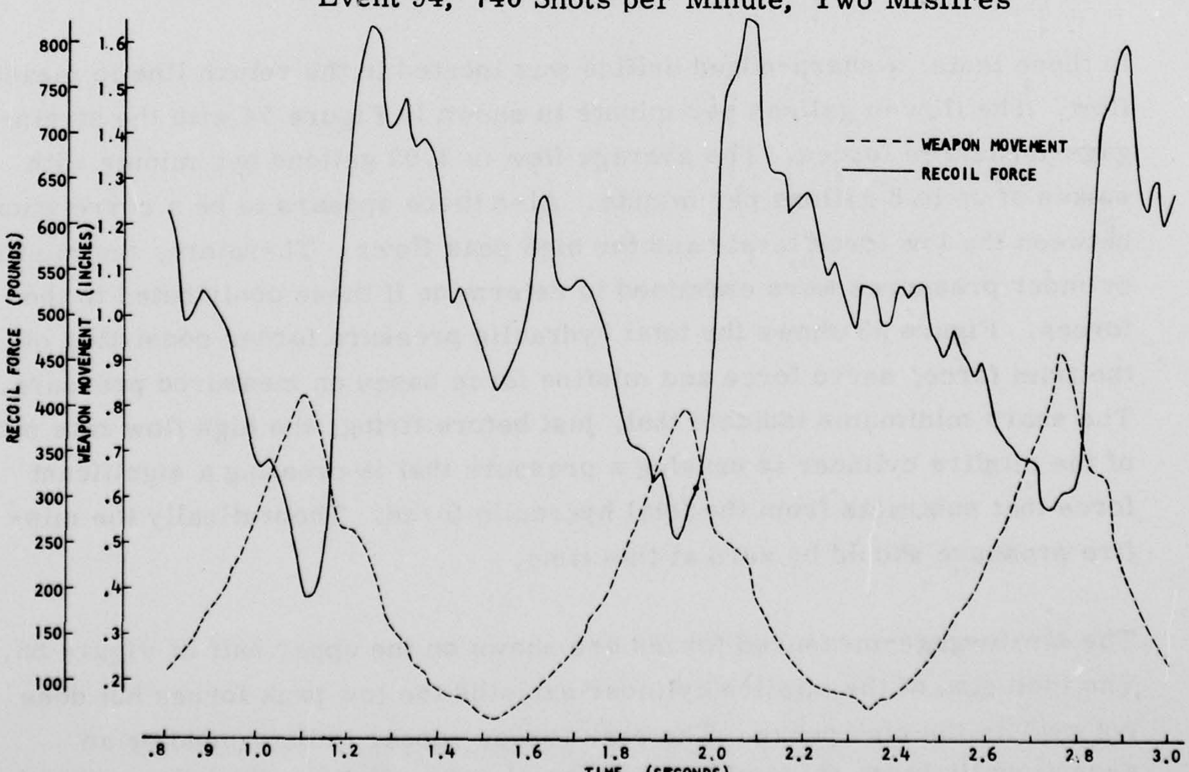


Figure 51. Recoil Force and Displacement for Rounds 11, 12 and 13 in a Burst

friction on the support shafts with little effect. It was determined that large friction forces could occur if the gun was not properly aligned with the rotary valve shaft. Bending of the shaft produced large friction forces between the spool and one-piece sleeve in static tests. Two universal joints were added between the rotary valve shaft and gun. These two revisions were shown in Figures 20 and 21, Section IV.

Event 114 was a 15-round burst fired at 750 shots per minute after both modifications had been made. Figure 52 shows the forces and displacement measured for the first five rounds. The trim pressure and recoil servo pressures were measured, multiplied by their respective areas and added to compute the forces generated by the recoil servo. These are shown in Figure 53. The hydraulic servo force is close to the theoretical design values. Providing viscous friction existed, the total force should be constant, not the jagged strain gage forces in Figure 52.

In these tests, a sharp-edged orifice was located in the return line to measure flow. The flow in gallons per minute is shown in Figure 54 with the strain-gage-measured forces. The average flow is 3.07 gallons per minute with spikes of up to 8 gallons per minute. Also there appears to be a correlation between the low force levels and the high peak flows. Therefore, the misfire cylinder pressures were examined to determine if these contributed to the forces. Figure 55 shows the total hydraulic pressure forces consisting of the trim force, servo force and misfire force based on measured pressure. The sharp minimums indicate that, just before firing, the high flow rate out of the misfire cylinder is causing a pressure that is creating a significant force that subtracts from the total hydraulic force. Theoretically the misfire pressure should be zero at this time.

The strain-gage-measured forces are shown on the upper half of Figure 55. The inclusion of the misfire cylinder explains the low peak forces but does not explain the high peaks. The peak forces appear to be caused by an exceptionally large value of friction shortly after firing. We believe this is due to the pitch-up motion of the weapon when it fires.

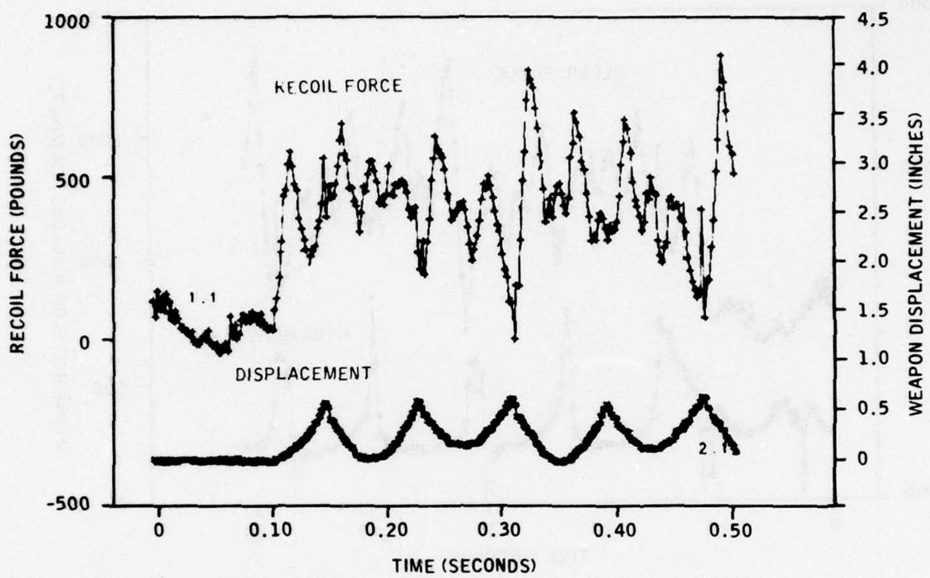


Figure 52. Recoil Force and Displacement Versus Time for Event 114, 750 Shots per Minute

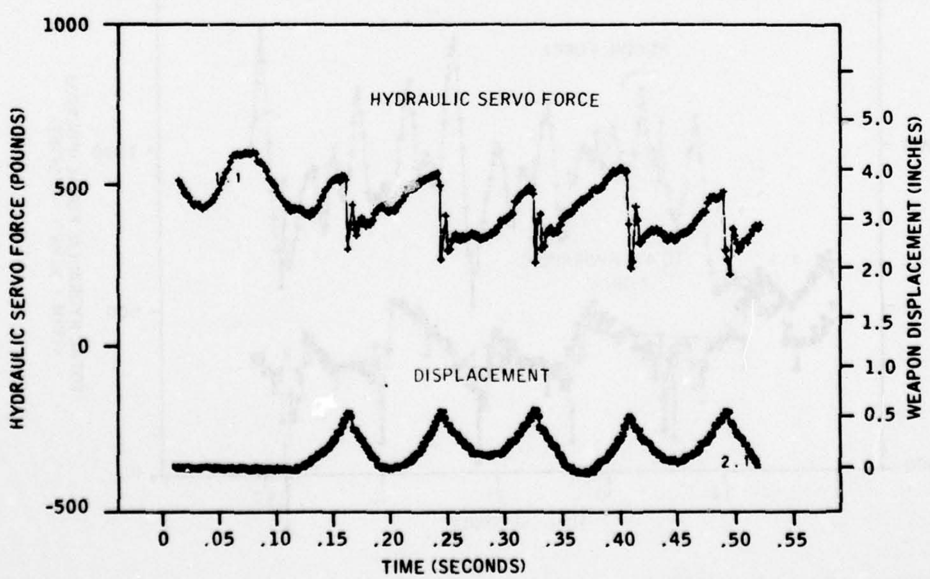


Figure 53. Hydraulic Servo Force and Displacement Versus Time for Event 114, 750 Shots per Minute

AD-A049 313 HONEYWELL INC HOPKINS MINN DEFENSE SYSTEMS DIV F/G 13/7
HYDRAULIC CONSTANT RECOIL PROGRAM.(U)
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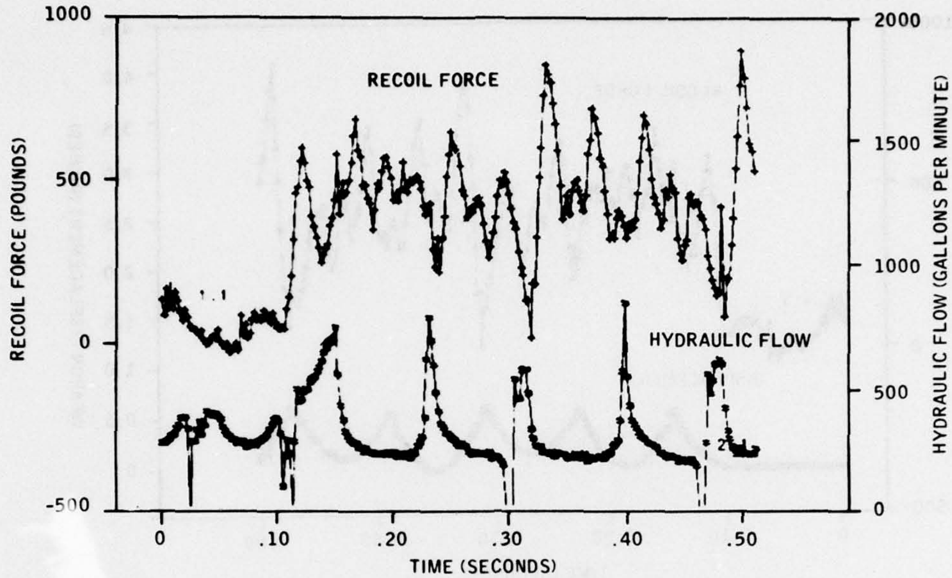

Figure 54. Recoil Force and Hydraulic Flow Versus Time for Event 114, 750 Shots per Minute

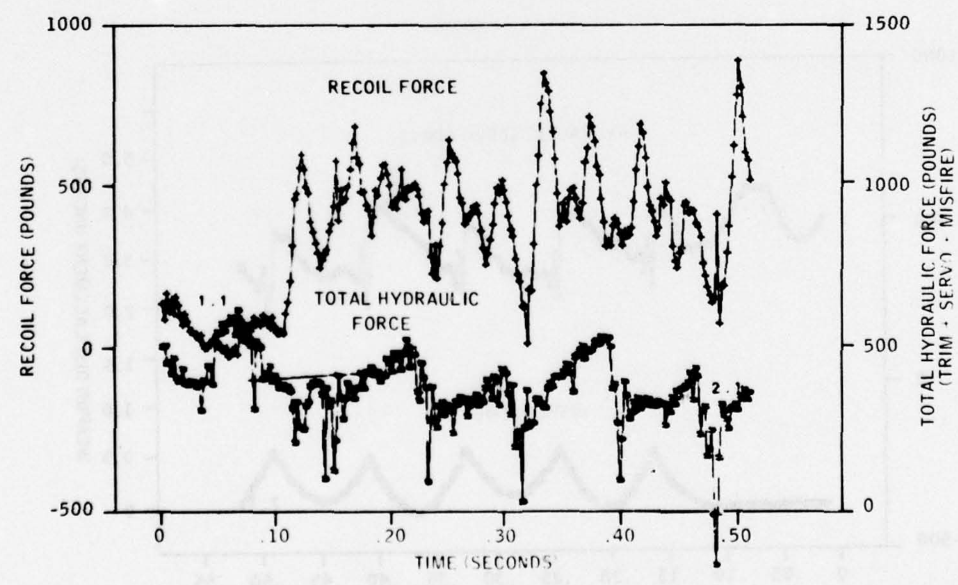

Figure 55. Recoil Force and Total Hydraulic Force Versus Time for Event 114, 750 Shots per Minute

SECTION VII
FLIGHTWORTHINESS TESTS

An extended flightworthiness test program was conducted with the saddle mounted in the M97 turret which in turn was mounted on a test stand. Before being mounted on the test stand, the turret with the recoil system and weapon was subjected to aircraft vibration in accordance with Mil-Std-810C, AH-1G schedule. The only deleterious effect noted was the loosening of one screw joint part way through the test. It was retightened and the vibration test completed.

In the flightworthiness firing tests the measurements recorded were:

- Servo pressure
- Trim pressure
- Displacement
- Triaxial acceleration of the nonmoving portion of the recoil system
- Triaxial accelerations of the test stand

The data was recorded on magnetic tape and the tape forwarded to Rock Island Arsenal. An example of the data recorded is shown in Figure 56.

Initially it was planned to use the turret control system to direct the pointing of the gun. There was not sufficient information with the controller to enable us to assemble the control modules to operate the azimuth and elevation controls. Nor were the personnel in the Army or at General Electric familiar with the turret controls available at this time. The elevation and azimuth gears were mechanically locked in place for each firing.

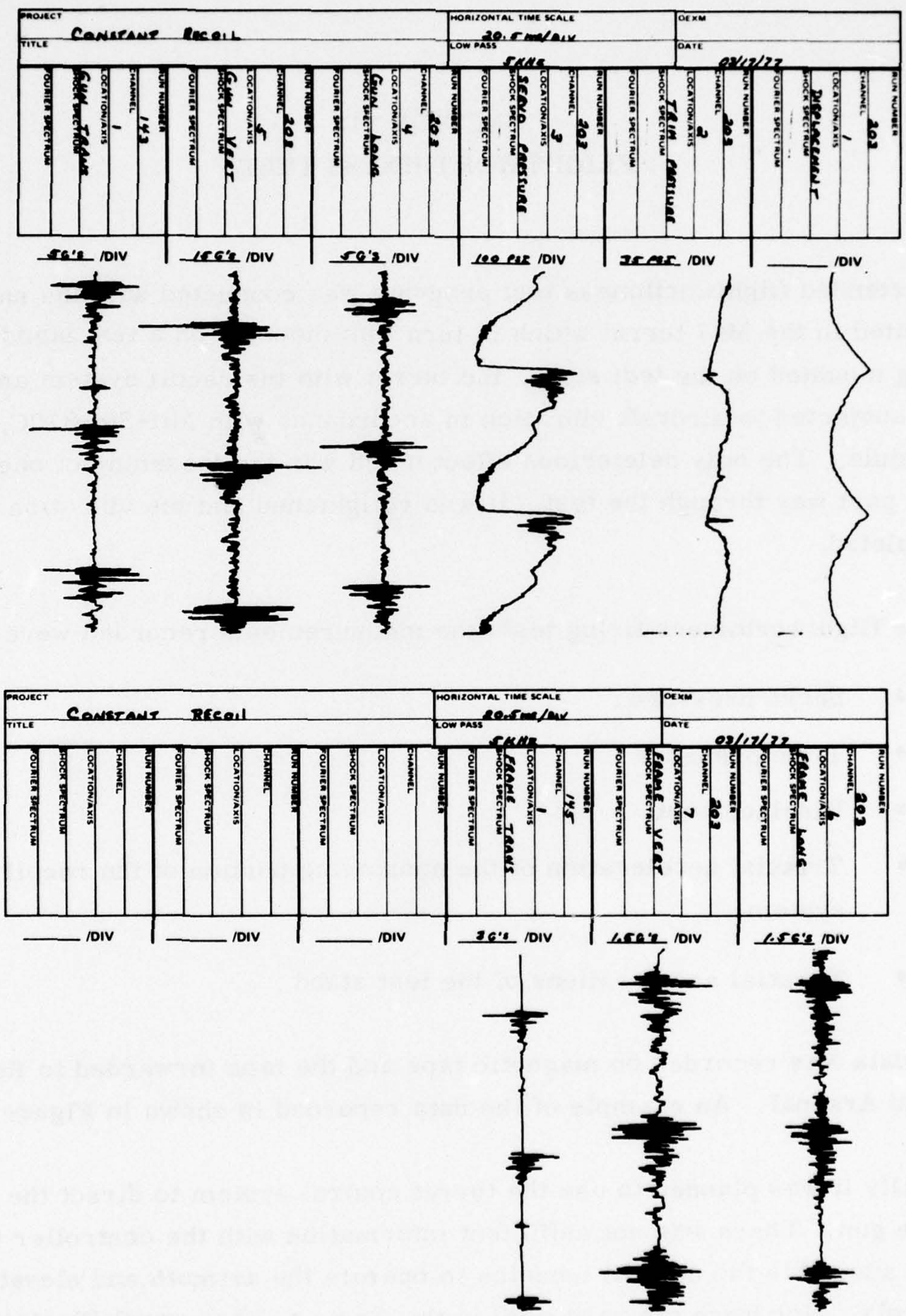

Figure 56. Flightworthiness Test Data Examples

Significant results of the test series included:

- The recoil system controlled the motion of the weapon at 11, 0 and -50 degrees and gun elevation at azimuths of 0, ± 45 and ± 90 degrees.
- A 250-round continuous burst was fired with no difficulty.
- The one serious stoppage occurred when a metal chip jammed the rotary valve spool.
- Some minor problems arose with the trim bladder. The last minor change was thought to have solved this problem when the 750 rounds were fired without bladder failure.

The entire test sequence is summarized in Table 2. Events in which the number of rounds fired do not equal rounds loaded are discussed in the following paragraphs.

- Event 124 -- This was the event in which a chip jammed the rotary valve spool as mentioned above.
- Event 193 -- This event was scheduled to be a 250-round firing consisting of ten 25-round bursts with a 1-minute interval between bursts. Between the 8th and 9th bursts the hydraulic power supply shut down because of overheating. The first round of the next burst was fired without the gun moving forward. The rear safety springs stopped the recoil motion without damage. The rear safety sensor shut down the firing relay preventing further firings. The overheating of the hydraulic power supply occurred in the interval between bursts; during this time the weapon is in the hold mode. During firing there is

Table 2. Flightworthiness Test Summary

Elevation (degrees)	Azimuth (degrees) (L-Left - R-Right)	Event Number	Number of Rounds	
			Loaded	Fired
0	0	120	25	25
0	0	121	25	25
-50	90L	122	25	25
-50	90L	123	25	25
-50	90L	124*	25	14
0	45R	139	25	25
0	45R	140	25	25
0	45R	141	25	25
0	45L	142	25	25
0	45L	143	25	25
0	45L	144	25	25
0	45L	145	25	25
0	90L	146	25	25
0	90L	147	25	25
0	90L	151	25	25
0	90R	153	25	25
0	90R	154	25	25
0	90R	155	25	25
11	45R	161	25	25
11	45R	162	25	25
0	0	193*	250	201
0	0	194*	50	50
0	0	195*	250	201
0	0	196*	49	49
0	0	197	250	250

* See discussion in text.

no perceptible increase in oil temperature. A hydraulic short circuit was later discovered at Aberdeen Proving Grounds when the system was in the hold mode (see Section VIII).

Event 193 was completed as event 194 — two 25-round bursts with a 1-minute interval between them.

- Event 195 -- This event was scheduled to be ten 25-round bursts with 10-second intervals. The system repeated the shut off of event 193. It was completed as event 196.

The last event, 197, was a continuous 250-round burst. Tracings of weapon displacement, trim pressure and servo pressure for this burst are shown in Figure 57. There is a slight shift in the displacement trace for the first two rounds. The next 246 rounds show identical displacement. The last two rounds move further forward as the gun is slowing in firing rate; the computer sequence shut the power to the gun motor at the end of the 248th round. The temperature of the hydraulic oil rose 1 degree during the burst.

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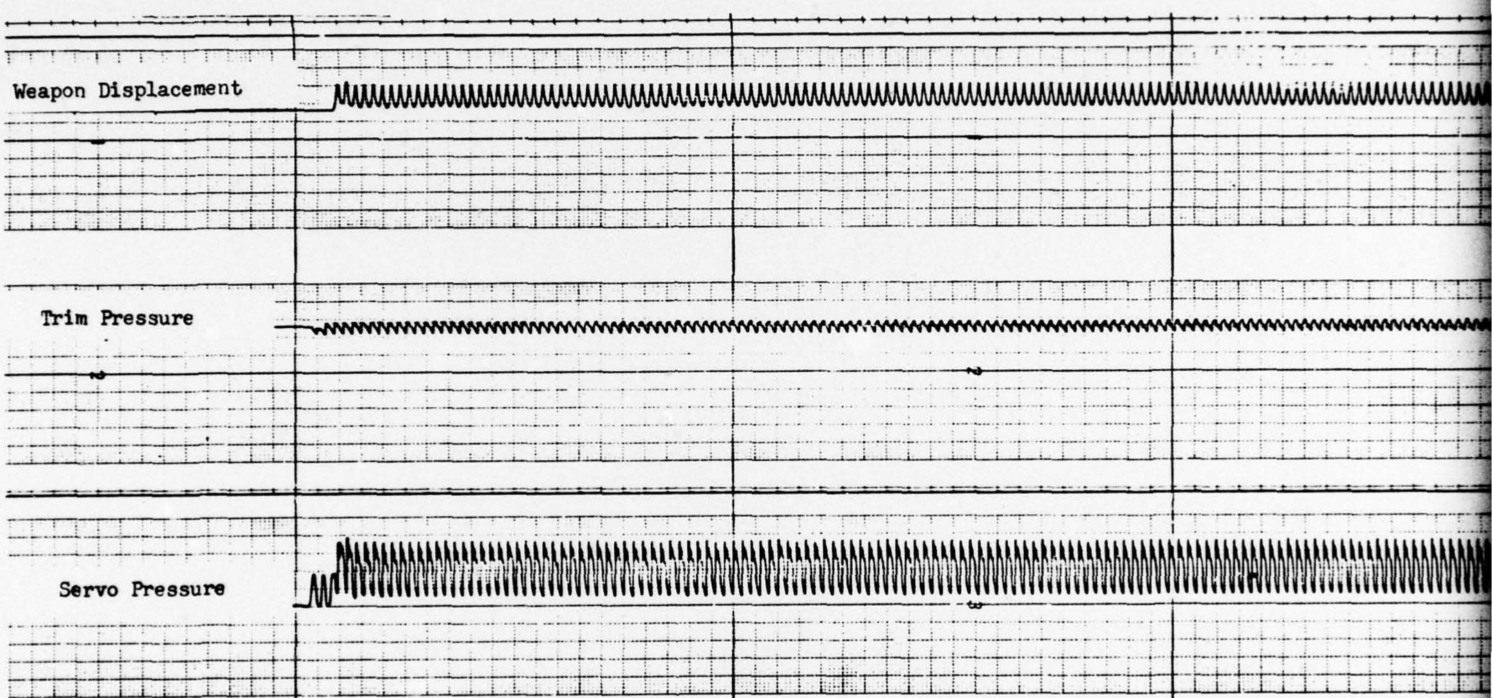
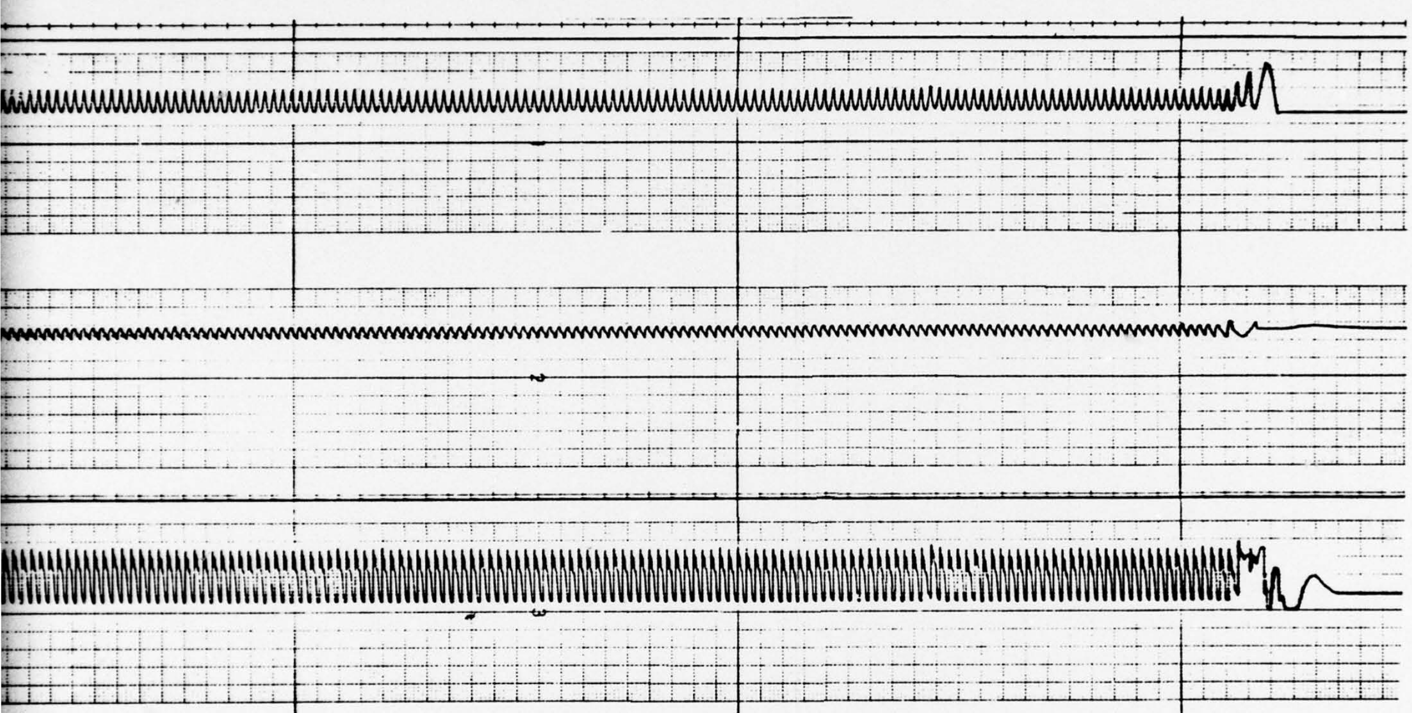


Figure 57. Displacement, Trim Pressure and Servo Pr



d Servo Pressure Recordings for 250-Round Burst

2

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SECTION VIII
FLIGHT TESTS

At the conclusion of flightworthiness testing, the turret, weapon and recoil system were shipped to Aberdeen Proving Ground and mounted on the AH-1G Multiweapon Helicopter. This helicopter is a specially modified craft used by Frankford Arsenal for fire control and associated equipment development tests. Successful ground-test firings were completed at Aberdeen, and the helicopter was then flown to the Naval Air Station at Patuxent River, Maryland. Some 2000 rounds were fired from the helicopter in flight. After an initial adjustment, the system performed perfectly.

As ground testing began at Aberdeen several problems were encountered:

- The accumulators used in the surge supply and trim cylinder were too large for the helicopter's supply reservoir.
- A hydraulic short existed at certain settings of the trim pressure regulator.
- The round sensor exhibited an intermittent open circuit.
- The trim bladder repeatedly failed when initially pressurized with nitrogen.

Each of these problems was successfully resolved as discussed in the following paragraphs.

The accumulators were reduced in size, and the nitrogen precharge was significantly increased. This resulted in the same volume of nitrogen in the system as tested in the flightworthiness tests and yet required much less oil, resolving the problem with the helicopter's supply reservoir.

The hydraulic short appeared when both the built-in trim pressure regulator and added trim pressure regulator were in the hydraulic circuit in the hold mode. The flow rate at this time was approximately 10 gallons per minute.

The hydraulic supply used in the flightworthiness tests could accommodate the high flow. However, the helicopter's secondary supply was limited to an average 3 gallons per minute for recoil system operation as the helicopter also needed hydraulic power for flight control activation. The hydraulic circuit was modified by shutting off the built-in trim pressure regulator, and only the added trim pressure regulator was used for all modes. This modification resolved the hydraulic short.

The initial ground firing tests at Aberdeen were plagued with a large number of rounds not being fired in a burst. The difficulty was eventually traced to a defective round sensor which produced premature turn-off of the firing line relay. When the defective round sensor was replaced, no further difficulty in the electronic logic system was encountered. Approximately 200 rounds were fired in the ground tests at Aberdeen.

A dimensional error in the trim bladder was finally noted and corrected. Only one further failure was encountered later in the program.

The last trim bladder failure occurred while the helicopter was in the hanger at Patuxent River Naval Air Station. At the time, the bladder was under nitrogen pressure. Examination indicated that turning the gun manually had caused grooves in the end of the trim piston to score the bladder, causing a fatigue-type failure. The trim piston was polished to eliminate the grooves, and the bladders were replaced before each firing. No further bladder failures were encountered.

In the first flight test on 20 January 1977, the trim pressure had not been adjusted to compensate for the -15 degree elevation of the gun. The recoil system allowed the gun to move forward into the misfire zone after 10 to 15 rounds in a burst. The misfire servo was not able to bring the gun back into the fire zone against the extra-high trim pressure. The helicopter pilot and gunner could feel the larger counter recoil forces. On subsequent firings the proper adjustment in trim pressure was made before flight. The next 1500 rounds were fired without malfunction of any type in the recoil system, including the final 92-round burst.

The flight tests consisted of firing 250 rounds (the special ammo can capacity) per flight in bursts of 20 to 30 rounds. Altitude, slant range to target, aircraft speed and azimuth to the target were varied for each burst. The aircraft altitude was either 1000 or 100 feet, with most of the firings done at 1000 feet. The aircraft speed was 0(hover), 80 or 120 knots. The slant range was primarily 2000 meters, with three bursts at 1000 meters. The azimuth to the target was 30 degrees left or right and 0 degrees (straight ahead). Frankford Arsenal personnel directed the tests and will publish the quantitative test results.

The pilot, Chief Warrant Officer Russell Gardner, was enthusiastic about the success of the recoil system in significantly reducing gun-recoil-caused vibrations in the helicopter. In particular, he noted that he could now precisely fly the helicopter during gun firing when, previously, the vibrations precluded precise control. He also felt that the helicopter and its avionics should now last much longer without the fatiguing heavy vibrations.

Figures 58 and 59 show the helicopter ground firing tests and the helicopter lifting off with the gun/recoil/turret assembly. The only change from normal operation of the gun is that the pilot must turn on a switch to energize the solenoid valve and provide hydraulic power to the turret. (This is the same valve used to energize the M28 turret.)

The presence of the recoil system with its larger stroke and hydraulic lines did not interfere with the feeding of ammunition to the gun or movement of the gun in the turret.

Figure 58. Helicopter Ground-Firing Test

Figure 59. Helicopter with Gun/Recoil/Turret Assembly Lifting Off for Flight Test

APPENDIX A
RECOIL SYSTEM SIMULATION
PROGRAM LISTING

A listing for the digital computer program for simulation of a rotary valve constant-force recoil system discussed in Section V is provided in this appendix. The program consists of:

- Main Program - The input and output data are read and stored. The computations in this program consist of summing the forces on the weapon, computation of acceleration, velocity and travel, and gun rotational angle.

- Valve Subroutine - The servo valve slot width and underlap are computed, and constants are used in the cam program.

- Cam Subroutine - The cam parameters are computed as a function of gun rotational angle.

- Servo Subroutine - The pressure of the hydraulic fluid in the servo cylinder is computed as a function of valve characteristics, cam position, weapon position and velocity, servo valve area, type of oil and previous pressure.

- Misfire Subroutine - The hydraulic pressure in the misfire cylinder is computed as a function of misfire valve characteristics, misfire cam shape, angular position of the gun, velocity and displacement of the weapon, area of misfire piston, oil type and previous pressure.

The following is a complete listing of the main program and the four subroutines.

PAGE 1

MAIN PROGRAM

```
COMMON  VAL(40),XD(300),YD(300,2),ID,MAXOUT,YMX(2),YMN(2),BX,SX,
 +  GUNID
      DIMENSION  NAMS(40,3), NAMR(3)
 +    ,TDELAY(15),  FMX(15), NAMFL2(3),YDX(300,5)
      REAL  MSEC, KE6
      EQUIVALENCE
 +     (VAL( 1),WMNT  ),(VAL( 2),TPRES ),(VAL( 3),TRISE )
 +    ,(VAL( 4),TINTO ),(VAL( 5),PS    ),(VAL( 6),PM    )
 +    ,(VAL( 7),A1    ),(VAL( 8),KE6   ),(VAL( 9),ATRIM )
 +    ,(VAL(10),BM    ),(VAL(11),CFP   ),(VAL(12),PHO6  )
 +    ,(VAL(13),PG    ),(VAL(14),PTRIM ),(VAL(15),OG    )
 +    ,(VAL(16),SPM   ),(VAL(17),VOL1  ),(VAL(18),CFPD  )
 +    ,(VAL(19),POTAF ),(VAL(20),TMN   ),(VAL(21),TMX   )
 +    ,(VAL(22),YMN1  ),(VAL(23),YMX1  ),(VAL(24),YMN2  )
 +    ,(VAL(25),YMX2  ),(VAL(26),SPCOM ),(VAL(27),VOLTR )
 +    ,(VAL(28),PLOT  ),(VAL(29),PRINT ),(VAL(30),X0    )
 +    ,(VAL(31),POSTRT),(VAL(32),RUNID ),(VAL(33),A2    )
 +    ,(VAL(34),THETA ),(VAL(35),OG2   ),(VAL(36),XNUL3 )
 +    ,(VAL(37),END   ),(VAL(38),FNAMIS),(VAL(39),ENDEND)
      DATA
 +     NAMS( 1,1),NAMS( 1,2),NAMS( 1,3)
 +    ,NAMS( 2,1),NAMS( 2,2),NAMS( 2,3)
 +    ,NAMS( 3,1),NAMS( 3,2),NAMS( 3,3)
 +    ,NAMS( 4,1),NAMS( 4,2),NAMS( 4,3)
 +    ,NAMS( 5,1),NAMS( 5,2),NAMS( 5,3)
 +    ,NAMS( 6,1),NAMS( 6,2),NAMS( 6,3)
 +    ,NAMS( 7,1),NAMS( 7,2),NAMS( 7,3)
 +    ,NAMS( 8,1),NAMS( 8,2),NAMS( 8,3)
 +    ,NAMS( 9,1),NAMS( 9,2),NAMS( 9,3)
 +    ,NAMS(10,1),NAMS(10,2),NAMS(10,3)
 +    ,NAMS(11,1),NAMS(11,2),NAMS(11,3)
 +    ,NAMS(12,1),NAMS(12,2),NAMS(12,3)
 +    ,NAMS(13,1),NAMS(13,2),NAMS(13,3)
 +    ,NAMS(14,1),NAMS(14,2),NAMS(14,3)
 +    ,NAMS(15,1),NAMS(15,2),NAMS(15,3)
 +    ,NAMS(16,1),NAMS(16,2),NAMS(16,3)
 +    ,NAMS(17,1),NAMS(17,2),NAMS(17,3)
 +    ,NAMS(18,1),NAMS(18,2),NAMS(18,3)
 +    ,NAMS(19,1),NAMS(19,2),NAMS(19,3)
 +    ,NAMS(20,1),NAMS(20,2),NAMS(20,3)
 +    ,NAMS(21,1),NAMS(21,2),NAMS(21,3)
 +    ,NAMS(22,1),NAMS(22,2),NAMS(22,3)
 +    ,NAMS(23,1),NAMS(23,2),NAMS(23,3)
 +    ,NAMS(24,1),NAMS(24,2),NAMS(24,3)
 +    ,NAMS(25,1),NAMS(25,2),NAMS(25,3)
 +    ,NAMS(26,1),NAMS(26,2),NAMS(26,3)
 +    ,NAMS(27,1),NAMS(27,2),NAMS(27,3)
 +    ,NAMS(28,1),NAMS(28,2),NAMS(28,3)
 +    ,NAMS(29,1),NAMS(29,2),NAMS(29,3)
 +    ,NAMS(30,1),NAMS(30,2),NAMS(30,3)
 +    ,NAMS(31,1),NAMS(31,2),NAMS(31,3)
 +    ,NAMS(32,1),NAMS(32,2),NAMS(32,3)
 +    ,NAMS(33,1),NAMS(33,2),NAMS(33,3)
 +    ,NAMS(34,1),NAMS(34,2),NAMS(34,3)
 +    ,NAMS(35,1),NAMS(35,2),NAMS(35,3)
 +    ,NAMS(36,1),NAMS(36,2),NAMS(36,3)
```

```
     + ,NAMS(37,1),NAMS(37,2),NAMS(37,3)
     + ,NAMS(38,1),NAMS(38,2),NAMS(38,3)
     + ,NAMS(39,1),NAMS(39,2),NAMS(39,3)
     + /
     +  2HWM,2HNT,2H
     + ,2HTP,2HRE,2HS
     + ,2HTR,2HIS,2HE
     + ,2HTI,2HNT,2HO
     + ,2HPS,2H  ,2H
     + ,2HPM,2H  ,2H
     + ,2HA1,2H  ,2H
     + ,2HKE,2H6 ,2H
     + ,2HAT,2HRI,2HM
     + ,2HBM,2H  ,2H
     + ,2HCF,2HR ,2H
     + ,2HPH,2HO6,2H
     + ,2HPG,2H  ,2H
     + ,2HPT,2HRI,2HM
     + ,2HOG,2H  ,2H
     + ,2HSP,2HM ,2H
     + ,2HVO,2HL1,2H
     + ,2HCF,2HRD,2H
     + ,2HPD,2HTA,2HF
     + ,2HTM,2HN ,2H
     + ,2HTM,2HX ,2H
     + ,2HXM,2HN ,2H
     + ,2HXM,2HX ,2H
     + ,2HFM,2HN ,2H
     + ,2HFM,2HX ,2H
     + ,2HSP,2HCD,2HM
     + ,2HVO,2HLT,2HR
     + ,2HPL,2HOT,2H
     + ,2HPR,2HIN,2HT
     + ,2HX0,2H  ,2H
     + ,2HPD,2HST,2HRT
     + ,2HOL,2HDR,2HUN
     + ,2HA2,2H  ,2H
     + ,2HTH,2HET,2HA
     + ,2HOG,2H2 ,2H
     + ,2HXN,2HUL,2H3
     + ,2HEN,2HD ,2H
     + ,2HFN,2HAM,2HIS
     + ,2HEN,2HDE,2HND
     + /
        NIVAR = 39
    MAXOUT=300
        XD=0.
        G = 32.174
        MSEC = .001
     WRITE(9,1112)
 1112FORMAT('IMPUT 2 IF FIRST RUN,1 FOR CONTINUATION')
    READ(9,1111)IDFI
 1111FORMAT(I2)
     IF(IDFI.EQ.1) GO TO 290
        DO 801  I=1,NIVAR
 801 VAL(I) = 0.
```

MAIN PROGRAM

```
      WMNT = 1.
      TINTO = .1
      WRITE(9,401)
  401 FORMAT('IDENTIFY INPUT DATA LOAD FILE:'/)
  207 READ(1,403) NAMR, RVAL
  403 FORMAT(3A2,E15.0)
      GO TO 202
  201 READ(9,403) NAMR, RVAL
  202 DO 802  I=1,NIVAR
      IF(NAMR(1).NE.NAMS(I,1))   GO TO 802
      IF(NAMR(2).NE.NAMS(I,2))   GO TO 802
      IF(NAMR(3).EQ.NAMS(I,3))   GO TO 203
  802 CONTINUE
      WRITE(9,404) NAMR
  404 FORMAT(3A2, ' NOT AN INPUT PARAMETER ...  '/)
      GO TO 201
  203 IF(I-(NIVAR-2))  204,205,206
  204 VAL(I) = RVAL
      GO TO (201,207), IDFI
  206 IF(I.EQ.NIVAR)  STOP RUNEND
      GO TO (208,209), IDFI
  208 READ(9,403) NAMFL2
      GO TO 210
  209 READ(1,403) NAMFL2
  210 CALL DEFINE(2,NAMFL2)
      READ(2,405) NRNDS,    (TDELAY(I),FMX(I), I=1,NRNDS)
  405 FORMAT(I2,/,(2E15.0))
      GO TO (201,207), IDFI
  205 RUNID = RUNID + 1.
  PAUSE CLEAR SCREEN
  211 WRITE(9,406) RUNID
  406 FORMAT(11X,'C O N S T A N T   F O R C E   R E C O I L  '
     + 'S I M U L A T I O N',//,
     + 25X,'(VERSION: ROTARY JUNE 74/RFG)',//,'RUN NUMBER 'F4.0)
      CALL ACCNT(1)
      NVAR = NIVAR - 3
      WRITE(9,402)  ((NAMS(I,J), J=1,3), VAL(I), I=1,NVAR)
  402 FORMAT(//,'DATA LOAD STATUS:',//,4(3A2,F8.2,4X))
      WRITE(9,411) NAMFL2
  411 FORMAT(/,'FIRING TABLE IS ',3A2)
      T = 0.
      X = X0/12.
      XD = 0.
      XDD = 0.
       GUNID=RUNID
       SPC=SPCOM*34.56*(SPM-750.)/(60.*ATRIM)
     BX=TMX
     SX=TMN
      XR = 100.
       FFIRE=0.
       XNULL=XNUL3*MSEC
       RKE=KE6*MSEC*MSEC
       RHO=RHO6*MSEC*MSEC
    MFCT=1
      VR = 100.
      AR = 100.
```

MAIN PROGRAM

```
      RM = G/WMNT
  DO 80 I=1,NRNDS
    TDELAY(I)=TDELAY(I)*MSEC
80 CONTINUE
      TPRESS = TPRES*MSEC
      TRISES = TRISE*MSEC
      TINT = TINT0*MSEC
      TEND = 100.
      THOLD=1000.
      YMN(1) = YMN1
      YMN(2) = YMN2
      YMX(1) = YMX1
     YMX(2)=YMX2
      Z=0.
      TFORCE=1000.
      TFMX=1000.
      TFO=1000.
      P1=PM
   LOUT =0
      PMFF=0.
      PMFR=0.
      QAVG=0.
      QAA=0.
      FLOWK=SQRT(2/RHO)
      NNN=1
      BR=BM/MSEC
      IO = 0
      DO 805  I=1,MAXOUT
      XO(I) = 0.
      DO 807  J=1,6
      YOX(I,J)=0.
807 CONTINUE
  DO 805   J=1,2
   YO(I,J) = 0.
805   CONTINUE
      FTRAN=(PTRIM-SPC)*ATRIM*(VOLTR/(VOLTR+12.*X*ATRIM))**1.4
     +    -PMFF*A2-P1*A1-CFR*XD
      FT1=FTRAN
      CALL GVLV40(RHO,OG,PG,PS,PM,A1,A2,ZP,XULP,AF,PSSR,
     + FA,CFRD,SPM,AA1,XD1M,X1M,XD2M,X2M,OG2,AF2,
      + XD3M,X3M,SFRAN)
    IF(ROSTRT)581,582,582
581     ITC=1
    ROTA=120.+ROSTRT
    GO TO 285
582 ROTA=ROSTRT
    ITC=2

584     DO 804     NRND=1,NRNDS
     FTMN=FT1-20.
     FTMX=FT1+20.
285 IF((ITC.GT.2).AND.(MFCT.GT.1)) GO TO 73
      IO = IO + 1
      XO(IO) = T
      YO(IO,1) = X*12.
      YO(IO,2) = FTRAN
```

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MAIN PROGRAM

```
      YOX(ID,1) = XD
      YOX(ID,2) = P1
      YOX(ID,3)=ROTA
      YOX(ID,4)=PMFF
     RITC=ITC
      YOX(ID,5)=RITC
      IF(ID.GE.MAXOUT)  GO TO 360
 73 MFCT=MFCT+1
      IF(MFCT.LT.21) GO TO 286
    MFCT=1
     GO TO 286
360    WRITE(9,408)  NRND, NRNDS
 408 FORMAT(/,'* * *   OUTPUT OVERLOADED DURING FIRING OF '
    + 'ROUND ',I2,' OF ',I2,' ROUND BURST   * * *',//)
 PAUSE CLEAR SCREEN
   GO TO 222
 289 IF(PLOT.EQ.0.)  GO TO 290
CALL CHAIN ('PLOT,')
 288 IF(PRINT.EQ.0.)  GO TO 289
      WRITE(9,1234)RUNID
 1234FORMAT('RUN MUMBER  ',F4.0,/)
      WRITE(9,409)  (XD(I),YD(I,1),YD(I,2),YOX(I,1),YOX(I,2),YOX(I,3
 +    YOX(I,4),YOX(I,5),I=1,ID)
 409 FORMAT/,' TIME       DISPL       TFORCE        VEL        P1'
  +    ,'       ROTA,       PMFF ITC',/,
  +           '(MSEC)      (IN.)        (LBS)         (FPS)      (PSI)',
  +    '         (DEG)       (PSI)',//,
  + (F6.4,X,F9.3,F9.0,F9.3,F9.0,F9.2,F9.0,F3.0))
  PAUSE COMPLETE LISTING
  GO TO 289
 290 IDFI = 1
      WRITE(9,407)
 407 FORMAT('INPUT NEXT RUN DATA:',//)
      GO TO 201
286   CALL GNCAM(ROTA,X1M,XD1M,X2M,XD2M,X3M,XD3M,PTRIM,ATRIM
   +   ,FA,SRM,PS,AA1,XULP,AF,Z,SFRAN,VOLTR,A1)
     CALL   GVPR33(PS,P1,PSSR,X,XD,Z,AA1,A1,A2,EV,DELP,P2,
     + XULP,AF,VOL1,PKE,BB,TINT,T,NNN,NO,OAA,OAVG,TO,BF,R)
    IF(NNN.EQ.2) GO TO 222
     CALL GMFIR(PS,PSSR,X,XD,AA1,A1,A2,ROTA,CFR,AF2,THETA,XNULL,
     + PMFF,AF,PKE,BB,TINT,T,NNN,LOUT)
    TINT=.0001
    T=T+TINT
    ROTA=SPM*2.*TINT+ROTA
   IF(ROTA.GE.120.) GO TO 920
50    IF(T.GT.TEND) GO TO 222
      IF(T.GE.THOLD) GO TO 281
      IF((T.GE.TFORCE).AND.(T.LE.TFMX)) GO TO 252
      IF((T.GT.TFMX).AND.(T.LE.TFO)) GO TO 253
      IF(T.GT.TFO) GO TO 281
      IF(ROTA.GE.58.35) GO TO  900
  GO TO 281
 920  TINT=(120.-ROTA)/(SPM*2.)+.0001
      ROTA=0.
     T=T-.0001+TINT
    TFORCE=1000.
```

MAIN PROGRAM

```
      TFMX=1000.
      TFD=1000.
     IF(ITC.EQ.2) GO TO 50
     IF(ITC.EQ.5) GO TO 919
     ITC=ITC+1
      GO TO 50
 919 ITC=2
   GO TO 50
 915 WRITE(9,6688)NRND,T,ROTA
   6688FORMAT('ROUND NO',I4,' INHIBITED AT TIME',F7.4,' SEC
  +     AND ANGLE',F8.2)
    ITC=5
    GO TO 281
  900 TINT=(58.35-ROTA)/(SPM*2.)+.0001
        T=T-.0001+TINT
        ROTA=58.35
        TFORCE=T+TDELAY(NRND)
        TFMX=TFORCE+TRISES
        TFD=T+TPRESS+TDELAY(NRND)
      GO TO  281
 252  IF(ITC.EQ.4) GO TO 915
  IF(ITC.GE.3) GO TO 281
     IF(FMX(NRND).LE.2.) GO TO 300
      FFIRE = FMX(NRND)*(T-TFORCE)/TRISES
       GO TO 155
 253 IF(ITC.GE.3) GO TO 281
        FFIRE = FMX(NRND)*(TFD-T)/(TPRESS-TRISES)
         GO TO 155
 300     ITC=3
    WRITE(9,6677)NRND,T,ROTA
     6677FORMAT('ROUND NO.',I4,'MISFIRED AT ',F7.4,'SECONDS,',
   +      'ROTATIONAL ANGLE OF',F8.4,)
    281   FFIRE=0.
 155     FTRAN=(PTRIM-SPC)*ATRIM*(VOLTR/(VOLTR+12.*X*ATRIM))**1.4
       +    -PMFF*A2-P1*A1-CFR*XD
  273 XDDN = (FTRAN - FFIRE)*RM
        XDA = XDDN*TINT
        XA = (.5*XDA + XD)*TINT
        XDN = XD + XDA
        XN = X + XA
        IF(X.EQ.0.)  GO TO 282
        XR = XN/X
  282 IF(XD.EQ.0.)  GO TO 283
        VR = XDN/XD
  283 IF(XDD.EQ.0.)  GO TO 284
        AR = XDDN/XDD
 284    X = XN
        XD = XDN
        XDD = XDDN
    IF((ITC.EQ.1).AND.(ROTA.EQ.0.)) GO TO 584
    IF(ITC.EQ.1) GO TO 285
    950  IF(ROTA.EQ.0.) GO TO 804
    IF(ITC.GT.2) GO TO 285
      IF(XR.LT.0.)  GO TO 285
       IF(VR.LT.0.)  GO TO 285
        IF(NNN.EQ.3) GO TO 285
```

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MAIN PROGRAM

```
      IF(AR.LT.0.)  GO TO 285
        IF(T.GE.TEND)  GO TO 285
  IF(FTRAN.GE.FTMN) GO TO 320
    FTMN=FTRAN-20.
    GO TO 285
 320 IF(FTRAN.LE.FTMX) GO TO 286
    FTMX=FTRAN+20.
    GO TO 285
804   CONTINUE
  TEND=T+ROTAF/(2.*SPM)
    THOLD=T
      TFORCE=1000.
      TFMX=1000.
      TFO=1000.
      FMX(NRND)=0.
        GO TO 285
222   CALL ACCNT(2)
 235 WRITE(9,410) IO,QAA,TQ,QAVG
 410 FORMAT('(',I3,' OUTPUT DATA POINTS GENERATED)',//,
     + 'FLOW MAX = ',F10.2,' CU.-IN/SEC AT ',F8.4,' SEC.',/,
     + 'FLOW AVERAGE = ',F8.2,' CU.-IN./SEC.',/)
      PAUSE OUTPUT READY
      GO TO 288
      END
      SUBROUTINE ACCNT(IENTRY)
      GO TO (201,202), IENTRY
 201 CALL DATE(IM,ID,IY)
      CALL TIME(SEC)
      IHR = SEC/3600.
      MIN = (SEC-FLOAT(IHR)*3600.)/60.
      APM = ' AM '
      IF(IHR-12)  203,204,205
 205 IHR = IHR-12
 204 APM = ' PM '
 203 WRITE(9,401) IM, ID, IY, IHR, MIN, APM
 401 FORMAT(//'DATE:   'A2,'-'A2,'-'A2,/
     + 'TIME:   'I2,':'I2,2A2,/)
      CALL CPTIME(SEC1)
      RETURN
 202 CPTRS = CPTIME(DUM1) - SEC1
      WRITE(9,402) CPTRS
 402 FORMAT(///'THIS SIMULATION REQUIRED 'F6.2,' HCN CP'
    + ' SECONDS.'/)
      RETURN
      END
```

PAGE 1

VALVE SUBROUTINE

```
      SUBROUTINE GVLV40(RHO,QG,PG,PS,PM,A1,A2,ZP,XULP,AF,PSSR,
     + FA,CFRD,SRM,AA1,XD1M,X1M,XD2M,X2M,QG2,AF2,
     + XD3M,X3M,SFRAN)
      C1=SQRT(PS-PM)
      C2=SQRT(PM)
      AF=QG*A1/(C1+C2)
      ZP=PM/PG
      SLWA=AF/SQRT(2/RHO)
      XULP=PS/PG
      PSSR=SQRT(PS)
      AF2=QG2*A2/PSSR
      SLW2=AF2/SQRT(2/RHO)
      SFRAN=34.56/.080
      SRM=32.174/187.6
      GPAF=(-SFRAN+PTRIM*ATRIM)/A1
      FA=CFRD/A1
      AA1=A1*12.
      XD1M=SFRAN*.0389
      X1M=.5*XD1M*.0389
      CC2=SFRAN-12800.
      CC3=SFRAN-25600./3.
      XD2M=.0006*CC2+XD1M
      X2M=(.5*CC3*.0006+XD1M)*.0006+X1M
      XD3M=CC2*.0021+XD2M
      X3M=(.5*SFRAN-25600./3.)*.0021*.0021+XD2M*.0021+X2M
      WRITE(9,1099)AF,SLWA,XULP,AF2,SLW2
 1099 FORMAT('AF,SLWA,XULPAF2,SLW2=',5F8.5)
      RETURN
      END
```

CAM SUBROUTINE

```
      SUBROUTINE GNCAM(ROTA,X1M,XD1M,X2M,XD2M,X3M,XD3M,PTRIM,ATRIM
     + ,FA,SRM,PS,AA1,XULP,AF,Z,SFRAN,VOLTR,A1)
        ROTAK=ROTA/1500.
        IF((ROTA.GE.0.).AND.(ROTA.LE.58.35)) GO TO 20
        IF((ROTA.GE.58.35).AND.(ROTA.LE.59.25)) GO TO 30
        IF((ROTA.GE.59.25).AND.(ROTA.LE.62.4)) GO TO 40
        IF((ROTA.GE.62.4).AND.(ROTA.LE.120.)) GO TO 50
       IF(ROTA.GT.120.)GO TO 70
 20     XD=SFRAN*ROTAK
        X=.5*XD*ROTAK
      GO TO 60
 30     RINC=ROTAK-.0389
        XD=(SFRAN-21333333.*RINC)*RINC+XD1M
        X=((.5*SFRAN-7111111.*RINC)*RINC+XD1M)*RINC+X1M
      GO TO 60
 40    RINC=ROTAK-.03950
        XD=(SFRAN-25600.+6095238.*RINC)*RINC+XD2M
        X=(((.5*SFRAN-12800.)+25600./.0126*RINC)*RINC+XD2M)*RINC+X2M
       GO TO 60
 50     RINC=ROTAK-.0416
        XD=SFRAN*RINC+XD3M
        X=(.5*SFRAN*RINC+XD3M)*RINC+X3M
 60 P2=(-SFRAN+PTRIM*ATRIM*(VOLTR/(VOLTR+12.*SRM*X*ATRIM))**1.4)/A1
     +  -XD*FA*SRM
        C3=SQRT(PS-P2)
        C4=SQRT(P2)
         Q=-AA1*XD*SRM
      ZV=(Q-XULP*AF*(C3-C4))/((C3+C4)*AF)
        Z=12.*SRM*X-ZV
      GO TO 90
 70   WRITE(9,1000)
 1000FORMAT('ANGLE TOO LARGE')
      KKK=1
 90 RETURN
      END
```

PAGE 1

SERVO SUBROUTINE

```
      SUBROUTINE GVPR33(PS,P1,PSSR,X,XD,Z,AA1,A1,A2,EV,DELP,P2,
     + XULP,AF,VOL1,RKE,BB,TINT,T,NNN,NO,OAA,OAVG,TO,BF,R)
      ERR=.0005
      K=1
      J=1
      PA=P1
        ZV=12.*X-Z
      OR=-AA1*XD
      IF((OR.LT.1.).AND.(OR.GT.-1.)) GO TO 10
      ERR=.0005*ABS(OR)
 10   B1=(XULP+ZV)*AF
      B2=(XULP-ZV)*AF
      IF(ZV.GT.XULP) GO TO 50
      IF(ZV.LT.-XULP) GO TO 60
      GO TO 70
 50   B2=0.
      GO TO 70
 60   B1=0.
 70   VOL=VOL1-A1*12.*X
      IF(VOL.LT..001) GO TO 360
      BC=(RKE+VOL/BB)/TINT
   IF(P1.GT.1500.) GO TO 325
 80   C1=SORT(PS-P1)
      C2=SORT(P1)
      O1B=B1*C1-B2*C2
      O2B=OR+BC*(P1-PA)
      OER=O1B-O2B
      IF((OER.LT.ERR).AND.(OER.GT.-ERR)) GO TO 500
      IF(J.GE.2) GO TO 600
      OMAX=B1*PSSR
      OMIN=-B2*PSSR
      O0=OR-BC*PA
      O15=OR+BC*(1500.-PA)
      D1=SORT(1.)
      D2=SORT(1499.)
      O14=B1*D1-B2*D2
      O05=B1*D2-B2*D1
     IF(O15.LT.OMIN) GO TO 300
     IF((O15.GE.OMIN).AND.(O15.LE.O14)) GO TO 250
     IF(O0.GT.OMAX) GO TO 305
     IF((O0.LE.OMAX).AND.(O0.GE.O05)) GO TO 260
 600        J=J+1
 620  DODP=-.5*(B1/C1+B2/C2)
    PC=(O1B-OR-DODP*P1+BC*PA)/(BC-DODP)
     IF(PC.LT..5) GO TO 635
     IF(PC.GT.1499.5) GO TO 636
   IF(J.GE.50) GO TO 380
    P1=PC
      GO TO 80
 635  P1=.5*P1+.25
      IF(P1.LE.1.) GO TO 260
      GO TO 80
 636  IF(K.GT.1) GO TO 250
  P1=.5*P1+749.5
      IF(P1.GE.1499.) GO TO 250
      GO TO 80
```

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SERVO SUBROUTINE

```
250 P1=1499.5
    GO TO 500
260 P1=.5
    GO TO 500
325 O15=OR+BC*(1500.-PA)
   OMAX=-B2*PSSR
   IF(O15.LT.OMAX) GO TO 300
   P1=1499.5
   GO TO 80
300 OOUT=-B1-B2*SQRT(1501.)
    O1B=OOUT
    IF(O15.GE.OOUT) GO TO 335
    P1=1501.
326 DD1=SQRT(P1-1500.)
   DD2=SQRT(P1)
    O1B=-B1*DD1-B2*DD2
   O2B=OR+BC*(P1-PA)
    OER=O1B-O2B
   IF((OER.LT.ERR).AND.(OER.GT.-ERR)) GO TO 540
   DODP=-.5*(B1/DD1+B2/DD2)
  PC=(O1B-OR-DODP*P1+BC*PA)/(BC-DODP)
   K=K+1
   IF(K.GT.30) GO TO 380
   P1=PC
  GO TO 326
335 P1=1501.
    GO TO 800
305 P1=.5
310 NNN=NNN+2
    IF(NNN.EQ.3) GO TO 320
    GO TO 540
380 WRITE(9,1500)T,J,K,P1,PC,O1B,O2B,ERR
  1500FORMAT('NO SOLUTION-T,J,K,P1,PC,O1B,O2B,ERR=',/,
   + F6.4,2I4,2F10.2,2F10.4,F6.3,/,'IMPUT P1    ID=1-REPEAT J
  +    ---ID=2-REPEAT K---ID=3-TERMINATE')
   READ(9,2000)P1
  2000FORMAT(F12.0)
   GO TO 800
 382 NNN=2
   GO TO 800
500 IF(NNN.GT.3) GO TO 340
    NNN=1
    GO TO 540
320 WRITE(9,1100)
  1100FORMAT('FLOW CONDITIONS NOT MET')
321 WRITE(9,1200)T, PA,P1,ZV,OR,B1,B2,X,XD,Z
 1200FORMAT('T,PA,P1,ZV,OR,B1,B2=',F8.4,2F8.2,4F10.4,/,
   + 'X,XD,Z=',3F10.4)
    GO TO 540
360 WRITE(9,1300)T,X
1300FORMAT('VOLUME IS NEGATIVE-T,X=',F8.4,F10.4)
    NNN=2
    GO TO  800
340 WRITE(9,1400)
 1400FORMAT(' FLOW CONDITIONS MET')
    NNN=3
```

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SERVO SUBROUTINE

```
      GO TO 321
  540 OA=B1*C1
     OAVG=(OAVG*T+OA*TINT)/(TINT+T)
      IF(T.GE.0.) GO TO 570
      OAA=OA
      TO=T
  570 IF(OA.LT.OAA) GO TO 800
      OAA=OA
      TO=T
  800 RETURN
     END
```

PAGE 1

MISFIRE SUBROUTINE

```
      SUBROUTINE GMFIR(PS,PSSR,X,XD,AA1,A1,A2,ROTA,CFR,AF2,THETA,
     + XNULL,PMFF,AF,RKE,BB,TINT,T,NNN)
      ROTAP  = ROTA - 90.
      IF(ROTA.LT.90.) ROTAP = ROTA + 30.
      ZULP   = XNULL*(1. - ROTAP/60.)
      IF(ZULP.LT.0.0) ZULP = 0.00
      IF((ROTA.GT.60.).AND.(ROTA.LT.90.))ZULP = XNULL
    AFC=THETA
      XINCH  = X*12.
      IF(XINCH.GE.0.94) GO TO 12
      PMFF       = .1
      ODOT1  =0.
      ODOT2  = 0.
      RETURN
   12 CONTINUE
    IF((ROTA.GE.0.).AND.(ROTA.LT.35.))   GO TO 400
      IF (ROTA.LT.57.) GO TO 415
      IF(ROTA.LE.60.) GO TO 410
      IF(ROTA.LT.90.) GO TO 420
      IF(ROTA.LE.120.) GO TO 430
  400 S        = (ROTA + 30.5)*.0006
     GO TO 440
  410 ZVC=0.
    OPP=-.66
    OPP=1.5706
      Y=.6512
     GO TO 490
  415 S        = (ROTA + 23.07)*.0006
      YDOT     = 3.74 - 153.18*S
      Y        = 12.*S*(3.74 - 153.18/2.*S)
      GO TO 441
  420 CONTINUE
      Y        =  0.0
 YDOT    = 0.
      OPP      =  ZULP
      OPP      = -.6
    GO TO 490
  430  S=(ROTA-89.5)*.0006
  440 YDOT     = 3.5 - 129.6*S
      Y        = 12.*(3.5*S - 129.6/2.*S*S)
  441   P=(1100.-YDOT*CFR)/A2
    CAMC2=SQRT(P)
     CAMC1=SQRT(1500.-P)
      IF(YDOT) 442,450,446
  446     ZVC=-YDOT*A2*12./(AF2*CAMC2)+ZULP
     OPP=ZULP-ZVC
    OPP=-.8
      IF(YDOT.GT..5) GO TO 490
     IF(ZVC.LE.-ZULP) GO TO 490
  461  AN=.125
   BN=(-YDOT*A2*12.+AN*CAMC2*AF2)/(AF2*AFC*CAMC1)
     C=(AN+BN)/2.
     D=C-ZULP
    OPR=AN
       ZULP=C
    OPP=BN
```

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MISFIRE SUBROUTINE

```
 1229    GO TO 490
 1230 450 ZVC=(-YDOT*A2*12./AF2+ZULP*(CAMC2-AFC*CAMC1))/(AFC*CAMC1+CAMC2
 1232    OPR=ZULP-ZVC
 1234    OPP=ZULP+ZVC
 1240     GO TO 490
 1270 442 ZVC=-YDOT*A2*12./(AF2*AFC*CAMC1)-ZULP
 1272    OPP=ZULP+ZVC
 1274    OPP=0.
 1280     IF(ZVC.GE.ZULP) GO TO 490
 1290      GO TO 461
 1300 490 CHR=1.5762-OPR-Y-.925
 1302    CHP=1.5762+OPP-Y-.925
 1303    IF((ROTA.GE.0.).AND.(ROTA.LE.11.)) GO TO 491
 1304    IF((ROTA.GE.25.).AND.(ROTA.LE.57.)) GO TO 492
1305    IF((ROTA.GE.60.).AND.(ROTA.LE.120.)) GO TO 493
 1306  GO TO 494
1307  491 CHP=.12
1308    GO TO 494
 1309' 492 CHR=.66
1310  GO TO 494
 1311 493    CHP=.12
 1310 494      ERR=.0005
 1330      K=1
 1340      J=1
 1350      PA=PMFF
 1370     OR=-A2*12.*XD
 1380      IF((OR.LT.1.).AND.(OR.GT.-1.)) GO TO 10
 1390      ERR=.0005*ABS(OR)
 1400 10  B1=(12.*X+CHP-1.5762)*AFC*AF2
 1410     B2=(1.5762-CHR-12.*X)*AF2
 1420    IF(B1.LE.0.) GO TO 60
1422       IF(PRINT.EQ.0.) WRITE(9,321) T,ROTA,PMFF
1423 321 FORMAT(1X,2HT=,F6.4,4X,5HROTA=,F8.4,4X,5HPMFF*,F6.0)
1425       PRINT =1.
 1430     IF(B2.LE.0.) GO TO 50
 1440      GO TO 70
 1450 50  B2=0.
 1460      GO TO 70
 1470 60  B1=0.
1475       PRINT = 0.0
 1480 70  VOL=2.-A2*12.*X
 1490      IF(VOL.LT..001) GO TO 360
 1500      BC=(RKE+VOL/BB)/TINT
 1510  IF(PMFF.GT.1500.) GO TO 325
 1520 80  C1=SQRT(PS-PMFF)
 1530      C2=SQRT(PMFF)
 1540      O1B=B1*C1-B2*C2
 1550      O2B=OR+BC*(PMFF-PA)
 1560      OER=O1B-O2B
 1570      IF((OER.LT.ERR).AND.(OER.GT.-ERR)) GO TO 800
 1580      IF(J.GE.2) GO TO 600
 1590      OMAX=B1*PSSR
 1600      OMIN=-B2*PSSR
 1610      O0=OR-BC*PA
 1620      O15=OR+BC*(1500.-PA)
 1630      D1=SQRT(1.)
```

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MISFIRE SUBROUTINE

```
     D2=SQRT(1499.)
     014=B1*D1-B2*D2
     005=B1*D2-B2*D1
    IF(015.LT.OMIN) GO TO 300
    IF((015.GE.OMIN).AND.(015.LE.014)) GO TO 250
    IF(00.GT.OMAX) GO TO 305
    IF((00.LE.OMAX).AND.(00.GE.005)) GO TO 260
600        J=J+1
620 DODP=-.5*(B1/C1+B2/C2)
    PC=(01B-OR-DODP*PMFF+BC*PA)/(BC-DODP)
    IF(PC.LT..5) GO TO 635
    IF(PC.GT.1499.5) GO TO 636
   IF(J.GE.50) GO TO 380
   PMFF=PC
     GO TO 80
635 PMFF=.5*PMFF+.25
     IF(PMFF.LE.1.) GO TO 260
     GO TO 80
636 IF(K.GT.1) GO TO 250
  PMFF=.5*PMFF+749.5
     IF(PMFF.GE.1499.) GO TO 250
     GO TO 80
250 PMFF=1499.5
     GO TO 800
260 PMFF=.5
     GO TO 800
325 015=OR+BC*(1500.-PA)
    OMAX=-B2*PSSR
    IF(015.LT.OMAX) GO TO 300
    PMFF=1499.5
    GO TO 80
300 OOUT=-B1-B2*SQRT(1501.)
     01B=OOUT
     IF(015.GE.OOUT) GO TO 335
     PMFF=1501.
326 DD1=SQRT(PMFF-1500.)
    DD2=SQRT(PMFF)
     01B=-B1*DD1-B2*DD2
    02B=OR+BC*(PMFF-PA)
     OER=01B-02B
    IF((OER.LT.ERR).AND.(OER.GT.-ERR)) GO TO 800
    DODP=-.5*(B1/DD1+B2/DD2)
   PC=(01B-OR-DODP*PMFF+BC*PA)/(BC-DODP)
    K=K+1
    IF(K.GT.30) GO TO 380
    PMFF=PC
  GO TO 326
335 PMFF=1501.
     GO TO 800
305 PMFF=0.
     GO TO 800
380 WRITE(9,1500)T,J,K,PMFF,PC,01B,02B,ERR
  1500FORMAT('NO SOLUTION-T,J,K,PMFF,PC,01B,02B,ERR=',/,
   + F6.4,2I4,2F10.2,2F10.4,F6.3,/,'IMPUT PMFF')
    READ(9,2000)PMFF
  2000FORMAT(F12.0)
```

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MISFIRE SUBROUTINE

```
      GO TO 800
  360 WRITE(9,1300) T,X
 1300FORMAT('VOLUME IS NEGATIVE-T,X=',F8.4,F10.4)
      NNN=2
  800 CONTINUE
      QDOT2  = B2*SQRT(PS)
      IF(PS.GE.PMFF) GO TO 888
      QDOT1  = 0.0
      RETURN
  888 QDOT1  = B1*SQRT(PS - PMFF)
      RETURN
      END
```
