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COMPOSITE FLIGHT-CONTROL ACTUATOR DEVELOPMENT[1]

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SUMMARY

The composite actuator is "jam resistant", satisfying a survivability requirement for the Navy. Typically, the push-pull force needed to drive through the wound area of the composite actuator is 73 percent less than that of an all-metal actuator. In addition to improving the aircraft's combat survivability, significant weight savings were realized. The current design of the survivable, composite actuator cylinder is 36 percent lighter than that of the production steel cylinder, which equates to a 15 percent overall actuator weight savings.

INTRODUCTION

Most actuators for flight critical control surfaces consist of two redundant hydraulic cylinders that are attached together and mechanically attached together in a dual-simplex or dual-tandem configuration. In conventional metal cylinder designs, deformation of one cylinder caused by ballistic impact will seize its piston. The second cylinder cannot develop the force required to push the seized piston past this deformation. Further, because the redundant actuators are fixed together mechanically, the undamaged cylinder jams as well.

The Naval Weapons Center, China Lake, California, contracted HR Textron Inc. (HR) in Valencia, California, to develop and produce a prototype, jam-resistant F/A-18 aileron actuator. Jam resistance is provided by an actuator cylinder constructed of filament-wound composite material. After ballistic impacts, the composite material shears away easily when the piston passes the deformed area. Actuators produced by HR under the Navy's contract were used for qualification, and for ballistic and flight testing.

A basic hydraulic actuator on the F/A-18 consists of two assemblies. The manifold assembly is a control unit that receives commands from the flight-control computers and provides

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pressurized hydraulic fluid to the cylinder according to those signals. The cylinder assembly actually does the work by moving the control surface. Because development of the composite actuator was accomplished (1) on a low-risk basis and (2) intended mainly as a combat survivability improvement to reduce jamming, little developmental work was done on the manifold. The main areas of concern were components in the cylinder assembly.

The contract currently is nearing completion. The composite actuator for this development is in its final configuration. The cylinder assembly is composed of Amoco's T50 carbon fiber and Shell Epon 828 resin system, filament wound in a geodesic pattern over a thin 15-5PH steel liner. The liner acts as a durable wear surface for the piston seal, but does not produce heavy petalling when impacted ballistically.

Mounted on the cylinder is a production-level F/A-18 aileron manifold. To minimize structural discontinuities caused by porting through the composite cylinder walls, an interface plate between the manifold and cylinder allowed routing of fluid inlets and outlets via the ends of the cylinder.

Four complete actuator assemblies have been produced by HR under the Navy contract. Two were for qualification testing, to verify that the composite actuators would pass all tests required of the original production models. Qualification testing is brutal and essentially destructive; therefore, these two actuators will not be used for flight testing. However, they made acceptable articles for performing those ballistic tests that verified the jam-resistance concept. The ballistic testing was performed at the Naval Weapons Center.

The remaining two actuators are to be used for flight testing. Flight testing is to be conducted at the NASA Ames Dryden Flight Research Facility at Edwards Air Force Base, California, in September 1991. Flight testing is intended to demonstrate the maturity of the technology and to promote future development and application to production aircraft.

Although the actuators have been developed and produced as an "aircraft, combat survivability improvement," there are other benefits to the design. Foremost among these is the significant weight reduction realized through the use of composite materials. The composite cylinder in its current configuration achieved a 36 percent weight savings over existing production steel cylinders. This savings equates to a 15 percent actuator weight reduction overall. Actuators are a significant contributor to the weight of hydraulic systems; therefore, composite actuator construction provides an excellent opportunity for weight reduction in any military or commercial aircraft using hydraulic flight-control systems.

HR Textron has undertaken the cost of considerable IR&D to investigate additional areas of potential improvements. These studies include the use of polyetheretherktone (PEEK) for end glands and fluid ports, and composite piston heads and push rods. With composites as a design feature at the start of a design cycle, there is little doubt that further weight reductions are possible.

GENERAL DESCRIPTION: FLIGHTWORTHY SURVIVABLE ACTUATOR

A direct replacement for the F/A-18 aileron servoactuator presents a difficult challenge because of the envelope in which the unit must fit. The current steel cylinder virtually fills the entire envelope. The production aileron servocylinder is a two-piece unit consisting of:

- An aluminum manifold that contains:
  - Electrohydraulic Servovalve
  - Solenoid Valve
  - Pressure Switch
  - Bypass Valve
  - Accumulator
  - Electrical Connector Interface

- A steel (15-5) cylinder that contains:
  - Monoball End Fittings
  - Piston Rod
  - Position Transducer
  - Cylinder End Closure (End Gland)
  - Associated Fluid Transfer Ports
  - Electrical Connector Interface
  - Cylinder-to-Manifold Bolting Provisions

The cylinder and some ancillary parts were redesigned, maintaining the identical interfaces with a manifold that was slightly modified for envelope reasons. Figure 1 shows the flight-verification, tested, and flight-test composite actuators.

Three major actuator components/areas were developed successfully with composite materials: cylinder, position-transducer, and mounting attachment. The following subsections describe the components/areas of the composite cylinder assembly.

Cylinder Design

The cylinder is a combination of filament-wound carbon fibers and unidirectional carbon fiber epoxy tape. Extensive evaluation -- to determine the exact location and orientation of each fiber -- is necessary to build a structure that is thick enough to withstand the system's pressure impulse cycles, yet thin enough to be within a reasonable envelope.

A liner is needed in the cylinder to prevent fluid permeation and provide a wear surface for the piston to ride upon. The liner must be selected judiciously so that strain and thermal coefficient compatibilities are met with the composite overwrap structure. In addition, metal inserts with internal threads are necessary to engage the tailstock on one end and the end gland/retainer at the other.

The cylinder, liner and metal inserts are filament wound and cocured together to form an integral unit (Figure 2). The cylinder is fabricated on a mandrel. The surface finish of the mandrel is critical, to prevent scratches or gouges of the actual part during the extraction process, as well as to maintain dimensions of the part. The first fabrication step is to insert the liner and metal inserts onto the mandrel. Then, the winding process commences (i.e., alternate layers of filament wound fibers and longitudinal unidirectional tape are applied).

The whole unit, mandrel included, is cured in an oven. Curing temperature, of course, must be higher than the highest operational temperature of the unit. After the cure process, the unit is separated from the mandrel. The outside of the wound cylinder is rough in texture because of the winding process. A grinding operation can be performed to specific portions of the cylinder where other parts must be bonded to it. A final honing operation may be necessary to ensure conformance of the internal diameter dimensions of the cylinder.

Position Transducer

The position transducer used on the F/A-18 aileron is a dual-channel, self-checking type using 10 wires. These characteristics were left intact to maintain the original built-in testing (BIT) check and redundancy management concepts within the flight control computer. Null adjustment and rigging of the actuator remained identical to that of the original unit.

The only change made was for survivability reasons: to thin down the walls of the steel case (existing walls are 0.080 inch thick), and replace them with carbon/epoxy filament-wound material (Figure 3). This approach decreases the size of the petals formed when a projectile passes through, thereby creating less tendency for the fragment petals to jam the piston.

Manifold-to-Cylinder Attachment

The "mounting boss" is a design-critical area. This is because the attachment of manifold and cylinder assemblies depends on the boss. The barrel-mounting boss also is bonded secondarily (Figure 4) and fiber wrapped around the cylinder for support. The vibration spectrum at the aileron location in the F/A-18 aircraft is very severe; the mounting stresses between the cylinder and the manifold were the design driver.

FLIGHT VERIFICATION TEST PROGRAM

The flight verification tests selected are critical to flight safety and operational requirements; they were completed in "Phase II" of the NWC program. A detailed review was conducted of the F/A-18 aileron Procurement Specification PS 74-690054 to identify critical tests for the composite actuator assembly and to qualify it as a flightworthy unit.

The actual flight-test time using the composite aileron actuator is to be a total of five hours. Thus, it seemed inappropriate to perform a complete spectrum of tests. The McDonnell Aircraft Company (MCAIR) aileron procurement specification (PS 74-690054), Paragraph 4.1.6 (Preflight Verifications), requires that only 10 percent of life cycling and impulse be performed prior to first flight. HR Textron suggested that time and funding resources would be saved if only 20 percent of the full test be performed; this suggestion was accepted by the Navy. In fact, after testing began, the composite servoactuators endured the full impulse cycling (ARP 1383), 40 percent life cycling and piston bottoming, and four low-temperature tests.

The tests (see Table 1) were conducted to demonstrate formally that the Hydraulic Aileron Composite Servoactuator Assembly is flightworthy and conforms to the Preflight Verification requirements of MCAIR specification PS 74-690054. Note that the tests described in Table 1, summarized for this paper, are but the highlights of a comprehensive flight verification/qualification program. A complete discussion of the actual test program (Ref. 1) appears to be beyond the intent of this conference.

Table 1. Critical Specifications for the Composite Actuator

Test Title	Objective	Conditions	Success Criteria
Life Cycling	Verify wear life without failure	200,000 cycles at 225°F fluid temperature	1) Dynamic seal of 1.013M cycles min. 2) No deterioration of performance. 3) No cracks or excessive wear.
Piston Bottoming	Verify actuator piston snubber is operating satisfactorily with impact load within limits.	13,000 cycles at 170°F fluid temperature.	1) Peak axial loads shall not exceed 3023 pounds. 2) There shall be no structural failure of the unit. 3) Disassembly inspection for damage.
Impulse Cycling	Verify fatigue strength of cylinder under pressure impulse conditions.	40,000 cycles at 230-4500-230 psi, 40,000 cycles at 0-2250-0 psi.	1) No external static seal leakage. 2) No deformation or structural failure.
Low Temperature	Verify satisfactory performance at -40°F.	-40°F ambient and fluid temperature	1) No excessive leakage. 2) No permanent performance deterioration.
High Temperature	Verify satisfactory performance at 275°F.	240°F ambient temp., 275°F fluid temp.	1) No excessive leakage. 2) No permanent performance deterioration.
Temperature Shock	Verify ability of actuator to withstand extreme temperature variations.	-40°to 240°F ambient temp., -40°F to 275°F fluid temp.	No binding or permanent damage during operation.

Vibration	Verify structural integrity under vibration.	Production F/A-18 aileron vibration spectrum.	1) No binding or excessive external leakage. 2) No cracks or loose parts. 3) Actuator shall work satisfactorily after test.
Proof Pressure	Verify actuator to withstand proof pressure.	4500 psi at 275°F ambient and fluid temp.	No deterioration or damage.
Burst Pressure	Verify safety under hydraulic overload condition.	7500 psi	Withstand burst pressure without rupture.

Test Environment

The standard test conditions during the program were as stated below:

- Supply Pressure: 3000 ± 100 psig
- Return Pressure: 235 psig ± 50
- Ambient Temperature: 55°F to 95°F
- Fluid Temperature: 70°F to 140°F
- Test Fluid: MIL-H-83282 in hydraulic system within fluid cleanliness limits of NAS 1638 Class 6
- Barometric Pressure: Local Ambient
- Relative Humidity: 20% to 90%

Test parameter tolerances were as follows:

- Temperature: ±2.5°F
- Barometric Pressure: ±5%
- Relative Humidity: ±5%
- Current: ±1% Full Scale
- Voltage: ±1% Full Scale
- Hydraulic Pressure: ±1% Full Scale
- Acceleration: ±10%
- Force: ±5%
- Position: ±0.010 inch

Some of the highlighted tests are illustrated in the following figures:

- Figure 5 - Life Cycling
- Figure 6 - Piston Bottoming
- Figure 7 - Impulse Cycling
- Figure 8 - Low Temperature

- Figure 9 - High Temperature and Temperature Shock
- Figure 10 - Vibration

Test Results

The flightworthiness testing was accomplished on two units. One qualification unit is used for structural testing (i.e., life and impulse cycling, piston bottoming, etc.); the other unit is used for environmental testing (i.e., temperatures, vibration, etc.). Note that the units did experience some "failures" during the test program. However, the failures were not associated with the composite structures and were remedied easily. For example, failures included electrical failures within the manifold and the fatigue failure of a metallic tube; they were corrected quickly.

The composite servoactuators passed successfully and, in some cases, exceeded program requirements. The structural qualification unit passed all the tests required, plus the following additions:

- Five Acceptance Test Procedures[2] (ATPs)
- 400,000 Life Cycles (200,000 cycles were required)
- 26,000 Piston Bottoming cycles (13,000 cycles were required)
- 200,000 High-Pressure Impulse Cycles (40,000 cycles were required)
- 200,000 Low-Pressure Impulse Cycles (40,000 cycles were required)

The environmental qualification unit passed all the tests required, plus the following additions:

- Four Acceptance Test Procedures (ATPs)
- Four low-temperature tests (one was required)

Ballistic Tolerance

As discussed earlier, ballistic tests were conducted on the F/A-18 aileron composite actuators. The Naval Weapons Center (NWC) test facility and its setup for the ballistic tests are shown in Figure 11. The tests employed different threats at specific impact velocities and various locations. Results indicated that the composite cylinders/actuators required

[2]An ATP consists of physical inspection for defects, proof pressure, insulation resistance, dielectric strength, operation, external and internal leakages, main ram friction, output travel, main ram LVDT, output ram velocity, frequency response, failure transient, damper operation, chatter and instability, performance duty cycle, and seven more pressure and electrical related tests.

significantly lower forces, (Fig. 12) to "drive through" the damaged areas than the all-metal version.

The Navy's tests verified the HR approach for flight control actuator design. The basic characteristics that an actuator must possess were demonstrated in the composite actuator: wear quality, fluid impermeability, endurance, thermal stability, and strength within the realm of the F/A-18 aileron actuator specifications. Jam-resistance of the composite actuator was substantiated. The replacement of metal actuator components (cylinder, position transducer housing and mounting attachments) with carbon epoxy materials is a reasonable option and has low design risks.

SUMMARY AND CONCLUSIONS

Significant accomplishments have been made in identifying the advanced materials technologies best suited to the flight control actuators. Some of these areas are discussed briefly in this paper. Other advanced material components -- such as thermoplastic end glands and fluid ports, and composite piston heads -- have shown promising results in tests (Ref. 2). The transition of composite technology to actuation technology is here. Different composite actuator designs are presently undergoing qualification testing; however, there is a need to extend the research and development for general applications.

A relatively large amount of metal components (at least 41 percent by weight) still exists in current composite actuator designs. The metal components have not yet been replaced by advanced materials because of high loads and tight envelope requirements. R&D activities are underway to look at these high-risk actuator components and develop new processes such as thermoplastic filament winding and molding techniques, and application of new materials (thermoplastics and metal-matrix composites).

In addition to the continuing investigation of new processes and materials, we recognize that fabrication and material costs must be competitive. The demands for fibers and resins are increasing; processes such as filament winding and injecting molding are combining to bring acquisition and support costs down.

Ongoing advanced development efforts will reduce the weight further and potentially, the cost. Also, these developments will increase the survivability of flight control components. Efforts in this challenging technology will help meet the demands of the 1990s and will contribute to the success of early twenty-first century vehicles.

REFERENCES

1. Ching, F., "Jam-Resistant Flight Control Actuator (F/A-18 Aileron) Development Program," NAWC WPNS TP 8009, March 1992.

2. Ching, F., "Advanced Materials Flight Control Actuators," SAE 901048, Apr. 1990.

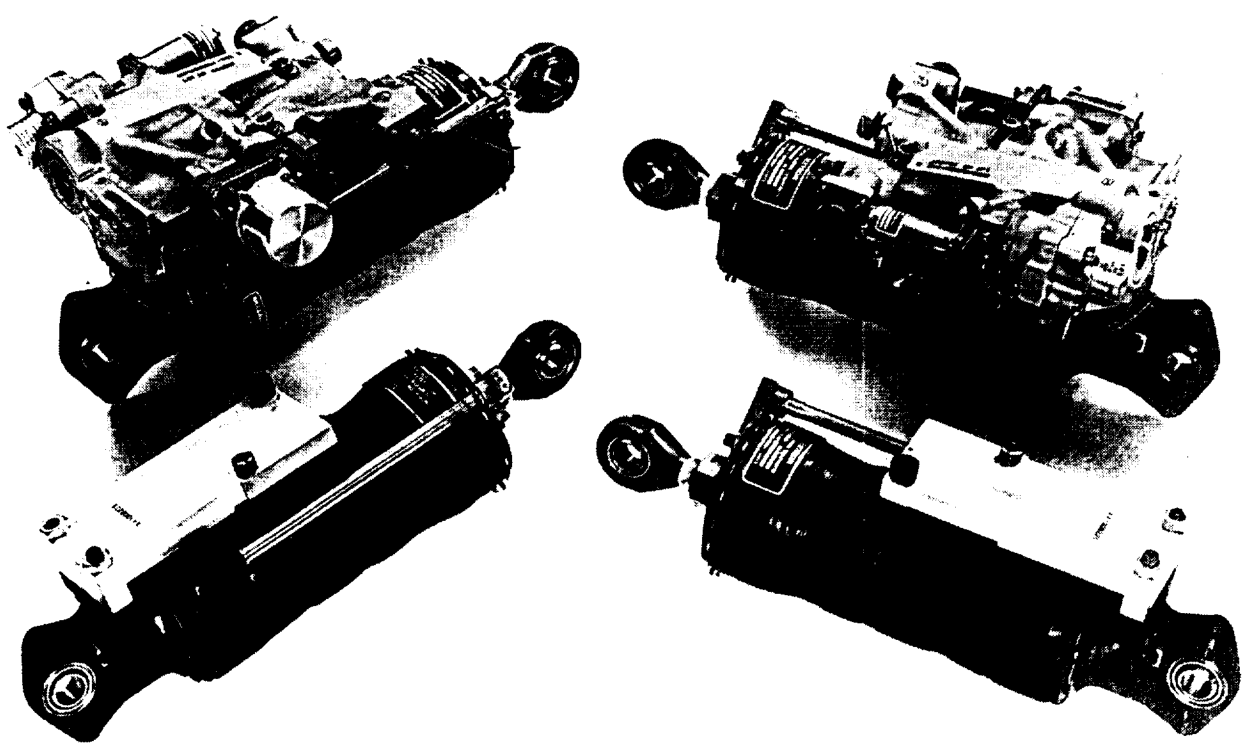

Figure 1. Jam-Resistant Flight Control Actuators (F/A-18 Aileron)

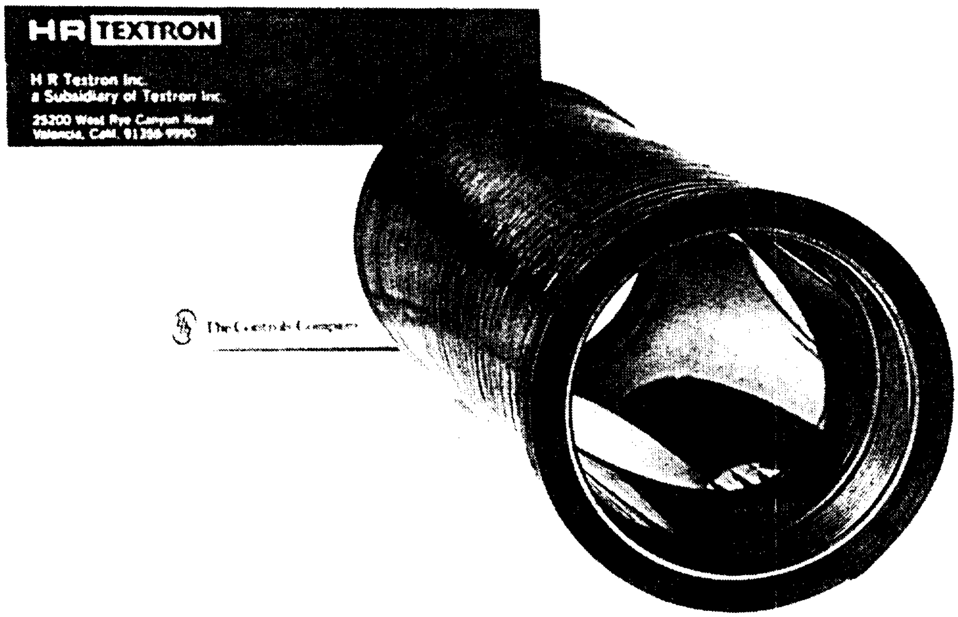

Figure 2. Carbon Epoxy Cylinder with Steel Liner and Thread Inserts

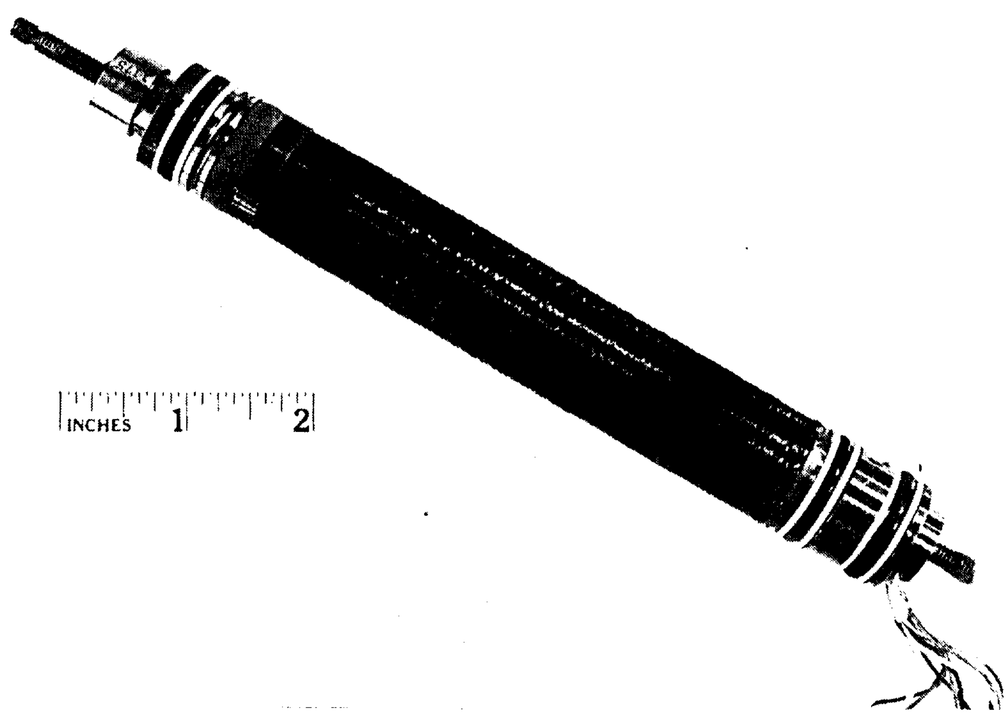

Figure 3. Composite-Wrapped LVDT

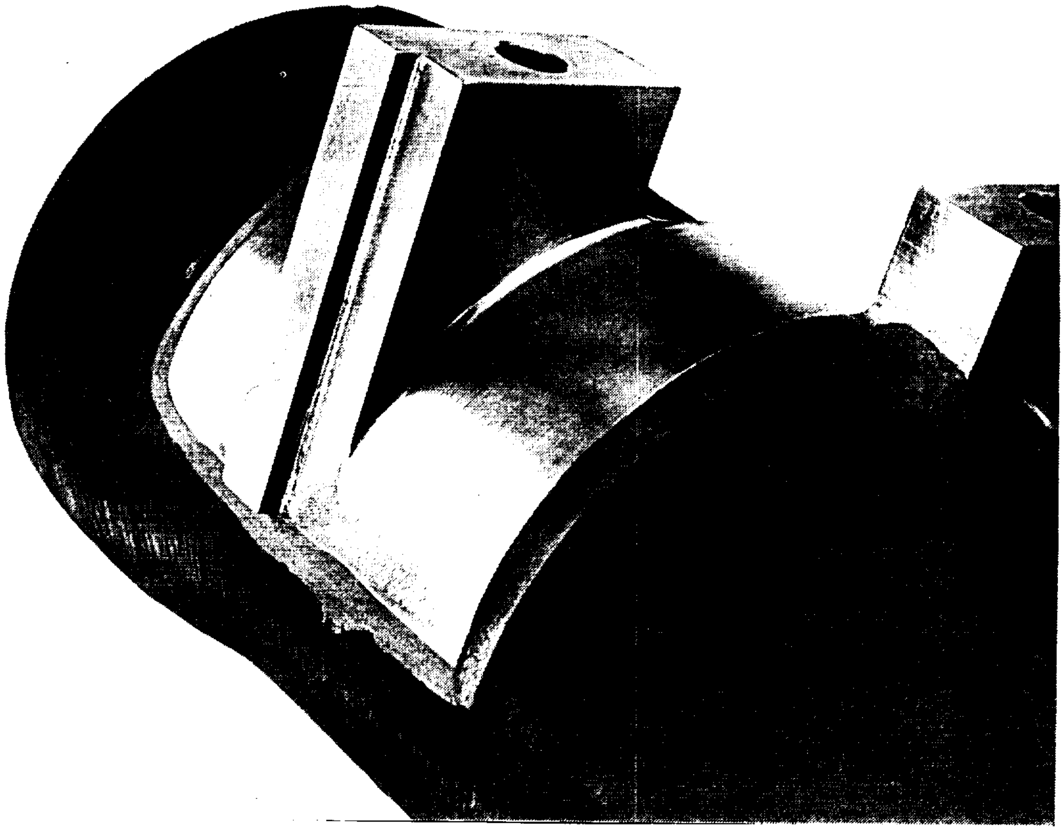

Figure 4. Bonded Mounting Boss (not wrapped)

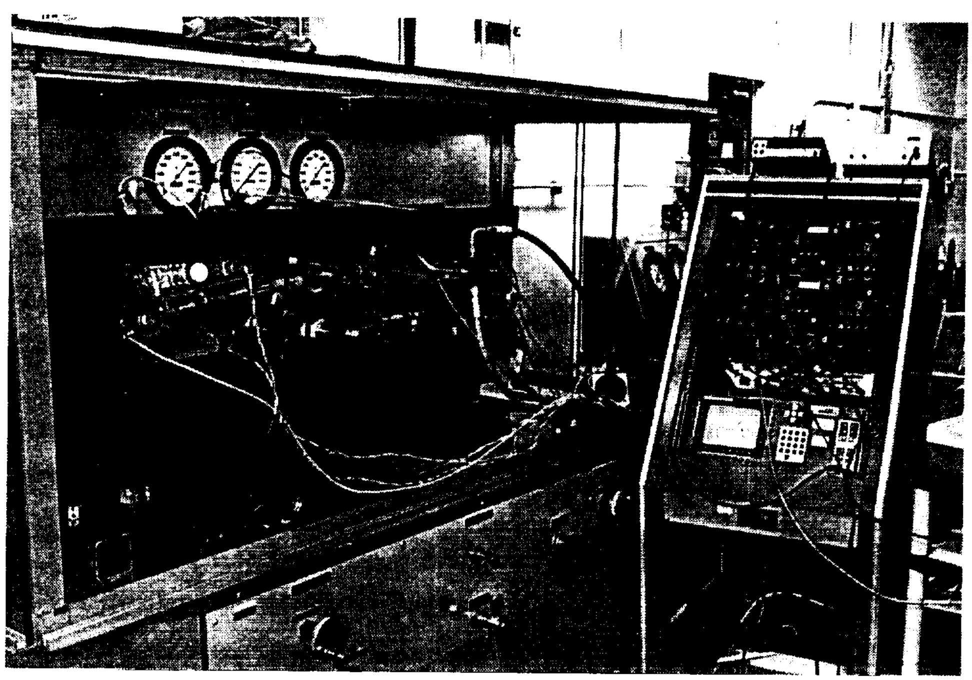

Figure 5. Life-Cycling Fixture and Instrumentation

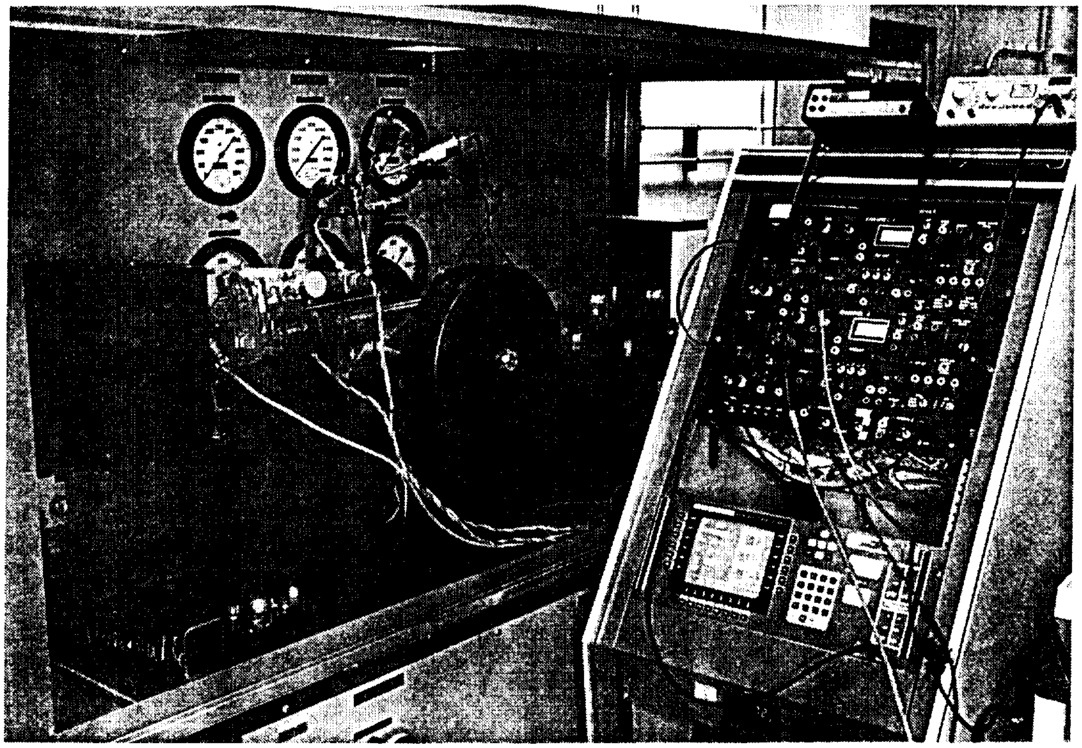

Figure 6. Piston Bottoming Setup

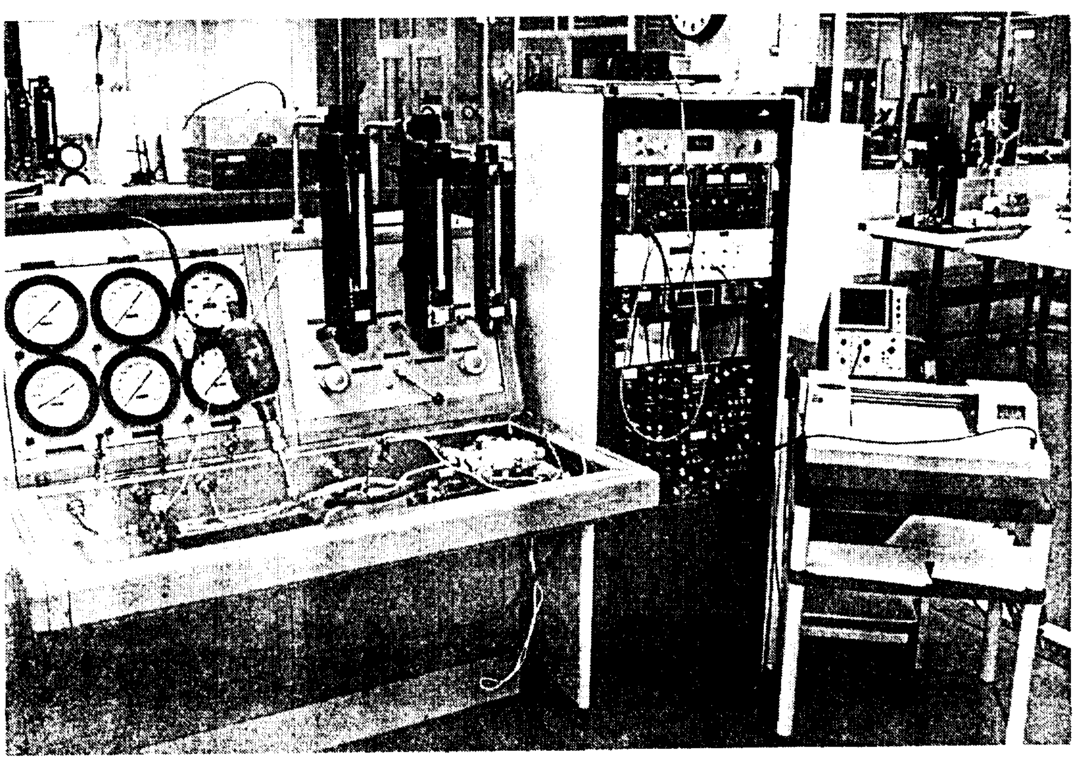

Figure 7. Impulse Setup and Instrumentation

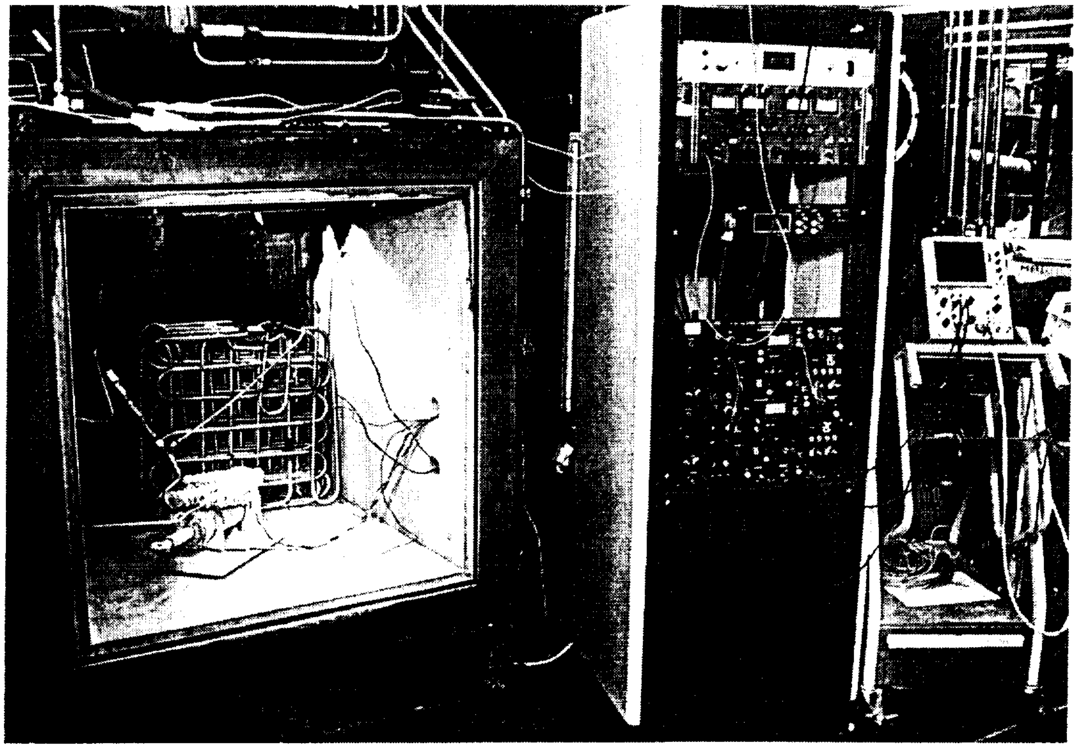

Figure 8. Low Temperature Setup

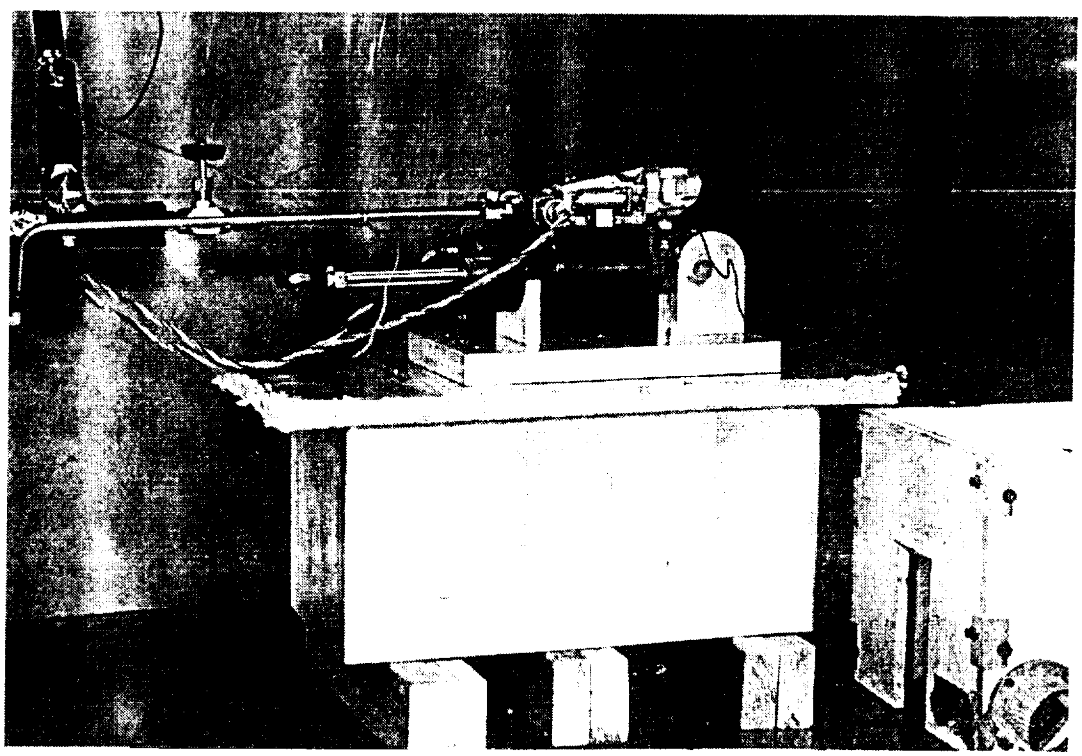

Figure 9. High Temperature/Temperature Shock Setup

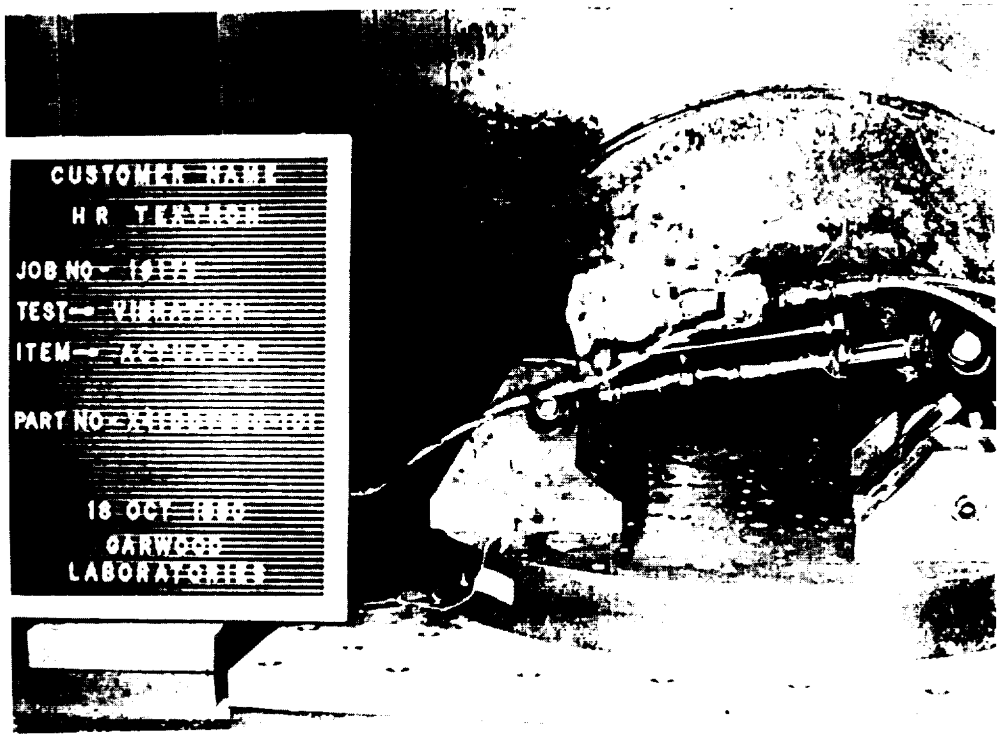

Figure 10. X-Axis Vibration Setup

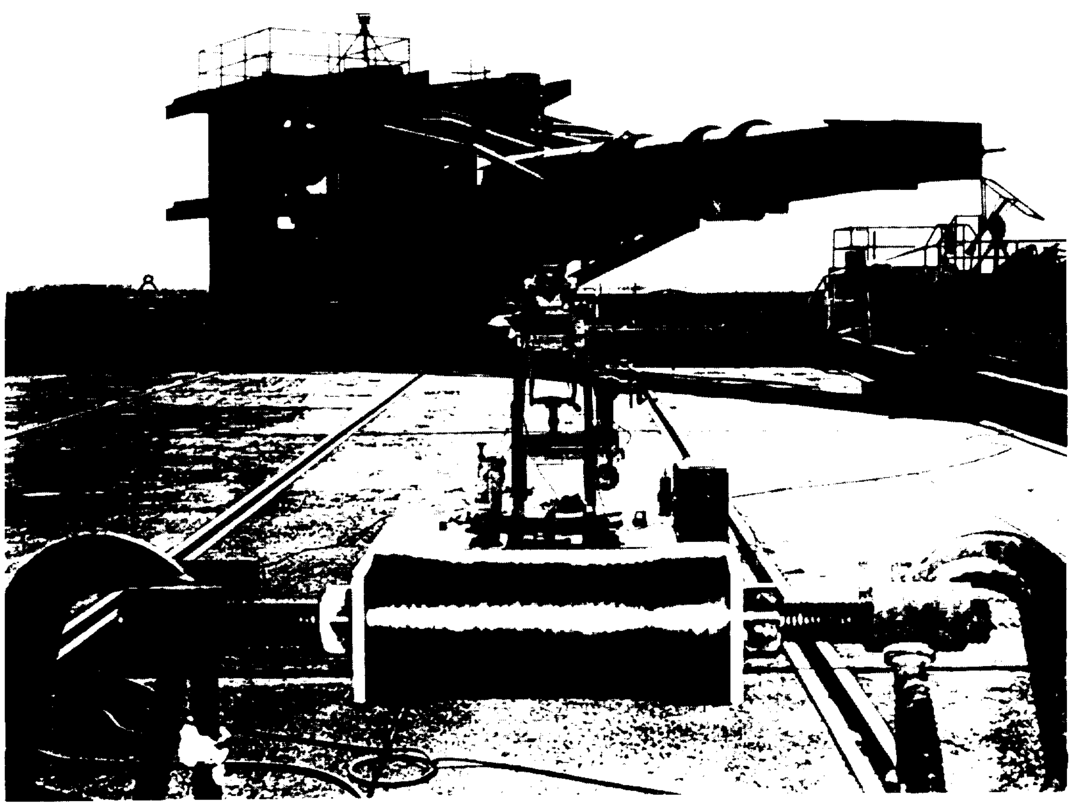

Figure 11. NWC Ballistic Test Facility

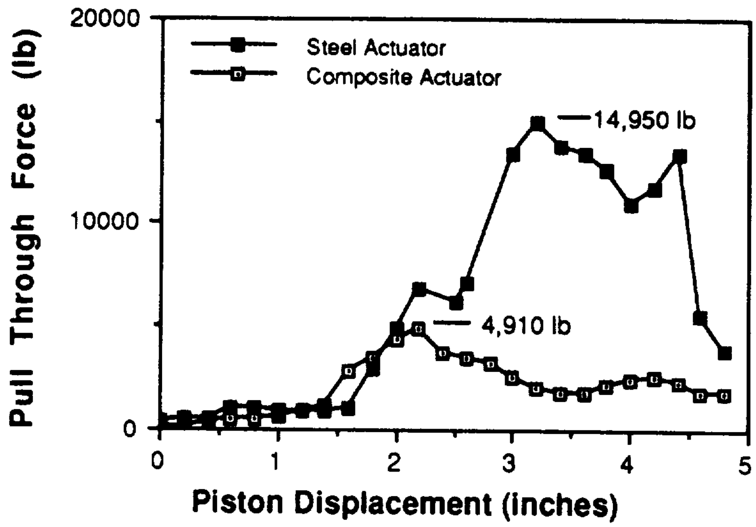

Figure 12. Ballistic Test Comparison