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377 Roll Control System: Summary Report

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C. J. Pignolet, M. H. Rogers

Sandia Laboratories

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B77 ROLL CONTROL SYSTEM: SUMMARY REPORT

C. J. Pignolet
Solar Components Division I, 8451

and

M. H. Rogers
W84 Project Division 8162
Sandia Laboratories, Livermore

ABSTRACT

The B77 roll control system evolved from a cold-gas driven assembly at its inception in 1974 to a warm-gas version at the time of program cancellation in 1978. This report documents that evolution. Included are descriptions of the analytical support calculations, the hardware, and the test results. We detail the problems encountered and the rationale which led to design choices. Although some problems had not been resolved as of cancellation, the designs provided the capability to meet B77 requirements.

DISCLAIMER

ACRONYMS

DTU	Drop Test Unit
EMR	Electromagnetic Radiation
FDL	Flight Dynamics Laboratory
GG	Gas Generator
GTU	Ground Test Unit
KCAS	Knots Calibrated Air Speed
PTU	Parachute Test Unit
RCS	Roll Control Systems
RFQ	Request for Quotation
RTV	Room Temperature Vulcanizing
SLL	Sandia Laboratories Livermore
TTR	Tonopah Test Range
WR	War Reserve

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B77 ROLL CONTROL SYSTEM: SUMMARY REPORT

Introduction

The purpose of this document is to summarize the development status of the B77 roll control system (RCS) design at the time the B77 program was cancelled. The intent is to provide a record for any potential user of a like or similar jet reaction system as it might apply to some future application. With this in mind, we have included some of the history of and rationale for the design decisions made at various stages of development, as well as discussion of the problems encountered. Also included are descriptions of the various system components and brief summaries of the numerous ground and flight tests.

System Overview

The roll control system performed a number of specific functions during the various delivery modes of the B77. For the high-altitude free-fall delivery mode, the RCS provided the torque required to spin the bomb to the 4 revolutions per second required for aerodynamic stability. For the low-altitude laydown delivery mode, the RCS maintained the upright orientation of the bomb prior to deployment of the lifting parachute. Under certain conditions, sufficient torque was available to maintain this upright orientation throughout the lifting parachute phase of the delivery. One additional requirement was imposed on the system when the B77 was delivered in the laydown mode from the lower carriage position of a B-52 aircraft: The bomb was carried at approximately 37 degrees from the upright position, which required the RCS to correct this orientation prior to the parachute deployment.

The requirements stated above determined the general system design parameters. The spin-up function required a torque impulse of approximately 720 ft-lb-sec. The roll control of the bomb and the lifting parachute required that torque be available for approximately 2 seconds. Additional requirements, imposed by a desire to minimize the time required to perform the 37-degree roll maneuver, dictated a minimum system frequency response of 50 Hz and required a constant output torque. Since gas generator output characteristics vary considerably with temperature, a pressure regulator was required to control the gas generator output.

Figure 1 shows the major system components and how they are inter-connected. The gas generator, thrust valves, and relief valves are integrated into a mechanical unit called the reaction system, which was the responsibility of Division 8158. A later section in this report provides a more detailed description of this subsystem. The basic reaction system specifications were to provide a nominal output torque of 360 ft-lb for 2 seconds over a temperature range of -65°F to +165°F. The rate sensor, designated the SA2590, was developed by Division 2326. It provided a voltage output proportional to roll rate for vehicle rates up to +/-250 degrees per second. The integrator/buffer, the switching decoder, and the valve drivers were all contained in the roll control module of the B77 programmer. This electronic package integrated the roll rate signal to obtain roll angle and used both signals, along with control inputs, to provide the valve control required for proper vehicle orientation. More specific information regarding the roll control module is available in the final report on the B77 programmer.*

Figure 1. B77 Roll Control System Components

*E. L. McKeelvey, "MC3046: A Microprocessor-Based Programmer for the B77 Bomb," SAND78-8952, report in preparation.

The control law implemented by the roll control module is shown in the phase-plane plot on Figure 2. The origin of the plot is the commanded roll position and roll rate. The various zones defined on the plot specify the active control valves and, therefore, the thrust required to drive the vehicle to the command orientation. The 220-degree/sec limits on Zone E are needed to prevent saturation of the rate sensor. The slope of the control lines is a function of roll dynamics and is chosen to minimize the 37-degree maneuver time. Within the inner Zones A and C, only two pairs of valves are active to provide a minimum limit cycle amplitude.

Figure 2. B77 Roll Control Algorithm

During the various phases of testing and evaluation of the B77 roll control system, a number of significant system-related problems were encountered. A phenomenon caused by an interaction between roll control gas jets and vehicle fins tended to reduce the effective roll torque being applied to the vehicle. Wind tunnel tests designed to model this phenomenon indicated the magnitude of the degradation to be a function of various parameters, such as Mach number, vehicle orientation, and thrust nozzle configuration. Peterson and Everett¹ indicated there was a torque degradation of 4 to 15 percent. A second problem encountered during the B77 flight test series was that the roll control jets generated aerodynamic forces which tended to produce a yawing motion of the test vehicle. This effect, which was not apparent during wind tunnel testing, would require additional testing and analysis to understand its overall effect on system performance.

To aid in the design and evaluation of the various system components, a mathematical model was developed and implemented on SLL's CDC 6600 and on a hybrid analog computer, the EAI 7600.² The hybrid was used primarily for real-time-in-the-loop hardware testing. The model was designed to evaluate performance on a system level, rather than a component level. Thus the behavior of individual components were put in empirically with available experimental data. The model was subsequently used to evaluate alternative control algorithms, optimize the control parameters, predict system performance over the range of operating environments, and aid in the evaluation of flight test results.

Reaction System Hardware

The following sections contain and historically document the design and development of the roll control reaction system. The reaction system includes the gas generator, the relief valves, the thrust valves, and the thrust nozzles. Included also is a summary of the qualification testing unique to this portion of the overall system.

Cold Gas Roll Control System

Historically, the roll control development program started in mid-1974 with a cold gas-driven system designed by Organization 8333 in response to a request from the B77 project group. A cold gas system was chosen on the basis of providing the best chance to obtain early hardware in support of lifting parachute/roll control feasibility testing. It employed state-of-the-art technology derived from other gas transfer systems, and utilized (more or less) off-the-shelf type components, i.e., squib-initiated opening valves, first- and second-stage pressure regulators, and solenoid-operated thrust control valves, all from Futurecraft Corporation of Industry City, California. Drawing K87624 shows the overall system employed for static ground and subsequent flight test evaluation. Results of those tests are documented elsewhere in this report.

Although operationally successful, the low-torque yield-to-system weight ratio (approximately 135 ft-lb vs. 120 lb) was not very practical, and effort was begun to investigate more efficient hot-gas thrust systems.

Mod-0 Hot (Warm) Gas Control System

After a thorough research of alternate system designs offered by the general rocket propulsion industry, it became apparent that proper use of a reliable, highly responsive control valve would be the keystone of a successful hot-gas system design. We had evaluated different "bang-bang" and proportional thrust valve designs (including "fluidic" control devices developed by G. E.), and concluded that MOOG, Inc. had the best design of the preferred "bang-bang" concept. It was a highly responsive, two-stage, tri-stable, shuttle-type valve design that they had developed and test proven for a previous Douglas Aircraft missile application.

The order for the Mod-0 RCS (purchases order 86-2455) was let in early 1975 to Thiokol-Elkton, the primary system contractor for the MOOG-supplied control and relief valves. The established external configuration of these valves resulted in some compromising of thrust potential, packaging, sealing, and weight considerations for the overall Mod-0 design, but their use did result in early availability and high performance reliability as the subsequent ground and flight test programs have demonstrated. Figure 3 (plus Performance Specification K92141) defines the overall Mod-0 RCS that was employed for the Tonopah Test Range (TTR) ground qualification tests (GTU's) and the flight test (DTU and PTU) series which started in early 1976 and concluded in late 1977. Results of those tests are documented elsewhere in this report. The scope and results of Thiokol's in-house development test program (which preceded Sandia's test series) are documented in Thiokol's summary report E213-75, dated December 17, 1975.

Although both the ground and flight test series were highly successful from an operational/performance view, there were problems associated with assembly, gas leakage, heat distortion, and refurbishment capability that were inherent in the "compromised" design of the Mod-0 system.

Mod-1 Warm Gas Roll Control System

Design and contract negotiations for the Mod-1 RCS began with Thiokol/MOOG in late 1975, with contract placement occurring in mid-1976 (Purchase Order 86-9383). This second-stage development program represented an initial effort to tailor the roll control system and its components to meet the weight, performance, packaging, shelf-life, and environmental requirements of the B77 bomb system. A photograph is shown in Figure 4. Although similar in concept to the Mod-0 design (thereby capitalizing on proven technology), some of the specific features afforded by the new Mod-1 design were:

1. Use of a higher-burn-rate propellant (but of the same TP-H-3314 formulation as used in the Mod-0 generator), resulting in a higher specific impulse and more efficient thrust-to-weight ratio.
2. Replacement of the direct mounting of individual control valves to the generator end closures with a single port/valve-mounting flange at each end. The double closure/adjustable "turnbuckle" feature of the Mod-0 generator was retained for the Mod-1 development test series, but was replaced with a more efficient single-joint/bolted pressure vessel design for the non-adjustable WR version. Rupture discs were

Figure 3. Hot Gas Roll Control

2

SECTION E-E
ALL DIMENSIONS IN INCHES
SCALE: 1/2"

SECTION G-G
ALL DIMENSIONS IN INCHES
SCALE: 1/2"

pl Interface

Figure 4. Mod-1 Roll Control System

incorporated into the outlet ports at each end of the generator as a means of providing "capsule" containment of the propellant. Hermetic sealing, ease of assembly, limited-life change-out (if necessary), and potential refurbishment of test-fired WR assemblies were all facilitated by the new Mod-1 generator design.

3. Integration of the previous pair of individual control valves at each end of the generator into a dual control/relief valve unit assembly incorporating the following features (Figure 5):
 - a. The new dual valve assemblies were secured directly to the aft case wall, with the integrated relief valve exhausting radially through the case wall at the centerline of each unit assembly. The resulting "pair" of relief valves in the system enhanced overall reliability in that a single relief valve (with the cross talk tube interconnecting) would still prevent over-pressurization of the system in the event one relief valve failed to function. Besides eliminating the separate relief valve mounting and the troublesome generator-to-relief valve tube required in the Mod-0 design, the radial porting of the exhaust gases eliminated the aerodynamic pitch/yaw influence which tangential porting caused in the early Mod-0 flight units.
 - b. The integral valve manifold/mounting flange permitted a simple face-seal connection for the gas generator, with a 20° face angle accommodating overall dimensional tolerances.
 - c. New "balanced pressure" poppet design in pilot stage operation of control valves eliminated pressure-sensitive limitation of prior Mod-0 "ball check" design.
 - d. Orientation of the pilot stage/solenoid axis was changed to be lateral to the vehicle axis (versus axial in Mod-0), thus minimizing affects of parachute deceleration loads on valve performance.
 - e. New valve design was "sized" to permit doubling of pressure/thrust output as an optional capability.

In summary, the new Mod-1 reaction system represented a significant advancement over the prior Mod-0 design, and a major step toward an ultimate WR solution. Figures 6 and 7 (along with Performance Specification K94160) define the overall Mod-1 system that was employed for the six TTR ground qualification tests and the two subsequent flight test units (PTU-20 and -37) which occurred after program cancellation. Results of those tests are documented elsewhere in this report. Again, Thiokol conducted a prior in-house development test program sufficient to demonstrate that the new Mod-1 design met system requirements. These tests ranged in scope from individual component qualification tests (i.e., separate igniter, gas generator, relief valve, and control valve performance tests) to partial and full system performance tests. The full scope and results of these tests are documented in Thiokol's summary report EL35-77, dated December 1, 1977.

Notwithstanding the significant system improvements enumerated for the new Mod-1 design, there were also new problems encountered. Some were carry-overs from the Mod-0 design, but others were inherent in the new Mod-1 features. The following outline summarizes the design and operational status of the Mod-1 RCS as evidenced by the ground and flight test results:

1. Use of two relief valves in parallel in the system may have enhanced safety and reliability considerations, but their interaction and new effect on system pressure regulation was not always predictable. In the initial development test series at Thiokol, the two relief valves were allowed to operate independently. As anticipated, one relief valve cracked first and did most of the work, while the other worked at partial capacity. The new effect was unbalance in the amount of exhaust gas discharged through the opposite ports. The addition of a "cross-talk" tube interconnecting the plenum chambers of the two relief valves alleviated the unbalance, and, at the same time, provided an additional pressure escape route if one relief valve failed to open.
2. One of the problems unique to the Mod-1 design was first revealed during our ground test series at TTR, when we encountered sporadic oscillations in the regulated pressure system. It varied in amplitude and duration, depending on the preconditioned temperature and adjusted regulating pressure of the different test units, but the frequency always began at approximately 50 cps and gradually diminished to about 20 cps, at which time it ceased oscillating. Interestingly, the new average regulated pressure during oscillation was correct and almost perfectly flat, resulting in the best regulation control we had ever experienced, including that in the Mod-0 history. Although not considered a serious problem, in the overall system performance or thrust control was not significantly degraded, the lack of understanding of this phenomenon cast a shadow of doubt on the soundness of the pending Mod-2 (WR) design. At the time the program was cancelled, various analytical efforts were underway by SLL, MOOG, and Thiokol to gain insight into the problem, but nothing was resolved.
3. Another unresolved problem unique to the Mod-1 design was the two incidents of "sticking" first-stage valve operation. The first incident occurred during testing of GTU-19, which consisted of an 8 rps spin-up test performed at a preconditioned temperature of -65°F. To achieve the torque impulse needed, all four control valves were initially commanded hard over in one direction for 1.6 seconds, and then to the null position for the balance of the burn time. Three of the four valves responded as programmed, but the fourth valve stuck in the hard-over position, resulting in slight overspin of the unit. The second incident occurred on a similar test unit, only this time the duty cycle was preprogrammed to include a hard-over-to-hard-over "dither" cycle at the conclusion of the sustained spin torque. Again, one of the valves stuck momentarily during the first "dither" cycle, but broke loose and performed normally for the balance of the burn time.

Figure 5. Roll Control Valve Assembly

rol Interface

TWO-QUE	
SECTION	NO.
1	2
3	4
5	6

Figure 7. Mod-1 Roll Control Subassembly

[illegible]

SECTION E-E

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At the time the B77 was cancelled, a multiple part test evaluation program was underway to isolate the cause, or at least eliminate many of the possibilities that existed. The effort did not get completed, but the consensus at the time was that sustained hard-over operation (unique to the spin-up mode) was resulting in byproducts of combustion "gluing" or otherwise restraining the poppet from returning to the null position within its preload spring force.

4. One of the carry-over problems from the Mod-0 experience was the adequacy of system sealing for both storage environmental conditions and during hot gas operation. Although the basic concepts of the Mod-1 design provided potential solutions to most of these problems, total solutions had not been perfected in all areas at the time of program termination. The "capsule" design of the gas generator assembly did provide an effective sealing solution for protecting the propellant against environmental degradation, but the adequacy of the C-ring seal to contain the hot gas operating pressure appeared marginal and required more developmental effort.

Similarly, the Mod-1 nozzle extension design represented a significant improvement over the Mod-0 design in so far as providing EMR and environmental sealing at the case-to-nozzle interface, but the nozzle-to-valve seal was not proven totally effective during burn operation. Several alternate rupture-type seal designs were being test evaluated at the time of program cancellation, but it became increasingly apparent that the "jack tight" installation feature of the Mod-1 design had inherent loading limitations that precluded adequate face sealing.

In general, the Mod-1 test program demonstrated significant improvement over the Mod-0 system relative to overall sealing considerations, but total solutions would have to be resolved in the (still) pending Mod-2 (WR) development effort.

Mod-2 (WR) Warm Gas Roll Control System

Because of the relatively long time (approximately 1-1/2 years) between design, contract placement, and eventual hardware delivery, negotiations with Thiokol and MOOG for the final Mod-2 development design were begun in mid-1977 with the intent of having initial test hardware available by the end of FY78. This would have supported a final ground test qualification series and the beginning of our planned flight test (FTU) and reliability assessment program. At the time of program cancellations, details of the new Mod-2 design had been largely defined, and RFQ's for both the valve components from MOOG and gas generator assemblies from Thiokol were in process for expected order placement by late January/early February 1978.

Although identical in concept to the Mod-1 system, the Mod-2 design basically optimized features of weight, cost, assembly, sealing, and/or shelf-life considerations as determined by the Mod-1 test results and subsequent evaluations. Some of the more significant design changes incorporated in the proposed Mod-2 RCS were as follows:

1. The adjusted regulating pressure of the two relief valves was increased from a nominal 1800 to 2200 psig, thereby realizing a corresponding 22% increase in torque yield from 365 to 446 ft-lb. This added operating pressure and torque output was essentially available within the existing structural integrity of the Mod-1 RCS and so no weight penalty was involved. Use of the increased torque output was considered worthwhile in further controlling inherent parachute roll behavior.
2. One of the principal changes was a new Ti-6Al-4V nozzle extension design which connected directly to the control valve via a captured coupling nut. This eliminated the outer sleeve part of the previous "jack tight" concept, and also provided a tighter, more positive preload to squeeze the burst seals installed in between. It was smaller, simpler to assemble, weighed and cost less, and accommodated thermal expansion with a slip-fit through the cylindrical bore in the case wall.
3. An impact of the new nozzle design was to change the connecting interface to the control valve. The requirement for an external threaded joint to accept the nozzle coupling nut, plus the need for a keying feature to maintain angular orientation of the scarfed nozzle, necessitated MOOG to go to a bolted flange adapter on their valves (vs. the threaded insert on the Mod-1). Because of space limitations to incorporate the bolted flange adapter, the center-to-center distance between the thrust nozzles had to be extended from 2.750 to 2.920 inches. Other minor changes to the valve design were made by MOOG to improve its sealing and regulating performance. The plenum chamber and downstream orifice of the relief valve were both enlarged and reshaped to net better flow characteristics and discharge efficiency, and the relief valve pintle was lightened to improve dynamic response. Also, consideration was being given to increasing the spring rate of the regulator spring, pending outcome of the oscillation problem. Because of some evidence of hot-gas leakage occurring at the relief-to-control valve interface during the Mod-1 test program, a metal C-ring was substituted for the prior elastomer face seal.

As part of a cost effective study, MOOG was evaluating the practicability of using Ti-6Al-4V investment (lost wax) castings for several of the intricate shaped parts of the valves. Prototype castings for the main control valve body, relief valve housing, and nozzle adapters were delivered by Jitech, Inc. to MOOG just prior to program cancellation, and so the evaluation effort was never concluded.

4. The design evolution for an ultimate WR gas generator (GG) assembly did not necessarily follow the Mod-0, -1, -2 development chronology. Because of the lack of dimensional precision typical of development-type hardware, the double-threaded "turnbuckle" concept was employed throughout the Mod-0 and Mod-1 development test programs, thus providing an added adjustment capability to accommodate assembly tolerances. It was recognized early, however, that the "turnbuckle" design could not readily be sealed, and a parallel effort was initiated to perfect a better WR solution.

Beginning with the Mod-1 design, the use of burst discs to achieve hermetic seal was incorporated under the squib initiator (MC2949) and in each of the two discharge ports at the generator ends. Since their use affected ballistic performance of the GG assembly, they were incorporated in the "turnbuckle" test version furnished by Thiokol, even though hermetic sealing was not a requirement per se of the relatively short-lived test units. They also fabricated their GG case parts from 4340 steel, since there was not a strict limitation on component weight in the test vehicles. Thiokol's Drawing E29475 shows the operational test version of the GG assembly that was employed for the Mod-1 ground and flight test series.

Because overall RCS weight was a constraint in the WR design (not to exceed 40 lb), the eventual use of titanium for the GG case parts, valve bodies, and nozzle extensions was decided upon early in the RCS development program. Independent of our contract with Thiokol for the Mod-1 development units, Sandia launched a separate program to develop a titanium WR generator design that would be cost effective as well as being optimized for structural and environmental considerations.

Following an analysis done by D. R. Chenoweth, 8124,⁴ a leak rate criterion of 3×10^{-4} cm³/sec He was determined to be tolerable, and a bolted joint/mechanical seal design was initiated in early 1977. Assembly Drawing K99362 shows the first version of a bolted joint design incorporating the following features:

- a. Constrained by the existing size of the propellant cartridge and a maximum allowable 7-in. external diameter for the GG assembly, an end-joint design was configured using both 24 and 30 #10-32 high-strength bolts.
- b. A metal C-ring made by Advance Products Company was employed to effect the combined low pressure hermetic seal and the high pressure/high temperature operational seal required.
- c. Because of shelf-life concerns for the bond that held the propellant cartridge in place for all previous Mod-0 and Mod-1 development generators, a mechanical retention concept was substituted. It involved adding a grip shoulder and O-ring seal groove to the outer end of the ABS cartridge liner, plus an RTV serrated "snubber" band to the other end. These combined to give axial and radial support against external dynamic loads, as well as providing internal sealing against circulating hot gas flow that would cause back heating of the propellant grain.
- d. Both the main case and closure cover were fabricated from pre-machined Ti-6Al-4V forgings that then had the port flanges, squib insert, support lugs, and rupture discs electron-beam welded in place. This procedure required extensive precision machining and exacting process control operations to achieve final dimensions and sound welds.

- e. A commercially available "Shock Strut" valve was added to the lower end of the GG assembly to facilitate leak testing, purging, and/or back filling as might be required in the final WR design.

Five of these welded end-joint designs were fabricated and test evaluated during the early-to-late 1977 time frame. Results of both hydrostatic proof tests and three hot-gas firings (GTU-38, -39, and -40) were very encouraging, but the relative high cost of welded/forging construction became of increasing concern. As a result of MOOG's investigation into using titanium castings for the valve parts, we became interested in their application to the GG design. The possible use of precision case material offered the following potential advantages:

- a. Significant cost savings could be realized from the reduction in machining time and the elimination of welding operations. The entire outside contour, including port flanges and support lugs, could be cast to size.
- b. The relative freedom to cast any shape desired permitted optimizing the wall thicknesses to achieve a more uniform stress design. (The prior welded design dictated uniform wall thickness to accommodate uniform weld penetration.)

While it is true that castings in general enjoy a rather indifferent reputation for reliability in highly stressed applications, titanium is one of a small class of materials for which the simple engineering properties as-cast are nearly the same as wrought. (Even the anxiety over casting defects tends to be exaggerated because properly chilled as-cast titanium is tougher than wrought. If the casting defects (shrinkage and porosity) can be eliminated or placed in innocuous regions by careful design of the castings, and/or healed by hot isostatic pressing, castings should be as reliable as forgings. Besides, 100% proof testing of all production GG case assemblies would alleviate the concern for defect influence, since the high generator burn pressure lasts for only 3 seconds maximum.)

Figure 8 shows the second and final version of a Mod-2/MC3212 (WR) bolted-joint GG design based on using Ti-6Al-4V investment castings. The bolted joint was relocated to the center of the assembly, making both halves symmetrical in shape and, therefore, machinable from a single casting definition. The center grip of the propellant cartridge also facilitated better stress distribution of the thermally induced loads through the ABS/propellant bond line. Cast ribs were added to each side of the bolted joint to support the bending moment and reduce net rotation at the sealing surfaces. Note that all wall thicknesses are nonuniform, thus accommodating in part the nonuniform stress distribution that revealed itself in the finite element analysis.⁵

Based on the aforementioned design layout, castings were ordered from Titech, Inc., in early July 1977 (P.O. 18-2213). At the time of program cancellation, partial deliveries had been made and the first set of castings has been machined for testing purposes. Because this casting process was thought to have potential application in future weapon

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Figure 8. Mod-2 Gas Generator Assembly (MC3212)

designs, it was judged worthy of continued effort to conclude the planned evaluation program. Therefore, the contract with Titech was not terminated, and Materials Organization B322 assumed responsibility to carry the evaluation program to its logical conclusion.

In summary, the overall Mod-2 RCS system as shown in Figure 9 reflects the intended third and final development phase prior to WR production. It never came to a state of hardware realization because of the sudden B77 cancellation (except for the limited achievement in the titanium GG development program). WR-like drawings and specifications were generated only for the MC3210 dual control/relief valve assembly (AY211062 and PS211062), since they were required to support Bendix's AER efforts to "tool up" MOOG-East for eventual production buy of the valves.

One system innovation that was thought of just prior to program cancellation was the inclusion of an "after-burner" concept to the thrust nozzles. By introducing oxygen piped into the nozzle extensions just beyond the throat diameters, the still combustible exhaust gases could be made to burn again, yielding another potential thrust increase of about 20-25%. "After-burning" would also have the added benefit of converting the objectionable black smoke (unburned hydrocarbons) to a more palatable white color. The higher burn temperatures would be encountered only in the expansion nozzles where they could be tolerated. Thiokol had confirmed that the idea was feasible, and plans were being formulated to evaluate a Mod-1 ground test unit when program termination occurred.

Test Results

The following sections briefly outline the functional tests performed with the roll control system. Included is a description of the basic test parameters, the test objectives, and the test results.

Cold Gas Roll Control Testing

The initial testing of the cold gas roll control system was performed in SLL's Flight Dynamics Laboratory (FDL). The reaction system and the control electronics were modeled on the FDL hybrid computer system in order to establish the feedback control parameters and investigate system performance. Subsequently, a number of tests were performed with the actual cold gas system in the FDL. A complete description of the tests and the test hardware can be found in a memo to S. G. Cain, 8412, from M. H. Rogers, 8158, dated October 28, 1974, title "FDL Test of the B77 Cold Gas Roll Control System." The test results indicated that the system produced approximately 136 ft-lb peak torque and would be able to return a test vehicle to 0 degrees from an initial roll position of 90 degrees. This testing also verified the control parameters to be used on the scheduled flight tests of this roll control system.

Figure 9. Mod-2 (WR) Ground Test Assembly

The B77 cold gas roll control system was successfully flight tested on two drops from an F-4 aircraft. These tests, PTU-3 and PTU-23, demonstrated that it is feasible to use a reaction system for roll control of the B77 and verified the analytical models used to predict system performance. Test results also provided data regarding the degradation of roll control thrust due to jet/fin interaction. Two reports by Schultz provide complete documentation of the flight test results.⁶

Mod-0 Warm Gas Roll Control Testing

The Mod-0 B77 warm gas roll control system previously described underwent two functional ground tests at the Tonopah Test Range to evaluate system performance. These ground tests, GTU-16 and GTU-17, provided significant data regarding the dynamic performance of the Mod-0 system and met the following program objectives:

1. Verified the performance of the roll control gas generator and servo valves under dynamic conditions.
2. Provided data for the computational models developed to predict system performance.
3. Functionally verified the control algorithm and proved system stability.
4. Experimentally tested the roll control maneuver to be flown on parachute test unit (PTU)-14.

These ground tests are described in greater detail elsewhere.⁷ The resulting test data are available on the B77 Data Bank.

From June 17, 1976 through December 8, 1977 there were a total of 12 aircraft drop tests of a B77 test vehicle which incorporated the Mod-0 warm gas roll control system. This drop test series, conducted from different Air Force and Navy aircraft over a wide range of delivery speeds and altitudes, demonstrated the performance of the Mod-0 system. The results of each test are briefly summarized below. Additional test information is available from the test unit pretest report, the test report, and the B77 data files.

PTU-14 (6/17/76), F-4, @ 425 KCAS): The roll control system was programmed to perform a +15 and a -15 degree roll of the test vehicle to investigate jet/fin interaction at a small angle of attack. The experiment was successfully conducted and the data showed a roll torque degradation of approximately 25%.

PTU-19 (8/31/76), B-52, @ 300 KCAS): The system was programmed to roll the test unit to the upright position from an initial carriage angle of 35 degrees. The roll control system properly oriented the test vehicle and maintained the unit upright within +/- 7 degrees through the lifting parachute phase. The effective roll torque was degraded by approximately 35% as a result of jet/fin interaction.

PTU-56 (10/28/76, F-4, @ 575 KCAS): This unit was programmed to perform a +/-15 degree roll maneuver to investigate jet/fin interaction at a large angle of attack. Because of a problem with the bomb ejection mechanism on the aircraft, the maximum angle of attack achieved was limited to 10 degrees. At this angle of attack and velocity the effective roll torque was reduced by an average of 23%.

PTU-16 (11/9/76, F-4 @ 700 KCAS): The roll control system functioned per design intent and maintained the test vehicle upright within +/-2 degrees until the lifting parachute was deployed. Subsequently, the parachute dominated the roll behavior of the bomb/parachute system and the vehicle rolled to 45 degrees. The cause of this roll behavior has not yet been fully explained.

PTU-18 (12/7/76, F-4 300 KCAS): The roll control system functioned properly and maintained the test vehicle upright within +/-5 degrees through the lifting parachute phase of the test.

PTU-15 (4/5/77, F-111 @ 425 KCAS): This test was the first demonstrated use of the roll control system in the spin-up mode. The test vehicle was successfully spun to 4 revolutions per second with a 2-second torque impulse from the gas generator.

PTU-54 (7/6/77, F-4 @ 740 KCAS): The roll orientation of the test vehicle was maintained within +/-10 degrees except for a brief excursion to 17 degrees when the lifting parachute was deployed. This test was the first operational use of the F-1 programmer, which implemented the WR control algorithm and used the SA2590 rate gyro to supply vehicle roll information. All roll control system components performed as expected.

PTU-77 (7/8/77, F-4 @ 300 KCAS): PTU-77 was the first 877 test vehicle to be impacted against a hard target and delivered from 100 feet above ground level. The roll control system, using a simplified electronic control package, maintained the vehicle upright within +/-10 degrees through the test. A complete assessment of control system performance was not possible because of the limited telemetry instrumentation.

PTU-40 (7/14/77), F-111 @ 290 KCAS): This test unit was used to study the interaction between the roll control jets and the F-111 delivery aircraft. Samples obtained both on the external surfaces of the aircraft and by a gas sampler inside the cockpit indicated no measureable contamination of the aircraft. Other aspects of the roll control system performance were within acceptable limits, with the test vehicle being controlled to within 5 degrees of upright through the first-stage parachute phase of the test.

PTU-78 (10/12/77), B-52 @ 370 KCAS): This test unit was delivered from an operational SAC B-52 bomber against the hard target at the Tonopah Test Range. The control system, identical to that used on PTU-77, maintained the test vehicle upright within 10 degrees through the initial 3.5 seconds of the test.

PTU-36 (11/4/77), F-4, @ 300 KCAS): The telemetry instrumentation indicated that all roll control system components functioned per design intent. The test vehicle was maintained upright through the lifting parachute phase within 8 degrees except for a brief excursion to -15 degrees when the lifting parachute was deployed.

PTU-80 (12/8/77), FB-111 @ 350 KCAS): This test unit was similar to PTU-77 and PTU-78 in terms of the roll control system used. From the limited on-board instrumentation, all roll control system components functioned properly.

The 2 ground tests and the 12 flight tests of the Mod-0 roll control system demonstrated the feasibility of using a warm gas system to control the roll orientation of the B77 bomb/parachute system. This test series also verified the computational models being used to predict system performance and demonstrated the stability and capability of the WR control algorithm.

Mod-1 Warm Gas Roll Control Testing

The Mod-1 B77 warm gas roll control system was subjected to an extensive functional test series prior to any flight testing. These ground tests (GTU-18, -19, -20, -38, -39, and -40) were intended to evaluate system performance over the wide range of environmental conditions specified for the B77. The following major program objectives were accomplished during this test series.

1. The gas generator performance was evaluated at "preconditioned" temperatures of 180°F and -65°F.
2. The structural integrity of the generator case and propellant grain was proven adequate for vibration and shock conditions designed to duplicate the B77 environmental specifications and the parachute deceleration loads.
3. It demonstrated the ability of a single relief valve to vent the gas generator properly and prevent catastrophic structural failure.
4. The static torque output was determined to be approximately 360 foot pounds for a system operating at 1800 psi and 450 foot pounds for a 2200 psi operating pressure.
5. Spin up to 8.5 revolutions per second was demonstrated and caused little performance degradation.

This ground test series did uncover two problems with the Mod-1 design. The results of four tests showed a tendency for the generator pressure to oscillate at 20 to 50 Hz within a pressure band of 300 to 400 psi. The oscillations are believed to be caused by interactions between the dual relief valves and the propellant burn characteristics. At the time the program was cancelled, work had begun at Thiokol and at Sandia to develop a mathematical model of the gas generator/relief valve system in order to isolate the contributing causes.

This oscillation tended to produce a dither of the relief valves, which aided in overcoming striction and resulted in better pressure regulation. However, it was disturbing not to know the cause of the oscillation and its sensitivity to various system parameters, so the analysis effort was being initiated. A second problem, also not resolved, was the two separate occasions where the first stage of a servo valve lodged in the activated position and made that valve inoperable. Both occurrences were during the comparatively long activation of the valve during a spin-up test and were partially attributed to the buildup of combustion products in the primary stage of the valve. Programs were underway to resolve these problems prior to release of the Mod-2 design.

In late January 1978, two flight tests of the Mod-1 roll control system were conducted. These tests demonstrated the performance and capabilities of the new design.

PTU-37 (1/24/78, F-4 @ 750 KCAS): PTU-37 was the first flight test application of the Mod-1 roll control system. The test vehicle roll orientation was maintained within 10 degrees of upright except for a 0.7-second excursion to 39 degrees just after deployment of the lifting parachute. The general performance of all system components, including the F-1 programmer, was well within design goals. The gas generator pressure oscillation previously encountered with the Mod-1 system also occurred on this test but lasted only 0.3 sec. The telemetry data indicated that the system performance was not degraded by this oscillation. This test demonstrated feasibility of operating the roll control system at 2200 psi, which results in approximately 450 foot pounds of torque.

PTU-20 (1/25/78, F-4 @ 300 KCAS): PTU-20 demonstrated the Mod-1 performance when operated at 1800 psi to produce 360 foot pounds of torque. The test vehicle was maintained upright except for a 0.3-sec excursion to 23 degrees. All system components performed as expected and, again, the pressure oscillation occurred for approximately 0.3 seconds.

Summary

The design of the B77 roll control system progressed from the original cold gas system devised in 1975 through the Mod-2 design just completed at the end of 1977. An extensive ground and flight test series proved the capability of both the Mod-0 and Mod-1 designs to meet the B77 system requirements. The problem of gas generator oscillation and the sticking valves discovered during the Mod-1 testing remain to be resolved. A number of other tasks, including final optimization of the control algorithm, assessment of jet/fin interaction and its impact on system performance, and final resolution of the undesirable yaw forces produced by the roll control jets need to be accomplished. The success of the flight test series indicates that the system design as it was proposed would have readily supported the remainder of the B77 flight test schedule and accomplished the major B77 system objectives.

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