PART V. SOLID ROCKET BOOSTER/REUSABLE SOLID ROCKET MOTOR

Introduction

The twin solid rocket boosters (SRBs), designed as the primary propulsion element of the STS, provided the Space Shuttle with 80 percent of the liftoff thrust during the first two minutes of launch. They burned more than 2,200,000 pounds of propellant and produced 36 million horsepower.[1487] Each SRB booster was comprised of both motor and non-motor segments. The motor segments, referred to as the solid rocket motor (SRM), and later renamed "reusable solid rocket motor" (RSRM), contained the fuel to power the SRBs.[1488] The SRMs/RSRMs were the largest and only human-rated solid-propellant rocket motors ever flown, and the first designed for recovery and reuse. The major non-motor segments included the nose cap, frustum, and forward and aft skirts. These structural components contained the electronics to guide the SRBs during liftoff, ascent, and ET/SRB separation, and housed the parachutes, which slowed the descent of the reusable boosters into the Atlantic Ocean after their jettison from the spacecraft.

Historically, SRM/RSRM development followed a path separate from the non-motor SRB components. Throughout the SSP, Thiokol, of Promontory, Utah, was the sole fabricator and prime contractor for the SRM/RSRM.[1489] Thiokol supplied NASA with the propellant-loaded forward motor case segment, with the igniter/safe and arm (S&A) device installed; the two propellant-loaded center motor case segments; the propellant-loaded aft motor case segment, with the nozzle installed; the case stiffener rings; and the aft exit cone assembly with the severance system installed. Over 400 suppliers, located in thirty-seven states and Canada, provided metal components, seals, insulation, fabrics, paints, and adhesives. In addition, six companies supplied the major ingredients that comprised the RSRM propellant. These included American Pacific (AMPAC) in Cedar Rapids, Utah (ammonium perchlorate); Dow Chemical in Freeport, Texas (epoxy resin); Alcoa in Rockdale, Texas (aluminum powder); Toyal America in Naperville, Illinois (spherical aluminum powder); American Synthetic Rubber Company (ASRC) in Louisville, Kentucky (polybutadiene-acrylic acid-acrylonitrile terpolymer [PBAN]); and Elementis Pigments in Easton, Pennsylvania (iron oxide). For the final flight motors, Mitsubishi Argentine ingot replaced the aluminum powder provided by Alcoa, and the ammonium perchlorate was provided by HCL-Olin in Becancour, Quebec, Canada, and Niagara Falls, New York.

[1487] ATK, "RSRM Overview" (presentation materials, MSFC, Huntsville, AL, April 8, 2010), 5.

[1488] Following the *Challenger* accident, the SRMs were redesigned. Effective November 1, 1987, the new motor configuration became known as the Redesigned SRM (RSRM). By 1995, they were renamed Reusable SRM (still RSRM).

[1489] The Thiokol Chemical Company, founded in 1929, experienced several mergers and splits, resulting in a series of name changes, including Morton Thiokol Incorporated (1982), Thiokol Inc. (1989), Cordant Technologies (1998), AIC (Alcoa Industrial Components) Group (2000), Alliant Techsystems (ATK) Inc. (2001), ATK-Thiokol, and ATK Launch Systems Group (2006). The company will be referred to as "Thiokol" throughout this document.

The major non-motor SRB components originally were designed in-house by MSFC engineers, and SRB hardware was the responsibility of MSFC during the development phase.[1490] MSFC designed the structural components and a number of the subsystems, then contracted to have them fabricated. Beginning with the seventh SSP mission, STS-7, United Space Boosters, Inc. (USBI) of Sunnyvale, California, a wholly-owned subsidiary of United Technology Corporation, replaced MSFC as the prime contractor for the SRB until 1999, when USBI became part of USA.[1491] At KSC, USA was the prime contractor for the fabrication, assembly, and refurbishment of primary SRB non-motor segments and associated hardware. One set of flight-ready SRBs contained approximately 5,000 refurbished parts.[1492] The major suppliers for the SRB program were located in twelve states across the U.S. These providers included the following: McDonnell Douglas Corporation, California (aft skirt, forward skirt, frustum, and ET attach ring); Hamilton Sunstrand, Illinois (APU); ATK-Thiokol Propulsion, Utah and Chemical Systems Division, California (booster separation motor); Moog-Servoactuator, New York (fuel isolation valve); Aerojet General Corporation, Washington (gas generator); Parker Abex, Michigan (hydraulic pump); L3 S&N, New Jersey (integrated electronic assembly); L3 Cincinnati Electronic, Ohio (command receiver/decoder); Honeywell Inc. Space Systems, Arizona (modulator/demodulator); Oceaneering Space & Thermal, Texas and Hi-temp Insulation, California (thermal curtain); BST Systems, Connecticut (batteries); LaBarge, Inc., Missouri (cables); and Goodrich UPCO, Arizona and California, and Pacific Scientific, Arizona (ordnance).

Historical Overview

Early Booster Concept Studies

A number of different booster concepts were under consideration by NASA and the aerospace industry when President Nixon gave the go-ahead to proceed with the development of the STS. The alternative configurations included a recoverable, reusable unmanned booster; a manned, reusable, flyback booster; and an expendable booster (See Part I. Historical Context).

Concurrent with the Phase B Space Shuttle definition studies, on September 28, 1970, MSFC chose McDonnell Douglas to study an expendable second stage for a reusable shuttle booster. Shortly after, the contract was modified for a period of one year to allow for testing the structural components of its proposed shuttle booster. In mid-1971, Phase B shuttle definition contracts with North American Rockwell-General Dynamics and McDonnell Douglas-Martin Marietta, and study contracts with Grumman-Boeing and Lockheed were extended to consider the phased approach to shuttle design and the use of existing liquid or solid propulsion boosters as interim

[1490] Dunar and Waring, *Power to Explore*, 308.
[1491] T.A. Heppenheimer, *Development of the Space Shuttle 1972-1981*, 174.
[1492] United Technologies Corporation, "Solid Rocket Booster Fact Sheet," n.d., MSFC History Office, Huntsville.

Shuttle launch vehicles. The Martin Marietta engineers concluded that the Titan launch vehicle could be used as an interim expendable booster for the shuttle; Grumman-Boeing suggested that the Saturn IC could serve as an interim shuttle booster and that a winged Saturn reusable booster was feasible.

Near the end of 1971, NASA awarded contracts for feasibility studies of pressure-fed engines for a water-recoverable shuttle booster to TRW, Inc. and to the Aerojet General Corporation. In addition, four parallel contracts were awarded by NASA on January 27, 1972, to the Thiokol Chemical Corporation (Contract No. NAS8-28430), the Lockheed Propulsion Company (Contract No. NAS8-28429), the Aerojet Solid Propulsion Company (Contract No. NAS8-28428), and the United Technology Center, United Aircraft Corporation (Contract No. NAS8-28431). The purpose of these contracts was to study the practicality of using 120" and 156" solid motors as part of the shuttle booster package.[1493]

Following the evaluation of the final shuttle system definition study data, on March 15, 1972, NASA completed the configuration for the STS with the selection of a solid propellant booster over the development of a new liquid-fueled system. This decision was made primarily on the basis of lower development costs.[1494] The configuration chosen by NASA officials called for unmanned, recoverable, and reusable 156"-diameter twin boosters that, when fired in tandem with the Shuttle's main engines, would lift the vehicle into space. North American Rockwell, in conjunction with NASA, defined the booster elements. However, driven by the need to reduce the overall weight of the Shuttle stack, the baseline for the SRMs continued to change. Within about one year, the final specification was for a 142"-diameter booster.

On December 12-13, 1972, about 350 industry and government representatives visited MSFC for a review of the latest information regarding the SRB program. Roughly six months later, prior to the issuance of a RFP, MSFC presented the results of the shuttle studies to potential developers of the SRB/SRM.

SRM Contracts

In May 1973, NASA administrator James Fletcher declared that with the exception of the SRM, the SRB was to be designed in-house.[1495] Aerojet General Solid Propulsion Company, Lockheed, Thiokol, and United Technology Center were provided the RFP for design, development, and testing of the SRM on July 16, 1973; proposals were due on August 27. As result, on November 20, 1973, NASA selected the Thiokol Chemical Company/Wasatch Division for the six-year SRM contract. Lockheed, one of the unsuccessful proposers, filed a formal protest with the GAO in January 1974. While the GAO carried out its investigation, MSFC issued a series of short-

[1493] Ezell, *Databook Volume III*, 121-124, table 2-57.
[1494] Dunar and Waring, *Power to Explore*, 286.
[1495] Heppenheimer, *Development of the Space Shuttle*, 174.

term contracts to Thiokol "in an effort to minimize the cost of schedule impacts."[1496] Following the GAO's recommendation to either retain Thiokol or to reconsider its selection, on May 15, 1975, NASA opted to award Thiokol a letter contract for SRM design, development, testing and engineering for the period July 26, 1974, through June 30, 1980.[1497]

MSFC's original contract with Thiokol (Contract No. NAS8-304940, Schedule A) called for the manufacture, assembly, test, checkout, and delivery of twenty-one SRMs, including six flight sets (SRMs 1-6) and nine test motors (Development Motors [DM] 1-5 and Qualification Motors [QM] 1-4). Also included were support equipment, tooling and support parts, SRM systems integration support and special studies, and data and documentation for the SRM.[1498] The value at the end of the contract totaled $395.9 million. This initial contract was supplemented by Increment 2, Buy 1 (Schedule B) and Buy 2 (Schedule D) which collectively covered thirty-two flight sets (SRMs 7-25 and RSRMs 1-13; sixty-four motors); fourteen test motors (DM 8, Engineering Motor [EM] 9, QMs 6-8, Engineering Test Motor [ETM] 1, Production Verification Motor [PVM] 1, and Technical Evaluation Motor [TEM] 1-11); plus launch site and flight support. Schedules B and D, collectively valued at more than $2,500 million, extended the period of performance through the end of 1995.

Schedule C, valued at $241.2 million, covered the manufacture, assembly, test, checkout, and delivery of three filament wound case (FWC) motors (FWC 1-3) and three test motors (DM 6-7, and QM 5) during the period between 1982 and 1988. Production Buy 3 (Contract No. NAS8-38100) provided for the purchase of 142 motors, including sixty-seven flight sets (RSRM 14-80) and eight test motors (Flight Support Motors [FSM] 1-8). The period of performance for this contract, valued at $4,001.4 million, extended from March 2, 1989, through September 15, 2001. The final RSRM contract (Contract No. NAS8-97238), Production Buy 4, covered the purchase of seventy-five motors, including twenty-eight flight sets (RSRMs 81-88, 92-99, and 101-113), one Launch-on-Need (LON), fifteen test motors (FSMs 9-15 and 17, ETMs 2-3, FVMs 1-2, TEMs 12-13, and Production Rate Motors [PRM] 90A and 91B), plus launch site and flight support. Valued at $3,992.5 million, this contract covered the period between October 1, 1998, and September 30, 2010.

SRB Hardware and Assembly Contracts

In accordance with NASA's decision to make separate procurements for the motor and non-motor components of the booster, the RFP for the production of SRB structures lagged behind that for the motors. The initial RFP for the booster structures was not released to industry until January 17, 1975.[1499] MSFC issued additional RFPs and contracts during 1975 and 1976 for the

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[1496] U.S. House, Committee on Science and Technology, Subcommittee on Space Science and Applications, *United States Civilian Space Programs, 1958-1978* (Washington, DC: U.S. Government Printing Office, 1981), 476.
[1497] Ezell, *Databook Volume III*, 121-124, table 2-57.
[1498] "Thiokol Awarded SRM Contract," *Marshall Star*, May 21, 1975, 4.
[1499] U.S. House, *United States Civilian Space Programs*, 456.

design, development, fabrication, testing, inspection, checkout, and delivery of other primary SRB hardware required for the first six Shuttle flights, including support equipment, tooling, and mockups. Separate contracts were awarded for the booster separation motors; APUs; electro-hydraulic servoactuators for the thrust vector control system; integrated electronic assemblies; pyrotechnic initiator controllers; and multiplexers/demultiplexers. MSFC also sought proposals and quotations from suppliers of dedicated signal conditioners and signal conditioner modules for both development and operational flight instrumentation, respectively; for flight pulse code modulation multiplexers and range safety receivers; as well as for wide band and strain gauge conditioners and frequency division multiplexers.[1500]

Proposals were received from six companies in response to the January 1975, RFP for the SRB Separation Motor Subsystem. As a result, a contract to supply the booster separation motors (BSMs) was awarded to the Chemical Systems Division of the United Technologies Corporation of Sunnyvale, California, on August 7, 1975. The contract specified a schedule for design (September 1975 to February 1976), development of twenty-three motors (September 1975 to July 1977), qualification testing of twenty-one motors (September 1977 to May 1978), fabrication of 119 flight motors (May to September 1978), and a staged delivery of 104 flight motors between September 1978 and February 1980.[1501]

The proposal for servoactuators called for the delivery of thirty-six actuator assemblies, including three development test units, three static firing support units, two prototype qualification units, two verification test units, and twenty-six flight units (including two spares) to support the first six flights. The period of performance for the $6.9 million contract was from March 1975 to March 1979.[1502] Moog, Inc. of Buffalo, New York, was the successful proposer.

In July 1975, MSFC awarded contracts totaling $538,835 to both the Aluminum Company of America of Pittsburgh, Pennsylvania, and the Weber Metals & Supply Co. of Paramount, California, for 356 aluminum hand forgings for the SRBs. Deliverables included forward skirt thrust post fittings, inboard aft skirt actuator support brackets, aft skirt splice fittings, and aft skirt holddown posts. The first items were specified for delivery by January 5, 1976; contract completion was dated June 4, 1976.[1503] Also in July of 1975, MSFC awarded a $5,768,612

[1500] "Signal Conditioner Modules Contract Awarded to Eldec," *Marshall Star*, December 24, 1975, 1; "SRB Multiplexer Quotations Sought From Industry," *Marshall Star*, May 24, 1976, 1; "Quotation Sought for Shuttle Range Safety Receivers," *Marshall Star*, July 28, 1976, 1; "MSFC Seeks Proposals on SRP Assembly," NASA MSFC News Release No. 76-52, March 25, 1976, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1976, MSFC History Office, Huntsville, AL.
[1501] The six proposers included the Aerojet Solid Propulsion Company, California; Atlantic Research Corporation, Virginia; Hercules Inc., Maryland; Talley Industries, Arizona; Thiokol Corporation, Alabama; and United Technology Center, California. "Shuttle-Booster Separation Motor Source Evaluation Board," March 1975, Drawer 28, Folder: SRB Separation Motors 1974-1975, File: SRB Separation Motors, MSFC History Office, Huntsville.
[1502] No title, no date, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: General, MSFC History Office, Huntsville.
[1503] "Marshall Contracts for SRB Forgings," *Marshall Star*, July 16, 1975, 3.

contract to Sperry Flight Systems of Phoenix, Arizona, for the procurement of thirty-seven multiplexers/demultiplexers.[1504]

MSFC selected the McDonnell Douglas Astronautics Company West of Huntington Beach, California, on August 22, 1975, to provide SRB structures, including the aft skirts, frustums, nose caps, attachment rings, and struts to support the test program for the first six shuttle flights. The value of this contract (No. NAS8-31614) was approximately $14.8 million. Deliverables included fourteen aft skirts and attachment rings, sixteen sets of three struts to connect the SRB to the ET, thirteen cable tunnels, thirteen forward aft skirt assemblies, fourteen forward ordnance rings and attachments, thirteen frustum assemblies, twenty nose cap assemblies and thirteen data capsule assemblies.[1505]

In September 1975, Bendix Corporation's Guidance Systems Division of Teterboro, New Jersey, received the contract to provide the integrated electronic assemblies (IEAs) and associated test equipment for the first six Shuttle flights. The $4,409,000 contract called for thirty-three units, including flight articles, spares, and development and test versions.[1506] Delivery was scheduled to begin in 1976 and continue through April 1, 1979. At roughly the same time, the Denver Division of Martin Marietta Aerospace was awarded a $1.9 million contract for the fabrication, acceptance testing, and delivery of 322 pyrotechnic initiator controllers, which were housed in the IEAs of each booster. The period of performance extended from January 1, 1976, through December 1, 1978.[1507]

MSFC selected Martin Marietta, Denver Division as the prime contractor for the SRB decelerator (parachute) system, with Pioneer Parachute Company as the subcontractor. One other firm, Goodyear Aerospace Corporation of Akron, Ohio, had submitted a proposal. The $9 million initial procurement contract (Contract No. NAS8-32122), awarded on July 6, 1976, specified the delivery of parachute decelerator subsystems for use in recovering twelve SRBs for the first six flights. Work was scheduled to begin on July 6, 1976, and end December 1980.[1508] The first procurement of twenty-four large main parachutes was accomplished by supplemental agreement to Contract No. NAS8-32122 in June 1983. A second procurement under the original contract followed, for an additional thirteen main parachutes.[1509]

[1504] "Sperry Rand Gets Shuttle Contract," *Marshall Star*, July 23, 1975, 4.
[1505] "Firm Chosen to Produce Solid Booster Structures," *Marshall Star*, August 27, 1975, 1.
[1506] RFPs were provided to twenty-four interested sources, of which seven submitted proposals. NASA MSFC, "Bendix Selected for SRB Integrated Electronics Assemblies Contract," NASA News For Release: Release No. 75-106, June 4, 1975, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1975, MSFC History Office, Huntsville; "Bendix is Awarded Booster Contract," *Marshall Star*, September 3, 1975, 2.
[1507] "Martin Receives $1.9 Million Shuttle Contract," *Marshall Star*, August 27, 1975, 1.
[1508] "Martin Selected for SRB Contract," *Marshall Star*, June 2, 1976, 1; NASA MSFC, "Contractor Selected for SRB Decelerator Subsystem Contract," News Release No. 76-96, May 28, 1976, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1976, MSFC History Office, Huntsville; "Martin Marietta gets $9 Million SRB Contract," *Marshall Star*, July 28, 1976, 1.
[1509] Theodore T. Siomporas to W.R. Lucas, "Request for Approval of Authority to Enter into a Sole-Source Contract," memo dated March 20, 1984, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder:

Since the SRB components were being procured separately, a stand-alone contract for SRB integration was needed.[1510] Therefore, the last major contract awarded by MSFC was for the SRB assembly, checkout, launch operations, and refurbishment in support of the first six flights, with options for additional flights.[1511] USBI was selected on December 17, 1976, as the SRB assembly contractor.[1512] Along with Boeing and McDonnell Douglas, USBI was one of three firms previously selected for negotiations leading to the award of a single contract for the assembly, checkout, launch operations, and refurbishment of the SRBs.[1513] The $122 million contract (Contract No. NAS8-32000) covered the period through March 1980, plus options for twenty-one flights, extending into 1982. USBI would be responsible to two separate NASA Centers: MSFC for the assembly, checkout, and refurbishment of the SRBs, and to KSC for final assembly, stacking, integrated checkout, launch operations and post-launch disassembly of the boosters.[1514] The original contract was amended in 1980 to extend USBI's services for STS-7 through STS-27.[1515]

Subsequently, Contract No. NAS8-36100, the SRB Third Procurement Buy, provided for USBI's support of twenty-one flights (STS-17 thru -35 and WTR-1 and -2[1516]), refurbishment of SRBs to support twenty-three flights (STS-15 thru -35 plus WTR-1 and -2), expendable and reusable hardware to support twenty-one builds (STS-28 thru -45 and WTR-1 thru -3), and long lead materials and parts to support eighteen builds (STS-46 thru STS-60 and WTR-4 thru -6).[1517] The contract also covered production for Booster Integration (BI)[1518]-009 through BI-020, refurbishment through BI-077, reusable flight hardware through BI-048, and reusable long lead

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SRB 1984, MSFC History Office, Huntsville.

[1510] U.S. House, *United States Civilian Space Programs*, 476.

[1511] "MSFC Seeks Proposals on SRB Assembly;" "Proposals Sought for Last Major Shuttle Program Contract," *Marshall Star*, March 31, 1976, 1.

[1512] "NASA Awards Final Major Shuttle Program Contract," *Marshall Star*, January 5, 1977, 1, 2.

[1513] "Three Firms are Selected on Shuttle SRB Contract," *Marshall Star*, September 1, 1976, 1; NASA MSFC, "Three Firms Selected for Contract Negotiations on Shuttle Booster," NASA News, MSFC Release No. 76-159, September 1, 1976, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1976, MSFC History Office, Huntsville.

[1514] Following a transition period which began six months prior to the seventh launch, all responsibilities previously vested with MSFC were transferred to KSC. SP/Manager to MSFC Manager, Shuttle Projects Office, "KSC Baseline Understanding for SRB Transition," memo dated November 7, 1975, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1975, MSFC History Office, Huntsville.

[1515] "Amendment No. 1, Contract No. NAS8-32000," no date, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1980, MSFC History Office, Huntsville.

[1516] WTR hardware was designated for launches from the Vandenberg Launch Site in California within the Western Test Range (WTR). The Western Test Range, which became the "Western Range" in 1991, was headquartered at Vandenberg AFB, California (30th Space Wing). The Range, consisting of a chain of shore and sea-based tracking sites, extended from the west coast of the U.S. to 90 degrees east longitude in the Indian Ocean, where it meets the Eastern Range. Shuttle launch and ascent was monitored by the Range. The Eastern Range, headquartered at Patrick AFB, Florida (45th Space Wing), supported missile and rocket launches from CCAFS and KSC.

[1517] Siomporas, "Sole-Source Contract."

[1518] Prior to integrated booster build-up, a Thiokol number was used to designate each SRM segment. After build-up, a Booster Integration (BI) number was used instead for each SRB set. Anthony (Tony) Bartolone, interview by Joan Deming and Patricia Slovinac, June 29, 2010, Kennedy Space Center, Florida.

material through BI-066. The value of this contract was $455.3 million, and the period of performance extended from September 26, 1983, through December 31, 1987. The succeeding Contract No. NAS8-36300, valued at an estimated $1,076 million, covered production for BI-021 through BI-084, refurbishment for BI-015 through BI-077, and reusable flight hardware through BI-084, as well as planned production for BI-085 through BI-154 and reusable flight hardware through BI-154. The period of performance, originally January 9, 1985 through September 30, 1999, was truncated, and the contract was consolidated into NAS9-20000/Space Flight Operations Contract, effective July 1, 1998.[1519]

SRM/RSRM Development and Test Programs

The shuttle SRMs were developed in three stages: the original baseline SRM, the succeeding high performance motor (HPM), and the redesigned/reusable solid rocket motor (RSRM). In addition to these successive design changes, NASA initiated projects to develop a lighter-weight motor case, the FWC, as well as an "advanced" solid rocket motor (ASRM). Both the FWC-SRM and the ASRM were designed, fabricated, and tested, but never used for flight.

The first SRMs were fabricated and tested in the late 1970s. Eight segments for the first two flight motors were shipped to KSC in the latter half of 1979 to support the first orbital flight. Three decades later, nearing the close of the SSP, the segments for the final flight motors, built to support the last five Shuttle flights (STS-131 through STS-135), were cast between March 2007 and October 2009.[1520] On May 27, 2010, the last RSRM segments, designated for the final program flight, arrived at KSC from Utah.

Baseline SRM

The original **SRM,** designed and fabricated by Thiokol, was tested and certified between July 1977 and February 1980, under the direction of MSFC. The SRM project full-scale test program was initiated in May 1976, with tests of the SRM nozzle flexible bearing. The objective of the test series, scheduled for completion in December 1976, was to evaluate the design and life expectancy of the flexible bearing by subjecting it to various stress levels and gimbal angles. A special test fixture was used to duplicate the motor chamber pressures and operational loads (stresses) expected to be felt by the bearing during flight. The results of the tests were evaluated in preparation for the manufacture and test of the complete nozzle, then scheduled for static testing as part of the first full-scale development motor, DM-1, in spring 1977.[1521]

[1519] NASA MSFC, Transition Project Office, "STS Stack Recordation Data Package," Tab C: MSFC Space Shuttle Element Contract History, Main Propulsion Elements, June 15, 2009.
[1520] ATK, "FSM-17 Pre-Brief" (presentation materials, MSFC, Huntsville, AL, April 8, 2010), 2.
[1521] "SRM Flex-Bearing Testing Entering Full-Scale Phase," *Marshall Star*, May 26, 1976, 2; NASA MSFC, "Testing Begins on Shuttle Motor Bearing," NASA MSFC News Release No. 76-95, May 26, 1976, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1976, MSFC History Office, Huntsville.

The test firings of four development motors (DM-1 through DM-4) and three flight-type qualification motors (QM-1 through QM-3) were conducted at Thiokol's facility near Brigham City, Utah. The cumulative run time for the seven tests was under 1,000 seconds. In comparison, a total of 726 tests were required to certify the main engines.[1522]

The first production case segment for DM-1 was delivered from subcontractor Rohr Industries of Chula Vista, California, to Thiokol on September 27, 1976. Fabrication of DM-1 was completed in 1977.[1523] Static firing of this first development motor on July 18, 1977, indicated problems that needed correction (Figure No. E-1).[1524] Testing of DM-2 took place on January 18, 1978, and lasted for just over two minutes, roughly equivalent to the duration of the motor during actual launch. During this test, the motor nozzle was gimbaled (swiveled) during roughly half the time. While the test was successful, detailed examination of the internal insulation of DM-2 indicated an unexpected erosion pattern[1525] As a result, the inhibitor was redesigned, and the motor was reworked, reassembled, and successfully tested. The inhibitor design change was incorporated into all subsequent SRMs.[1526]

Because of the reworking of the propellant inhibitor, the static firing of DM-3 was delayed for five months. DM-3, designed as the first SRM in flight configuration, was tested on October 19, 1978. The development motor contained the first flight-type nozzle TVC hydraulic actuation system to move the motor nozzle.[1527] Also, a linear-shaped explosive charge designed to sever the aft exit cone of the nozzle was in place for the first time throughout the test.

The succeeding DM-4 test also was delayed, due to problems with two motor segments. One segment required replacement because of an excessive number of propellant voids. This finding later led to improvements in tooling and process techniques for the motor casings. The second segment (DM-4 aft segment) had been seriously damaged on December 2, 1978, during a breakover operation at the large motor casting pits at Thiokol's Wasatch Division plant. The damage was discovered after the segment was removed from the breakover fixture, a hydraulically-operated device used to rotate the motor case segment from vertical to horizontal. Following an investigation, it was determined that unclear procedures in how to operate the fixture contributed to the cause of the accident. Recommendations included redesign of the breakover fixture with adequate operational margins, and a revision of the procedures for using

[1522] Jenkins, *Space Shuttle*.
[1523] NASA MSFC, "First SRB Motor Case Segment Delivered," NASA News, MSFC Release No. 76-173, September 29, 1976, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: General, MSFC History Office, Huntsville.
[1524] "First Solid Rocket Motor Firing Said Near Perfect," *Marshall Star*, July 6, 1977, 1.
[1525] "SRM Passes Second Test Successfully," *Marshall Star*, January 25, 1978, 1.
[1526] "Statement of James M. Stone, Group Vice President, Government Systems, Thiokol Corporation before the Subcommittee on Space Science and Application of the Committee on Science and Technology, U.S. House of Representatives," January 28, 1979, Series: Space Shuttle Program, Program/Project Files, Drawer 26, Folder: January – July 1979, MSFC History Office, Huntsville.
[1527] "Third Static Test Set for Solid Rocket Motor," *Marshall Star*, October 18, 1978, 1, 2; "Third Solid Rocket Motor Test Firing Is Successful," *Marshall Star*, October 25, 1978, 2.

it.[1528] Test firing of DM-4 on February 17, 1979, marked the successful end of the development series and paved the way for qualification firings later in the year.[1529]

In a January 28, 1979, statement before the U.S. House Subcommittee on Space Science and Application, Thiokol Corporation's Group Vice President for Government Systems, James M. Stone, reported that the SRM project was near the end of a peak period of development activity. Stone noted that the last motor had entered the initial stages of manufacture, and only two qualification motors remained to be fired. Testing of a structural test article in early fiscal year 1978 confirmed the ability of the motor structure to withstand design loads (external forces). "It is important to note that . . . shipping, handling and assembly operations at Thiokol, MSFC and KSC have verified the design concepts, the equipment for transportation and handling, and the vehicle interface for the solid rocket motor," Stone concluded.[1530]

Between June 1979 and February 1980, qualification motors QM-1, QM-2, and QM-3 were fired in flight configuration (Figure No. E-2). This series served as the acceptance testing of the SRM. The 122-second static firing of QM-1, conducted on June 15, 1979, proved the ablative safety of the motor nozzle. During the test firing, the nozzle was gimbaled to simulate control properties during a launch.[1531] Two months later, the second SRM qualification test achieved a maximum thrust of 3.1 million pounds, and accomplished all objectives.[1532] The final static test, QM-3, was successfully accomplished on February 14, 1980.[1533] The baseline SRM was flown on STS-1 through STS-7.

<u>High Performance Motor</u>

The HPM featured a number of enhancements, compared with the baseline SRM. These included a modified propellant grain pattern, reduced nozzle throat diameter, increased nozzle expansion ratio, and increased chamber pressure. Collectively, as the result of these changes, an additional 3,000 pounds of payload was made possible.[1534] The maiden flight of the HPM was preceded by two static tests, HPM DM-5 in 1982, and HPM QM-4 in early 1983. The DM-5 static test had been scheduled for September 14, 1982, but was delayed due to a joint leak discovered during preliminary checkout. The HPM debuted as the new baseline motor in August 1983 with STS-8.

[1528] Thiokol Wasatch Division, "Summary of Board Investigation Report," December 2, 1978, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1976, MSFC History Office, Huntsville.
[1529] "Final SRM Development Firing Slated., *Marshall Star*, February 14, 1979, 1; "Final Development Test Firing of SRM is Conducted Saturday," *Marshall Star*, February 21, 1979, 1.
[1530] "Statement of James M. Stone."
[1531] "First Qualification Firing of SRB Scheduled Today," *Marshall Star*, June 13, 1979, 1.
[1532] "Second SRM Qualification Test Passed," *Marshall Star*, October 3, 1979, 1, 4.
[1533] "Solid Rocket Passes Final Static Firing," *Marshall Star*, February 20, 1980, 1, 2.
[1534] ATK, "FSM-17 Pre-Brief," 8.

Redesigned/Reusable SRM

In the aftermath of the *Challenger* accident, the thirteen-member Rogers Commission concluded that the loss of the spacecraft was caused by a failure in the joint between the two lower segments of the right SRM. The specific failure was the destruction of the seals that were intended to prevent hot gases from leaking through the joint during the propellant burn of the rocket motor. According to Royce Mitchell, NASA's post-*Challenger* RSRM project manager, there was putty in the place of what eventually became the J-seal and the sealed insulation. "As the two segments that were being mated were brought together . . . it was impossible to avoid trapping air between the joints as you brought those two segments together . . . Over time this air would work its way to the surface and leave what was called a "blowhole." A blowhole in the putty let the flames impinge on one part of the O-ring. When the flame had pushed its way through the putty, as the motor continued to supply pressure, hot gas started filling up the circular tunnel in that joint. The jet of hot gas that was hitting the O-ring did not stop. As more and more gas tried to fill the circular tunnel, burn through of the O-rings resulted.[1535]

John Thomas, who led NASA's SRM redesign team, believed that there were three contributing causes to the *Challenger* accident. In addition to the faulty design of the field joint, the cold temperature on the day of the launch did not permit the sealing O-rings to be resilient enough to follow the opening of the joint. Thirdly, failure of the insulation that keeps the 6,000 degree F temperature from burning the metal and the seals contributed to the breaching of the joint by hot gas.[1536]

On June 13, 1986, President Reagan directed NASA to implement the recommendations of the Rogers Commission. A redesign team was established which included participation from MSFC, Thiokol, other NASA centers, contractors, and experts from outside NASA.[1537] Design changes were recommended for a number of areas, including the field, factory, and case-to-nozzle joints; the nozzle; the local propellant grain shape; and the ignition system. Changes to the ground support equipment also were recommended.

Initially, the NASA design team and a team from Thiokol worked independently to reconfigure the field joint. By the end of 1986, the two teams joined together at the Thiokol plant site in Promontory, Utah, to derive a final design. A fundamental challenge, according to John Thomas, was how to seal the joint at the insulation to keep the joint from opening when the motor was pressurized.[1538] If it did not open, the O-rings would stay in place. A related objective was to provide the ability to leak-check the O-rings in the direction that they would be sealing.

[1535] Mitchell, interview.
[1536] John Thomas, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project,* June 29, 2010, http://www.jsc.nasa.gov/history/oral_histories/sts-r/ThomasJW/ThomasJW_6-29-10.htm.
[1537] NASA, *NSTS Shuttle Reference Manual*, 1988, http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts_asm.html.
[1538] Thomas, interview.

Each SRM had three field joints, which marked the locations where the four primary motor segments were fitted together in a tang-to-clevis fashion (cf., tongue-and-groove joint). In the RSRM field joint, the modified tang, known as the "capture feature," served to dramatically reduce joint deflection and rotation, both of which played a role in the loss of the *Challenger*. "Machined into the capture feature is a groove designed to hold an additional O-ring in place. The capture feature O-ring functions as a thermal barrier should the superheated gases of ignition reach it."[1539] The internal insulation configuration also was redesigned, which included adhesive bonding of the tang and clevis insulation surfaces. In addition, a J-shaped relief flap was designed into the tang-side insulation to assure an even tighter fit. This relief flap put pressure to work in preventing hot gases from reaching the motor's metal components.

Redesign also entailed lengthening of the 177 joint pins spaced around the field joint, and the addition of customized pin retainer shims to enhance fit. Other new features included a leak test port in front of the primary O-ring, joint heaters so the O-rings would not get cold if launched at below 50-degree F temperatures, as well as weather seals. "With the combination of the capture feature and the J-seal insulation and the method of being able to leak-check and the heaters to maintain the temperature of the joint, we successfully overcame the cause of the accident," John Thomas reported.[1540]

Changes to the factory joint included an increase in the insulation thickness, and the addition of larger pins. The retainer band was reconfigured, and a new weather seal was added. The O-ring and O-ring groove size were changed, consistent with the field joint modification. The motor propellant forward transition region was recontoured to reduce the stress fields between the star and cylindrical portions of the propellant grain. Modifications to the ignition system included thickening of the aft end of the igniter steel case, which contained the igniter nozzle insert. This was done to eliminate a localized weakness. Also, the igniter internal case insulation was tapered to improve the manufacturing process.

The RSRM also featured modifications to the case-to-nozzle joint that affixed the nozzle to the aft motor segment; the factory joints, which were put together before the motor was cast with propellant; and the igniter joint. To improve both the performance and strength of the case-to-nozzle joint, changes were made to the ply angles of the nozzle's nose inlet and throat rings, the cowl and outer boot ring, as well as the aft exit cone ablative liner. Redundant and verifiable seals were added to the nozzle's internal joints. Up through *Challenger's* final mission, each of the five different nozzle joints had a single O-ring as a seal. The RSRM included two O-rings at each nozzle joint. To reduce case rotation, 100 radial bolts were added, and insulation surfaces were adhesively bonded, eliminating the need for putty filler. A third O-ring, referred to as a wiper O-ring, was incorporated into the RSRM design for additional thermal protection.[1541]

[1539] Morton Thiokol, Inc., "Thirty-Two Months to Discovery" [1986], Box 1986H, MSFC History Office, Huntsville.
[1540] Thomas, interview.
[1541] Morton Thiokol, "Thirty-Two Months."

Other modifications included redesign of the attachment ring where the SRBs were connected to the ET. The ring was changed from a C-form, which encircled the motor case 270 degrees, to a complete 360-degree circle. This alteration was made following analyses indicating areas of distress in some of the fasteners, attributed to the stresses encountered during water impact.[1542] Also, detection of an anomaly in a critical weld between the hold-down post and skin of the aft skirt resulted in the addition of reinforcement brackets and fittings to the aft skirt ring. Changes to the attachment ring and reinforcement brackets added about 450 pounds of weight to each SRB.

In accordance with the Rogers Commission's recommendations, GSE was redesigned to meet a number of objectives:

- To minimize the case distortion during handling at the launch site;
- To improve the segment tang and clevis joint measurement system for more accurate reading of case diameters to facilitate stacking;
- To minimize the risk of O-ring damage during joint mating; and
- To improve the leak testing of the igniter, case, and nozzle field joints.[1543]

The Rogers Commission recommended that the tests to certify the new RSRM design be configured to duplicate the full range of operating conditions, including temperature. Full consideration of testing in a vertical attitude was recommended.[1544] However, after intensive study, NASA selected the horizontal test attitude for the RSRM because it was "the most demanding test of the redesigned joint for pressure and flight-induced loads and thus best satisfies the Commission's intent."[1545]

Royce Mitchell believed that "the most important part of the redesign effort was the many many tests that we ran."[1546] Further, "as different designs were proposed, it was always the test that was the ultimate referee for choosing the evaluation of this redesign."[1547] NASA conducted laboratory and extensive component tests, full segment environmental simulation tests (with loads applied), and full-scale static test firings to verify and certify the RSRM for flight. For the first time, the motor was tested at low temperatures (near 30-35 degrees F) to demonstrate that it could operate properly under these conditions. In addition, NASA deliberately introduced flaws

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[1542] NASA, "SRB Overview," 2002.
[1543] NASA MSFC, *Solid Rocket Motor Redesign*, NASA Fact Sheet (Huntsville, AL: George C. Marshall Space Flight Center, July 1988), MSFC History Office, Hunstville; NASA, *NSTS Shuttle Reference Manual*.
[1544] Historically, the motors were tested in a horizontal position, and because of its advantages, horizontal testing was continued. Important considerations favoring testing in the horizontal position included flexing (sagging) of the motor which approximated the bending of the stack at the launch pad at ignition, as well as the greater efficiency in measuring thrust and simulating loads. Mitchell, interview.
[1545] NASA Headquarters, "NASA Selects Horizontal Configuration for Joint Test," Release No.: 86-139, October 2, 1986, Folder RA01 SRM Redesign-J. Thomas, Drawer 28, MSFC History Office, Huntsville.
[1546] Mitchell, interview.
[1547] Mitchell, interview.

to demonstrate satisfactory performance. This approach, advocated by NASA's former SSME Project Manager J.R. Thompson, had been successfully applied during the engine test program. Thus, NASA "actually introduced the flaws in the re-certification of the joint that failed during the *Challenger* mission," which included cutting the O-rings.[1548]

To meet the goal of a 1988 RTF launch schedule, both unique test facilities and full-scale test articles were built.[1549] For example, a field joint test article was constructed at MSFC that included two full-scale segments of a motor with a forward dome, aft dome, and a nozzle simulator. Differing amounts of propellant were used to simulate what the joint looked like as the pressure built up at ignition on the pad.[1550]

Six full-scale, full-duration static motor tests were conducted between May 27, 1987, and August 18, 1988, prior to the STS-26 RTF mission in September 1988. This RSRM test program was initiated on May 27, 1987, with static testing of ETM-1A. Test firing of DM-8 on August 30, 1987, was designed to evaluate the performance of the capture feature and the redesigned case-to-nozzle joint (Figure No. E-3). Four months later, on December 23, 1987, DM-9 was tested to further study the performance of major redesign features. Static testing of QM-6 on April 20, 1988, was the first full-scale/full-duration motor to qualify major features of the RSRM. Successful test firing of QM-7 followed on June 14, 1988.[1551] The final test of the series was of PVM-1 on August 18, 1988. This "J-leg and Capture Feature O-ring Flaws Test" featured flaws deliberately machined into the test motor to provide initial full-scale margin testing of the redesigned RSRM joints.[1552]

Full-scale, short-duration motor tests, as well as structural tests, also were conducted to evaluate the redesigned motor.[1553] Short duration meant that pieces of propellant were carefully sized and located to generate the heat and pressure to pressurize the case without going into a full-scale full-duration firing.[1554] The full-scale, short-duration motor test series included a total of twenty-two tests. Among these were seven Joint Environment Simulator tests completed between August 14, 1986, and July 28, 1988, to evaluate field joint hardware, insulation, and seal performance. Thiokol's Dr. Joseph E. Pelham designed a joint environmental simulator for the case-to-nozzle joint, and nine Nozzle Joint Environment Simulator tests were performed between February 8, 1987, and August 14, 1988. From October 3, 1987, to September 1, 1988, six Transient Pressure Test Article tests were conducted at MSFC to evaluate both field joint and case-to-nozzle joint performance. In addition, two structural tests were performed on December 18, 1987, and April 1, 1988, to evaluate the structural margins of the redesigned hardware.

[1548] Thompson, interview.
[1549] "SRM Redesign – J. Thomas," 1986, Drawer 27, Folder: RA01, MSFC History Office, Huntsville.
[1550] Thomas, interview.
[1551] Static testing of QM-7 marked the first use of Thiokol's new T-97 test stand.
[1552] ATK, "FSM-17 Pre-Brief," 12.
[1553] Morton Thiokol, Inc., "Thirty-Two Months."
[1554] Mitchell, interview.

Overall, NASA's SSP spent about $10 million per day, or roughly $4 billion per year, on redesign of the SRM, and virtually every element of the motor saw some changes.[1555] While NASA funded initiatives to replace the RSRM (see ASRM), such projects ultimately led nowhere. The RSRM designed by Thiokol in the aftermath of the *Challenger* tragedy was the motor that flew on all missions through the end of the SSP.

Filament Wound Case SRM

Prior to the *Challenger* accident and the development of the RSRM, which followed, NASA planned to launch to polar orbit from Vandenberg AFB, beginning in 1986. To offset the needed increase in payload capability, NASA looked for ways to reduce the total weight of the SRBs. Towards this goal, Thiokol proposed a composite material of plastic reinforced with graphite fibers as a replacement for the cylindrical steel sections of the SRM case. Compared with the metal cases, the graphite-epoxy FWC reduced the case weight by approximately 28,000 pounds. As a result, the payload capacity of the Shuttle would be increased by about 5,000 to 6,000 pounds.[1556] The graphite case segments were fabricated in Clearfield, Utah, by the Hercules Aerospace Company, a subcontractor to Thiokol. Following manufacture, the cases were shipped to the Thiokol plant for attachment of the steel end-rings, the domes on the forward and aft segments, and the ET attachment section on the aft segment. Thiokol also installed the rubber insulation, polymer lining, and propellant. Three test motors were fabricated, as well as segments to equip two complete sets of flight motors, plus most of a third set.[1557]

The static test program for the FWC-SRM included the firing of two development motors, DM-6 and DM-7, and one qualification motor, QM-5. DM-6, static fired on October 25, 1984, contained two design features that Thiokol believed would improve the field joint O-ring performance and help overcome a nozzle erosion problem identified after STS-8. The FWC-SRM field joints included a metal capture lip on the tang side that made it easier for the O-rings to maintain a seal during pressurization.[1558] To eliminate the erosion problem on the nozzle, the angle at which the carbon-cloth-phenolic tape was placed on the mandrel (spindle) was changed. DM-7 was tested on May 9, 1985. All the elements new to the FWC-SRM performed as expected, and the nozzle and field joints were in excellent condition after the tests.

The first FWC-SRM segments arrived at Vandenberg on May 30, 1985; all of the first flight set had arrived by mid-July.[1559] In January 1986, the FWC-SRM was stacked on the Vandenberg launch pad in preparation for the first west coast launch of the SSP. However, following the *Challenger* accident, the FWC project was ended. The test firing of qualification motor QM-5,

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[1555] Mitchell, interview.
[1556] Allan J. McDonald, with James R. Hansen, *Truth, Lies, and O-Rings* (Gainesville, Florida: University Press of Florida, 2009), 29; NASA MSFC, *Lightweight Booster*, NASA Fact Sheet (Huntsville, AL: George C. Marshall Space Flight Center, no date), MSFC History Office, Huntsville.
[1557] Jenkins, *Space Shuttle*, 432.
[1558] McDonald and Hansen, *O-Rings*, 31.
[1559] Jenkins, *Space Shuttle*, 432.

scheduled for February 1986, was cancelled.[1560] The segments remained in storage at Vandenberg until mid-1988, when they were returned to Thiokol in Utah. Use of the FWC-SRM was briefly reexamined in 1994, after cancellation of the ASRM project, but was rejected.[1561]

Advanced Solid Rocket Motor Program

In the wake of the *Challenger* disaster, the single-source contractor and production site for the SRM was raised as an issue of concern.[1562] Concurrent with the SRM redesign efforts, in September 1986, NASA MSFC awarded ninety-day, $500,000 contracts to study new "advanced" SRM designs to five aerospace firms: Aerojet Strategic Propulsion Company of Sacramento, California; Atlantic Research Corporation of Alexandria, Virginia; Hercules Aerospace Company of Salt Lake City, Utah; Morton Thiokol, Inc. of Brigham City, Utah; and United Technologies Chemical Systems Division of San Jose, California.[1563]

NASA administrator James Fletcher decided to move forward with "Phase B" design and definition studies, and on June 3, 1987, MSFC released the RFP for the ASRM study contract. All five companies that had participated in the earlier studies submitted proposals, and all five were awarded nine-month contracts. The early concepts included both a segmented motor design and a joint-free monolithic design.[1564] Based on the results of the "Phase B" studies, NASA released the RFP for the ASRM contract on August 22, 1988. The ASRM development and test program was expected to take about six years. NASA planned to phase in the new motor during the mid-1990s, with the first flight slated for 1996. Four of the five companies submitted proposals as two teams, Hercules-Atlantic and Lockheed-Aerojet.[1565] Thiokol opted to "no bid" the ASRM contract and continued its work on SRM redesign. However, the company agreed to support the Lockheed-Aerojet team, if selected, as a subcontractor for the ASRM nozzle assembly.[1566]

From the perspective of Allan J. McDonald, Thiokol's SRM project director at the time of the *Challenger* accident, "NASA had sold the ASRM program . . . to Congress on the basis that the new motor would have higher reliability at lower cost than the RSRM." He, however, regarded

[1560] An exhaustive investigation by a Senate subcommittee resulted in the cancellation of NASA's plans to activate the Vandenberg Launch Site (VLS) in California. The facilities were ordered mothballed in 1988, and the SSP at VLS was officially terminated in December 1989.
[1561] Jenkins, *Space Shuttle*, 432.
[1562] Harry F. Schramm and Kenneth W. Sullivan, "An Evaluation of the Total Quality Management Implementation Strategy for the Advanced Solid Rocket Motor Project at NASA's Marshall Space Flight Center," NASA, MSFC, NASA Technical Memorandum, NASA TM-103533, May 1991, 4, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19910015285_1991015285.pdf.
[1563] "NASA awards contracts for solid rocket booster designs," *Florida Today,* September 7, 1986: 9, Microfiche collection, MSFC History Office, Huntsville.
[1564] "Marshall Invites Industry to Study Advanced Booster," *Spaceport News*, June 19, 1987, 7.
[1565] Jenkins, *Space Shuttle*, 461-462.
[1566] McDonald and Hansen, *O-Rings*, 489.

the ASRM as a political "pork barrel project," being conducted "to punish Thiokol" and bring jobs into the district of Jamie Whitten, Chairman of the House Appropriations Committee.[1567]

NASA selected the Lockheed-Aerojet team, and preliminary design efforts started in December 1989, under interim contracts between NASA and Lockheed. On May 11, 1990, MSFC formally awarded a five-year contract (Contract No. NAS8-37800) to Lockheed Missiles and Space Company, Inc. and their subcontractor, Aerojet Space Booster Company. The basic contract, valued at $971 million, called for production of twenty new motors.[1568] Lockheed also was chosen to develop NASA's proposed government owned – contractor operated facility at Yellow Creek. This former Tennessee Valley Authority nuclear power plant located near Iuka, Mississippi, would house the ASRM manufacturing operations.

Physically, the major difference between the ASRM and the RSRM was in the number of motor case segments – three in the ASRM and four in the RSRM. All factory joints, the ET attach ring, and more than 2,000 individual parts were eliminated in the ASRM.[1569] The "advanced" motor also featured an improved igniter and nozzle design and a new propellant grain design. In addition to motor design enhancements, improvements were planned for the ASRM manufacturing process. These included the use of more automation in the application of insulation, and a continuous casting process where the propellant was mixed close to the casting pit and then piped to the motor.[1570]

The first ASRM-related test was conducted at MSFC on April 10, 1991, with more tests performed through 1992.[1571] In March 1992, John S. Chapman and Michael B. Nix of NASA's MSFC, presented a paper at the AIAA Space Programs and Technologies Conference in which they projected a 1995 delivery for the first set of flight ASRMs, and first launch in early 1997.[1572] In reality, as a way to trim its budget, NASA's FY 1993 request to Congress contained no funding for ASRM development or production. The ASRM program was continued for one more year at the FY 1992 level. In consideration of projected delays in the design of the Space Station, which the ASRM was intended to support, in July 1993, the U.S. House voted to end the ASRM program.[1573] Subsequently, on October 27, 1993, the ASRM contract was officially terminated "for convenience of the Government."

[1567] McDonald and Hansen, *O-Rings*, 489, 552.
[1568] NASA, "NASA Awards Contract to Develop Advanced Solid Rocket Motor," Release: 90-68, May 14, 1990, http://www.nasa.gov/home/hqnews/1990/90-068.txt.
[1569] Jenkins, *Space Shuttle*, 462.
[1570] Thomas, interview; Mitchell, interview.
[1571] Jenkins, *Space Shuttle*, 464.
[1572] John S. Chapman and Michael B. Nix, "Overview of the Manufacturing Sequence of the Advanced Solid Rocket Motor," Paper presented at the AIAA Space Programs and Technologies Conference, March 24-27, 1992, 10, Box 1992A, MSFC History Office, Huntsville.
[1573] Jenkins, *Space Shuttle*, 464.

Flight Support Motor Test Program

Beginning in 1987, Thiokol initiated a FSM test program to annually evaluate, validate, and qualify new improvements or changes to the motor. After testing, the test article components, including the metal case segments and nozzle components, were refurbished for reuse. Between August 15, 1990, and February 25, 2010, a total of sixteen full-scale FSMs were tested, typically one per year.[1574] For example, the June 10, 2004, full-scale static firing helped to evaluate modifications to the shape of the propellant grain in the forward motor segment. This modification was designed to increase propellant strength and to enhance safety by decreasing the risk of cracks in the propellant.[1575] On February 25, 2010, FSM-17 was tested to obtain full-scale performance data to validate the integrity of the final flight motors (RSRM-110, -111, -112, -113, and -114) to support the last five Shuttle flights of the program (STS-131 through STS-135). This was Thiokol's 52nd and final static test firing of a RSRM (Figure No. E-4). Among the forty-one test objectives, the FSM-17 static test was performed to demonstrate the performance of asbestos-filled nitrile butadiene rubber (ASNBR) insulation made with a new primary cure accelerator; the performance of propellant fabricated with new polished piping; and the performance of propellant fabricated with materials procured from new sources.[1576]

The FSM tests, noted David Beaman, NASA's RSRM Project Manager, "have built a base of engineering knowledge that continued engineering development of the reusable solid rocket motor system and the continued safe and successful launch of space shuttles. They have provided an engineering model and lessons learned for additional applications in future launch systems."[1577]

RSRM Improvements and Changes: ca. 1990 – 2006

Improvements to the design, materials, and manufacturing processes in the RSRMs were on-going throughout the SSP, and ground testing was a key part of certifying a change. However, according to Jody A. Singer, Deputy Manager of the MSFC Propulsion Office and SRM/RSRM Manager, unlike the SSMEs, each new motor did not get tested before flight, or have a "green-run."[1578]

[1574] FSM-16 was not fabricated and tested. Testing of FSM-17 followed that of FSM-15. ATK, "FSM-17 Space Shuttle Reusable Solid Rocket Motor Static Test, February 25, 2010," (presentation materials, MSFC, Huntsville, AL, April 8, 2010).
[1575] NASA MSFC, "Successful test leads way for safer Shuttle Solid Rocket Motor," 2004, http://www.nasa.gov/centers/marshall/news/news/releases/2004/04-163.html.
[1576] ATK, "FSM-17 Static Test."
[1577] NASA, "NASA's Space Shuttle Program Successfully Conducts Final Motor Test in Utah," http://www.nasa.gov/mission_pages/shuttle/behindscenes/final_motor_test. html.
[1578] Jody A. Singer, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project*, June 21, 2010, http://www.jsc.nasa.gov/history/oral_histories/sts-r/SingerJA/SingerJA_7-21-10.htm.

In general, between 1990 and 2006, the igniter joints were redesigned, and changes were made to the nozzle structural adhesive, high-fired carbon phenolics, propellant fin, and O-rings. To verify the new materials and manufacturing processes, static test firings of ETMs were conducted at Thiokol's facility in Promontory, Utah. "An engineering test motor (ETM) offers the opportunity to spot any flaws, as well as to conduct 'push the envelope' testing to gauge the components' ability to meet flight requirements."[1579] On November 1, 2001, testing of ETM-2 was performed to evaluate a new low temperature seal (O-ring) material (as a replacement for the standard Viton material) in the aft field joint. Another test objective focused on a new asbestos-free nozzle flexible boot, a thermal barrier that keeps hot gases off the nozzle's guiding mechanism. Several potential nozzle improvements also were tested, including a new adhesive that bonded metal parts to phenolic parts; new environmentally-friendly solvents; a new nozzle ablative insulation; carbon fiber rope thermal barriers in the nozzle joints; and a modified bolted assembly design on one of the nozzle joints.[1580]

According to Jody Singer, in the aftermath of the *Columbia* tragedy, NASA was focused on "ensuring the integrity of our hardware and flight processes with less emphasis on hardware change."[1581] For example, ETM-3, static tested on October 23, 2003, during the RTF activities, was conducted as a "margin test" to help "understand the physical performance limits of the hardware, as well as the physics of the hardware."[1582]

Motor age and age life limits[1583] also were post-*Columbia* areas of concern. Accordingly, the motors stacked and ready for the next launch were destacked and returned to Utah for testing. Flight Verification Motors (FVMs), FVM-1 (the destacked RSRM-89B) and FVM-2 (the destacked RSRM-89A), were the focus of two "Mid-Life and Full-Life Validation" tests on February 17, 2005, and May 1, 2008, respectively. A case-by-case hardware age life extension was performed on the motor segments, and the mixture date of the propellant also was checked.[1584]

Redesign of the SRB bolt catcher was an additional focus. A large bolt holds together the SRB and ET. One-half is contained in the SRB and the other half in the ET. At ET/SRB separation, a cartridge in the bolt fires and breaks the bolt. Half of the broken bolt is thrown into the SRB, where it is caught by the bolt catcher. The other portion is caught by the ET. As a result, there is no debris when the Shuttle is fired up. Following the *Columbia* accident, NASA was concerned that the bolt catcher did not have the proper strength and might come apart, or become a debris source. The housing was redesigned and welded as one piece, rather than the original two-piece.

[1579] NASA MSFC, "Engineering test firing of shuttle SRB called a success," news release, November 2, 2001, http://spaceflightnow.com/news/n0111/03srbtest/.
[1580] NASA MSFC, "Engineering test firing."
[1581] Singer, interview.
[1582] Singer, interview.
[1583] Each RSRM had a certification life of five years and stack life of one year. Singer, interview.
[1584] Singer, interview.

Also, the softer material within each half that helped absorb the bolt was improved, as was the cartridge that split the bolt.[1585]

STS-114, the RTF mission, which launched on July 26, 2005, incorporated the redesigned SRB bolt catcher. It also marked the first use of an ET and SRB three-camera system to help assess the performance of the Shuttle's TPS.[1586] The three video-cameras, one mounted on the ET and one on each SRB, provided views of the orbiter's underside and the ET up until the tank separated from the orbiter at T+8.5 minutes. The "External Tank Observation Camera" was an off-the-shelf video camera and tape recorder installed in each forward skirt of the boosters. It offered a view of the orbiter's nose, ET intertank, and, at ET/SRB separation, the booster opposite the camera. Recording began at launch and continued until after deployment of the drogue parachute. At that time, the recorder switched over to a second identical camera looking out the top to record main parachute deployment. The video was reviewed after recovery of the SRBs.

Another post-*Columbia* change was redesign of the frangible nut, which secured the Shuttle to the MLP. STS-126, launched on November 14, 2008, was the first Shuttle vehicle to incorporate the newly designed frangible nut crossover assembly in each of the eight hold-down locations on the SRBs. The new assembly pyrotechnically linked the two booster/cartridges/detonators in each frangible nut, resulting in faster detonation. With the time reduction, a greater initiation velocity was achieved, and the safety margin was increased.[1587] The redesign of the frangible nut was a recommendation of the CAIB, as a means to minimize "stud hang-ups" that occurred on twenty-three shuttle launches since SSP inception.[1588]

Two TEMs were tested for the RSRM. The first of the two, TEM-12, was a full-scale, full-duration test of RSRM-91B, returned from KSC and tested at the Thiokol facility on March 9, 2006. This test was intended to provide unique information about motor components that had experienced extended exposure to the Florida environment. TEM-13 was a test of the destacked RSRM-90B, conducted on November 1, 2007.[1589]

1585 Singer, interview.

1586 The SRB camera, originally certified to provide a closer look at the foam on the ET's intertank, had previously flown on five missions: STS-93 in July 1998, STS-95 in October 1998, STS-96 in May 1999, STS-101 in May 2000, and STS-103 in December 1999. NASA MSFC, *Space Shuttle External Tank and Solid Rocket Booster Camera Systems*, NASA Facts, (Huntsville, AL: George C. Marshall Space Flight Center, April 2005), http://www.nasa.gov/centers/marshall/pdf/114016main_ET_SRB_Cam_FS.pdf.

1587 NASA MSFC, *Space Shuttle Solid Rocket Booster Frangible Nut Crossover System*, (Huntsville, AL: George C. Marshall Space Flight Center, November 2008), http://www.nasa.gov/centers/marshall/pdf/290339main_8-388221J.pdf.

1588 CAIB, *Report*, *Volume I*, 121. A stud hang-up occurs when the hold-down post system stud, located at the base of the aft skirt, is not ejected prior to the first space shuttle liftoff motion. The frangible nut held the stud in place at the top. NASA MSFC, 2008; Chris Bergin, "New SRB modification completed for STS-125 debut," 2008.

1589 T. Davis, "Static Test Information," (presentation given March 2, 2010).

SRB Non-motor Component Development and Testing

SRB-related testing began early in the STS development period. Between February 10 and March 10, 1973, the U.S. Navy at the Long Beach Naval Shipyard in California, conducted water impact and towing tests on behalf of MSFC (Figure No. E-5). The objective of the test series was to help determine design characteristics for the shuttle boosters. During the water impact tests, an 85 percent-scale model of a SRM casing was dropped from a crane into the ocean.[1590] Later, during November 1973, MSFC conducted drop tests of a SRM scale model and a three-parachute recovery system.

MSFC engineers, developers of the TVC system, assembled two complete TVC subsystems at the Center for use in testing. One was the focus of hot fire tests at MSFC between September and October 1976, to confirm the design of the steering system. The resulting data were evaluated by the MSFC Structures and Propulsion Lab engineers to refine the design of the system. After all modifications were completed, a second test series was conducted at MSFC to certify the TVC system. Later, in 1978, a TVC system installed in the aft skirt of an SRB was tested under actual firing conditions at the Thiokol facility in Utah.[1591]

Various structural tests on complete SRB assemblies were conducted at MSFC, beginning in late 1977, and completed by the end of May 1980 (Figure Nos. E-6, E-7).[1592] A five-ton aft skirt built by McDonnell Douglas Astronautics Company in Huntington Beach, California, was the first large piece of hardware for SRB structural testing to arrive at MSFC.[1593] The aft motor casting segment portion of a SRM was delivered by Thiokol in October 1977.[1594] During the latter part of 1977, one test series at MSFC used a short version of the SRB, known as the "short stack." The three basic test set-ups and about thirty different test phases duplicated as nearly as possible the configuration of the booster at various phases of a shuttle mission. Stresses (loads) were exerted on the test vehicle to prove that it could withstand a variety of conditions during launch, flight, parachute deployment, and water impact and recovery.

Another early test, conducted in January 1977, used the SRB Frustum Location Aid and Drop Test Wedge to simulate the shock environment of the location aid, and to test its reusability. The location aid was attached to a simulated frustum and dropped into the Tennessee River from a crane.[1595]

[1590] "Water Impact Test" (photo caption), *Marshall Star*, April 18, 1973, 4.
[1591] "Hot Firing Test Begins on SRB Steering System," *Marshall Star*, September 15, 1976, 1; NASA MSFC, "Tests of Solid Rocket Booster Steering System Begin," NASA News MSFC Release No. 76-163, September 3, 1976, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1976, MSFC History Office, Huntsville.
[1592] Jenkins, *Space Shuttle*, 228.
[1593] "SRB Hardware Due at MSFC," *Marshall Star*, July 27, 1977, 1.
[1594] "Motor Segment for Structural Testing," *Marshall Star*, October 5, 1977, 1.
[1595] "Drop Tests Being Conducted," *Marshall Star*, January 12, 1977, 4.

Development tests of the BSMs, conducted at the Chemical Systems Division of United Technologies Inc. facility near San Jose, California, were designed to qualify the SRBs for flight. BSM tests continued throughout the SSP for requalification and verification (Figure No. E-10). Tests of the SRB electrical system and pre-launch checkout system also were underway in 1978.[1596] The checkout tests used flight-type hardware to simulate the right-hand and left-hand SRBs. The hardware was interfaced with the launch processing system and the tests run by computer at MSFC. These SRB checkout tests served two purposes. They verified that the SRB hardware was compatible with itself, and demonstrated that the launch processing system could be used to check out the SRB system.[1597]

On March 24, 1978, the delivery of a SRB nose cap to KSC marked the arrival of the first Space Shuttle hardware in support of STS-1. This element was placed in storage until the first SRB module assembly began.[1598] By the end of November 1978, almost all of the major structural elements and systems for the initial two flight SRBs had been delivered, with the exception of the motor case segments, scheduled for shipment between March 20 and mid-May 1979.[1599] The first Decelerator Subsystem, which included a clustered assembly of the three main parachutes, a drogue and pilot parachute assembly, and load cells and fittings, arrived in November 1978, for installation in the first assembled SRB. In May 1979, the first TVC system was hot-fired in KSC's Hypergol Maintenance Facility by USBI.[1600]

Following the successful launch of STS-1, three significant issues related to SRB hardware reusability were identified during the post-flight assessment: aft skirt ring structural integrity, aft skirt internal reentry temperatures, and electrical cable salt-water intrusion.[1601] As a result, modifications were made to the aft skirt ring, including the addition of clamps and stiffening brackets. These changes were incorporated in STS-3 and subsequent flights. To address the issue of aft skirt reentry temperatures, beginning with STS-2, changes were made "to strengthen the thermal curtain retainer rings and delay initiation of the nozzle severance charge until after main chute deployment."[1602] A failure investigation was conducted regarding the issue of salt-water intrusion. In a September 21, 1981, summary of SRB reuse assessment activities, George Hardy, NASA's Project Manager of the SRB program, reported that current plans were to return the reusable hardware to flight inventory by April 1982. The first flight scheduled to fly refurbished hardware (other than parachutes) was STS-7 using STS-3 hardware; the parachutes were scheduled for reflight on STS-4.[1603]

[1596] "Variety of Tests Proving SRB Flight Worthy," *Marshall Star*, March 8, 1978, 4.
[1597] "Test Series on SRB Run at Marshall," *Marshall Star*, March 1, 1978, 2.
[1598] "SRB Nose Cap Arrives at KSC," *Marshall Star*, April 19, 1978, 2.
[1599] "Most Major Structural Elements of First Two SRBs Delivered to KSC," *Marshall Star*, November 15, 1978, 4.
[1600] "First Thrust Vector Control System Fired," *Marshall Star*, May 30, 1979, 1.
[1601] George Hardy to Dr. Lucas, "SRB Quarterly Review Action Item No. 4, Summary of SRB STS-1reuse assessment activities/results to data," September 21, 1981, Drawer 27, Folder: SRB 1981, MSFC History Office, Huntsville.
[1602] Hardy, "SRB Quarterly Review."
[1603] Hardy, "SRB Quarterly Review."

On June 27, 1982, after the STS-4 launch, the decelerator system failed, and both SRBs were lost.[1604] The SRBs sank with their descent flight data recorders. Only the frustums with attached drogue parachutes were recovered. The cause of the failure was determined to be the premature separation of one of the riser lines on each of the parachutes. This resulted from a faulty g-switch, which sent a premature signal through the system. The switch sensed the frustum separation at about 5,500' and triggered the riser line separation. The problem was corrected for STS-5 by disabling the separation nuts and ultimately by installing salt-water activated cutters on the riser lines.[1605]

SRB Parachute Testing

Tests for SRB parachute development ran parallel with the SRM test program in 1977 and 1978. In early 1977, prior to the start of the parachute drop test program, prototype parachutes underwent dynamic strip-out tests at the Martin Marietta Corporation facility in Denver, Colorado. Scheduled for completion by March 31, 1977, these tests simulated in-flight parachute deployment from the SRB. A high-tension, quick-release mechanism was used to achieve high velocities for the simulation. The test sequence was filmed, and the film analyzed to confirm proper parachute deployment.[1606] Also in early 1977, the SRB parachutes passed the trial pack and pull-out tests conducted by the Pioneer Parachute Company of Manchester, Connecticut, a subcontractor of Martin Marietta. The static pull-out tests were slow extractions of the parachutes from their bags to provide initial verification of proper parachute packing and deployment.[1607] In March 1978, high-speed sled tests were conducted at the Sandia sled track in Albuquerque, New Mexico. The tests, which involved deployment of the pilot chute only, were designed to determine if the nose cap, when ejected, would clear the vehicle without becoming entangled.[1608]

Between June 1977 and September 1978, the successful performance of six drop tests verified the SRB parachute system design, performance, and structural integrity (Figure Nos. E-8, E-9). The drop test series was conducted over the National Parachute Test Range in El Centro, California, located about one hour's flight from Edwards AFB. A Memorandum of Agreement between DFRC and MSFC defined the responsibilities, policies and operating principals governing this test program.[1609] While MSFC designed and managed the drop tests, DFRC provided the B-52 aircraft and flight and maintenance crews, and performed the testing. The test

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[1604] NASA MSFC, "Investigation Board Report STS-4 Solid Rocket Boosters Recovery System Failure," June 27, 1982, Box 1982A, MSFC History Office, Huntsville.
[1605] Robin C. Ferebee, personal communication with James M. Ellis, MSFC, August 31, 2011.
[1606] NASA MSFC, "SRB Parachutes Undergoing Dynamic Strip-Out Tests," MSFC Release No. 77-45, March 11, 1977, Microfiche Collection, SHHDC-0924, MSFC History Office, Huntsville, AL.
[1607] "Dynamic Strip-Out Tests."
[1608] "Sled Runs to Test Parachute System for Shuttle's SRB," *Marshall Star*, January 25, 1978, 4.
[1609] W.R. Lucas to David R. Scott, "MOA between MSFC and DFRC for the Shuttle SRB Parachute Drop Test Program," March 24, 1976, Series: Space Shuttle Program, Program/Project Files, Drawer 27, Folder: SRB 1976, MSFC History Office, Huntsville.

program used a simulated SRB test vehicle designed by MSFC to be aerodynamically compatible with the B-52. The simulator weighed approximately one-third the actual empty SRB (about 50,000 pounds). The 11.5'-diameter pilot, 54'-diameter drogue, and three, 115'-diameter main flight-type parachutes were attached to the test vehicle, singly or clustered, and the vehicle was dropped from the B-52 at an altitude of approximately 19,000'. Several different parachute configurations were used to provide various conditions (e.g., reefed and full open canopy shapes).[1610]

The objective of the first drop test, conducted on June 15, 1977, was to measure drogue parachute performance under design load conditions. During this test, the drogue parachute, followed by the three main parachutes, were deployed successfully.[1611] The second test was designed to determine loads on the main parachutes. Test three of the series, conducted on December 14, 1977, focused on the integrity of the drogue chute under overload condition. Fins were added to the test vehicle to increase speed, improve stability, and produce less drag.[1612] During this test, the drogue parachute failed, as a result of insufficient reefing system design, and the test vehicle sustained severe damage.[1613] The successful fourth drop test in May 1977, which deployed the three main parachutes plus the pilot and drogue parachutes, tested the parachute recovery system to its full design limits.[1614] The fifth test, on July 26, 1978, successfully deployed the drogue and three main chutes. The parachute drop test program concluded on September 12, 1978, with the successful sixth drop test.[1615]

Physical and Functional Descriptions

Each SRB (Figure No. E-11) measured approximately 149' long, 12' in diameter, and weighed approximately 1,255,000 pounds fueled, with the propellant accounting for about 1,107,000 pounds, or roughly 88 percent of the total weight. Assembly items and attachments added approximately 1,230 pounds to the overall weight. With few exceptions, the left and right SRBs were almost identical and interchangeable.[1616] The boosters incorporated seven major subsystems (Figure Nos. E-12, E-13): 1) Structural; 2) Reusable Solid Rocket Motor (RSRM); 3) Separation; 4) Electrical and Instrumentation (E&I); 5) Recovery/Deceleration; 6) Thrust Vector Control (TVC); and 7) Range Safety System (RSS). A description of each follows.

[1610] "SRB Parachute Drop Tests Set," *Marshall Star*, June 8, 1977, 1, 4; "Agreement Reached on SRB Parachute System Testing," *Marshall Star*, May 19, 1976, 1, 2.
[1611] "SRB Recovery System Tested," *Marshall Star*, June 29, 1977, 1.
[1612] "Third Air-drop Set for SRB System," *Marshall Star*, November 30, 1977, 1.
[1613] George B. Hardy to Dr. Lucas, "SRB Parachute Drop Test # 3 Failure report," December 16, 1977, Drawer 28, File: SRB Quarterly Reviews 1977, MSFC History Office, Huntsville.
[1614] "Air Drop Test Set for SRB Parachutes," *Marshall Star*, April 19, 1978, 3; "Fourth SRB Parachute Drop Test is Success," *Marshall Star*, May 31, 1978, 2.
[1615] "Parachute Drop Test Successful," *Marshall Star*, August 9, 1978, 3; "SRB Parachute Recovery System Passes Drop Test," *Marshall Star*, September 20, 1978, 1, 4.
[1616] Among the differences were those in the E&I subsystem, the BSM locations, the SRB/ET attach ring orientations, and the forward skirts. USA, *Solid Rocket Booster Illustrated Systems Manual* (Huntsville: United Space Alliance, May 2005), 1.

Structural Subsystem

The SRB structural subsystem provided support for the Shuttle stack on the launch pad, held the vehicle on the pad during SSME thrust buildup and RSRM ignition prior to liftoff, and transferred thrust loads to the orbiter and ET. It also provided structural support for the SRB recovery, range safety, and TVC subsystems, as well for electrical components and the BSMs.[1617] Physically, the major structural subsystem components included the nose cap, frustum, forward separation ring, forward skirt, forward SRB/ET attach fitting, aft SRB/ET attach ring and struts, systems tunnel, and aft skirt (including the thermal curtain). The nose cap, frustum, and forward skirt collectively comprised the forward assembly.

The SRB structural subsystem components were protected by two primary types of thermal protection materials. These included cork and MCC, a spray-on ablative. MCC was used on the nose cap, frustum, forward and aft skirts, and on a portion of the systems tunnel. Cork was used on the SRB aft skirt, SRB/ET attach ring, booster separation motors, struts, and systems tunnel.[1618]

Nose Cap

The nose cap (Figure Nos. E-14, E-15) measured 68” in diameter at the base and 75” in overall length. This structure, made of 2024 aluminum sheet skins, was comprised of four formed ring segments, a spin-formed cap/dome, machined fittings, and an aft machined frustum separation ring.[1619] The nose cap housed the pilot and drogue parachutes, and typically was not recovered. The nose cap was separated from the frustum by three frustum-mounted thrusters.[1620]

Frustum

Also composed of aluminum (2219 forging and 7075 formed skins), the frustum measured 10’ in height, with a 68” minor base diameter and a 146” major base diameter (Figure Nos. E-14, E-15). It incorporated rings, fittings, separation motor housing, main parachute supports, and flotation devices for recovery. The frustum housed the three main parachutes, the altitude sensor, and the forward booster separation motors. The main parachute support structure was mechanically attached, but not considered part of the frustum structural assembly.[1621]

[1617] USA, *Solid Rocket Booster Familiarization Training, Revision K* (Florida: United Space Alliance, 2009), DVD, STR-2; USA, *Booster Manual*, 10.
[1618] USA, *Booster Manual*, 13.
[1619] Over time, there have been three different nose cap vendors, including USBI in Huntsville. James Carleton, interview by Joan Deming and Patricia Slovinac, June 29, 2010, KSC, Florida.
[1620] USA, *Booster Manual*, 10.
[1621] USA, *Familiarization Training*.

Forward Separation Ring

The forward separation ring, machined from 2219 aluminum forgings, was located between the frustum and forward skirt assemblies. It provided a mount for the linear-shaped charge used for separation of the frustum from the forward skirt assembly after the SRBs were jettisoned.

Forward Skirt

The forward skirt, made from 2219 aluminum, measured approximately 125” long and 146” in diameter (Figure No. E-16). It provided the necessary structure to react to parachute loads during deployment and descent, and also provided the hardpoint connection for parachute risers used during retrieval operations.[1622] The forward skirt included secondary structures for mounting components of the E&I subsystem, RSS panels, and the systems tunnel components.[1623] The left forward skirt and right forward skirt were not identical.

Forward SRB/ET Attach Fitting

The forward SRB/ET attach fitting (Figure No. E-17), manufactured from 2219 aluminum, was located on the external wall of the forward skirt. The forward separation bolt that held the ET to each SRB was fixed to this attachment point.

Aft SRB/ET Attach Ring and Attach Struts

The aft SRB/ET attach ring (Figure No. E-18) was comprised of four individual ring segments of steel construction. The segments were made from high strength nickel-chromium based alloys, 4130 and 4340, plus the high strength nickel-cobalt based alloy, Inconel 718. It measured 164” in diameter and 16” high. Located on the forward end of the aft motor segment, the aft SRB/ET attach ring housed the aft IEA and provided attachment points for the three aft struts. Protective covers for the struts and aft IEA encircled the entire ring assembly. The four ring segments were bolted to the motor case at 532 locations, and were joined by sixteen splices and eight angle caps including splice buildup over the systems tunnel.[1624] The attach ring/strut cavities were filled with silicone foam and a layer of silicone rubber was placed between the foam and covers to restrict the flow of hot gases.[1625]

The lower, diagonal, and upper SRB/ET aft attach struts physically attached the SRB to the ET. Each strut contained one bolt and one NASA standard initiator pressure cartridge at each end. The upper strut also carried the umbilical interface between the SRB and the ET, and that

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[1622] USA, *Booster Manual*, 11.
[1623] USA, *Familiarization Training*.
[1624] USA, *Booster Manual*, 12.
[1625] USA, *Booster Manual*, 14.

extended on to the orbiter.[1626] The tubular struts, constructed of Inconel 718, were made in two halves and were held together by the aft separation bolt. At separation from the ET, the bolt was split by a pyrotechnic device, and the two halves of the bolt were caught inside the strut halves by honeycomb energy absorbers on each end of the struts.[1627]

Systems Tunnel

The systems tunnel (Figure No. E-19), located on the outside of each SRB, extended from the forward skirt to the aft skirt. It measured about 10" wide and 5" high, and housed electrical cables associated with the E&I subsystem, ground environmental instrumentation (GEI), heater system, and linear-shaped charge. The tunnel floor assemblies were bonded to the SRM case. Tunnel covers, made from 2219 aluminum, were attached to the tunnel floor assembly, and provided lightning, thermal, and aerodynamic protection.[1628]

Aft Skirt

The conical-shaped aft skirt, fabricated from aluminum, measured 90.5" long, with a minor diameter of 146" and a major diameter of 208.2" (Figure No. E-20). It featured integral stringer/skin construction welded to four forged hold-down posts with bolted-in rings. These rings, made of 2219 aluminum, provided structural support and attach points to the MLP. Bolted-in clips and gussets provided additional strength for water impact. The aft skirt provided both aerodynamic and thermal protection. It also provided support mounts for the TVC subsystem and the aft-mounted BSMs. The twin booster aft skirts supported the approximate 4.5 million pound Space Shuttle vehicle on the launch pad prior to SRB ignition.[1629] The thermal curtain assembly, installed circumferentially between the aft skirt aft ring and the SRM nozzle ring with mechanical fasteners, provided thermal protection. It was made from three layers of quartz cloth, fiberfrax insulation, and fiberglass cloth.[1630]

Reusable Solid Rocket Motor (RSRM) Subsystem

Each RSRM measured approximately 126' in overall length, 12.2' feet in diameter at the forward end and 12.72' at the aft (nozzle) end, and had a general wall thickness of 0.5". The major components of the RSRM subsystem were the segmented motor case loaded with solid propellant, and the movable nozzle with exit cone. Other elements of this subsystem included the igniter assembly and joint heaters. All of the RSRM major components were designed to be refurbished and used up to twenty times.

[1626] United Space Alliance (USA), *Shuttle Crew Operations Manual* (Houston: United Space Alliance, 2004), 1.4-7.
[1627] USA, *Familiarization Training*, STR-24, STR-25; NASA MSFC, *External Tank and Booster Camera Systems*.
[1628] USA, *Familiarization Training*, STR-29.
[1629] USA, *Familiarization Training*, STR-3, STR-32.
[1630] USA, *Booster Manual*, 14.

Motor Case Segments

Each RSRM contained four motor segments: forward, forward center, aft center, and aft. The forward motor segment measured 31.5' long and weighed up to 332,000 pounds fueled (Figure No. E-21). Each of the two center segments was 27' long and weighed a combined total of 593,874 pounds fueled (Figure No. E-22). The aft segment was 33' long and weighed 320,464 pounds. The RSRM segments were connected by pinned tang/clevis joints with O-ring seals (Figure Nos. E-23, E-24).

The motor case was of segmented construction to facilitate manufacture, shipping, assembly, and recovery. In total, eleven case segments (cylinders) comprised each motor. These manufacturing segments included the forward dome (3.88' total length), six cylinders (two forward segments, two forward center segments, and two aft center segments, each measuring 13.67' in length), the SRB/ET attachment segment (7.50' in length), two case stiffener segments (10.34' length each), and the aft dome (5.00' in length). The cylindrical segments had a nominal wall thickness of 0.506".[1631] The walls of the aft dome were 0.362" thick.

Each of the motor case segments was a weld-free cylinder produced by the joint efforts of Rohr Industries of Chula Vista, California, and their two subcontractors, the Ladish Company of Cudahy, Wisconsin, and Cal-Doran Metallurgical Services of Los Angeles, California. The metal components of the RSRMs began as ingots, procured from Latrobe Steel in Pennsylvania. The steel ingots, or billets, weighed approximately 31,000 pounds each. The Ladish Company forged the raw steel billets to make pre-forms, then "punched out the centers and formed case segments in a series of forging and roll-forming operations."[1632] Ladish shipped the cylindrical segments to Cal-Doran for tempering (heat treatment) to toughen the steel. The final machining was done by Rohr Industries. The clevis joints were machined and 180 holes were drilled in each joint for the retaining pins, which would couple the segments together.

The cylinders and domes, as well as the igniter chamber and adapter, were roll-formed from D6AC steel, a high strength, medium-carbon steel alloy. The cylinders were joined together with pins via a tang and clevis mechanical joint for a weld-free assembly. The pins were made from MP35N, a high strength multiphase alloy. The pin retainer band and shims were of Inconel 718, and the stiffener T-rings were of 4340 steel. For corrosion protection, the cylinders were painted with rust proof paint, and the bare metal areas were covered with HD-2 grease.

At Thiokol, the case segments were assembled into the forward, aft, and two center casting segments. These were then insulated, lined, filled with solid propellants, and cured.[1633] Rubber was vulcanized to the inside of the steel case segments to insulate them from the heat of propellant combustion (about 6,000 degrees F). The insulation was designed to partially burn

[1631] USA, *Booster Manual*, 156.
[1632] "First SRB Motor Case."
[1633] "First SRB Motor Case."

away during motor operations, but to leave enough material to protect the case. The rubber thickness was greatest in the aft dome (more than 5”) and least in the center segment cylinder sections (about 0.15”). Before propellant was cast into a case segment, a liner composed of liquid rubber with a curative added was applied to the insulation. This liquid also had “asbestos floats” in the mixture. The typical thickness of the liner was 0.060”. The propellant adhered to the liner better than it did to the insulation.

The forward cast segment was filled with 310,000 pounds of propellant, with 270,000 pounds each in the center forward and aft segments, and 260,000 pounds in the aft segment. The solid propellant was a mixture of ammonium perchlorate as the oxidizer (70 percent by weight; 1.1 million pounds), aluminum powder for fuel (16 percent), plus a polymer binder, PBAN (12 percent) that held the mixture together. An epoxy curing agent (2 percent) also was added, as well as a small amount of iron oxide powder (0.7 percent), which served as a catalyst to increase the burning rate. The solid propellant was a battleship gray in color and had the consistency of a hard rubber eraser. Each of the four motor segments for each pair was loaded with propellant from the same batches of ingredients to minimize any thrust imbalance.

Approximately 167, 600-gallon mixes were required to cast all four segments. Propellant was cast around a mandrel (spindle) inserted into the case, which gave the propellant surface inside the motor a specific shape. There was a different cast configuration for the forward segment, the two center segments, and the aft segment. The propellant was an eleven-point star shape in the forward motor segment and a double-truncated-cone in each of the center segments and the aft segment. The propellant was cured by heating in the cases at 135 degrees F for four days to achieve the desired mechanical properties, then cooled down to shrink back the propellant for core removal. The propellant was storable and stable.[1634]

The individual segments were connected by either a factory joint or a field joint. The field and factory joints prevented hot gas from reaching the O-rings. Factory joints were assembled at the Thiokol plant in Utah.[1635] The joints were located in seven places, mating the: 1) forward dome to the forward case segment (“Forward Y”); 2) the two forward case segment cylinders; 3) the two forward center segment cylinders; 4) the two aft center segment cylinders; 5) the SRB/ET attachment segment to the aft stiffener segment; 6) the two aft segment cylinders; and 7) the aft segment cylinder to the aft dome (“Aft Y”). Each factory joint was internally pressure sealed with dual V1115 fluorocarbon O-rings and full internal insulation. The forward dome featured a forward tang for skirt attachment with 195 pinholes, including eighteen extra pinholes in the thrust bearing attachment. The aft dome had an aft tang for skirt attachment with 177 pinholes and three alignment slots equally spaced around the circumference.

[1634] NASA MSFC, *A Primer on Propellants*, NASA Fact Sheet (Huntsville, AL: George C. Marshall Space Flight Center, no date), Folder: 35, MSFC History Office, Huntsville.
[1635] During stacking in the VAB, three field joints connected the forward segment to the forward center segment; the forward center segment to the aft center segment; and the aft center segment to the attach ring. Field joints were internally pressure sealed with three O-rings and bonded insulation.

Prior to shipment to KSC, Thiokol grit-blasted and installed the systems tunnel and handling rings to all segments, and installed the igniter in the forward segment, the nozzle in the aft segment, and instrumentation in the center segment.

Nozzle Assembly

The nozzle weighed roughly 24,000 pounds and had an approximate 54”-diameter throat and 146” exit diameter.[1636] It was built and shipped in two parts, the forward assembly and the nozzle aft cone (see Figure No. E-23). The forward assembly components were made from D6AC steel and 7075-T73 aluminum. The aft cone assembly housing was made of 7075-T73 aluminum. Metal components were fabricated by Kaiser Aerotech, while the ablative components and flexible bearing joints were made by Thiokol, who also subassembled and assembled the components. The nozzle was of modular-type construction with parts grouped into assemblies to facilitate reuse and refurbishment.[1637] The seven major nozzle subassemblies were: 1) nose inlet; 2) throat inlet; 3) flexible bearing; 4) cowl; 5) fixed housing; 6) forward exit cone; and 7) aft exit cone. The primary assemblies were bolted together, and the nozzle assembly was attached to the aft motor segment with 100 radial and 100 axial bolts.[1638]

The nozzle contained five sealing joints, each including dual redundant O-ring seals. A silicon rubber thermal barrier was used to protect the O-rings. The flexible bearing weighed about 7,000 pounds and measured almost 100” in diameter. It connected the fixed and movable portions of the nozzle, and allowed the nozzle to be moved eight degrees in any direction. Thermal protection for the flexible bearing core was provided by a multi-layer rubber boot and a silicon rubber bearing protector. The housing ablative liner was made from carbon cloth phenolic from North American Rayon Corporation/Cytec Engineered Materials. The structural over-wrap for the carbon cloth phenolic, boot and protector rings was made of glass cloth phenolic from Advanced Glass Fiber Yarns/Cytec Engineered Materials. The aft exit cone subassembly contained the severance system, designed to separate the aft 6’ of the aft exit cone prior to ocean impact. This was done in order to reduce splashdown loads on the nozzle flexible bearing.[1639]

Igniter Assembly

The igniter assembly, contained in the forward motor case segment, was comprised of the igniter, S&A device, and pressure transducers (see Figure No. E-21). The assembly was attached to the forward segment by bolts. The igniter was a small rocket motor measuring 48” long and 17” in diameter. It contained 134 pounds of solid propellant with a 40-point star grain. The S&A

[1636] T.L. Elegante and R.R. Bowman, “Nozzle Fabrication for the Space Shuttle Solid Rocket Motor,” in *Proceedings from the 14th American Institute of Aeronautics and Astronautics and Society of Automotive Engineers, Joint Propulsion Conference, Las Vegas, Nev., July 25-27, 1978* (Reston, VA: American Institute of Aeronautics and Astronautics, Inc., 1978).
[1637] USA, *Booster Manual*, 159.
[1638] USA, *Booster Manual*, 155.
[1639] USA, *Booster Manual*, 160.

device, mounted to the forward end of the igniter, ensured that the motor fired only when commanded. It provided the first ignition pulse via a pyrotechnic charge.[1640]

Electrical Heaters

Each of the three field joints and the igniter joint had an electrical heater which provided environmental protection during pre-launch countdown. The field joints and igniter joints were fabricated by Tayco Engineering of Cypress, California. The 40'-long field joint heaters were installed at KSC. The igniter joint heater was installed at the Thiokol plant. Field joint heaters were active between T-8 hours and T-1 minute. The igniter heater was active between L-18 hours or T-8 hours (if above 55 degrees F) and T-9 minutes. It was deactivated prior to the S&A arm command (barrier-booster rotor rotation).

Hardware

The three stiffener rings were fabricated in 120-degree sections, insulated, and bolted together with splice plates to encircle the case.[1641] A total of 180 high-strength pins were used to join one segment to another. These included three tooling pins, positioned at approximate 120 degrees around the case for case alignment, and 177 cobalt alloy pins for holding.

Separation Subsystem

The separation subsystem provided for the structural release of the SRBs from the orbiter/ET. The primary components of this subsystem were the total sixteen forward and aft BSMs on both SRBs, plus the forward and aft separation bolts.

Booster Separation Motors

Each SRB contained eight small BSMs. One four-motor cluster was installed on the frustum (Figure No. E-25) and another was located in the aft skirt (Figure No. E-26). The BSMs fired simultaneously and provided the force to move the SRB away from the orbiter/ET at separation during flight. Each BSM measured 31" long, 12.865" in diameter, and had a maximum weight of 167 pounds, inclusive of explosive devices and aeroheat shields or aft heat seals with mounting hardware.[1642] The BSMs burned solid propellant which had a sixteen-point star grain configuration. They fired only about one second each to accomplish the separation, with a thrust of about 20,000 pounds. The BSMs were designed to produce no debris that would be damaging to the orbiter tiles.

[1640] ATK Thiokol, *Reusable Solid Rocket Motor RSRM Design and Manufacturing Baseline, Revision C*, (Utah: ATK Thiokol, 2005), DVD.
[1641] USA, *Booster Manual*, 155.
[1642] USA, *Familiarization Training*, SEP-24.

Each BSM contained a motor case, nozzle, igniter, structured attach fittings and pyrotechnic connectors.[1643] The cylindrical-shaped motor case, made from 7075 aluminum, measured 25.83” in length and had a maximum wall thickness of 0.315”. The forward end of the case had eight threaded holes and a guide pinhole to provide an alignment interface to the SRB.[1644] The BSM case liner material, specifically formulated for use with the propellant, served as a case wall insulator.[1645] The nozzle/aft closure assembly, attached to the motor case, was made from 7075 aluminum, and the exit cone part of the assembly was carbon steel.[1646] The nozzle was canted 20 degrees to permit installation in the frustum. The BSM igniter consisted of a simple perforated steel tube containing propellant. The small initiator charge was triggered by two (redundant) stainless steel confined detonating fuse initiators loaded with pentaerythrite tetranitrate charges.[1647]

<u>Separation Bolts</u>

Forward and aft structural attachment separation was accomplished with double-ended separation bolts. The forward and aft bolts were of a different size, but functionally identical. Pressure cartridges installed in each end of the bolts provided the explosive force to fracture and separate the bolts, which were designed to separate without producing debris.

The forward separation bolt measured 25” long, 3” in diameter, and weighed 70 pounds, and featured a groove about 11.5” from the top that allowed it to break when the pyrotechnic device fired. After separation, one-half of the bolt remained with the booster, secured within the forward skirt thrust post. The other half was retained with the ET. Although mounted on the ET, the bolt catcher was considered part of the SRB element design.[1648]

Electrical and Instrumentation Subsystem

The E&I subsystem, which connected the SRBs with the orbiter vehicle, controlled a number of functions during the prelaunch, ascent, ET/SRB separation, and deceleration phases. During the prelaunch phase, the data processing elements and cabling supported testing, calibration, and monitoring activities. The E&I subsystem’s interconnecting cabling also was used for signal conditioning, power distribution, data processing, and operational flight sensors to support the

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[1643] “Contractor Chosen for Shuttle Booster Separation Motors,” *Marshall Star*, August 13, 1975, 1, 3.
[1644] USA, *Familiarization Training*, SEP-46.
[1645] USA, *Familiarization Training*, SEP-8.
[1646] USA, *Familiarization Training*, SEP-47; USA, *Booster Manual*, 101.
[1647] USA, *Familiarization Training*, SEP-37, SEP-50.
[1648] The bolt catcher was redesigned in 2005 and built by General Products of Huntsville, Alabama. It was changed from a two-piece welded design to a one-piece machined design to eliminate the weld and thereby improve the safety margin. Made from a stronger aluminum alloy, AL7050, the modified bolt catcher featured increased wall thickness (from .125 to .25 inches) and a more open cell texture. Thermal protection, provided by USA at KSC, changed from the original super lightweight ablator to a machined cork covered with a protective paint finish. NASA MSFC, *Bolt Catcher Modifications on the Solid Rocket Booster*, NASA Facts (Huntsville, AL: Marshall Space Flight Center, April 2005), http://www.nasa.gov/centers/ marshall/pdf/114018main_Bolt_Catcher_FS.pdf.

SRB during ascent. It also contained controllers used to regulate the speed of the TVC system's APUs. In addition, the E&I subsystem supported the initiation of the SRM nozzle extension severance and release of the nose cap and frustum during recovery functions.[1649] The primary components of the E&I subsystem included the IEAs and the rate gyro assemblies (RGAs); also included were the altitude switch assembly, the camera system, and the enhanced data and acquisition system.

Integrated Electronic Assembly

Each SRB had two IEAs which contained electronic circuits and wiring (Figure No. E-27). The forward and the aft IEAs were not interchangeable with one another.[1650] The aft IEA was cabled to the orbiter for power; the forward IEA was cabled to the aft IEA from which it received power.[1651] Designed and manufactured by L-3 Communications (formerly Bendix), each box-shaped IEA measured 45" long, 12" high, and 12" wide. The complete aft IEA with its internal components weighed 182 pounds; the complete forward IEA weighed 188 pounds.[1652] Both the forward and aft IEAs were fabricated from the same machined A356 aluminum casting. The top and bottom covers were made from 6061 aluminum sheet and were attached to the casting with ninety screws. The IEAs were hermetically sealed and watertight. The glass-sealed external connectors also were watertight.[1653] The IEAs processed signals for a variety of functions. Specifically, after burnout, the forward IEA initiated the release of the nose cap and frustum, jettison of the SRM nozzle, detachment of the parachutes, and turn-on of the recovery aids. The aft IEA, mounted in the ET/SRB attach ring, connected with the forward assembly and the orbiter avionics systems for SRB ignition commands and nozzle thrust vector control.[1654]

Each IEA had a MDM, an electronic device, which sent or received electrical signals from a sensor and inputted the signals to tape recorders on the SRB and in the orbiter. They were designed and manufactured by Honeywell (Sperry). Also housed in the IEAs was the dedicated signal conditioner, manufactured by the Eldec Corporation of Lynnwood, Washington. This component received an electrical signal from a sensor and changed it to ac or dc and raised or lowered the power level required to perform the intended function. [1655]

Rate Gyro Assembly

Mounted in a watertight compartment of the forward skirt were two RGAs, each containing two gyroscopes with auxiliary components. Each RGA measured 8.25" long, 7.6" wide, and 6.8" in height, and weighed 9.2 pounds. The external case material was aluminum alloy A356 class

[1649] USA, *Booster Manual*, 32.
[1650] USA, *Booster Manual*, 47.
[1651] USA, *Booster Manual*, 31.
[1652] USA, *Booster Manual*, 33, 38.
[1653] USA, *Familiarization Training*, E&I-11.
[1654] "Sperry Rand Gets Shuttle Contract," *Marshall Star*, July 23, 1975, 4.
[1655] "Signal Conditioner Modules Contract Awarded to Eldec," *Marshall Star*, December 24, 1975, 1

II.[1656] The RGAs, designed and manufactured by Northrop Grumman, provided vehicle angular rates (pitch and yaw) to the orbiter control system. The forward IEA powered one RGA, while the other received power directly from the orbiter.

Altitude Switch Assembly

The altitude switch assembly, mounted in the frustum, was designed and manufactured by Clifton Precision. It measured 5.5" high, 3.00" wide, 3.75" deep, and weighed about 2.8 pounds. The case was made of Monel QQ-N-281. The altitude switch assembly initiated the logic signals necessary for deployment of the drogue and main parachutes, and also initiated a timer for nozzle extension jettison.

Camera System

The camera system included the ET observation camera, aft-looking camera, and two solid state video recorders, all located within the forward skirt, as well as the forward-looking camera, housed in the ET attach ring.[1657] These components and interfacing cables were fabricated and assembled "in-house" by USA.

Enhanced Data and Acquisition System

STS-91 in June 1998, marked the first time that the Shuttle carried up to five enhanced data and acquisition system units, mounted on the SRB forward skirt ring. Beginning just after lift-off, these instruments recorded information from the ET and SRB sensors, including internal gas temperatures and pressures, skin temperatures, shock, and vibrations. After recovery, the units were disassembled, and the information uploaded and disseminated.[1658]

Recovery/Deceleration Subsystem

The Recovery/Deceleration subsystem included the assemblies required to "separate, deploy, disconnect, float, and retrieve all recoverable system components."[1659] This subsystem included elements of other SRB subsystems, such as the E&I subsystem altitude switch assembly, and the nose cap and frustum of the structural subsystem.[1660] The decelerator components, which provided attitude and terminal velocity control of the SRBs for water impact, included the pilot and drogue parachute pack assemblies located in the nose cap, plus the altitude switch and the three main parachute pack assemblies and main parachute support structure in the frustum. Collectively, the parachutes sequentially slowed the descent of the expended SRBs. Originally,

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[1656] USA, *Familiarization Training*, E&I-25.
[1657] USA, *Familiarization Training*, E&I-33.
[1658] USA, *Booster Manual*, 29; USA, *Familiarization Training*, E&I-30.
[1659] USA, *Booster Manual*, 114.
[1660] USA, *Booster Manual*, 118.

all SRB parachutes and bags were manufactured by the Pioneer Parachute Company of Manchester, Connecticut, a subcontractor to Martin Marietta Corporation. More recent parachutes were made by Irvin Parachute. NASA had a total of sixty-eight large main parachutes built, fifty-six of which were still in active inventory at the end of the program. All were initially certified for ten flights and subsequently recertified for fifteen flights. Twenty-nine drogue parachutes were built and, as a result of attrition, thirteen were in active inventory at the end of the program. The drogue parachutes were initially certified for ten uses and then recertified for thirteen.

The SSP initially used smaller main parachutes, with a 115'-diameter. During the first few flights of the SSP, some single main parachute failures were experienced; the parachutes were impacting the water at higher velocities (109 feet per second versus 88 feet per second). This resulted in more damage to the boosters. NASA switched to a larger, 136'-diameter main parachute, first used on STS-41D, to mitigate this damage. If one large main parachute were to fail, the booster would impact the water at approximately 90 feet per second under two large main parachutes, about the same force as under three small mains.[1661]

The pilot parachute assembly (Figure Nos. E-14, E-15, E-28) included the chute canopy assembly with suspension lines, deployment bag, nose cap bridle, and an energy absorber. The pilot parachute measured 11.5' in diameter and weighed 55 pounds. It was of sixteen-gore, 20-degree conical ribbon construction with a 16 percent uniform porosity.[1662] The drogue parachute measured 54' in diameter and weighed 1,100 pounds, and was of the same sixteen-gore, 20-degree conical ribbon construction as the pilot parachute. The drogue parachute had sixty 102'-long suspension lines clustered in twelve suspension line groups. The retrieval line was 175' long. Each of the three large main parachutes measured 136' in diameter and weighed 2,200 pounds. They were of 160-gore, 20-degree conical ribbon construction with a 15.4 percent uniform porosity. Each main parachute pack assembly featured eight 40' risers, with four risers per deck fitting; eight 98.5' dispersion bridles with ten legs per bridge; and 160, 64' suspension lines with two suspension lines per bridle leg.[1663]

The three main parachutes were packed in deployment bags housed in individual compartments formed by the main parachute support structure within the frustum. This structure, designed to maintain separation of the main parachutes during installation and deployment, measured 62.06" in height by 92.0" in diameter.[1664] Each of the three panel assemblies, spaced 120 degrees apart, extended 54.965" out from the center of the structure.

Included in the main parachute assembly was the Salt Water Activated Release (SWAR). In the early days of the SSP, some of the SRB forward skirts were buckling because of the way the

[1661] Jack Hengel, personal communication with James M. Ellis, MSFC, August 31, 2011.
[1662] USA, *Familiarization Training*, REC-17.
[1663] USA, *Familiarization Training*, REC-27.
[1664] USA, *Familiarization Training*, REC-20.

motor splashed down when the parachutes were released at water impact. A solution to this was to keep the main parachutes attached at water impact and allow the boosters to lay down in the water without slapping down.[1665] The SWARs then separated the main parachute dispersion bridles from the risers. The SWARs were self-contained and required no electrical input from the SRB recovery subsystem electronics.[1666]

Thrust Vector Control Subsystem

The TVC subsystem (Figure No. E-29) controlled the direction of flight during the first two minutes of a mission through movement of the nozzles. Two complete TVC subsystems were housed in the aft skirt of each booster. Their primary function was to power the booster nozzle to aid the steering of the Shuttle during ascent. The TVC system for each SRB contained two separate hydraulic power units (HPUs), one to control nozzle position in the rock plane and the other to control nozzle position in the tilt plane.[1667] The HPU components were mounted on the aft skirt between the rock and tilt actuators. The HPUs were driven by the hydrazine-powered turbine, the APU. The APU drove the hydraulic pump through the gearbox to provide a pressurized fluid flow to the servoactuator.[1668] Rock and tilt systems supplied hydraulic power to the TVC electro-hydraulic servoactuators "to effect mechanical positioning of the SRB nozzle in response to steering commands."[1669] The dual action servoactuators were connected to the aft skirt attach point and RSRM nozzle by a clevis pin arrangement. They were hydraulically interconnected to each HPU for operating redundancy in the event of a failure of either HPU.[1670]

Each APU contained a fuel pump, gas generator and gas generator valve module, turbine, gear box, electrical controls, control valves, instrumentation, monitoring system, and the mechanical and electrical connectors required to interface with the other SRB subsystems. Each fuel tank contained twenty-two pounds of hydrazine.[1671] Two APUs, each driving a hydraulic pump, provided hydraulic power to the TVC subsystem of each SRB during the pre-launch and ascent phases of shuttle flight.

During prelaunch, the TVC subsystem was controlled by the APU controller assembly located in the aft IEA in each SRB. After lift-off, all command and control functions of the TVC subsystem originated in either the orbiter's GNC computers or the ascent TVC electronics of the orbiter.[1672] The TVC subsystem was designed to operate from approximately T-26 seconds through the

[1665] Jack Hengel, personal communication with James M. Ellis, MSFC, August 31, 2011.
[1666] USA, *Booster Manual*, 117.
[1667] USA, *Familiarization Training*, TVC-2.
[1668] USA, *Booster Manual*, 54.
[1669] USA, *Booster Manual*, 54.
[1670] USA, *Familiarization Training*, TVC-51.
[1671] Chris Bergin, "Shuttle Boosters to sport APU fuel pump safety redesign from STS-134," February 28, 2010, http://www.nasaspaceflight.com/2010/02/shuttle-boosters-sport-apu-fuel-pump-redesign-st.
[1672] USA, *Booster Manual*, 55.

powered flight of the SRB. The electrical power supplied to both of the HPUs was terminated at separation. The total operating time for each HPU was approximately 150 seconds.[1673]

Range Safety Subsystem

The RSS was designed as the shuttle destruct system in the event of a major malfunction or event. The RSS terminated flight by splitting the cases of the SRBs, which eliminated thrust.[1674] Dual (redundant) subsystems, A and B, were provided on each SRB, and these were "cross-strapped" to the opposite SRB through the ET. The RSS was active from T-10 seconds until approximately five seconds before ET/SRB separation.

Located in the forward skirt of each SRB, the RSS included a linear-shaped charge destruct assembly, two command receiver decoders, distributors, a directional and a hybrid coupler, two command antennas, two silver-zinc batteries, a S&A device containing two NASA Standard detonators, four confined detonating fuse assemblies, two confined detonating fuse assembly bulkhead connectors, and harness assemblies with all interconnecting cables.[1675]

The linear-shaped charge assembly, which measured approximately 80' long, was mounted along the SRB length in the systems cable tunnel. Six linear-shaped charge subassemblies were used in each SRB destruct assembly, including one forward, four intermediate, and one aft.[1676] The S&A device consisted of a longitudinal shaft with explosive transfer charges. Explosive leads at this device started the pyrotechnic reaction with the explosive transfer and ignition of the confined detonating fuses. The confined detonating fuse traveled through the forward skirt bulkhead and into the systems tunnel to the linear-shaped charge, which detonated, splitting the SRM case and terminating thrust.[1677]

Part of the RSS was the SRB Tracking System, which permitted tracking of the relative location of each SRB during shuttle ascent. It also provided interim tracking after liftoff, and served as a backup to the skin tracking radar by the Eastern Range. The SRB Tracking System data were used to determine the necessity of flight termination. Components of the tracking system, located on each SRB, included two C-band antennas, a power divider, a C-band transponder, and a C-band controller.

SRB/RSRM Process Flow

"The flow is always improving," noted Jim Carleton, USA's SRB Program Manager. After the *Challenger* accident, the flow changed considerably with a new focus on efficiency, and a

[1673] USA, *Booster Manual*, 56.
[1674] USA, *Booster Manual*, 141.
[1675] USA, *Booster Manual*, 141.
[1676] USA, *Familiarization Training*, RSS-27.
[1677] USA, *Familiarization Training*, RSS-23.

dramatic reduction in the size of the workforce.[1678] The completion of the Solid Rocket Booster Assembly and Refurbishment Facility (SRB ARF) complex at KSC, officially dedicated on August 1, 1986, facilitated such improvements. The SRB ARF Manufacturing Building was specially designed and constructed to support the fabrication and processing of Shuttle SRB non-motor components. Some of this work had historically been completed at the VAB, Hangar AF, and other facilities.[1679] Operations began in 1987 at the SRB ARF, designed to process up to eighteen flight sets of forward skirts, aft skirts, frustums, nose caps, and various smaller components per year. In addition to the fabrication of non-motor SRB components, other activities included the replacement of thermal protection materials, installation of electronic and guidance systems, integration of SRB recovery parachutes into the forward skirt, assembly and testing of steering elements of the TVC system, installation of explosive devices (ordnance) for booster separation, and automated checkout.[1680]

From recovery of the SRBs after splashdown in the Atlantic Ocean through refurbishment, subassembly, and final preparations for the next mission, the SRB/RSRM process flow activities occurred not only at the SRB ARF, but also in multiple contractor-run facilities at KSC, as well as the Thiokol facilities in Utah. An overview of the process flow follows.

Recovery

<u>Parachute Deployment Sequence</u>

About five and one-half minutes after lift-off, and approximately 215 seconds after the SRBs detached from the ET, the pilot, drogue and main parachutes began the process of decelerating the boosters to water impact, about one minute later (Figure No. E-30). Working sequentially (Figure No. E-31), the parachutes slowed the fall of the SRBs from about 360 mph to 50 mph at splash down in the Atlantic Ocean (Figure No. E-32). Water impact occurred approximately 122 nautical miles down range of the launch site.

First, the nose cap separated from the frustum and the pilot parachute was extracted from the nose cap and released. Deployment occurred at an altitude of about 15,200’ and a speed of 364 mph. Next, the pilot chute extracted the drogue chute, and pulled the drogue pack away from the SRB. The drogue parachute was attached to the top of the frustum. Inflation of the drogue parachute provided the initial deceleration and proper orientation for the SRB to hit the water. The drogue parachute inflated in stages; this process is known as “disreefing.”[1681] Initial

[1678] Carleton, interview.
[1679] ACI, *Survey and Evaluation of NASA-owned Historic Facilities and Properties in the Context of the U.S. Space Shuttle Program, John F. Kennedy Space Center (KSC), Brevard County, Florida* (survey report, NASA KSC, October 2007), Appendix C.
[1680] The forward and aft skirts, separation motors, frustum, parachutes, and nose cap were originally manufactured by USBI in Huntsville, Alabama, with other parts made in-house at MSFS. Beginning in October 1999, the USBI functions were absorbed by USA at KSC.
[1681] During the disreefing process, each of the inflation stages was accomplished by pyrotechnically-actuated cutters

deployment to 60 percent occurred at an altitude of approximately 14,500' and speed of 360 mph. The first stage reefing line cutters fired after a seven second delay from deployment and first inflation. This allowed the canopy to grow from 60 percent to 80 percent of full inflation. At this point, approximately 363 seconds after separation, the altitude was roughly 11,400' and the velocity was 320 mph. The second stage reefing line cutters fired after a twelve second delay from deployment, or five seconds after the first disreef. As a result, the canopy enlarged from 80 percent to 100 percent of full inflation.[1682] The drogue parachute opened to 100 percent at an approximate height of 9,200' and speed of 292 mph.

Roughly eleven seconds later, at a height of 5,500' and velocity of 243 mph, the drogue parachute pulled the frustum away from the SRB and deployed the three main parachutes from the frustum. Like the drogue parachute, the main parachutes went through a "disreefing" process involving their gradual opening to slow down the fall of the SRB. Approximately five seconds after deployment, the main parachutes were at 20 percent inflation. Altitude was now 4,110' and velocity was 238 mph. The first stage reefing line cutters fired after a ten second delay, allowing the canopy to grow from 20 to 40 percent at an altitude of 2,100' and velocity of 115 mph. The second stage disreefed after a seventeen second delay allowed the canopy to increase to 100 percent. At full inflation, the altitude was 1,115' and speed was 73 mph.

The SRB nozzle extension was jettisoned just before splashdown, in order to prevent damage to the TVC hardware, located inside the aft skirt, from water impact forces.[1683] This occurred about the time the canopies reached 100 percent of inflation.[1684] The dispersion bridles of the main parachutes separated from the risers via the SWAR, and the main parachutes remained attached to the booster via their 50'-long Kevlar retrieval lines. Air trapped in the motor casing of the booster allowed it to float vertically, with the forward end about 30' out of the water (Figure No. E-32).

The frustum impacted the water at 60 feet per second after being decelerated by the drogue parachute. The frustum floated apex down, with the drogue parachute attached and submerged. The frustum was self-buoyant because of its foam content. The pilot parachute remained attached to the drogue bag. The pilot parachute and drogue bag were recovered, if located. The SRB nose cap and nozzle extension typically were not recovered.

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that servered a reefing line that keeps the skirt of the parachute gathered until the line was cut.

[1682] USA, *Familiarization Training*, REC-8.

[1683] USA, *Booster Manual*, 117.

[1684] Early in the SSP, when the frustum was separated at a higher altitude, the main chutes reached full inflation before the nozzle was jettisoned (about 13 seconds prior). Later, to allow more time for the drogue to dampen SRB oscillation, the frustrum separation was set to occur at a lower altitude and the nozzle jettison occurred about the same time as the main chutes disreefed to full inflation. Jack Hengel, personal communication with James M. Ellis, MSFC, August 31, 2011.

Recovery at Sea

The expended SRBs, pilot/drogue parachutes, and main parachutes were recovered at sea after each launch by the ships *Liberty Star* and *Freedom Star.* Twenty-four hours prior to launch, the *Liberty Star* and *Freedom Star* travelled to their stations in international waters about 135 miles downrange of the launch site. Both vessels, positioned about 1 mile apart, had to be at their stations four hours prior to launch.[1685] At the time of splashdown, the ships were positioned about 8 to 10 nautical miles from the SRBs' impact area. Each ship was designed to recover one SRB, including its parachutes and frustum (Figure No. E-33).[1686]

According to Joe Chaput, Captain of the *Liberty Star* and manager of USA's Marine Operations at KSC, prior to retrieval, the dive team conducted a search and recovery (if found) of the pilot parachute and drogue bag, and an above water and below water visual/photographic damage assessment.[1687] Divers installed floats and cut the main parachute retrieval lines.[1688] The three main parachutes were wound onto three of the four reels on the ship's deck. The frustum and attached drogue chutes were reeled in next.[1689] The frustum was lifted from the water by the ship's 10-ton crane. The SRBs were recovered last. Two dive teams, of nine persons each, were deployed from two inflatable boats to recover the boosters. An Enhanced Diver-Operated Plug was launched from the ship and towed to the booster by a small boat. The first team, comprised of five divers, inserted the plug into the booster nozzle and pumped air from the ship into the booster. The second team double-checked the aft skirt and plug installation to ensure there were no problems. After inspection, the dewatering process began. This operation, which took approximately twenty minutes, forced out all the water, causing the booster to shift position from vertical (spar mode) to horizontal (log mode). During the final step, a tow line from each ship was connected to a booster, and each booster was towed about 1,800' behind the respective ship. At Port Canaveral, each booster was brought from the stern tow position to the hip tow position alongside the ship for the remainder of the trip to the dock near Hangar AF at Cape Canaveral (Figure No. E-34). The tow was shortened before entering Port Canaveral. The return to Hangar AF typically took twenty-six hours.

Disassembly

At the Hangar AF SRB recovery slip, an approximate twenty-two-day disassembly workflow began with the lifting of the left-hand and right-hand SRBs out of the water by a 200-ton straddle lift crane (Figure No. E-35). After the saltwater was washed off, the SRBs were placed onto

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[1685] Joseph Chaput, interview by Joan Deming and Patricia Slovinac, KSC, June 29, 2010.
[1686] Typically, *Liberty Star* retrieved the right-hand booster and *Freedom Star* the left-hand booster (USA, *Booster Manual*, 119). Features on the exterior of the SRB, such as the ET attach struts, required that the right-hand SRB be hipped on the starboard side of the towing ship, and the left-hand SRB on the port side.
[1687] Chaput, interview.
[1688] USA, *Booster Manual*, 33.
[1689] The pilot/drogue chute deployment bag assemblies were not always recovered. Replacements were fabricated at KSC's Parachute Refurbishment Facility. ACI, *Kennedy Space Center*, Appendix C.

parallel rail dolly trains. The frustum and parachutes were off-loaded from the ship deck (Figure No. E-36). A two-week open assessment period preceded the start of disassembly operations. During assessment, the SRBs were thoroughly inspected and checked to see if large pieces of TPS or other materials had come off that might have damaged the orbiter. The main parachutes were moved and transported to the Parachute Refurbishment Facility (PRF) at KSC for cleaning and refurbishment.

The frustum was moved into the Hangar AF high bay for assessment and disassembly. It was rinsed with water, and the drogue and pilot parachutes removed and kept wet prior to their transfer to the PRF. The BSMs were inspected for residual propellant and then removed for further disassembly and inspection. The frustums were verified as “safe” by inspecting and removing the confined detonating fuses. All remaining frustum components were removed and staged for refurbishment, reuse, or scrap.

The forward skirt was initially safed, and the data acquisition system, solid state video recorders, S&A device, related ordnance, and batteries, as well as the operational pressure transducer, and ET ball fitting from inside the forward skirts, were removed and cleaned (Figure No. E-37). The TPS materials were removed by hydrolasing.[1690] The TVC system was depressurized, and the IEAs were flushed, washed, and rinsed. The TVC components were removed and refurbished at several places, including the suppliers Hamilton Sundstrand (APUs), Moog (actuators), and Parker Abex (hydraulic pumps).[1691]Also removed were the blast container, struts, nozzle exit cones, ground electrical and instrumentation cables, and linear-shaped charge. The RSS command receivers/decoders were returned to the manufacturer (L3 Cincinnati Electronic, Ohio) for testing and analysis before reuse.

During the second week of operations, the aft skirt and ET attach/stiffener ring were removed; the forward skirt was demated; and the nozzle and igniter were removed, inspected, and prepared for shipment to Thiokol. The demated forward skirts were prepared for further disassembly, inspection, and refurbishment.

Typically during the second and third weeks of processing at the Hangar AF complex, the four RSRM case segments of each booster were separated, inspected, assessed, and cleaned. Joints were assessed, washed, and cleaned, and live propellant was removed. The nozzle-to-case joint was examined for overall erosion and the condition of the joint insulation. The internal insulation was checked for overall performance, remaining liner patterns, debris hits during splashdown (which may have punctured the insulation and led to case hardware corrosion), and unburned propellant in the center forward segment. The joints were preserved immediately after inspection. All corrosion was addressed immediately. Each segment was cleaned out and washed to remove debris, propellant by-product, and nozzle phenolics. The insulation was pressure

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[1690] Hydrolasing is a pressure cleaning process, which uses water, sprayed at 17,000 pounds per square inch, to strip off insulation and other materials.
[1691] Carleton, interview.

washed 6' back from both ends to prevent joint corrosion during shipment to Thiokol. Handling rings were installed to prepare the segments for transport to Utah. The segments were then moved from the rail dollies to trailers, and subsequently moved by trailer to the railhead where they were loaded onto special rail cars, covered, and prepared for overland travel back to Utah (Figure No. E-38).[1692]

In the High Pressure Wash Facility at the Hangar AF complex, high pressure cleaning (hydrolasing) of the frustums, forward skirt and aft skirt was performed by a robot to strip off the TPS. The nose cap, almost always lost, was not part of the process. Next, the non-motor components were moved to the explosion-proof Multi-Media Blast Facility where high-pressure impact with glass beads removed paint coatings, primer and sealants, stripping them down to bare metal. After a water-break test and the application of alodine, the components were taken to Hangar N, also in the Industrial Area of CCAFS, for inspection and non-destructive evaluation, including the inspection of welds. The parts were returned to the Hangar AF complex where protective finishes were applied in the SRB Paint Building. Frustum processing was completed with periodic phenolic island replacement and the installation of baro-tube and drain tubes.[1693] In the words of Jim Carleton, at the completion of processing at the Hangar AF complex, the frustums, forward skirts and aft skirts looked "like a new car."[1694]

Refurbishment and Subassembly

Following completion of disassembly and initial cleaning at the Hangar AF complex, during separate but parallel processes, the RSRM segments were returned to Thiokol's refurbishment facility in Clearfield, Utah, for processing, the parachutes were moved to the KSC PRF for cleaning and refurbishment, and the inert or non-propellant SRB elements, including the forward and aft skirts and frustums, were moved to the SRB ARF for refurbishment and subassembly by USA. During the refurbishment process, any outstanding modifications and structure repairs were made. Refurbishment operations at Hangar AF for each flight set of hardware typically required forty-five days for disassembly; 120 days for aft skirt processing; sixty days for the ET attach rings; fifty-five days for the frustums; sixty-five days for the forward skirts; and 300 days for component small parts.[1695]

<u>RSRM Segments</u>

The four motor case segments, igniter components, and nozzle were returned from KSC on railcars and trucks to the Thiokol facilities in Clearfield and Promontory, Utah, for cleaning, inspection, refurbishment and reloading with solid propellant. The components shipped by truck

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[1692] USA, *Familiarization Training*, DRO-19 through -24.
[1693] USA, *Familiarization Training*, DRO-28.
[1694] Carleton, interview.
[1695] USA, "STS Recordation, Phase I SRB Hardware Process Flow," (presentation to Joan Deming and Patricia Slovinac of ACI, KSC, June 2010), SRB-6.

were received at the Clearfield facility. Following inspection, further disassembly, and processing, they were shipped by truck to Thiokol's main plant in Promontory. The metal parts were surface cleaned and prepared for coating and bonding. Nozzle refurbishment included phenolic tape wrap and machining. Following reloading with propellant, final assembly operations were performed. This entailed installation of the nozzle and igniter, the aft exit cone linear-shaped charge, S&A processing, systems tunnel bonding, and installation of flight and shipping instrumentation.[1696]

The propellant-loaded RSRM segments were returned to KSC via special 200-ton fiberglass-covered railcars (Figure Nos. E-39, E-40). During overland travel, environmental data recorders monitored shock and vibration, as well as the temperature, of the RSRM exit cones and segments. The nozzle components, igniters, stiffener rings and other smaller components were shipped by truck. The joint pins remained at KSC and were refurbished by Thiokol personnel.

At KSC, the reloaded RSRM segments arrived at the Rotation Processing and Surge Facility (RPSF) where they were inspected and rotated (Figure No. E-41).[1697] Processing at this facility included the installation and/or close-out of the stiffener rings, tunnel cables, tunnel covers, thermal curtains, rain curtains, and aft exit cone. In addition, foam was applied to the stiffener, aft skirt and internal rings, and the field joints were closed out. Completed aft skirt assemblies from the SRB ARF were mated to the aft RSRM segment. Left and right aft booster assembly operations in the RPSF required approximately forty-five work days.[1698] Once this work was completed, the booster segments were placed on transporters, and moved to one of the ancillary surge buildings for storage. Sometime thereafter, they were moved to the VAB for integration with the other flight-ready booster components.

<u>Parachutes</u>

The deployed pilot, drogue and main parachutes recovered from the Atlantic Ocean arrived at the PRF from the Hangar AF complex on eight reels. The parachutes were kept wet to prevent ocean salt from crystallizing on the fabric. They were unrolled and untangled in the "defouling" area (Figure No. E-42), then hung on an overhead monorail system and conveyed to the 30,000-gallon capacity washer, where a water wash removed the salt (Figure No. E-43). Each parachute was backed out of the washer and moved into the dryer, where 140-degree F hot air dried it over an average period of five to seven hours. Next, the cleaned and dried parachute was moved to the refurbishment area inside the PRF (Figure No. E-44). Here, all parachutes were hand-inspected, and red flags were placed on damaged areas. An inspector decided whether to make the repair, or to use as is. Typically, each main parachute required hundreds of repairs. The smaller parachutes and deployment bags also were repaired. Following repairs, inspection, and acceptance, all

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[1696] ATK, "RSRM Overview," 13-17.
[1697] Rotation of the RSRM segments, a critical component to the preparation of the space shuttle vehicle for launch, originally was performed in High Bays 2 and 4 of the VAB. ACI, *Kennedy Space Center*, Appendix C.
[1698] USA, "STS Recordation, Phase I SRB Hardware Process Flow," SRB-5.

performed at the PRF, the parachutes were folded and placed in canisters. The packing process began with a deployment bag, which was placed into a wood or metal container. The parachute was folded into this bag, and compacted with a hydraulic press. The suspension system was placed on the bottom and the parachute went on top. On average, it took four people five days to pack a main parachute (Figure No. E-45). The three main parachutes were placed into a single parachute support structure.[1699] Overall, parachute refurbishment operations at the facility typically required sixty workdays.[1700]

The processed main parachutes were transported to the SRB ARF via flatbed truck; the drogue and pilot parachutes were moved to this facility separately. Replacement pilot parachutes and pilot/drogue chute deployment bag assemblies, or replacements for non-recoverable items, were made at the PRF. Typically, there was about a 50 percent loss of pilot parachutes in use. They were then delivered to the SRB ARF for further processing and integration. Each flight set was typically stored for six months to one year before its next use. Nine parachute flight sets were maintained in the PRF.[1701]

<u>SRB Non-motor Segments</u>

Refurbishment operations for the non-motor segments were performed in the SRB ARF (Figure No. E-46). These included the application of thermal protection; painting; installation of electronic and guidance systems; integrated assembly of the refurbished parachutes; rebuilding of the TVC system; and the installation of explosive devices (ordnance) for booster separation.[1702] Following processing, the SRB components underwent final automated checkout before they were moved to the VAB for integration. The amount of time required for assembly and check out operations performed in the SRB ARF varied by component. Typically, the left and right aft skirts required 190 workdays; the forward skirts/forward assemblies, 160 days; the frustum, ninety-eight days; the ET attach rings, thirty-four days; and the struts, twenty-two days.[1703]

At the SRB ARF, the initial step was to test the critical dimension of the aft skirt before processing started. Next, the TPS, MCC was applied to the aft skirt.[1704] This mixture of small glass spheres, cork, and epoxy was mixed right in the gun at the time of application. Curing of the TPS took twenty-four to forty-eight hours. After the TPS was cured, a coat of exterior paint was put on the TPS to seal the aft skirt and keep moisture out of the cork. Thus, the aft skirt was

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[1699] ACI, *Kennedy Space Center*, Appendix C.
[1700] USA, "STS Recordation, Phase I SRB Hardware Process Flow," SRB-5.
[1701] NASA KSC, *Parachute Refurbishment Facility*, NASA Facts, (Florida: Kennedy Space Center, no date), http://www-pao.ksc.nasa.gov/kscpao/nasafact/pdf/PRF.pdf.
[1702] "Inside SRB Refurbishment," *Spaceport News*, July 20, 2001, 4-5.
[1703] USA, "STS Recordation, Phase I SRB Hardware Process Flow," SRB-5.
[1704] Following a trend towards the use of more environmentally friendly materials, three different types of TPS have been used over time, originating with Marshall Sprayable Ablative (MSA) and followed by MSA-1. MCC was first used ca. 1988-1990. The most recent solvents were all water-based. Carleton, interview.

painted twice: once on the bare metal and once on the TPS.[1705] After painting, the aft skirt went to the high bay for subassembly installation, including the TVC system. Following aft skirt build up, it was hot-fire tested at the SRB ARF.

Build-up and testing of the forward assembly, including the forward skirt, frustum, and nose cap, plus attachments, followed a TPS application and painting process similar to the aft skirt and aft assembly. In addition, parachutes brought over from the PRF were installed in the frustum. Prior to installation, the main parachute support structure also underwent hydrolasing to remove sealant, and media blasting to remove the protective finish. Mechanical operations included shim fabrication and fairing assembly installation, nut plate replacement, and helicoil installation. The process was completed with a finishing touch-up, sealant application, and part marking.[1706]

SRB Integration

The four RSRM segments were joined with the SRB forward and aft assemblies to form the flight configuration boosters. This integration process was conducted in three phases. The first phase of the "buildup process" began in the RPSF with the aft and forward segments. Each SRB aft booster assembly consisted of one SRB aft skirt, one RSRM aft motor segment, three RSRM stiffener rings, one RSRM aft exit cone, one ET attach ring, several aft skirt electrical cables, aft system tunnel covers (including covers commonly known as a "rooster tail"), ancillary attach hardware, and several different thermal protection systems. The aft skirt clevis was mated to the aft motor segment tang. The joint was held together using 177 stainless steel pins. After pin insertion, the steel pin retainer band was installed and covered with cork and TPS materials, and the valley of the aft skirt kick ring was filled with RT-455.[1707] Next, the transition floor plate assembly was installed between the aft motor segment floor plates and the rooster tail.[1708] This buildup process took approximately four to six weeks.[1709] The assembled aft boosters were stored in the surge buildings at the RPSF until their transport to the VAB High Bay 1 or 3 integration cell. All segments remained vertical on their pallets until they were transferred to the VAB for stacking (Figure No. E-47).

The second phase of integration entailed SRB stacking operations and Space Shuttle buildup in the VAB. The aft booster assemblies, transported from the RPSF, were mated to the MLP hold-down posts and bolted down (Figure No. E-48).[1710] After installation of hold-down post hardware, the aft center, forward center, and forward motor segments, followed by the forward

[1705] Carleton, interview.
[1706] USA, *Familiarization Training*, DRO-33.
[1707] RT455 is a trowelable thermal ablative compound.
http://rtreport.ksc.nasa.gov/techreports/2002report/700%20Process%20Human%20Fac/701.html.
[1708] USA, *Familiarization Training*, INT-3, INT-4.
[1709] Until 2004, this process was done in the VAB High Bay 4. Bartolone, interview.
[1710] Since 1984, following transport from Utah, the fueled SRB segments have been received at the Rotation, Processing, and Surge Facility. Here, they are rotated to vertical, inspected, processed, and stored until their turn in the Space Shuttle stacking process. ACI, *Kennedy Space Center*, Appendix C.

assembly, were brought in to build up the SRB from bottom to top (Figure Nos. E-49, E-50). The stacking process typically alternated left- and right-hand boosters, rather than completing the buildup of one SRB before beginning the other. The forward assembly was connected to the forward motor segment with 195 stainless steel pins. The last step was the installation of the forward skirt access kit, a "pie-shaped flooring to prevent damage to the RSRM igniter and associated cables."[1711] The S&A device was installed after the forward skirt was installed.

During shuttle vehicle mating, the ET was attached to each SRB aft frame by two lateral sway braces and a diagonal attachment. The forward end of the ET was attached to each SRB forward skirt.[1712]

Operations in the VAB typically required about forty-four workdays. This period included nineteen work days for stacking of the left and right boosters, eighteen days for mating with the ET and integrated close outs, and seven days for mating to the orbiter, followed by systems tests.[1713]

Launch

The launch countdown for the SRB/RSRM began about three days prior to launch. RSRM systems became operational approximately eighteen hours prior to launch with activation of the igniter heater. The operational pressure transducers and the joint heaters were powered up at nine hours and eight hours before launch, respectively; the transducers were checked out at T-90 minutes. At T-5 minutes before launch, the igniter heater was deactivated and the S&A device was armed. The SRBs came to life when the TVC system was activated at T-28 seconds before launch.

At T-0, or liftoff, the SRBs were ignited by an electrical spark that sent flames from the igniter down the center of the propellant. The boosters went to full power in two-tenths of a second. At the same time, the frangible nuts on each of the four hold-down bolts were exploded, freeing the Shuttle for lift-off. Operating in tandem with the SSMEs for the first two minutes of flight, the SRBs provided about 80 percent of the thrust to escape the Earth's gravitational pull. Propellant in the forward segment of the RSRM, designed to provide fast acceleration, burned out fifty seconds after launch. The remaining propellant, shaped to burn at a slower rate, was all consumed after about two minutes. Exhausted of their fuel, the boosters burned out and separated from the orbiter and ET. Momentum continued to carry the SRBs upward for another 70 seconds to an altitude of about 43 miles (apogee) before they began their controlled descent back to Earth and splashdown into the Atlantic Ocean. At an approximately 1,100' altitude, firing of a pyrotechnic initiator card activated a linear-shaped charge on the RSRM nozzle to jettison the nozzle extension. This prevented water impact damage to the TVC hardware located inside the

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[1711] USA, *Familiarization Training*, INT-15.
[1712] NASA, "SRB Overview," 2002, http://spaceflight.nasa.gov/shuttle/reference/ shutref/srb/srb.html.
[1713] USA, "STS Recordation, Phase I SRB Hardware Process Flow," SRB-5.

aft skirt. The timing of the nozzle extension jettison served several purposes. It prevented detonation of the thrust vector control system hydrazine fuel during reentry. Also, it minimized heat and flame damage to the aft skirt heat shield curtain (caused by booster exhaust gas), and prevented contact between the SRB and the severed nozzle extension at water impact.[1714]

[1714] USA, *Familiarization Training*, REC-12.