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

---

[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

---

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

---

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,

---

[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

---

[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.