

NASW-4003

# THE SPACE SHUTTLE ADVANCED SOLID ROCKET MOTOR

## QUALITY CONTROL AND TESTING

(NASA-CR-188800) THE SPACE SHUTTLE ADVANCED  
SOLID ROCKET MOTOR: QUALITY CONTROL AND  
TESTING (NAS-NRC) 65 p

CSSL 21H

N92-10043

G3/20

Unclass  
0039570

NATIONAL RESEARCH COUNCIL

The Space Shuttle  
Advanced Solid Rocket Motor

*Quality Control and Testing*

Committee on Advanced Solid Rocket Motor  
Quality Control and Test Program  
Aeronautics and Space Engineering Board  
Commission on Engineering and Technical Systems

National Research Council

National Academy Press  
Washington, D.C. 1991

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the panel responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Frank Press is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Robert M. White is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Stuart Bondurant is acting president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Frank Press and Dr. Robert M. White are chairman and vice-chairman, respectively, of the National Research Council.

This study was supported by Contract NASW-4003 between the National Academy of Sciences and the National Aeronautics and Space Administration.

Available in limited supply from  
The Aeronautics and Space Engineering Board  
National Research Council  
2101 Constitution Avenue, N.W.  
Washington, D.C. 20418

Printed in the United States of America

**COMMITTEE ON ADVANCED SOLID ROCKET MOTOR  
QUALITY CONTROL AND TEST PROGRAM**

Laurence J. Adams, Consultant and Former President, Martin Marietta Corporation,  
Potomac, Md., *Chairman*

Janice L. Beadell, Manager, Advanced Supportability Technology, Douglas  
Aircraft Company, Long Beach, Calif.

Jack L. Blumenthal, Assistant Director, Center for Automotive Technology, TRW,  
Redondo Beach, Calif.

Yvonne C. Brill, International Maritime Satellite Organization (Ret.), Skillman,  
N.J.

Charles P. Fletcher, Vice President, Engineering, Alcoa, Pittsburgh, Pa.

Paul M. Johnstone, Eastern Airlines (Ret.), Saint Michaels, Md.

Harold W. Lewis, Professor Emeritus, University of California, Santa Barbara,  
Calif.

James W. Mar, Professor Emeritus, Massachusetts Institute of Technology, Pacific  
Grove, Calif.

William A. Owczarski, Director of External Technology Development, United  
Technologies, Washington, D.C.

**Advisors to the Committee**

Donald L. Anton, Senior Research Scientist, Materials Technology, United  
Technologies Research Center, East Hartford, Conn. (*June 24-September 1,  
1991*)

William S. McArthur, NASA Astronaut Corps, Houston, Tex.

**Staff**

JoAnn C. Clayton, Study Director

Allison C. Sandlin, Senior Staff Officer and Principal Study Officer

Martin J. Kaszubowski, Senior Staff Officer

Christina A. Weinland, Senior Project Assistant

A.J. Medica, Consultant

## AERONAUTICS AND SPACE ENGINEERING BOARD

- Duane T. McRuer, President and Technical Director, Systems Technology, Inc., Hawthorne, Calif., *Chairman*
- James M. Beggs, Partner, J.M. Beggs Associates, Arlington, Va.
- Richard G. Bradley, Director, Flight Sciences, Ft. Worth Division, General Dynamics, Ft. Worth, Tex.
- Robert H. Cannon, Jr., Charles Lee Powell Professor and Chairman, Dept. of Aeronautics and Astronautics, Stanford University, Stanford, Calif.
- Eugene E. Covert, Professor, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, Mass.
- Ruth M. Davis, President, Pymatuning Group, Inc., Arlington, Va.
- Wolfgang H. Demisch, Director of Research, UBS Securities, New York, N.Y.
- Charles W. Ellis, Retired Vice President V-22 Program, Boeing Vertol Company, Newtown Square, Penn.
- Owen K. Garriott, Vice President, Space Programs, Teledyne Brown Engineering, Huntsville, Ala.
- John M. Hedgepeth, Retired President, Astro Aerospace Corporation, Santa Barbara, Calif.
- Robert G. Loewy, Institute Professor, Dept. of Mechanical and Aerospace Sciences, Rensselaer Polytechnic Institute, Troy, N.Y.
- John M. Logsdon, Director, Space Policy Institute, George Washington University, Washington, D.C.
- John H. McElroy, Dean of Engineering, University of Texas at Arlington, Arlington, Tex.
- Garner W. Miller, Retired Senior Vice President for Technology, USAir, Naples, Fla.
- Franklin K. Moore, Joseph C. Ford Professor of Mechanical Engineering, Cornell University, Ithaca, N.Y.
- Harvey O. Nay, Retired Vice President of Engineering, Piper Aircraft Corporation, Vero Beach, Fla.
- Frank E. Pickering, Vice President and General Manager, Aircraft Engines Engineering Division, General Electric Company, Lynn, Mass.
- Anatol Roshko, von Karman Professor of Aeronautics, California Institute of Technology, Pasadena, Calif.
- Maurice E. Shank, Retired Vice President, Pratt & Whitney of China, Inc., Bellevue, Wash.
- Thomas P. Stafford, Vice Chairman, Stafford, Burke, and Hecker, Inc., Alexandria, Va.
- Martin N. Titland, Chief Operating Officer, CTA, Inc., Rockville, Md.
- Albertus D. Welliver, Corporate Vice President, Engineering and Technology, The Boeing Company, Seattle, Wash.

**Staff**

JoAnn C. Clayton, Director

Martin J. Kaszubowski, Senior Staff Officer

Allison C. Sandlin, Senior Staff Officer

Susan K. Coppinger, Senior Secretary

Anna L. Farrar, Administrative Coordinator

Maryann Shanesy, Senior Secretary

Christina A. Weinland, Administrative Secretary

# Contents

EXECUTIVE SUMMARY	1
Introduction, 1	
Test Program, 2	
Quality Assurance Program, 3	
Principal Findings and Recommendations, 4	
TERMS, ACRONYMS, AND ABBREVIATIONS	7
1. INTRODUCTION	10
Overview, 10	
The Task, 12	
Approach, 13	
2. CASE	14
Description, 14	
Materials Properties, 14	
Welding Properties and Processes, 15	
Structural Design, 16	
Development Testing, 17	
Verification of the Structural Design, 17	
Quality Assurance, 18	
Overall Case Findings and Recommendations, 18	
3. INSULATION	20
Description, 20	
Development Testing, 20	

Development Testing Findings and Recommendations, 21	
Quality Assurance, 22	
Quality Assurance Findings and Recommendations, 22	
4. LINER	23
Description, 23	
Development Testing, 23	
Development Testing Findings and Recommendations, 24	
Quality Assurance, 24	
Quality Assurance Findings and Recommendations, 25	
5. PROPELLANT	26
Description, 26	
Development Testing, 27	
Quality Assurance, 29	
Overall Propellant Findings and Recommendations, 29	
6. IGNITER	32
Description, 32	
Development Testing and Quality Assurance, 32	
7. NOZZLE	34
Description, 34	
Development Testing, 35	
Quality Assurance, 36	
Overall Nozzle Findings and Recommendations, 36	
8. OVERALL EVALUATION	38
The ASRM Test Program, 38	
Quality Assurance Program, 39	
Schedule and Cost Risk, 39	
Availability of Skilled Personnel, 39	
Relationship Between Testing and Quality Assurance and Reliability and Safety, 40	
Use of Probabilistic Risk Assessment, 40	
Automated Manufacturing Processes, 41	
BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS	43
APPENDIXES	
A Overall ASRM Test Program	47
B Nondestructive Evaluation Methods	51
C Component NDE Methods	52
D Schematic of ASRM Test Program	54



# Executive Summary

## INTRODUCTION

The Congressional committees that authorize the activities of the National Aeronautics and Space Administration (NASA) requested that the National Research Council (NRC) review the testing and quality assurance programs for the Advanced Solid Rocket Motor (ASRM) program. This program is in its early development stages, with preliminary design review scheduled for February of 1992. Thus, the NRC review committee could only address design concepts, not final design; the plans for testing and quality assurance relating to these design concepts; and the results of testing accomplished to date. Changes are likely to occur as more understanding is developed from the analysis and test programs.

The proposed ASRM design incorporates numerous features that are significant departures from the Redesigned Solid Rocket Motor (RSRM) and, in some cases, from previous experience on other programs. The NRC review concentrated principally on these features. Primary among these are the steel case material, welding rather than pinning of case factory joints, a bolted field joint designed to close upon firing the rocket, continuous mixing and casting of the solid propellant in place of the current batch processes, use of asbestos-free insulation, and a light-weight nozzle. Additionally, significant amounts of automation are to be incorporated in the manufacturing processes.

This report contains the Committee's assessment of these and other features of the ASRM in terms of their potential impact on flight safety. The Committee's principal focus was on the maturity of the technology used, the potential effectiveness of the analysis and test program in establishing the capability of the design to

provide safe flight, and the effectiveness of the quality assurance program in ensuring that the flight units are manufactured in compliance with the design requirements.

The Committee generally accepted the ASRM design as a given and concentrated on evaluating the testing and quality assurance programs. However, design details and technology maturity strongly influence the testing and quality assurance programs.

### TEST PROGRAM

The Committee's review of the test program included the complete range of tests from basic materials characterization through full-scale motor firing tests (a detailed description appears in Appendixes A and D). The use of new materials for the case, its insulation, and the nozzle, as well as the case welding process requires the successful completion of a large materials characterization experimental program prior to finalization of the design. The plans presented to the Committee indicate that these issues are being addressed. However, the Committee notes that this aspect of the ASRM program requires the amassing of a very large data base that presently does not exist.

Characterization of the case material is important since the selected material has not been widely used and there is limited experience in welding it. In addition to the material's mechanical properties, the contractor must address items such as weld seam properties, characterization of the heat affected zone adjacent to the welds, residual stresses after welding, and potential stress corrosion cracking.

The test program for the case, as described to the Committee, is intended to uncover unanticipated problems that result from using this material in the welded condition. The scope of the test program appears to the Committee to be adequate, but, because of the lack of previous experience with the particular alloy, may lead to surprises that may require its augmentation.

Another major innovation in the ASRM design is the use of continuous mixing and direct casting of the propellant to replace the batch mixing and casting process employed on most previous systems, including the RSRM and Titan III and IV. The continuous mix process offers the potential for greater control of the mixing process, as well as for processing greater amounts of propellant with less waste. The program for developing the continuous mix processes is being carried out by Aerojet at a pilot plant in Sacramento, California. The principal challenge is to provide, with a high confidence level, a homogeneous mix containing the correct amounts of the propellant mix constituents. While the selected propellant formulation is different than that used in the RSRM, it belongs to a family of propellants that has been used for similar applications in the past. However, this particular formulation is unique to the ASRM. The test program must develop an experience base sufficient to provide the level of confidence required for human flight.

A visit to the pilot plant by a subcommittee of the Committee revealed that the pilot plant is well-designed and that the testing plan for process development is well-conceived. Once the process has been developed and proven in the pilot plant,

it must be scaled up by a factor of ten to a full-scale facility that is being built in Yellow Creek, Mississippi. The Committee considers this to be a critical step with significant risk of delay in achieving the results promised by the pilot plant. This concern is based on other experiences in working out the initial problems encountered in automated manufacturing process equipment in a first-time, full-scale application.

The component, subsystem, and system test program has been based, in large part, on experience from other large solid rocket motor development programs, especially the RSRM. The program includes firing of large numbers of small motors, a series of ten 48-inch motors, and seven full-scale motors. These tests are designed to fully characterize propellant performance, evaluate new insulation and nozzle materials, evaluate the full-scale motor components, detect deficiencies in the design, and ultimately to qualify the flight motors. Other major tests will qualify the case for reuse and demonstrate the structural integrity of the new motor. The many new design features incorporated in the ASRM require a comprehensive test program to provide assurance for safe flight. The program described to the Committee appears to incorporate the proper elements to do this but may need to be adjusted as more knowledge is gained. Strict test disciplines are mandatory. These include (prior to each test) establishment of pass/fail criteria, prediction of the performance and test results of each test article, and development of retest requirements in the event of a test failure or anomalous results. At the time of this study, for example, a decision had not been made whether or not the field joint structural test article (FJSTA) test of August 6, 1991, which was not successful, will be repeated. Such criteria should exist in advance of testing. In general, the Committee believes that the objectives of a major test program should not be abandoned because of loss of the test article unless the objective of the test can be achieved as well or as expeditiously by other means.

### QUALITY ASSURANCE PROGRAM

The Committee's review of the ASRM Quality Assurance Program included the complete range from basic material formulation through final inspection of completed segments.

A program that characterizes the critical constituents and properties of raw materials, called "fingerprinting," is planned for all critical raw materials used in the motor. Each batch or shipment of material received will be subjected to fingerprinting inspections to assure that the supplier has not made changes that could affect final product quality. This program was initiated for the RSRM and is being expanded on for the ASRM. At the time of this report, a lack of details concerning the parameters to be monitored prevented the Committee from evaluating the fingerprinting program planned for ASRM, but the Committee endorses the program in concept.

The ASRM program team is implementing extensive nondestructive evaluation (NDE) procedures for monitoring the effectiveness of the process control program and for verifying the integrity of critical components (see Appendixes B and C).

These evaluations will be used to verify the quality of adhesive bonding in the case, liner, and nozzle; case metal; case welds; cast and cured propellant; and other critical components. It was indicated to the Committee that the newest technology in NDE would be applied, including real-time radiography, ultrasonics, and electromagnetic acoustic transducers. The new insulation, propellant, propellant-to-insulation liner, and nozzle materials require these NDE processes. Although the Committee endorses such an NDE program, it cannot provide a detailed evaluation until further developments have taken place.

An important feature of the quality assurance program is the segment hydroproof test. This test is being designed to apply internal pressure to the motor case segments in excess of the maximum expected flight pressures and sufficiently high to detect the presence of defects that could result in failure in flight. Such proof tests, combined with an effective NDE program, have provided high assurance of flight integrity on previous programs. Final evaluation of the ASRM proof test program must await completion of other analyses and tests.

The ASRM program team also expressed its intent to establish an extensive statistical process control program. Such a program has the potential to provide data that signal process deviations and that can lead to the identification of the root cause of repeated defects in manufactured components. Complete details of the ASRM program are not yet available and were not reviewed, but the Committee believes that well-designed statistical process control could provide increased confidence in the control of critical manufacturing processes.

In total, the Committee believes that the quality assurance program, as presented during this study, has the potential to minimize the probability of a defective flight article, to the extent attainable with the current technology.

### PRINCIPAL FINDINGS AND RECOMMENDATIONS

The Committee has prepared numerous findings and recommendations on ASRM components and processes. These appear throughout the body of the report. The following list, however, summarizes those findings and recommendations that have an overall application, or that were deemed by the Committee to be of such importance that they warranted greater visibility.

- The numerous new developments of design features and manufacturing processes raise concerns as to the degree to which schedule and cost reserves have been incorporated in ASRM program plans. These reserves must, without compromising the test and quality objectives, permit effective resolution of the unanticipated problems that will surely arise. The Committee did not conduct a detailed review of schedule and cost reserves, so its concern is based on what seems to be a success-oriented plan. **It is recommended that program schedules and budgets be reviewed to ensure that reasonable reserves have been allocated for unanticipated problems.**
- Experience has shown that even in the most well-designed programs, unanticipated events occur during the testing and the first few flights due to undetected

marginal designs and/or manufacturing process deviations. Tests yield the best results when the objectives are well understood and criteria are defined in advance. **The Committee recommends that strict discipline be adhered to in defining test objectives, in establishing pass/fail test criteria, and in establishing and meeting retest requirements.**

- A major objective stated for the ASRM is improved reliability and safety. While the Committee believes that, overall, the new design features and automated manufacturing processes of the ASRM hold the potential for a more reliable, safer system than the current RSRM, the degree to which the ASRM is safer and more reliable than the RSRM is difficult to estimate in the absence of a quantification (including uncertainty) of the safety and reliability of the two designs. **The Committee believes that there is much to be learned from such an exercise and recommends that quantification criteria for reliability and safety be identified and that a means for measuring progress in meeting the criteria be developed.**
- The Committee was divided on the issue of a general application of probabilistic risk assessment (PRA) to the ASRM design. However, it was in agreement that selective applications could prove beneficial in assessing the risks of various design features as indicated in the body of the report. **The Committee recommends that NASA evaluate the potential benefit to be derived from a general application of PRA at this point in time and of its application in the specific instances that are discussed in the body of the report.**
- The new metal case utilizes a steel alloy that has not been extensively used in either aerospace or commercial applications. Such large solid rocket motor cases previously have not been welded and flown, and the new case design employs a welding process, to join the forged cylinder elements, that has not been proven. **Several technical recommendations appear in the body of this report that, if adopted, would, in the Committee's evaluation, increase the confidence level in the structural integrity of the case. We call particular attention to those recommendations that concern stress corrosion since, if present, stress corrosion has the potential to create defects after completion of postmanufacturing tests and inspections, but prior to flight.**
- Solid rocket motors, of necessity, employ extensive adhesive bonding of elements. The ASRM is no exception. Recent developments in process control techniques and in nondestructive evaluation technology have tended to improve bond quality through the ability to detect defective bonds in the completed assembly. The Committee examined current bonding processes and NDE plans for the ASRM program. It appears that current technology is being used for adhesive bonding processes and inspections. **The Committee recommends that the ASRM program team continue the strong emphasis on achieving and verifying adhesive bonding integrity and continue the work aimed at development of NDE processes for the nozzle bonds.**
- The continuous mix and cast process being developed for the solid propellant

is critical to the potential reliability and flight safety of the ASRM. The system for monitoring the properties and constituents of the propellant mix is especially important to developing a high level of confidence in the flight performance of the motors. Some activity is planned to determine the effect of process variations on motor performance and safety. The more tolerant the propellant mix is to process variations, the higher the confidence level in achieving reliable flight. **The Committee recommends that the planned propellant development and test program, which will investigate the effect of process variations, be expanded to include demonstration, in the five-inch motor tests, of the performance of propellant that is deliberately manufactured at the limits of the propellant specifications. In addition, the Committee also recommends that several of the 48-inch test motors be direct cast from propellant from the continuous mix pilot plant and compared with earlier 48-inch motors cast from the batch mixed process.**

- The ASRM incorporates a new, lighter-weight nozzle. Most of the weight reduction stems from a newly designed flexible bearing and seal that is used to enable nozzle gimbaling during flight. The weight of this bearing and seal assembly is reduced by approximately 50 percent from that of the RSRM nozzle. **Therefore, the Committee recommends, in view of the dramatic weight reduction that has been promised, a more thorough review be made of the nozzle design as soon as details permit quantitative assessments of its safety and reliability.**

Additional detailed recommendations that are specific to the major components of the ASRM design appear in the following chapters of the report.

The conclusions of this report are necessarily tentative because of the early stage of development of the ASRM. Issues raised here might fruitfully be revisited after 12-18 months when a more accurate assessment of progress toward planned goals should be possible.

## Terms, Acronyms, and Abbreviations

AE	Acoustic Evaluation
Al	Aluminum
AP	Ammonium Perchlorate
ASRM	Advanced Solid Rocket Motor
ATA	Assembly Test Article
Burst Test	Test in which pressurization exceeds the acceptable limit, resulting in bursting of the test article
CCP	Carbon Cloth Phenolic
CEI	Contract End Items
CFD	Computational Fluid Dynamics
CIL	Critical Items List
COQ	Certification of Qualification
CP	Center Perforation (Test Motor)
DM	Development Motor
EMAT	Electromagnetic Acoustic Transducer
ET	Eddy Current Test
Extrusion	Manufacturing and application process in which insulation material is forced to flow plastically through an orifice
FA	Fluorescence Analysis
Factor of Safety	Number specified by the NASA Contract End Items Specification and by the Marshall Space Flight Center Handbook 505, which is used to calculate a margin of safety

FHA	Functional Hazard Analysis
FJSTA	Field Joint Structural Test Article
Flexbearing	Structural element that allows engine gimbaling and carries thrust loads. It is composed of layers of material that shear to enable movement
Flexseal	Protects the flexbearing from hot gases
FMEA	Failure Modes and Effects Analysis
Fracture Toughness	Factor used to indicate the intensification of applied stress at the tip of a crack of known size and shape (see Toughness)
FTIR	Fourier Transform Infrared Spectroscopy
HTPB	Hydroxyl-terminated polybutadiene, a solid rocket propellant binder
ICD	Interface Control Document
Isp	Specific Impulse
JPL	Jet Propulsion Laboratory
KSC	Kennedy Space Center
LCE/HBTA	Life Cycle Endurance/Hydroburst Test Article
LDCCP	Low-Density Carbon Cloth Phenolic
LT	Leak Test
Margin of Safety	Defined as the allowable stress divided by the actual stress and the safety factor. The number 1 is subtracted from this calculated total
Max-Q	Maximum aerodynamic pressure
MEOP	Maximum Expected Operating Pressure
MNASA	48-inch test articles
MT	Magnetic Particle Test
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation
NRC	National Research Council
OSEE	Optically Stimulated Electron Emission
PBAN	Polybutadiene-acrylic acid-acrylonitrile, a solid rocket motor propellant binder
PRA	Probabilistic Risk Assessment
psi	Pounds per square inch
PT	Penetrant Test
QM	Qualification Motor
RSRM	Redesigned Solid Rocket Motor
RT	Radiography Test
RTR	Real-time Radiography
SRM	Solid Rocket Motor
SSC	Stennis Space Center
SSME	Space Shuttle Main Engine
STA	Structural Test Article
TEM	Technical Evaluation Motor



Toughness	Ability of a material to absorb energy and deform plastically before fracturing
TPTA	Transient Pressure Test Article
Turnkey Operation	Complex operation that can be initiated with little or no design, process, or hardware delays
TVC	Thrust Vector Control
Twang Load	A short-duration, side load imposed on the Space Shuttle system upon ignition of the Space Shuttle main engines
UT	Ultrasonic Testing
VAB	Vehicle Assembly Building
YC	Yellow Creek
Yield Strength	The stress at which a specified amount of permanent deformation (usually 0.2%) is produced

## Introduction

### OVERVIEW

The Advanced Solid Rocket Motor (ASRM) is being developed to replace the current Redesigned Solid Rocket Motor (RSRM) on the Space Shuttle. It is intended to improve flight safety and reliability by reducing catastrophic failure modes relative to the RSRM and the pre-Challenger Solid Rocket Motor (SRM). Another goal of the program is to enhance producibility by building automated, dedicated facilities with efficient production tools while enhancing performance through increased amounts of a more energetic propellant and reduced inert weight.

The ASRM is intended to increase Space Shuttle payload capability by at least 12,000 pounds. When flying 12 missions a year, it should be able to carry the equivalent payload of 14 current missions. This additional capability is gained primarily through an increase in the diameter of the ASRM, which increases the propellant by approximately 100,000 pounds and adds an additional 10 seconds of burn time.

The ASRM consists of six major components, each of which is dealt with in detail in separate sections of this report (see Figure 1). However, because of time constraints, the Committee was not able to perform a detailed evaluation of the igniter. Briefly, the components are:

- *Case*: Three cylindrical steel welded segments bolted together to form the main body of the motor, which will be approximately 126 feet in length.
- *Insulation*: Material that protects the case from the heat generated by the burning propellant.

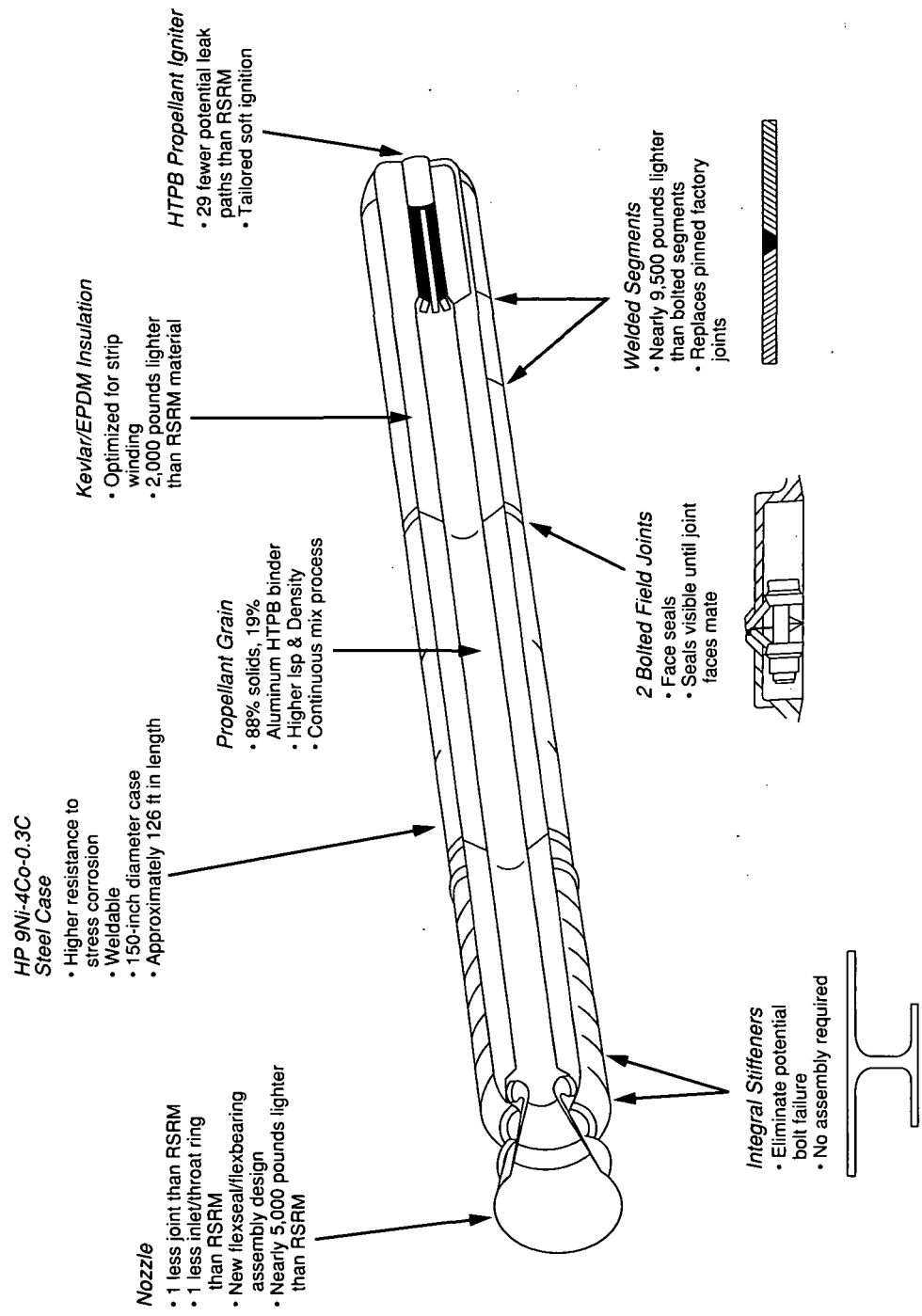


FIGURE 1 Advanced solid rocket motor design highlights.

- *Liner*: Material that provides critical bonding between the propellant and the insulation.
- *Propellant*: Material that provides thrust when burned.
- *Nozzle*: Part that accelerates the exhaust gasses from the combustion chamber to a high velocity and through which the propellant exhaust gases are released to guide the direction of the rocket's thrust.
- *Igniter*: Mechanism that, when triggered, starts the propellant burn process, which produces the rocket booster thrust.

The ASRM is an untested design that makes use of materials and processes that are either new or that vary from previous applications. These new features and processes are a principal focus of this review and will be discussed in the following pages. They are:

- a different, more readily weldable, case alloy;
- welded, rather than bolted, factory joints;
- bolted field joints which are designed to close, rather than open, during propellant burning;
- new O-ring materials;
- new, asbestos-free, insulation applied by a new automatic strip winding process;
- new liner material and new application process;
- a propellant whose exact formulation has not previously been used;
- a continuous mix and cast process for the propellant;
- a water-soluble core around which the propellant will be poured;
- a different solid rocket igniter design; and
- new nozzle design with new materials.

Lockheed Missiles & Space Company, Inc. was selected as the ASRM prime contractor in April of 1989 by the National Aeronautics and Space Administration (NASA). Lockheed is teamed with the Aerojet ASRM Division, which is the principal subcontractor responsible for the design, development, and production of the new motor. Currently, Lockheed and Aerojet are working in offices in Iuka, Mississippi, located about eight miles from the eventual plant site at Yellow Creek. RUST International, in Birmingham, Alabama, is the contractor responsible for construction of the Yellow Creek facility. Thiokol Corporation will manufacture the nozzle at the NASA Michoud Assembly Facility near New Orleans, Louisiana. Babcock & Wilcox is responsible for manufacturing the case at locations in Indiana and Ohio.

Development of the ASRM is expected to take approximately six years, with the first new motors planned for a Space Shuttle flight in 1996.

### THE TASK

In response to the NASA Authorization Act for Fiscal Year 1991, the NASA Administrator requested that the National Research Council (NRC) assess the qual-

ity and test program planned for the ASRM. The NRC was asked to review and evaluate program plans for quality assurance and testing and to assess their adequacy for ensuring safety and reliability. The NASA/ASRM program and its contractors provided the Committee with documentation and briefings describing the ASRM program and plans, focusing on the areas of quality assurance (including safety, reliability, and maintainability) and testing (including sub-scale tests, full-scale development tests, full-scale qualification tests, and other means of verification).

### APPROACH

The full NRC Committee on ASRM Quality Control and Test Program met on May 23-25, June 24-25, July 16-17, and August 5-7, 1991. The first two meetings were held at the National Research Council in Washington, D.C. The third meeting was held at the Lockheed/Aerojet facilities in Iuka, and the final meeting at the NRC Beckman Center in Irvine, California.

On June 5, 14, and 21, subcommittees met at the Marshall Space Flight Center to examine technical details concerning the propellant; the Aerojet pilot plant in Sacramento, California, where the continuous propellant mixing process is being developed; and at the Babcock & Wilcox Research Center in Alliance, Ohio, where research and development are taking place for the ASRM case materials and processes. On July 31, another subcommittee visited the Thiokol Corporation facility in Wasatch, Utah, where the design and development of the ASRM nozzle and its production tooling and other processes are taking place.

At its first full meeting, the Committee familiarized itself with the ASRM program plans, including design, systems integration and engineering, verification methods, and safety analyses. At the second meeting, the Committee explored the roles and responsibilities of the various NASA and contractor participants in program planning and execution, the proposed materials and processes, and the ASRM testing and risk assessment program philosophies. At its third meeting, the Committee examined the Yellow Creek facility layout, including the implementation plan, safety issues, and checks and balances between NASA, Lockheed, and Aerojet. Also included were detailed reviews of the development test plans and quality assurance plans. The final meeting consisted of clarification of outstanding issues, Committee discussions, and report writing.

The Committee requested a large number of written responses on various issues and wishes to thank NASA and its contractors for their cooperation in providing existing information and in researching some of the issues that arose. Throughout the short period of the study, ASRM program personnel were consistently forthcoming and helpful to the Committee in its work.

The ASRM program is still in the early stages of design and development. Approximately 25 percent of the design is firm, and the preliminary design review is scheduled for February of 1992. Many materials and processes (from the pilot facilities, for example) are not yet well established. Therefore, the Committee believes that the issues raised in this report should be reconsidered by a similar panel in 12-18 months to assess progress of the program in meeting safety, reliability, and quality standards.

## Case

### DESCRIPTION

The ASRM motor case consists of three segments that require 11 welded factory joints, two bolted field joints, an integral external tank attach ring, and integral external stiffeners to resist the buckling loads induced by splashdown.

In contrast, the RSRM motor case is composed of four segments that require three bolted field joints, seven pinned factory joints and bolted external stiffeners.

The ASRM case is 150 inches in diameter, four inches greater in diameter than the RSRM case. This larger diameter increases the amount of propellant by approximately 100,000 pounds. The ASRM case is essentially the same weight as that of the RSRM, since the weight gain associated with increased diameter is offset, primarily, by the weight reduction due to the elimination of the factory pinned joints.

### Materials Properties

Due to the incorporation of welded joints in the ASRM case design, a weldable alloy was required. The RSRM is made of a well-characterized, highly studied alloy, D-6ac. A nickel-cobalt steel alloy (HP 9Ni-4Co-0.3C commonly referred to as HP 9-4-30) was selected for the ASRM case material because of its high strength, good fracture toughness, improved stress corrosion resistance, and weldability.

A significant drawback of HP 9-4-30 is that it has not been as extensively used, and its behavior under complex loads, temperature, and strain rate conditions is not well understood. In addition, commercial utilization of HP 9-4-30 has not included welding, even though it is classified as a weldable alloy. As part of the ASRM case

development process, base metal and weld characteristics are being evaluated in detail.

The HP 9-4-30 metal ingots, weighing approximately 40,000 pounds each, will be obtained from two suppliers, Republic Steel and Latrobe. The ingots required will be the largest produced by either supplier to date. Currently, more than 16 HP 9-4-30 ingots have been produced.

Ladish Company, which forges the RSRM ingots, will also roll forge and cold size the ASRM ingots. Previous to the ASRM program, they had not forged an ingot this large, nor had they forged the HP 9-4-30 alloy. As of the date of this study, they have gained some limited experience using four 146-inch diameter development forgings of the ASRM alloy. The ASRM HP 9-4-30 alloy is harder to work than the RSRM D-6ac alloy and may push the equipment at the Ladish Company to the extent of its capabilities. However, analysis and experience at the Ladish Company to date suggest that the chosen alloy can be successfully forged for ASRM applications.

### **Welding Properties and Processes**

The welded ASRM design, which eliminates the seven pinned factory joints, is new to the large solid rocket motor industry. Successful welding of the very large cylinders, maintaining their concentricity, and relieving stress in the weld areas are significant challenges in the ASRM program.

Historically, welding of very large solid rocket motor cases has been avoided due to the concern over the ability to repeatedly produce high integrity weld joints and to detect critical defects through nondestructive evaluation. The ASRM program team justifies welding the factory joints over pinning on the following basis:

- Advances in weld process technology (plasma arc process; real-time TV monitoring; process automation—all of which will be used in the ASRM program).
- Advances in nondestructive evaluation technology (real-time radiography and ultrasonic testing).

The welding process introduces residual stresses in the area of the weld. A stress relief cycle of the case segment at a moderately high temperature (900°F) will be used to partially relieve these residual stresses. Since a higher stress relief temperature would result in undesirable base metal properties, significant levels of residual stress are expected to remain in the finished case. To provide a margin for this residual stress, as well as minor undetected welding flaws and joint inefficiencies, the material at the weld joint will be 25 percent thicker than the remainder of the case material.

The maximum residual stress arising from the welding process, after stress relief, is expected by the ASRM program personnel to be reduced to approximately 40 percent of the yield strength, which is still quite significant. It is the Committee's understanding that each individual weld will not be assessed after heat treatment to determine the adequacy of the stress relief.

The automated plasma arc welding process is expected to produce higher-quality weld joints than previous processes; however, repairs of defective welds will still be required. Repair procedures are being developed concurrently with the welding process. The ability to make high-quality repairs, and to verify their integrity with nondestructive evaluation techniques, is of crucial importance.

Currently, a thorough evaluation is being carried out at Babcock & Wilcox (B&W) on the welding parameters to be used in manufacturing the case segments. B&W has had little prior experience with HP 9-4-30, and the industry data base is small. Thus, an extensive research program is necessary. Joint geometry and welding parameter variations are being assessed. Also planned, but not completed, are extensive strength and fracture toughness tests of the weld and heat affected zone adjacent to the welds. Until these tests are completed, it will not be possible to definitively qualify the welded joint geometry.

### Structural Design

The ASRM program team stated the following as advantages over the current RSRM design:

- Field joints that close during firing instead of opening, as for the RSRM.
- Welded factory joints that eliminate potential failure modes associated with the pinned factory joints used in the RSRM.
- Face type seals that are designed to make it easier to assemble the field joints.
- An HP 9-4-30 ASRM alloy that has a higher fracture toughness than the D-6ac RSRM alloy and is more resistant to stress corrosion cracking.
- O-ring seal material that retains its resiliency at low temperatures (thereby enabling the elimination of O-ring joint heaters) and that will be compatible with the required grease application.

However, the Committee believes:

- The ASRM field joint is more complex in that the bolts are in tension rather than in shear, the joint itself is more difficult to machine, and fit-up stresses are more likely to occur. Additionally, the joint is more difficult to analyze.
- The weld and the heat affected zone surrounding the weld present potential new failure modes that are not currently completely understood.
- Proof testing is the process whereby structural safety is assured for the next flight of the case and hence fracture toughness, per se, is not a measure of goodness. (For analytical purposes, it should be noted that both the ASRM and the RSRM use the same value of plane strain fracture toughness. However, fracture toughness does not affect the design of the case.) A more appropriate measure of goodness is the square of the ratio of fracture toughness to tensile yield stress, which is the critical crack size. Using this comparison, the RSRM D-6ac alloy is somewhat better than the ASRM HP 9-4-30 alloy, although both appear to be acceptable.



## DEVELOPMENT TESTING

### Verification of the Structural Design

The existing material data base for the case alloy is not extensive since there have been very few prior applications. Consequently, a comprehensive test program has been planned to gather the data base required for the ASRM design. It should be noted that the necessary material data base is much larger than that needed for the RSRM because of the additional welding parameters that must be assessed.

The stresses in the bolted field joint were scheduled to be verified by strain gage measurements in the Field Joint Structural Test Article (FJSTA), which was a 146-inch diameter, geometric replica of the full-scale ASRM joint made from D-6ac steel. The D-6ac alloy was used because of its availability, which would allow the test to be conducted sooner than using HP 9-4-30 forgings. On August 6, 1991, the scheduled FJSTA failed prematurely at approximately one-fourth of the maximum expected operating pressure. It has been ascertained that the failure was in the case, not in the joint. NASA has appointed an investigation team, which, at the time of this report, has not published any findings. Important objectives of the test were to verify that the joint closes upon pressurization and to evaluate the complex stress patterns previously noted. These and other test objectives were not achieved.

The FJSTA was the first scheduled major test that was unique to the ASRM. The Committee believes it is important that another test article be fabricated as soon as possible in order that the originally planned series of tests can be completed or that an alternate test program be developed that can acquire the necessary data on an equivalent time scale.

Other critical parameters of the ASRM case design are expected to be verified by a series of tests that appear to faithfully duplicate the tests that were used to verify the SRM and RSRM designs. These tests bear the acronyms TPTA, LCE/HBTA, STA, DMs, and QMs, and include the Pathfinder test article (see Appendixes A and D). The ASRM requires additional testing beyond that required for the RSRM, because new materials are being used as well as because of the use of welded joints.

The structural integrity requirements imposed on the ASRM case are the same as those imposed on the RSRM. According to the results of theoretical calculations using computer models, case membrane thickness and the geometry of the machined pockets for the bolted field joint are sufficient to show positive margins of safety against the yield and ultimate tensile strengths of the HP 9-4-30 alloy. The geometry and thickness in the area of the weld also show positive margins of safety against the properties of weld and heat affected zone. The stiffeners on the aft segment are sized to show positive margins of safety against the loads imposed during splashdown. Positive margins are also shown for the stresses induced by the so-called "twang" loads. It should be noted that detailed stress analyses are still in progress.

The structural adequacy of the ASRM will be further assured for each flight by subjecting each segment to a hydroproof test together with nondestructive evaluation. Different test configurations will be used for the forward, center, and aft

segments to ensure faithful simulation of the end conditions. This represents an improvement over the RSRM. At the present time, the parameters of the hydroproof test have not been determined pending fracture mechanics evaluation and other analyses and tests. For the RSRM, the hydroproof pressure is 12 percent higher than maximum expected operating pressure (MEOP). The hydroproof test, which, in reality, is a form of inspection (albeit potentially destructive) uses a state of stress as the means to interrogate the structure for critically sized cracks. Final evaluation of the effectiveness of the ASRM hydroproof test can be made only after the test parameters are established.

It should be noted that the hydroproof test simulates only the pressure arising from the firing of the motor and does not simulate the stress conditions associated with either the "twang" or splashdown loads.

### QUALITY ASSURANCE

Inspection and quality assurance tests are performed throughout the case manufacturing process. Initial ingot castings of approximately 40,000 pound melts are being produced by Latrobe and by Republic Steel. The testing at this stage concentrates on the quality of the material using standard metallurgical practice, including spectral analysis, to ensure chemistry conformance to within alloy specifications.

The ingots are shipped to the Ladish Company for roll forging and are rough machined into case sections. Quality assurance tests ensure conformance to dimensional, mechanical property, and defect specifications, before the case sections are sent to Babcock & Wilcox.

At B&W, the forgings will be further cleaned, machined, and welded into the final configurations. They also will be given several heat treatments to produce the desired microstructure and to relieve the residual stresses in the weld heat affected zone. Throughout these processing steps there will be frequent nondestructive inspections for flaws. A variety of techniques will be used, which include eddy current testing, dye penetrant tests, ultrasonic tests, and real-time radiography. Of all these, only the ultrasonic and radiography techniques are capable of detecting small, wholly subsurface flaws.

The Committee's judgement is that the overall production testing program is sound in concept.

### OVERALL CASE FINDINGS AND RECOMMENDATIONS

- The FJSTA test failure leaves several important questions unanswered concerning the anticipated performance of the new field joint design; the circumstances that led to the unexpected failure on August 6, 1991, in the RSRM steel case; and whether the test will be rescheduled. At this writing, a decision has not been made regarding the construction of a replacement test article. **It is recommended that another FJSTA be fabricated with a sense of urgency because these data are needed to verify the joint integrity and structural performance, i.e., that the joint really closes, or that an alternate test**

**program be developed that can acquire the necessary data on an equivalent time scale.**

- **The margins of safety are calculated using the von Mises criterion for material failure, to account for the complex states of stress in the membrane and the joint. The Committee recommends that some pressurized cylinder tests be conducted to validate the von Mises criterion for the HP 9-4-30 ASRM alloy.**
- **The loads imposed on the case during splashdown have caused extensive damage to the SRM and RSRM case. The Committee believes a new examination of the loads induced by entry into the ocean, referred as the cavity collapse loads, should be initiated.**
- **Data indicate the HP 9-4-30 ASRM alloy has a stress corrosion cracking threshold superior to the D-6ac RSRM alloy. However, the ASRM case has welded factory joints and field joints that are in tension. These welded joints make the ASRM design potentially more sensitive to stress corrosion cracking when compared to the RSRM. Stress could also result from hydrogen embrittlement and time-delayed phase transformation. The Committee recommends detailed investigation of the stress corrosion cracking susceptibility of the welds and of the weld heat affected zone.**
- **An extensive study should be initiated to evaluate the temperature and strain rate effects and the forging production effects on fracture and crack growth. Also, more extensive stress corrosion analysis, as well as biaxial and complex loading studies, should be performed on the HP 9-4-30 ASRM alloy.**
- **An inspection process should be implemented to ensure that the postweld anneal has sufficiently lowered the residual stresses in each weld.**
- **A statistical analysis should be made of the weld defects that are detected. These data, when presented in the form of a probability of occurrence, will be of value to the quality assurance program. Some of these defects may require an evaluation to determine their effect on fracture and strength. An effective framework for quantifying the safety and reliability implications of these defects would be a probabilistic risk assessment.**

## Insulation

### DESCRIPTION

The purpose of the case insulation is to protect the steel case from the very high-temperature propellant flame. The RSRM insulation contains a large amount of asbestos, which is both an environmental and manufacturing concern. Accordingly, the ASRM design team has elected to change to an asbestos-free insulation (a Kevlar fiber-reinforced rubber material). It is, of course, critical that the new insulation provide the proper thermal protection and be adequately bonded to both the steel case and the propellant liner material. The development and verification test program planned for the new insulation is aimed at verifying the adequacy of insulation and bonding properties of the new material system.

An automated stripwinding technique is planned for applying the insulation to the primed steel cases. The RSRM design does not use an automated stripwinder but rather applies the insulation by a manual process. Thus, since the stripwinding process, as applied to the inside of the very-large-diameter ASRM cases has only been used on the new Titan IV solid rocket motor, it will require further development.

### DEVELOPMENT TESTING

Aerojet has completed a comprehensive laboratory investigation to develop an optimum formulation for the ASRM insulation and the proposed stripwinding application technique. A baseline specification was developed for the selected for-

mulation, and four commercial vendors are producing products to meet the requirements.

A pilot plant is being built in Sacramento to develop the stripwinding process to apply the new ASRM insulation. The technology developed in the Sacramento pilot plant will be the basis for the design of the full-scale equipment located in Yellow Creek. The pilot plant will be capable of demonstrating the stripwinding extrusion process on full-scale diameter cylinders but will have only a four-foot axial traverse, while the actual production plant operation will be required to travel the entire length of the ASRM segment (approximately 40 feet).

The process development program will concentrate on establishing stripwinder extrusion parameters and controls and will evaluate materials supplied by the four vendors from the same specification. Both nominal operating conditions and acceptable parameter tolerances will be developed, extremes of equipment capability will be established, and parameters and controls will be established for the cure process.

The ablative performance of the ASRM insulation material prepared in the Sacramento pilot plant will be initially evaluated in 48-inch diameter motors. Two of the five 48-inch test motors will contain four manually-applied insulation liner "swatches" manufactured from specification material supplied by the four material vendors. These materials will be compared with RSRM insulation in the same test motor. The remaining three motors will be insulated by the pilot plant stripwinding process. Insulation for the seven full-duration, full-scale motor tests will be applied with the full-scale manufacturing equipment at Yellow Creek.

#### DEVELOPMENT TESTING FINDINGS AND RECOMMENDATIONS

The Committee believes that the plan for developing and testing the insulation manufacturing process and the resulting product is well thought out and thorough. There is a high probability that pilot plant material will be successfully applied to the test articles. The likelihood of quick success in moving from pilot plant to full-scale production is, however, less certain. It is likely that significant development will still be required with the full-scale equipment before the process is fully proven.

While it is expected that the ASRM insulation will perform as well as the RSRM insulation, the ASRM program team will not have a significant indication of this until the 48-inch motors are tested and cannot be really confident until after some full-scale testing. The Committee recommends that:

- Contingency planning be done to account for the possibility that a greater than expected ablation rate may occur with the new insulation.
- The program team consider a backup approach to the automated stripwinder that utilizes manual application of the insulation.
- The program team should plan for some additional development work in the full-scale stripwinding facility, which may go beyond the currently planned tooling dry runs, full-scale test articles, and the Pathfinder motor.

### QUALITY ASSURANCE

Quality assurance for the automated stripwinding insulation process includes nondestructive evaluation of both the critical bondlines and insulation thickness, as well as destructive testing of witness samples that are produced at the same time that the cases are insulated. The automated ultrasonic approach to nondestructive testing is reported to be more sensitive than the current RSRM method and to provide better resolution of unbonded areas.

### QUALITY ASSURANCE FINDINGS AND RECOMMENDATIONS

The planned approach to both nondestructive and destructive evaluation of the case insulation is, in the opinion of the Committee, well conceived. The ultrasonic testing equipment to be used on the ASRM should lead to a thorough evaluation of the critical bondlines and, hence, a high confidence in the soundness of the insulation product.

The approach to controlling the incoming insulation materials planned for the ASRM should also lead to a superior product. This includes second-tier specifications of raw materials prepared by the ASRM project team and a program of detailed chemical characterization of the incoming materials, called fingerprinting. **The Committee has no recommendations in this area.**

## Liner

### DESCRIPTION

The ASRM liner provides the bond between the propellant and the insulation. This is a critical area, since loss of bonding between the propellant and the insulation can lead to catastrophic failure. The ASRM liner must bond successfully to both the propellant, with its HTPB (hydroxyl-terminated polybutadiene) binder, and the insulation. The liner consists predominantly of a carbon-reinforced HTPB polymer. A bonding agent, HX752, is used to increase mechanical strength. For Space Shuttle applications, this is an entirely new liner material system. However, there is a substantial history of use with the HTPB-based ASRM propellant family on other programs. The liner material will be batch mixed and applied to the insulation by an automated spray process to reduce contamination and enhance reproducibility.

### DEVELOPMENT TESTING

The liner development and verification program is aimed at selecting detailed formulations, defining the sensitivity of material properties to variations in composition and processing conditions, establishing material and process specification limits, and verifying that the material properties of the manufactured liner satisfy the requirements. One of the key requirements is that the factor of safety for the propellant/liner bond be greater than or equal to 2.0 during the total shelf life of the ASRM.

The current plan involves developing the liner manufacturing and control processes by laboratory and pilot plant experimentation at the same time that the allow-

able ranges of liner composition are determined. This ensures adequate process control over the allowable range of liner composition. The laboratory and pilot plant work is being carried out at the Aerojet facility in Sacramento, and the process data will be used to design the full-scale facility at Yellow Creek.

### DEVELOPMENT TESTING FINDINGS AND RECOMMENDATIONS

The Committee believes that the plan for obtaining key data on baseline liner formulation, allowable ranges of compositional variance, and process controls is well designed and thought out. It also believes that developing the proper liner chemistry and specification limits will not turn out to be a major issue. The scaling of the mechanical and automated control parts of the spray process from the relatively small pilot facility to a full-scale motor segment could, however, turn out to be more of a problem. In addition, the process must be qualified to cover the range of cleanliness and water vapor that may be present in the full-scale motor processing during scale up of the liner application process.

**The Committee recommends that after the liner specification is complete, one or two longer pilot plant runs be made at the extremes of the allowable liner compositional ranges to ensure that bonds that meet design strength requirements can be made even when the composition is near the limits of the specification.** If feasible, it is desirable to use the automated spray facility pilot plant to prepare liner at the limits of the specification on the 48-inch motor insulation.

The Committee believes that the transfer of automated liner spraying technology from pilot plant to full-scale production will not be a "turnkey" operation, that is, there will be considerable work needed to make the process work effectively once the process has been proven and the facilities are constructed. **Accordingly, the Committee suggests that the contingency planning for the activation of the manufacturing facility include the time and resources to do additional developmental testing with the full-scale equipment.**

### QUALITY ASSURANCE

The Committee believes that the ASRM program team has centered its approach to liner quality assurance on extensive and careful control of the manufacturing unit operations and incoming raw materials. The ASRM program team feels, and the Committee also believes, that keeping the processes and raw materials under control is the key to keeping the liner product within specifications. Accordingly, major emphasis is aimed at monitoring and controlling the processes and starting materials.

The ASRM program team has selected an automated ultrasonic inspection system for nondestructive evaluation of the propellant-to-insulation bondline. This will provide greater resolution for unbonded areas than is possible by x-ray analysis. All NDE tests should be checked and calibrated with deliberately-introduced and mapped voids in such a way as to characterize test effectiveness.



### QUALITY ASSURANCE FINDINGS AND RECOMMENDATIONS

The Committee believes that the program planning in the area of liner quality assurance and nondestructive testing is well thought out and should result in a good product. It was pleased to see that many of the lessons learned from the original SRM program regarding the need for very careful control of the physical and chemical properties of the raw materials will be carried out. The Committee also believes that automated ultrasonic inspection of the critical bondlines should lead to a more reliable product.

While the Committee believes that the quality assurance plans for manufacturing the liner are good, successful implementation has yet to be proven. **The Committee believes that the ASRM program team should be prepared for anomalies and surprises in this area and, as in other critical areas of ASRM design and production, should be aware of the need for adequate schedule flexibility.**

## Propellant

### DESCRIPTION

The ASRM propellant composition was selected to satisfy requirements for continuous processability, while enhancing safety and reliability. The baseline propellant will contain 88 percent solids in a HTPB polymer binder. Table 1 compares the principal constituents of the ASRM/HTPB propellant and the RSRM/PBAN propellant currently in use.

The ASRM propellant grain was designed to reduce or eliminate Space Shuttle main engine (SSME) throttling. (See endnote.)

The propellant grain configuration will be formed by using a water-soluble mandrel, or core, enclosed in a flexible bag. Use of the water-soluble mandrel should reduce the stresses on the cast propellant that result from the metal mandrels currently used in the RSRM program and increase personnel safety. Such mandrels

**TABLE 1** ASRM and RSRM Propellants

Application	RSRM	ASRM
Binder	PBAN	HTPB
Ammonium Perchlorate (AP)	69.73%	68.86%
Aluminum (Al)	16.0%	19.0%
Ferric Oxide (Fe <sub>2</sub> O <sub>3</sub> )	0.27%	0.14%
Total Solids	86.0%	88.0%

have been used in this application primarily in small intercontinental ballistic missile programs.

A significant experience base exists in the solid propellant industry with the family of HTPB propellants. On the order of 80 to 100 million pounds per year is produced for the Multiple Launch Rocket Systems, Delta Launch Vehicle Castor IV, Peacekeeper, and Titan IV. However, the continuous mix and cast process being used for the ASRM requires a unique formulation.

Based on the potential for improved safety and quality, the ASRM program team selected an automated continuous mixing process which is a significant change from the batch mixing process currently used to produce the RSRM propellant. In addition, there is limited experience with the continuous mix and direct cast process, and the rate of propellant production will be almost ten times larger than has been previously demonstrated.

### DEVELOPMENT TESTING

An extensive series of tests has been planned and is being implemented to complete the development of the propellant formulation and the manufacturing process.

A pilot plant of the proposed propellant manufacturing facility has been built by Aerojet in Sacramento and is currently in operation. The purpose of the pilot plant is to develop an understanding of all key process parameters required to develop a manufacturing process that is controllable and capable of producing a motor that meets all specifications. Laboratory and pilot plant data are being used to develop the material and process specifications.

Figure 2 shows a schematic of the continuous mixing process that will be used at Yellow Creek. During this startup period, the Committee believes there may be more difficulties than the project team expects in bringing the plant on-line to produce specification grade propellant. After the facility shakedown, Aerojet plans to manufacture about 1.2 million pounds of inert propellant and up to 800,000 pounds of live propellant prior to producing propellant for full-scale motor testing.

The ASRM program team will implement many complex analytical techniques during the motor design phase to achieve the desired motor ballistics and performance characteristics. A complete, three-dimensional computational fluid dynamics (CFD) analysis of the ASRM internal flow fields is being performed. A detailed knowledge of the flow field around such components as the aft dome, nozzle, and joint designs is essential. The ASRM project team intends to verify CFD analyses with cold flow analyses at the Marshall Space Flight Center. This analysis will support insulation design, thermal effects assessment, flow instability predictions (particularly around insulated motor joints), and ballistic performance predictions.

Some aspects of full-scale motor performance prediction depend on empirically derived factors. The ASRM program team is utilizing the RSRM data base to the extent possible, but the final empirical data base will come only from full-scale motor tests.

Existing data on the effect of humidity on cured HTPB ASRM propellant are not sufficiently definitive to preclude the possibility of detrimental effects. The ASRM

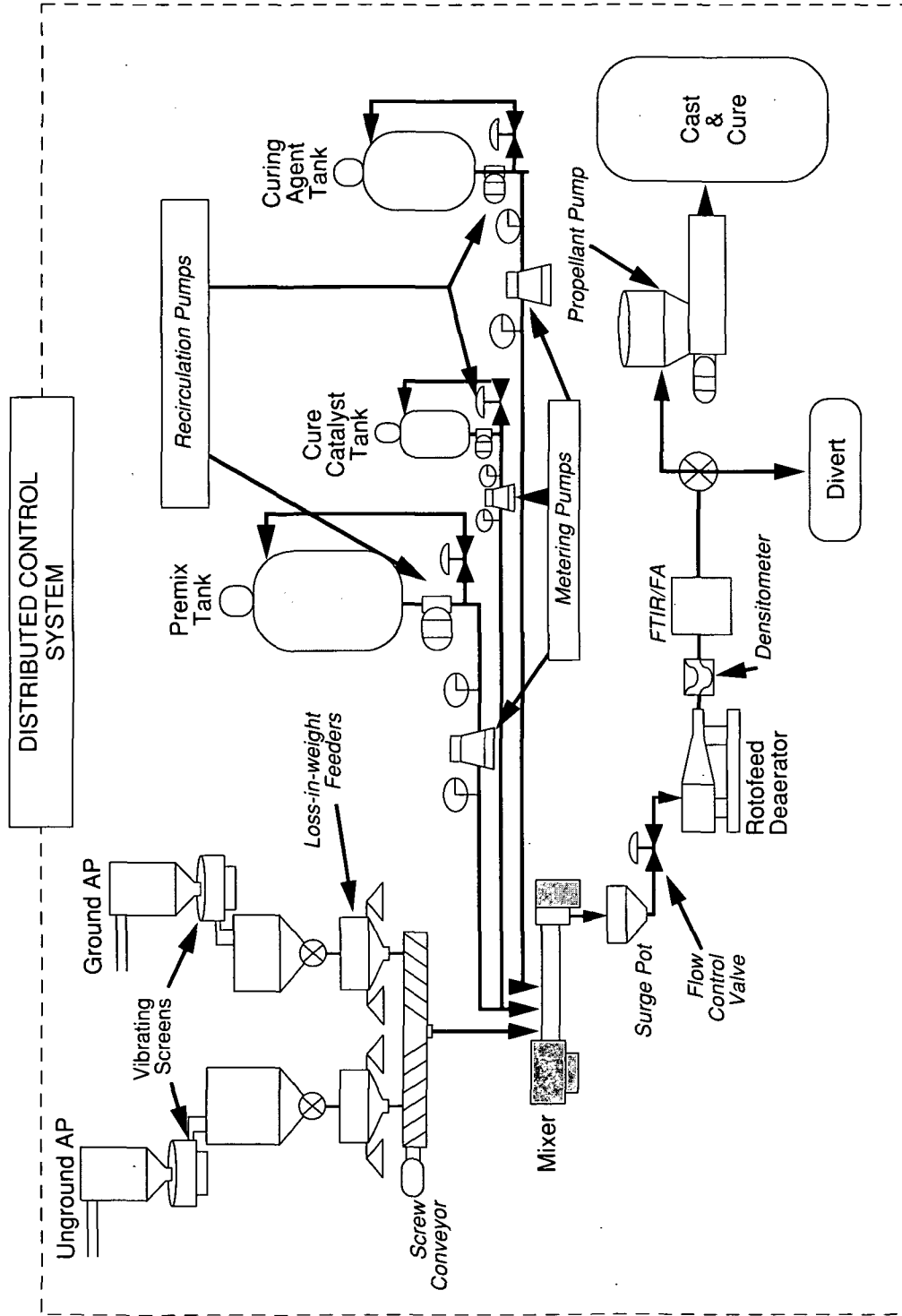


FIGURE 2 Yellow Creek continuous mix process.

program team is cognizant that humidity control requirements for ASRM propellant differ from RSRM propellant, and it is the Committee's understanding that this will be accommodated by a combination of testing (to determine humidity effects on the propellant characteristics) and provision for propellant protection during mixing, after casting, and when shipped to Kennedy Space Center (KSC). At KSC, exposure to humidity will be minimized by end caps on the segments and a nozzle plug. A full-scale motor "aging test article" is planned to demonstrate the five-year service life requirement.

### QUALITY ASSURANCE

During the continuous mix process, the system for monitoring the properties and constituents of the propellant mix is critical in producing an acceptable propellant for the flight motor. The propellant composition will be monitored and verified prior to casting by in-line densitometer analysis and by laboratory tests that will be taken every 20 minutes to assure compliance with mix standards. If the test results are unacceptable, the propellant will be diverted to scrap. There is a 30-minute delay loop in the continuous mix line to accommodate the necessary laboratory tests. There are plans for additional in-line techniques, such as Fourier Transform Infrared Spectroscopy (FTIR) and x-ray fluorescence analysis (FA), that promise superior control and which would permit automation of the quality monitoring process. The Committee urges the ASRM program team to continue developing these additional in-line techniques.

During the continuous casting of the ASRM motor segments, typical small test motors (e.g., five-inch CP and ballistic motors) will also be cast and cured for later evaluation as is done at present in the RSRM program. After casting, x-ray and ultrasonic techniques will be used to inspect each completed ASRM segment after the core has been removed.

Ten 48-inch test motors used primarily for insulation and nozzle tests will also provide propellant burn rate data, but not propellant ballistic data. The number of these motors that will be continuously mixed and direct cast has not yet been determined.

The seven planned full-scale development and qualification motor tests will provide critical information on propellant performance characteristics. The test objectives of these DM and QM tests are described in Appendix A.

### OVERALL PROPELLANT FINDINGS AND RECOMMENDATIONS

- From a conceptual standpoint, the Committee believes that after proper documentation and instrumentation, the continuous mix process promises adequate process control. With proper characterization of the individual operations, it should be possible to bring the mixing process under a state of statistical control that will allow the production of reliably mixed propellant with a consistent composition.
- Significant development activity will be required to provide design parameters

for the full-scale process, the necessary process controls, and the allowable composition ranges that must be controlled to ensure that the propellant product meets operational requirements. The plant equipment at Yellow Creek will have to be ten times larger than the equipment in the pilot plant, and there necessarily will be significant learning, debugging, and, in some cases, redefinition of characteristics. There is very little margin in the planning to accommodate anomalies. **The Committee recommends schedule and budget flexibility for additional pilot plant runs (which are not identified at this time) that will be required to retest and understand anomalies when and if they occur.**

- The ASRM program team believes that the continuous mix process will be able to control the compositional variances and product inhomogeneity better than current batch mix processes. The data to prove this, however, do not yet exist and must come from the pilot plant testing program. It is likely that the continuous liquid feeders to the mixer will provide liquid stream variance that is as low as batch mixing processes. There is some concern over the ammonium perchlorate powder feeders, which operate under different control modes (gravimetric operation over a large part of the cycle and volumetric operation over a second, smaller part). **The Committee recommends a thorough evaluation of the burning rate and chemical composition of material produced during volumetric operation. It also recommends that several of the 48-inch test motors be direct cast from propellant from the continuous mix pilot plant and compared with earlier 48-inch motors cast from the batch mixed process.**
- Current planning for pilot plant runs of propellant at the extremes of the specification limits is incomplete. Understanding the sensitivity to process variables is very important. Increased tolerance to these variables decreases flight risk. **In view of this, the Committee recommends that the ASRM program team make one or two longer pilot plant runs, after the propellant specification has been finalized, at the extremes of the propellant specifications, using the continuous mix process. This material then should be cast into five-inch CP motors and tested. Burn rate results should be compared with nominal propellant mix.**
- There are no test motor firings planned for motor sizes between the five-inch CP motors, with 10 pounds of propellant, and the full-scale ASRM tests that will specifically address the propellant qualities. The fact that propellant processing and ballistic suitability cannot be determined until the first full-scale development motor test presents the risk of delay in the event that predicted results are not achieved. Current scheduling of subsequent development motor firings allows minimum time for adjustments to the propellant mix if that should be required. The initiation of qualification motor casting before the development motor tests are complete compounds the problem. **The Committee recommends that the schedule be reexamined to ensure sufficient distancing between full-scale development motor tests to enable moderate propellant reformulation if required.**

**NOTE**

1. During launch, as the Space Shuttle speed increases, the system is subjected to large aerodynamic forces (Max-Q). During this time, the thrust of the engines is reduced (throttled) to reduce stresses imposed on the system. Once the Shuttle system has passed Max-Q, the aerodynamic forces subside and the SSME thrust is increased. Even though no catastrophic failure has occurred, there are potential failure modes associated with SSME throttling. The ASRM grain is being designed to inherently reduce thrust to limit Max-Q, which would eliminate or reduce SSME throttling.

## Igniter

### DESCRIPTION

The igniter contains solid propellant that, when burned, sends high-temperature gases into the motor which, in turn, ignites the ASRM propellant.

The objective of the new ASRM igniter design was to improve the performance and enhance safety through elimination of a large number of potential leak paths and to reduce pressure upon ignition through the use of multiple ports, new propellant and insulation, and a different grain design. The igniters will be manufactured at the Aerojet facility in Sacramento, shipped to the Yellow Creek facility, and installed into the assembled ASRM.

### DEVELOPMENT TESTING AND QUALITY ASSURANCE

The comprehensive development and test program for the ASRM igniter includes component pressurization tests, pressure seal verification tests, component burst tests, and ballistic performance tests. In addition, a heavyweight igniter will be fired in September 1991 to evaluate the start characteristics of the igniter grain. A flight-weight ASRM igniter, installed in a technical evaluation motor (TEM) and loaded with RSRM propellant, will be test fired early in 1993. The TEM test will evaluate the multiport igniter and confirm the ignition transient model. Further igniter characteristic data will be obtained from the three DM tests and the four QM tests.

Material process controls for the new ASRM igniter design will be ensured by fingerprinting.



During the briefings, the Committee received the impression that NASA and the contractor were applying the lessons that had been learned from RSRM igniter experiences. However, the Committee did not perform an in-depth examination of the igniter and has no recommendations.

## Nozzle

### DESCRIPTION

The design of the ASRM nozzle is intended to improve the overall performance of the motor, when compared to the RSRM design, while also enhancing both reliability and safety. The performance gains are accomplished primarily through a reduction in the overall weight of the nozzle. A new, compact flexbearing/flexseal design reduces the weight of the nozzle, from that of the RSRM, by approximately 4,250 pounds. The use of a new low-density carbon cloth phenolic (LDCCP) ablative material in the nozzle's aft exit cone and fixed housing saves approximately 700 pounds. The total weight reduction from two ASRM nozzles per launch is on the order of 9,900 pounds, which translates to an increase in Shuttle payload of approximately 900 pounds.

During firing, the nozzle must withstand hot gas temperatures in excess of several thousand degrees. In the past, there have been instances on other programs where the material erosion rate was greater than expected, resulting in severe safety concerns regarding burnthrough of the nozzle. A critical factor in protecting the nozzle from burnthrough during propellant burning is the selection of the ablative material. As stated above, use of LDCCP is currently planned in the ASRM aft exit cone. It will be applied by a newly developed automated process, as opposed to the manual system used in RSRM nozzle production. An alternate plan using the standard density carbon cloth phenolic is being pursued in the event the LDCCP does not prove satisfactory.

In addition to the use of the LDCCP materials, weight reduction is also achieved by decreasing the number of parts. Automated manufacture and assembly processes

with increased use of statistical evaluation of the process parameters will also be initiated.

The ASRM nozzle will be manufactured by the Thiokol Corporation, the contractor currently responsible for the RSRM nozzle. Thiokol has identified five areas of concern that remain regarding the design and verification of the ASRM nozzle:

1. **There is a lack of full-scale data on the ablative throat erosion rate with the ASRM propellant.** Data are to be obtained from 48-inch motor tests.
2. **LDCCP aft exit cone erosion may be an important factor in the new nozzle design.** The effect of the LDCCP material and the degree of particle impingement on the aft exit cone erosion is under investigation. The current design with LDCCP materials will be tested in 48-inch motor tests and the technical evaluation motor (TEM) test. If necessary, the LDCCP will be replaced by CCP, resulting in a weight penalty of approximately 700 pounds.
3. **There is question regarding the effectiveness of the planned curing process.** It is planned to use a nitrogen-based medium at 300 psi to cure thick parts rather than a water-based medium at 1,000 psi. The 300 psi process was selected to reduce cost, and to minimize scrap due to water intrusion, but has yet to be proven in actual use.
4. **The two-dimensional structural analysis of the flexbearing is inadequate.** A three-dimensional, nonlinear analytical model is being developed and a one-fourth scale experiment is proposed to validate the modeling assumptions.
5. **It has been predicted that the worst-case thrust vector control system torque requirement will be greater than the certified capability of the actuator.** There is some discrepancy between RSRM and ASRM requirements, which, when clarified, may lessen this issue. Tests are proceeding to develop a bearing with less torque than that of the RSRM. Test plans for verification of the control system bearing have not been finalized.

As indicated, the ASRM program team is proceeding with activities to resolve these issues.

#### DEVELOPMENT TESTING

The ASRM nozzle design will be evaluated via a number of full-scale, subscale, and component tests. Component tests include three characterization tests of the flexbearing/flexseal, an ultimate pressure load test of the flexbearing/flexseal, and a burst test of the fixed housing. Five subscale tests will be performed, using 48-inch motors, to evaluate the performance of the selected materials, including the LDCCP ablative material and to evaluate the accuracy of the thermal and structural predictive models.

A full-scale prototype of the ASRM nozzle will be tested on the TEM. This prototype will actually be a hybrid configuration, since it will have metal parts and in-line contour from the RSRM design and nonmetallic parts and exit cone contour from the ASRM design. In this test, the nozzle's ablative materials, the throat, and

aft exit cone will be evaluated. It will also be determined if the analytical models are verified.

The first full-scale, full-duration tests will occur with the first of three planned development motor tests. The DM tests are meant to confirm the ASRM design using hardware that is as close as possible to that eventually flown. Full-scale tests will also be performed via four qualification motor tests. The QM series of tests will use hardware built from the final ASRM design to provide system-level flight certification.

The set of tests described to the Committee are designed to verify compliance with all nozzle and insulation material safety factor requirements and demonstrate the reusability of major components.

### QUALITY ASSURANCE

The new ASRM nozzle design includes large quantities of new composite materials joined by adhesives. Nondestructive evaluation (NDE) techniques will be used to assess the quality of the composite parts. The development of the NDE processes to verify the integrity of the adhesive bonds is in its early stages. Because of the critical nature of the nozzle in achieving safe flight and because of the early stage of development of the NDE processes, rigid control of materials and processes is mandatory. The quality of raw materials will be evaluated through extensive characterization of the parameters that are critical to the integrity of the final product and through assurance that all materials used actually conform to the required characteristics (fingerprinting). The success of this program is dependent upon careful evaluation of the critical parameters. This is not yet complete.

Numerous in-process assessments will be made using witness panels that accompany each production unit through the manufacturing cycle. Critical process parameters will be monitored and controlled with extensive instrumentation.

Automated processes will be used to apply multiple-layer composites. This is expected to reduce process variations over those that typically occur when manual processes are used. The effectiveness in achieving this objective cannot be determined until more experience is gained using the automated process.

### OVERALL NOZZLE FINDINGS AND RECOMMENDATIONS

- The ASRM nozzle design represents a departure from the RSRM nozzle, including changes in ablative materials, changes in physical configuration, changes in seals, elimination of the radial bolts in the case-to-nozzle joints, and changes in the manufacturing processes. Relatively little information about the overall system performance of this new nozzle will come from subscale testing. Full confirmation of the design must await the full-scale, full-duration motors. The ASRM program team should recognize the likelihood of unanticipated results and plan accordingly.
- The ASRM program team has stated that performance, safety, and reliability

will be enhanced with the new nozzle. However, there is a considerable reduction in the weight of the ASRM nozzle, compared to the RSRM nozzle (approximately 4,250 pounds per nozzle). In similar systems, enhancing safety and reliability has led to weight gains. Thus, while a detailed analysis has not been made by the Committee and the test program as described is designed to detect design inadequacies, there is concern over the possible impact this weight reduction will have on safety and reliability. **It is recommended that the ASRM program team review and fully evaluate the implications of the nozzle weight reduction.**

- While the ablative material and the automated application process differ from those used in the RSRM aft exit cone and housing, there have been promising test and analysis results to date. The final decision to use the LDCCP, rather than a standard-density carbon-carbon phenolic material, has not been made, pending further tests of the material during firing and continued tests of the automated processes. The Committee stresses that safety and reliability should not be sacrificed for performance in using this material.
- The Committee believes that the plan for development and testing of automated processes to be utilized in manufacturing the nozzle has been well thought out and has the potential for a higher-quality product. However, the transition from the present prototype manufacturing installation (and associated process development) into the fully automated insulation and bonding process may be difficult. It may be that development of full-scale equipment and sensing instrumentation along with the necessary processes will require additional effort to fulfill the objectives of enhanced flight safety and reliability. **Thus, the Committee recommends that the ASRM program team continue to develop contingency plans in order to accommodate unanticipated results.**
- The program team plans to test the new case-to-nozzle joints with purposely inserted flaws in the transient pressure test article (TPTA) test. At this point plans have not been prepared to carry this type of flaw testing or margin testing into the full-scale, full-duration development motor tests. Similarly, the nozzle duty cycles have yet to be determined. **The Committee recommends that case-to-nozzle joints with preengineered flaws that remove some of the sealing redundancy be tested in the full-scale, full-duration development hardware as well as in the TPTA as final confirmation that the seals in the joints are truly redundant. The Committee also recommends that nozzle duty cycles be tested under the projected, worst-case flight situation.**
- In the view of the Committee, the quality assurance program has incorporated experience from previous programs and will be at least as effective as that of past programs. **The Committee recommends that efforts be continued to develop effective NDE techniques for the nozzle adhesive bonds. It also recommends that the automated processes be enhanced wherever practical with dual redundancy of critical process monitoring and control parameters.**

## Overall Evaluation

### THE ASRM TEST PROGRAM

Appendixes A and D show the elements of the total test program. The test program plans have applied the lessons learned from previous large solid propellant rocket motor developments, particularly the RSRM. The ASRM incorporates numerous new materials, design features, and manufacturing processes. The development test program is intended to evaluate these new features. Program plans should have the flexibility to accommodate a reasonable level of test failures and test program modifications as more is learned of the new design. The Committee did not perform a detailed review of the program schedules but received the impression that the program is more success oriented than the relatively large number of new or revised designs and materials would justify.

The seven, full-scale tests are very important in ensuring the safety and reliability of the ASRM. After much discussion, the Committee found no basis for recommending a change in the number of DM and QM full-scale tests, but recommends the following:

- **In the detailed test plans, the criteria for success of each subsystem and system test should be defined and an analysis predicting the expected performance of each test should be prepared and documented in advance, clearly delineating pass/fail criteria. (See endnote 1.)**
- **The qualification motor tests should be conducted under firm discipline with regard to constant design, components, and processes. If a change occurs, additional tests should be planned to validate the change. In the**

**event of failure to pass the test criteria or of a major anomaly, retest should be required to demonstrate the effectiveness of corrective action. This will require an appropriate number of full-scale tests, possibly larger than the number now planned.**

### **QUALITY ASSURANCE PROGRAM**

The quality assurance program described in earlier chapters incorporates lessons learned from previous large solid rocket motor developments. It is planned to use the most advanced forms of nondestructive evaluation techniques (NDE, see Appendixes B and C). This, combined with the material fingerprinting program and the anticipated statistical process control program, should provide confidence in the integrity of the completed motors.

Currently, NDE techniques are being developed to inspect the integrity of the nozzle bonds. Such a process is highly desirable. While NASA anticipates that large margins of safety will be present in these bonds, the Committee believes precise process control is required to ensure bond integrity and flight safety. It is recommended that efforts be continued to:

- **Develop an effective NDE process for the nozzle bonds.**
- **Implement a statistical process control program for all critical elements of the ASRM.**

### **SCHEDULE AND COST RISK**

The Committee's charter for this study did not include an evaluation of schedule and cost risk factors. However, it is believed that these factors may have an impact on potential flight safety if they result in reduced testing and quality assurance measures. It is the impression of the Committee that the test program is highly success oriented and, for this reason, there is some probability that the current schedule will not be achieved. Further, test failures frequently result in the need to manufacture and test replacement test articles, resulting in cost increases. The Committee recommends that:

- **Program schedule and cost assumptions be examined and amended as necessary to assure that they account for a reasonable level of test failures.**
- **Firm criteria be applied such that the test program, as outlined, will not be compromised for schedule and cost reasons.**

### **AVAILABILITY OF SKILLED PERSONNEL**

The remote location of the development and production facility at Yellow Creek, Mississippi, could create a problem in acquiring and retaining the engineers, managers, and technicians required to develop and produce a high-quality motor. The

current work force of the area does not possess the necessary skills. This requires that either skilled personnel be relocated into the area or that the local workers be provided with the prerequisite skills through training programs. It is likely that technicians can be trained from local recruits, and the ASRM program team is currently instituting training programs. However, previous experiences have shown that this can be a time consuming and frustrating experience with many failures.

- **It is recommended that technician training be started early and that the number of trainees be sufficient to account for attrition during the early years of operation.**

### **RELATIONSHIP BETWEEN TESTING AND QUALITY ASSURANCE AND RELIABILITY AND SAFETY**

In deliberating on the need for quantitative goals for reliability and safety, Committee members concluded that a rational approach to risk management should have three parts:

1. An explicit safety objective, whatever its basis. For example, it may be through comparison of the risk to other risks that are generally deemed to be acceptable.
2. A management plan and a budget suitable for limiting the risk to the desired level.
3. A figure of merit, that is, a means of assessing whether the plan implementation is yielding risk levels commensurate with the objective. Probabilistic risk assessment is one way of performing this function.

Essentially, the ASRM has only a management plan and lacks both an articulated safety objective and a means of judging whether the objective will be met. Thus, the Committee could only judge whether the program is compatible with the current state of the art. This is an important evaluation to make, but falls short of providing a definite evaluation related to astronaut safety, which could be performed if the criteria and priorities were more explicit.

- **The Committee recommends that NASA establish numerical objectives for reliability and safety and develop a means for assessing the degree to which the program is meeting these objectives.**

### **USE OF PROBABILISTIC RISK ASSESSMENT**

The ASRM program is not currently applying probabilistic techniques to assess the potential safety risks of the various elements of the system. The ASRM system, by its nature, is not amenable, except in isolated instances, to the application of redundancy to reduce risk and is susceptible to single-point failure modes in the case, propellant, insulation, nozzle, and other elements. Probabilistic risk assessment (PRA) has proven effective in similar situations, for example, in some aero-



space applications and nuclear reactor systems, in identifying the highest potential risk areas, thus enabling more informed decisions on design options and allocation of resources to minimize risk.

While quantitative risk assessment is not risk management, it can serve to assess the consequences of management, and thereby become an effective tool for the discovery of weak points and the assignment of priorities. It can perform the function of the third item on the list in the preceding section. It also can serve to identify items that do not require much attention, freeing resources for more important matters. In the context of the test and quality assurance programs, it can provide an underlying rationale for myriad choices of safety margins and pass/fail criteria.

The Committee was divided on the issue of a general application of probabilistic risk assessment to the ASRM design. However, it was in agreement that selective applications could prove beneficial in assessing the risks of various design features. One example would be to determine if the O-ring leak checks, which require drilling holes in the case metal and inserting plugs after performing checks for leakage, add or detract from overall flight risk. Additional areas for application of PRA, such as the flight risk from welding defects, should also be identified. (See endnote 2.)

- **The Committee recommends that NASA evaluate the potential benefit to be derived from a general application of PRA at this point in time and of its application in the specific instances discussed above.**

#### AUTOMATED MANUFACTURING PROCESSES

The ASRM program is introducing numerous automated processes with the intent of enhancing process control and thus improving repeatability from unit to unit and enhancing product quality. The Committee agrees that a well-implemented automated manufacturing process has the potential for more consistent quality. It is concerned, however, with the complexity of the task of bringing this extensive automation on-line and with potential problems in the scale-up from pilot plant to the full-scale Yellow Creek facility. The Committee's review indicates that the development program for these automated processes are soundly planned, but, even in the best of worlds, the start up of a complex automated facility is difficult and time consuming. The Committee recommends that:

- **The program schedule be reviewed to assure that ample time has been allocated for start up of each full-scale automated manufacturing process.**
- **Where practical, manual or semiautomatic backup processes be identified in a contingency plan for implementation if required.**

#### NOTES

1. Similar conclusions were reached during an earlier NRC study and appear in the *Collected Reports of the Panel on Technical Evaluation of NASA's Redesign of the Space Shuttle Solid Rocket Booster* (Chairman, H. Guyford Stever), National Academy Press, 1988.

2. NRC, *Post-Challenger Evaluation of Space Shuttle Risk Assessment and Management* (Chairman: Alton D. Slay), National Academy Press, 1988. The report states, "Top management and program attention should be focused on those items with the greatest risk to the safety of a system by means of a prioritization of all contributors to the overall risk. Acceptable levels of risk should be set by the Administrator of NASA. However, suitable quantitative measures of risk, such as probabilistic risk assessment, are required to objectively define the acceptable levels, track progress toward achieving these levels, and evaluate alternate courses of action to reduce risk."

## Biographical Sketches of Committee Members

LAURENCE J. ADAMS is the retired President of the Martin Marietta Corporation, where he spent his entire professional career. His technical experience includes assignments as Stress Analyst; Chief of Structures Design; Technical Director for the Titan III development program; Director of Engineering, Denver Division; Vice President, Special projects; and President, Martin Marietta Aerospace. Mr. Adams is a member of the National Academy of Engineering and served on the National Research Council committee that reviewed the redesign of the Solid Rocket Motor after the Space Shuttle Challenger accident. He is a Past President of the American Institute of Aeronautics and Astronautics, a member of the NASA Advisory Council and the U.S. Air Force Scientific Advisory Committee, and Chairman of the NASA Space Station Advisory Committee. Mr. Adams received his B.S. in Aeronautical Engineering from the University of Minnesota.

JANICE L. BEADELL is a manager of Advanced Supportability Technology, Douglas Aircraft Company, in Long Beach, California. Over the past 11 years at Douglas, she has held technical positions as a statistical analyst and a logistics maintainability specialist, and has been a section manager, branch manager, and currently a business unit manager. She developed the Cost of Ownership Model for the Douglas MD-90 program and developed a number of reliability, maintainability, and logistics systems for the C-17 aircraft. Ms. Beadell holds a B.A. in Economics from the University of California at Santa Barbara and completed the course work towards an M.A. in Econometrics at California State University at Long Beach.

JACK L. BLUMENTHAL is Assistant Director of the TRW Center for Automotive Technology. He has spent over 25 years at TRW in line and project management positions involving the development, testing, and application of materials and chemical systems and processes. Before assuming his present position, he was Chief Engineer for Engineering Operations in TRW's Space and Technology Group. His primary interests include high-temperature materials and ablative material systems, combustion and propulsion, surface chemistry and catalysis, thermodynamics, and reaction kinetics. Dr. Blumenthal holds 12 U.S. patents. He received his B.S., M.S., and Ph.D. degrees in Chemical Engineering from the University of California at Los Angeles, where he has been an Adjunct Professor of Engineering. He served on the NRC committee that reviewed the redesign of the Space Shuttle Solid Rocket Booster.

YVONNE C. BRILL recently retired from the International Maritime Satellite Organization (INMARSAT), where she was a staff engineer in Space Segment Engineering. She began her career as a mathematician with the Douglas Aircraft Company and subsequently served as a research analyst with the RAND Corporation, then as a project engineer and consultant at several aerospace firms throughout the 1950s, 1960s, and 1970s. In 1978, she became Manager of NOVA Propulsion Systems for RCA Astro-Electronics Division, and later served as Manager of the Solid Rocket Motor program in NASA's Office of Space Flight. Her expertise lies in spacecraft and spacecraft propulsion engineering, as well as program planning and management. Ms. Brill received her B.Sc. in mathematics from the University of Manitoba, Canada, and her M.S. in Chemistry from the University of California at Los Angeles. She is a member of the National Academy of Engineering and a Fellow of both the American Institute of Aeronautics and Astronautics and the Society of Women Engineers.

CHARLES P. FLETCHER is Vice President for Engineering at Alcoa. With Alcoa since 1957, he held a succession of engineering, operations, and general management positions in the company's overseas operations before becoming Operations Director for primary products research and development at Alcoa Laboratories in 1981. Since 1984, Mr. Fletcher has been named to a succession of vice presidencies culminating in his current position. He received a B.S. degree in Mechanical Engineering from Cornell University and an M.S. in 1973 from the Massachusetts Institute of Technology, where he was a Sloan Fellow.

PAUL M. JOHNSTONE spent his career in engineering design, development, acquisition, and operation of commercial aircraft. After obtaining his B.S. in Aeronautical Engineering from the University of Notre Dame in 1946, he joined the Douglas Aircraft Company, where he was first an aircraft performance engineer and then a stability and control engineer engaged in aircraft design and certification. After five years as an Operations Engineer and later head of Technical Operations for Hawaiian Airlines, he joined Eastern Airlines as Manager of Economic and Performance Analysis in the Development and Engineering Group. At Eastern, Mr. Johnstone rose to Vice President, Engineering, and later Senior Vice President,

Operations Services. In those positions, he directed evaluations and was responsible for engineering, quality assurance, maintenance, inventory management and control, production planning and control, and purchasing. In addition, he was corporate technical representative at all Eastern accident investigations. Mr. Johnstone is a Fellow of the American Institute of Aeronautics and Astronautics.

HAROLD W. LEWIS, Professor Emeritus of the University of California at Santa Barbara, was Professor of Physics at the University of California at Santa Barbara, specializing in theoretical physics. He was a member of the technical staff at AT&T Bell Laboratories from 1951-1956 and later a physics professor at the University of Wisconsin, before coming to UCSB in 1964. He was director of the Quantum Institute at UCSB from 1969 to 1973. Dr. Lewis has served on the Defense Science Board and on a number of national committees relating to nuclear safety. He earned his B.A. at New York University and his M.A. and Ph.D. in Physics at the University of California. He is the author of *Technological Risk*, published in 1990.

JAMES W. MAR, Professor Emeritus of the Massachusetts Institute of Technology, recently retired as Hunsaker Professor of Aerospace Education in the Department of Aeronautics and Astronautics. He was Director of the MIT Space Systems Laboratory and the Technology Laboratory for Advanced Composites as well. He is a member of the National Academy of Engineering and has served on National Research Council panels on thermal protection systems, thermal protection of aerospace vehicles, and structural design with fibrous composites. Dr. Mar also served on the NRC committee that reviewed the redesign of the Solid Rocket Motor after the Space Shuttle Challenger accident. In addition, he is a past member of the NRC's National Materials Advisory Board and was a consultant to NASA's Committee on Space Vehicle Structures. He was Chief Scientist of the Air Force from 1970 to 1972 and Department Head of the Department of Aeronautics and Astronautics at MIT from 1980 to 1982. Dr. Mar is a Fellow of the American Institute of Aeronautics and Astronautics. He received his doctorate in Civil Engineering from MIT in 1949.

WILLIAM A. OWCZARSKI is the Director of External Technology Development and a member of the staff of the United Technologies Research Center. Previously, he was a Senior Policy Analyst and Industrial Research Institute Fellow at the White House Office of Science and Technology Policy. While at OSTP, he served as Chairman of the Committee on Materials of the Federal Coordinating Council on Science, Engineering, and Technology. Dr. Owczarski spent 25 years with Pratt & Whitney, United Technologies Corporation, contributing to development of materials, processes, and manufacturing methods used to produce jet engines. His career has spanned positions in research, engineering development, program management, and technology planning. He has been issued 11 patents and is a Fellow of the ASM International. Dr. Owczarski received his B.S. degree in Electrical Engineering from the University of Massachusetts and an M.S. and Ph.D. in Physical Metallurgy from Rensselaer Polytechnic Institute.

**ADVISORS TO THE COMMITTEE**

DONALD L. ANTON heads the Advanced Materials Testing Group and is a member of the Materials Sciences staff of United Technologies. Dr. Anton has had experience in the fatigue and fracture characterization of Ni-base superalloy castings and weld processing of 4140 steel, as well as development of castable stainless steels. Currently, his primary duties include development of advanced intermetallic alloys and composites for advanced aero-propulsion engines. As a contributor to the Titan 34D Recovery team, he lead the fracture, fatigue and stress corrosion cracking studies related to D-6ac case materials. Dr. Anton earned his B.S. degree from Purdue University in metallurgical engineering and a Ph.D. from Northwestern University in Materials Science and Engineering.

WILLIAM S. McARTHUR, a U.S. Army Lieutenant Colonel, is currently assigned to NASA as an Astronaut (Mission Specialist). He received his commission in 1973 upon graduation from the United States Military Academy. Subsequent assignments included flying helicopters and airplanes both overseas and in the United States. LTC McArthur received an M.S. degree in Aerospace Engineering from the Georgia Institute of Technology in 1983, after which he was assigned as an Assistant Professor of Aerospace Engineering at the Military Academy. Following graduation from the U.S. Naval Test Pilot School in 1987, he was assigned to NASA to support launch and landing operations. Selected as an astronaut candidate by NASA in January of 1990, LTC McArthur completed a one year training and evaluation program in July 1991, qualifying him for assignment as a mission specialist on future Space Shuttle flight crews. LTC McArthur currently represents the Astronaut Office on all Space Shuttle solid rocket programs.

# Appendix A

## Overall ASRM Test Program

### **SUBSCALE, 48-INCH DIAMETER MOTORS (MNASA)**

It is planned to test ten, 48-inch diameter motors. All of the motors will use the new ASRM propellant. However, even though the propellant in the final flight motors will be produced by the continuous mix/cast process, in at least eight of the 48-inch test motors, the propellant will be continuous mixed and batch cast. Continuous casting is under consideration.

Five of the 48-inch motors will be used to evaluate the ASRM nozzle design. The other five 48-inch motors will be used to evaluate the ASRM insulation materials. The tests will be carried out at Marshall Space Flight Center.

### **FIELD JOINT STRUCTURAL TEST ARTICLE (FJSTA)**

The FJSTA will confirm the field joint analytical model and mechanical behavior. The test will utilize two RSRM domes and two short, 146-inch diameter cylinders connected by an ASRM bolted field joint. However, the case material used in FJSTA will be the RSRM case alloy rather than the ASRM case alloy. This test will take place at Marshall Space Flight Center.

### **LIFE CYCLE ENDURANCE/HYDROBURST TEST ARTICLE (LCE/HBTA)**

The objective of this test is to verify the overall structural integrity of the ASRM case. In addition, the service life of 19 reuses will be demonstrated by subjecting a 150-inch diameter short stack case to multiple pressure cycles. The performance of

the bolted field joints and welds through the service life will also be evaluated. A final hydroburst cycle will certify yield and ultimate safety factors and determine the burst pressure of the assembled case. This test will take place at Marshall Space Flight Center.

#### **TRANSIENT PRESSURE TEST ARTICLE (TPTA)**

The TPTA program consists of a series of short-duration, hot-fire dynamic load tests to certify the sealing capability of the ASRM field joints, nozzle joints, and igniter, under a simulated motor pressurization cycle and the application of external loads. The test article will be composed of a 150-inch diameter short stack with two field joints and an aft skirt attached. Progressively worse flaws will be introduced into the seals during the test series. These tests will take place at Marshall Space Flight Center.

#### **STRUCTURAL TEST ARTICLE (STA)**

A multitest program will demonstrate the ASRM case structural integrity when subjected to prelaunch, lift-off/maximum dynamic pressure, and splashdown load conditions. It will also verify that the case and aft skirt meets the 1.4 safety factor when subjected to maximum internal operating pressure and when maximum operational loads are applied. The test article will be comprised of a heavy-weight, nonflight, forward skirt; a shortened 150-inch diameter forward case segment; a full-length aft case segment; one bolted field joint; and an aft skirt. These tests will take place at Marshall Space Flight Center.

#### **ASSEMBLY TEST ARTICLE (ATA)**

The ATA will consist of 150-inch diameter forward and aft segments and will be used to certify vertical stacking at Kennedy Space Center.

#### **TECHNICAL EVALUATION MOTOR (TEM)**

A TEM (Space Shuttle SRM, manufactured prior to the Challenger accident) full-duration test will be conducted at the Thiokol facility in Wasatch, Utah to confirm the nozzle materials and evaluate multiport igniter performance.

#### **DEVELOPMENT AND VERIFICATION TEST PROGRAM**

The currently planned development and verification test program includes one full-scale Pathfinder motor with inert propellant, three development motors, and four qualification test motors. The testing of all of these motors will be complete prior to the first flight. However, on the current schedule, the qualification motors are in the process of being built before all of the development testing is complete.



### PATHFINDER

The Pathfinder motor will be the first full-scale ASRM motor that will be produced with the new automated processes and materials in place. The major difference, however, is that inert propellant (with similar properties to the live ASRM propellant) will be used. The Pathfinder motor will later be refurbished with live propellant at Yellow Creek to demonstrate the five-year service life requirement.

The objectives of the Pathfinder test are:

- Verify Yellow Creek manufacturing and processing operations, equipment and facilities;
- Demonstrate case segment assembly operations (including Igniter and Nozzle);
- Confirm that the loading and barge transit to Stennis meets requirements;
- Verify Stennis functional flow operations, equipment and facilities, including horizontal assembly;
- Demonstrate loading, transit and off-load operations from Stennis to Kennedy Space Center;
- Verify Kennedy Space Center receiving, transfer, and storage operations;
- Verify facility interfaces; and
- Demonstrate and confirm Vehicle Assembly Building stacking operations, procedures, equipment, and facilities.

### THREE, FULL-SCALE DEVELOPMENT MOTORS (DM)

The three development motor (DM) tests are designed to provide confirmation of the ASRM design, materials, processes and performance. The DM-1 and DM-2 horizontal static test firings will provide data to evaluate the capability to meet the configuration end item (CEI) requirements. Necessary modifications will be incorporated and verified in the DM-3 horizontal static firing prior to committing to the qualification testing.

The objectives of the development motor tests are:

- Define ignition and ballistic performance at 40°F, 60°F and 90°F;
- Confirm or modify analytical models;
- Acquire full-scale, full-duration performance data on case, insulation, and nozzle materials;
- Confirm pressure sealing integrity during motor operation;
- Verify the nozzle vectoring capability meets CEI requirements;
- Demonstrate exit cone severance; and
- Acquire performance data on other ASRM subsystems, flight test instrumentation, system tunnel components, and field joint environment protection.

### FOUR, FULL-SCALE QUALIFICATION MOTORS (QM)

The four qualification motor test series will provide performance data necessary for flight certification of the ASRM at the system level.

The test objectives are:

- Verify that the ASRM meets all performance requirements over its operational temperature range (40°F, 60°F, 90°F);
- Verify that the matched flight set performance is within CEI specification requirements;
- Verify compliance with all nozzle and insulation material safety factor requirements;
- Demonstrate/certify reusability of major components; and
- Confirm successful operation or response of installed subsystems during exposure to static firing environments.

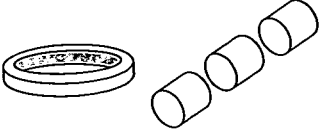
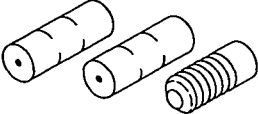
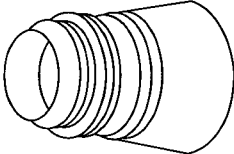
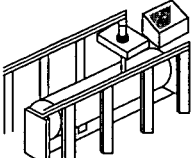
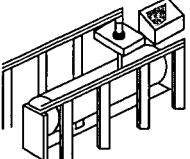
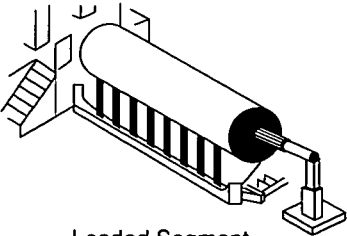
## Appendix B

### Nondestructive Evaluation Methods

- Electromagnetic Acoustic Transducer (EMAT): Detects surface and subsurface anomalies
- Eddy Current Test (ET): Detects surface and subsurface anomalies
- Fourier Transform Infrared Spectroscopy (FTIR): Identifies organic substances, particle size, and quantitative analysis of mixtures.
- Leak Test (LT): Verifies O-ring seal integrity
- Magnetic Particle Test (MT): Detects surface and near surface anomalies
- Optically Stimulated Electron Emission (OSEE): Detects surface contamination
- Penetrant Test (PT): Detects surface anomalies
- Radiography Test (RT): Detects surface and subsurface anomalies
- Real-Time Radiography (RTR): Detects surface and subsurface anomalies
- Ultrasonic Test (UT): Detects surface and subsurface anomalies
- X-ray Fluorescence (XRF or FA): Allows bulk qualitative and quantitative analysis of solids and liquids

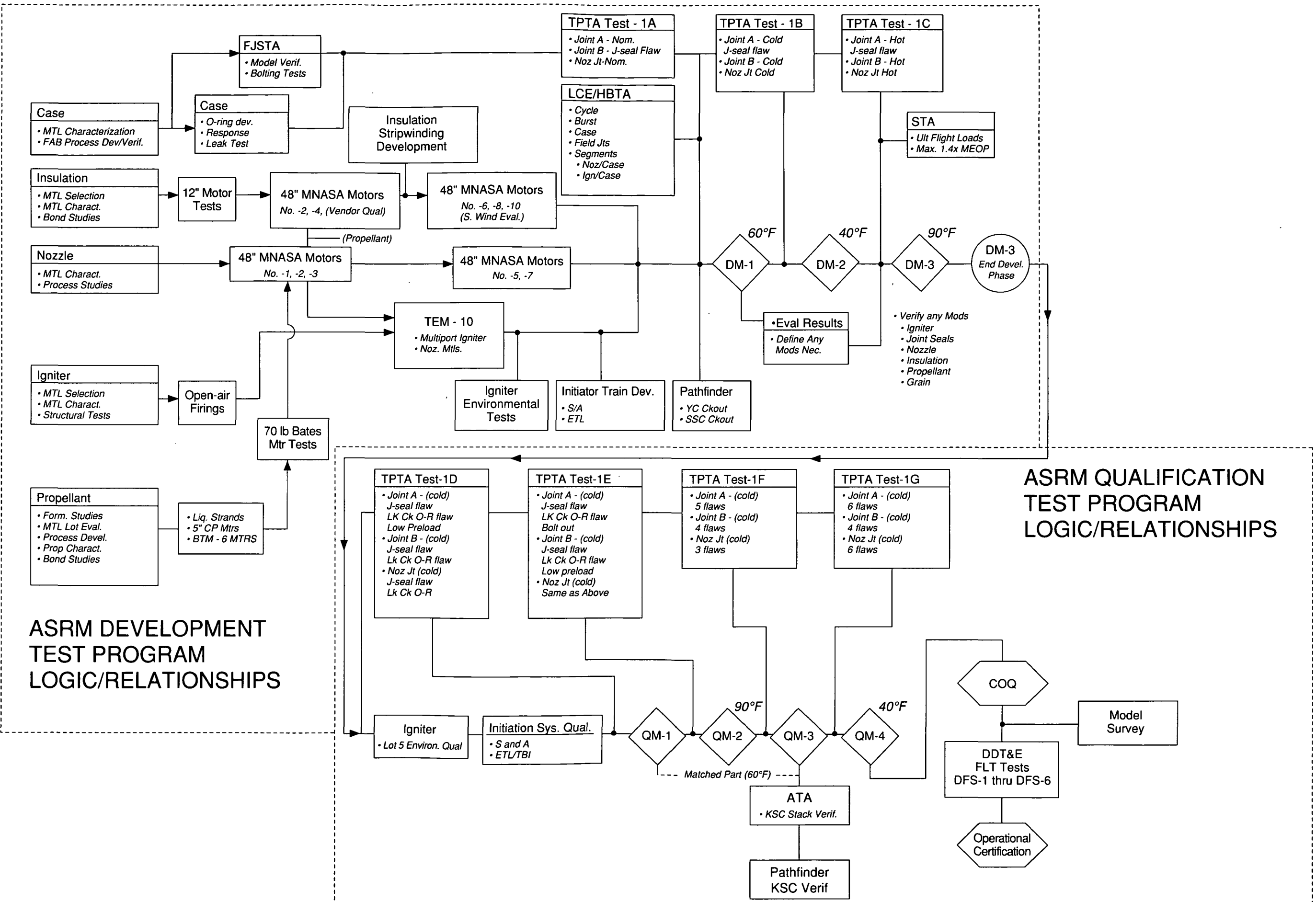
## Appendix C

### Component NDE Methods

COMPONENT	COMPONENT/NDE	CONTRACTOR
 <p style="text-align: center;">Forgings</p>	<p>Forgings:</p> <ul style="list-style-type: none"> <li>• UT</li> </ul>	<p>Ladish</p>
 <p style="text-align: center;">Welded Case Segments</p>	<p>Case Segments:</p> <ul style="list-style-type: none"> <li>• MT</li> </ul> <p>Welds:</p> <ul style="list-style-type: none"> <li>• RTR</li> <li>• MT</li> </ul>	<p>Babcock &amp; Wilcox</p>
 <p style="text-align: center;">Nozzle</p>	<p>Nozzle Assembly:</p> <ul style="list-style-type: none"> <li>• LT Joints</li> </ul> <p>Flexseal:</p> <ul style="list-style-type: none"> <li>• Acceptance Tests</li> </ul> <p>Exit Cone:</p> <ul style="list-style-type: none"> <li>• UT</li> <li>• RT</li> </ul> <p>Nozzle:</p> <ul style="list-style-type: none"> <li>• UT</li> <li>• RT</li> </ul>	<p>Thiokol Corp.</p>
 <p style="text-align: center;">Case Segment</p>	<p>Case Segment:</p> <ul style="list-style-type: none"> <li>• OSEE</li> <li>• MT</li> <li>• ET</li> <li>• AE</li> </ul> <p>Insulation:</p> <ul style="list-style-type: none"> <li>• UT</li> </ul>	<p>Lockheed/Aerojet</p>
 <p style="text-align: center;">Loaded Segment</p>	<p>Loaded Segments:</p> <ul style="list-style-type: none"> <li>• UT of Bondlines and Propellant</li> </ul>	<p>Lockheed/Aerojet</p>
 <p style="text-align: center;">Loaded Segment</p>	<p>Loaded Segments:</p> <ul style="list-style-type: none"> <li>• RTR of Propellant</li> <li>• Visual Inspection of Grain</li> </ul>	<p>Lockheed/Aerojet</p>

## Appendix D

### Schematic of ASRM Test Program



**NATIONAL ACADEMY PRESS**

The National Academy Press was created by the National Academy of Sciences to publish the reports issued by the Academy and by the National Academy of Engineering, the Institute of Medicine, and the National Research Council, all operating under the charter granted to the National Academy of Sciences by the Congress of the United States.