N93-22103

SPACE TRANSPORTATION STRUCTURES AND MATERIALS WORKSHOP

Reliability of Solid Rocket Motor Cases and Nozzles

by J.G. Crose

A recent article in Aerospace America* claims that "the average success ratio of the current U.S. stable of launch vehicles, including upper stages, is about 92% (without upper stages it is close to 95%). The 8% failure probability implies an expected loss of $12M per flight, not including the lost opportunity costs." Since payload costs are likely to be much greater than launch costs and even more so for the new launch vehicles for the Advanced Launch Development Program (ALDP), the cost of rocket motor unreliability at the current 8% rate can run into billions of dollars if expected increases in demand are realized.

At an 8% failure rate, it is extremely unlikely that failure will occur during the first few ground tests of a new system. At that time, most of the design, analysis and tooling costs of the program have been expended. Since most systems are expected to be used ten to a hundred or more times, the likelihood of one or more failures is very large, and it can be expected that the above losses will be realized in the future. This will occur unless the problems are addressed and remedied. Recent trends suggest the problem is not being addressed adequately.

The obvious causes of failure are poor design, lack of quality control of raw materials entering the manufacturing process, lack of quality control during the manufacturing process and inadequate NDE or proof testing. The root causes of failure relate to an inadequate understanding of the influence of design variables on performance and reliability, an inadequate understanding of raw material and process parameter variations on performance and reliability and the inability to find and recognize defects in manufactured parts. It is believed that solid rocket motor reliability can only be improved by addressing the above issues in a highly disciplined scientific approach. The build and test system presently used cannot assure reliability beyond the present levels.

The predictability of material behavior lies at the base of reliability improvement and feeds into the above issues relating to design variables, raw material and process variations and defect identification. The keys to predicting material behavior are the performance of tests which enable one to measure the response to a variety of environmental conditions, the development of verified behavioral theories, and the implementation of measured data and verified numerical algorithms into verified performance predictions. Because of the geometric and environmental complexity of rocket motor systems, these procedures require computer automation.

The above translates into a need for effective computer programs for design/analysis, a comprehensive materials data base, process environment modeling, defect identification and improved materials. Mathematical algorithms are needed to simulate physical behavior and

* Tragola, J.R., "A Second Look at Launch System Reliability, Aerospace America, November 1991, pp. 36-39.

predict behavior with confidence beyond the envelope of the data base. Additional testing of material response to produce data in appropriate environments and during processing needs to be performed and the data organized into easily accessible computerized materials data bases. Scientific labor must be expended to develop appropriate material response tests, interpret test data, innovate physically based models of behavior and implement this knowledge into computer aided engineering tools for use by the solid propulsion industry. Appropriate industry representation needs to be a part of the process through seminars, publications, shared data bases and round robin verification of design/analysis techniques. Acceptance tests must be upgraded to monitor relevant responses to SRM performance.

The current Solid Propulsion Integrity Program (SPIP) at Marshall Space Flight Center should be considered a model for future efforts to improve solid rocket motor (SRM) reliability. However, the current funding levels are not sufficient to accomplish much more than a small subset of the overall need. A key issue confronting the community is the need for a change in the "culture". Interviews with designers of SRM's have convinced this author that they are very apprehensive of the first firing of a new design, even if it involves a small change. This means that the design is heavily based on experience and not on the level of technology that goes into many other products that exhibit more reliability such as jet engines on commercial aircraft. This results in SRM's with lower response and reliability than could be achieved with a physically based model of material response.

The solid rocket motor community has tried throughout the years to adapt technology developed elsewhere to their needs. This has been largely due to economics. Many of these technologies are credible in their prior use, but lack specific features that would make them more relevant to solid rocket motors. For example, the SRM community was quick to adopt finite element methods for analysis of grains and nozzles in the late 60's, but has been very slow in further developments to reflect the unique nonlinear behavior of the materials used in SRM's. It is no wonder that the methodology has been found to be inadequate. Unfortunately, the community seems to have resolved the problem with mistrust of available methods and a design philosophy that precludes substantial change from one system to the next. The economic consequences of unreliability are severe enough to have warranted the further development of analytical methods and material behavior studies, but the lack of customer pressure in a highly competitive arena has in effect traded reliability for low system development cost. Therefore, a clear need exists for a change of emphasis and NASA should provide a leadership roll due to the enhanced sensitivity to reliability related to manned vehicles and to heightened public awareness. The key technology requirements offering the potential to significantly reduce overall systems cost, improve reliability and performance of solid rocket motors are common across all subsystems:

- Understanding and control of material and process variability
- Analytically driven test methodology development and improved constitutive models
- Establishment of improved failure criteria
- Understanding effects of defects

- Design for inspectability
- Environmentally driven process and technology development
- Design and optimization of materials for the environment.

This workshop identified specific technology needs directly related to known problem areas in solid rocket motors. The issues were separated between cases, nozzles, bondlines/propellant and insulation. Bondlines, propellants and insulation are covered in a separate narrative elsewhere in this report. The following problem areas require funding support to improve the reliability of U.S. solid rocket motors:

- Nozzles
  - Inadequate material property data base
  - Lack of knowledge of influence of process variables on performance and reliability
  - Inadequate failure criteria, influence of material variability and effects of defects
  - Inadequate design/analysis codes
  - Inadequate nozzle design methodology
  - Inadequate flex bearing design data
  - Inadequate cleaning for bonding
  - Lack of relationships between materials chemical constituency and material properties
  - Need for low cost materials
  - Need for design data on structural adhesives
  - Need for better material property characterization and micro-mechanical modeling
  - Constitutive modeling of nozzle materials
  - Erosion modeling of nozzle materials
  - Large nozzle technology requirements.

- Cases
  - Inadequate understanding of case joint and attachment
  - Need for definitive case design and analysis methodology
  - Environmental concerns over materials used in processing
  - Costs for high rate production
  - Inadequate case codes
  - Need for self insulating case designs
  - Need lower cost/quicker turnaround case tooling.

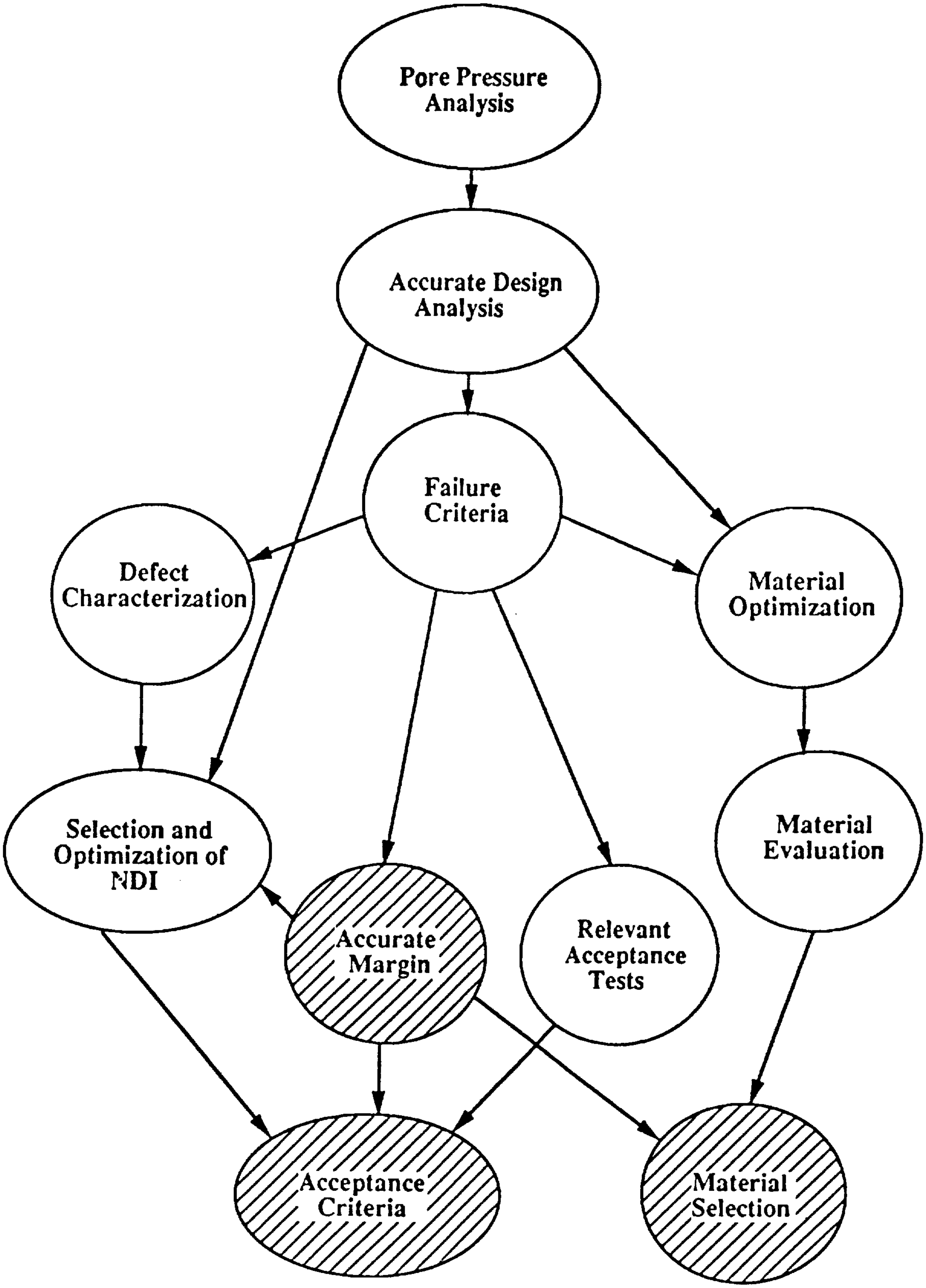
The attached figure illustrates the interrelationships between the various functions of design and analysis. Improvements in one area can benefit others while in other cases, multiple improvements must be made simultaneously to realize the expected benefits. The shaded boxes represent the end points where improvements will lead to improved performance and reliability.

Approaches have been defined which can be implemented to achieve the goals associated with increased reliability of solid rocket motors. The quad charts outline these specific programs. There are some key concerns that have driven the recommendations in the nozzle and case areas. Lessons learned from previous ground and flight failures provide much of the background.

In the nozzle area, design analysis is a major shortfall. More accurately measured material properties, verified modeling procedures and comprehensive failure criteria are badly needed to assess designs before programs are committed to them. A major deficiency is lack of treatment of pyrolysis gas flow through the materials and bondlines of the nozzle. Resultant pore pressures are a source of loads not accounted for in contemporary designs. This deficiency may have been partly or totally responsible for failures of the IUS and STAR 48 motors. Also, anomalous erosion in the SRM is attributed to pocketing, ply-lift and wedgeout failure modes involving pore pressure loadings.

In the case area, design analysis is also a major shortfall. In addition to the need for more accurately measured material properties, verified modeling procedures and comprehensive failure criteria, a unique need is to be able to predict the detailed geometry of a wound case as a function of design and manufacturing variables. This includes definition of residual stresses in the cured case and/or changes in geometry resulting from cure. Large cases need joints. The recent Challenger disaster highlights a number of problem areas requiring attention such as the need for highly detailed nonlinear 3D analysis of joint action and need for material properties as a function of all environmental variables (temperature, humidity, etc.). One of the results of a weak technology base is that engineers lose credibility when their methods produce mixed or erroneous results. The resulting mistrust of engineering conclusions by management can lead to disastrous decisions as was the case in the Challenger disaster when engineers could not convince management that real dangers were present in a cold launch of the shuttle.

The preliminary efforts conducted by SPIP and elsewhere have illustrated the potential for design improvements which will result in both high reliability and improved performance. The increase in asset allocation required to carry these efforts to an appropriate level are nominal when compared to the cost of projected failures based on current design reliability. Significant improvements in future design can be accomplished with the basic technology described above.



TECHNOLOGY TRANSFER TO RELATED APPLICATIONS

9.4.3 Solid Propulsion Integrity Program (SPIP) for Verifiable Enhanced Solid Rocket Motor Reliability

by Barry L. Butler