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SOUNDING ROCKET RELIABILITY REASSESSMENT

by Abrom Hisler

Goddard Space Flight Center
Greenbelt, Md.

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SUMMARY

Reputedly reliable sounding rocket propulsion systems have occasionally experienced motor failures with the attendant waste of time, effort, and money. Presented herein is an approach which culls past rocket failure data for an organized failure modes attack on rocket motor malfunctions. The life history of a rocket motor is used to ferret out failure modes and thereby raise the level of reliability.

CONTENTS

Summary i

INTRODUCTION 1

REASSESSMENT OF REPUTEDLY RELIABLE MOTORS 1

THE FAILURE MODE APPROACH 2

AN UP-TO-DATE FAILURE MODE CHECKOUT 4

CORRECTIVE ACTION TO DESIGN OUT SUSPECTED FAILURE MODES 5

References 5

Appendix A—The Thinning Grain Structure Collapse Theory 9

Appendix B—Sustainer Trouble-Shooting Layout 11

Appendix C—Checklist of Failure Modes 13

Appendix D—Rocket Failures Study Chart 21

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INTRODUCTION

Succinctly stated, a sounding rocket carries scientific instruments into the upper atmosphere for observation and measurement purposes. The cost of the rocket covers not only the rocket vehicle but also the research instrumentation, logistic and operational support, and personnel expenses. That this cost not be wasted requires reliable instrumentation, vehicles, and propulsion systems.

Also required is a continuing need to focus attention on the rocket's level of reliability so that it in no way deteriorates. This paper then discusses an approach for reassessing the reliability of a given solid propellant propulsion system.

REASSESSMENT OF REPUTEDLY RELIABLE MOTORS

Rocket motors are selected for sounding purposes after a high level of reliability has been demonstrated by past launch and flight experience. Occasionally, rocket motor failures have occurred with these reputedly reliable motors. In view of the high costs and the time and effort involved, sounding rocket propulsion systems must be continually reassessed for reliability. This analysis may be performed prior to a flight attempt or after the failure of a reputedly reliable motor. In the former situation, an imminent failure is assumed so that some action can be taken to forestall an actual launch and flight failure. A leading question would be, "Have *all* modes of failure been considered in the reliability scheme?" To do so requires a certain vigilance to prevent new defects from creeping into the motor assembly or components; an alert reliability organization (Reference 1) is necessary at all times. As familiarity with the nature of the quality control organization (Reference 2-4*), the motor fabrication and assembly, and the motor drawings increases, so does confidence in the motor's reliability.

On the other hand, the failure of a reputedly reliable motor requires additional effort to troubleshoot that failure and determine the cause(s). These causes possibly could be found by a

*See also: Miller, Robert, "Trip Report: Discussion of Various Reliability and Quality Assurance Aspects of the Propulsion Portion of the WASP-MECA Project," NASA Lewis Research Center, Office of Reliability and Quality Assurance, January 15, 1963.

close analysis of the design drawings; a search of the reliability and quality control organization to uncover poor inspection where inadvertent omission, or commission, has occurred; and a study of the possible existence of new or different circumstances of operation. It is usually this last study which proves most worthwhile.

When a rocket is operating under a different set of circumstances than it did previously, a more severe environment may be involved. This environment could combine various levels of operation so that new *temperature, pressure,* and *force* differentials must be considered simultaneously. Temperature differentials may lead to motor failures because of thermal expansion when there is insufficient component clearance and especially when the adjacent materials are dissimilar. The pressure differential is another problem; this differential, in one instance, made igniter restart difficult at high altitudes. This condition arose because the pressure differential at the upper altitudes, greater than that experienced during the igniter sea level tests, caused structural damage to the igniter housing (Reference 5).

Operating at higher G levels and vibration levels introduces higher force differentials which can be sufficiently above the critical level to produce motor failures. Higher G level considerations have led to the grain structure collapse theory (Appendix A), and consequently to additional design considerations.

Somewhat related to temperature, pressure, and force differentials as failure modes are the *time* differentials of temperature and pressure, or the rate of application of heat and pressure. Thermal shock thus may be explained in terms of the time interval required to build up to a certain magnitude of the temperature differential. Igniter blast is also an example of the very low rate of heat transfer to the grain surface; there is insufficient time to ignite the propellant despite the very hot ignition gases flowing by. High rates of pressurization occur when the burning surface of the grain is increased above the critical burning surface area. This area value depends to a large extent on the ability of the case to withstand not simply proof pressures but also these rates of pressurization.

It is therefore advisable to consider design drawings of rocket motor systems, assemblies, and components from the viewpoint of differentials and rates of application of temperature (heat), pressure, and force. Many failure modes experienced in the past could have been predicted with this type of analysis.

THE FAILURE MODE APPROACH

In the attempt to uncover the causes of motor failure, it is reasonable to assume that, for a successful launch and flight, no mode of motor failure has occurred. What may not be as obvious is the importance of focusing attention on all modes of possible failure. This, then, is the *failure mode approach* to solid motor reliability reassessment. The basic problem may be stated, "Where and how have modes of failure crept into a rocket motor because of quality control breakdowns, or during new conditions of operation?" And the answer requires constant attention to detail.

Only recently has appreciation developed for the massive amount of failure data gathered in the solid propellant rocket motor field (References 2 and 6): The present trend in other allied fields of aerospace emphasizes attention to failure modes and their obvious direct adverse effect on system reliability. From the failure data it is possible to gather and arrange the possible modes of failure in terms of where they may creep into the life cycle of the motor. This presents an organized framework of reference for a particular motor's history, covering: (1) familiarity with the motor design drawings; (2) the trouble areas encountered in the development program which may again arise as recognized particular modes of failure in the production and assembly of the motor unit; (3) unusual delivery, storage, and handling occurrences; (4) the prelaunch preparations; and (5) the parts examination of the motor unit which failed, if recovered.

What is the best way to review a rocket motor design after a failure? It undoubtedly would include a review of the initial requirements for the motor, the manner in which these requirements were incorporated into the motor specifications and drawings, and the manner in which the operating conditions of the motor which failed call for more stringent or additional requirements. A drawing analysis should consider the interrelation of the parts. The propellant liner is a case in point: Poor liner bonding at the grain end could lead to poor insulation of the grain with subsequent grain restriction failure, thus resulting in an excessively high propellant area being exposed to burning and, finally, motor overpressurization and blow.

Modes of failure usually become evident when trouble areas in rocket motor development programs are overcome successfully. Too often the same trouble areas recur again and again, in more than one development program, and their true nature is not understood until a previously known mode of failure is recognized.

Inspection criteria employed during production must cover failure modes which might creep in as a result of changes in personnel (Reference 7), sources of supply, design, production techniques, and materials. Otherwise, the normally reliable motor may fail.

The same holds true during the storage, handling, and delivery stages of a motor. Temperature storage limits must be maintained, shipping containers employed at all times, and manufacturer's manuals consulted.

Prelaunch preparations should also include (1) knowledge of the data of the last motor inspection—possibly at the test site (with the possibility of returning the motor to the manufacturing facility for a complete inspection), and (2) the basis on which a motor is accepted after an inspection. These motor acceptance criteria may be modified for a specific motor.

After a launch attempt and flight failure, the nature of the failure may be discovered by considering the sequence of events. This sequence starts with the initiation of the igniter, which must have sufficient confinement and produce a satisfactory energy flux. The propellant surface composition must be sufficiently sensitive to the energy flux emitted; and the propellant grain, as it burns, must be sufficiently sound structurally not to break up prematurely and present too large a propellant surface to burning. The chamber must be sufficiently strong to contain the developed pressure and temperature, and the nozzle must maintain its structural integrity and fixed throat area.

If the motor parts are recoverable, then metallurgical tests may reveal where the motor has failed.

A troubleshooting worksheet has been included in this report (Appendix B) to demonstrate the manner in which a necessary sequence of events can be used as a framework of reference in the attempt to run down the modes of failure responsible for a particular motor failure. Appropriate questions and suggested courses of action can be added to the worksheet.

AN UP-TO-DATE FAILURE MODE CHECKOUT

To keep track of the very many possible modes of failure requires great care and attention to detail, as previously noted. A checklist of all known failure modes should be prepared, and it should be updated with newer failure modes as they arise (References 8-13). A start in this direction has been made by incorporating Appendix C, "Checklist of Failure Modes," into this report.

It is easy to run down a list of failure modes to inquire which mode is present in the motor under consideration. But a faster appraisal of possible failure modes can be made by arranging the modes as shown in this checklist. Often the nature of the motor failure gives a general hint of the particular failure mode and indicates whether it involves the general motor assembly or a specified component. In Appendix C the failure modes are organized in this manner. This point-by-point checkout for possible modes of failure is not as simple as it may appear; it requires familiarity with the motor fabrication techniques, assembly sequence of the motor assembly, and component drawings. The very basic problem of detecting a particular failure mode also is involved (Reference 14). Each failure mode may call for a different detection technique which could include the disassembly, inspection, and reassembly of rocket motors similar to the one which failed; selective nondestructive tests; metallurgical techniques; experimental stress analysis procedures; and chemical analysis. The tabulation of Appendix C has the dual advantage of including not only new failure modes in their respective listings but also new failure mode detection techniques, with associated references for both the mode and the technique. In this way, the checklist may be kept up to date by systematically gathering available information on past failure modes and present detection techniques.

Appendix C (and the Appendix B worksheet) also can be used as a springboard for pertinent queries on motors which have failed in terms of specific failure modes which may be under suspicion. When used with motor drawings and the motor's assembly sequence, the checklist also can highlight possible design errors. In short, Appendix C can be applied for improved motor design, improved quality control, forestalling launch and flight failures via inspection checklists for engineers and mechanics, and troubleshooting in terms of the required sequential performance of the motor and its components.

In regard to design, the essential purpose is to remove modes of failures and thereby design reliability into systems. To do this, the possible gauntlet of failures which are apt to creep in must be kept foremost in the designer's mind. These failures must also be passed on to quality control organizations; and there must be constant feedback among the design, quality control, and troubleshooting people. The Appendix C checklist may provide the means to establish this necessary communication.

CORRECTIVE ACTION TO DESIGN OUT SUSPECTED FAILURE MODES

With failure modes sifted and appropriate detection techniques employed, the nature of the failure may be surmised and a theory evolved. This may require consultation with an ever-expanding array of specialists (Reference 15) most familiar with their particular areas—welding, materials (igniter charge, propellant, liner, throat material), component design, assembly inspection, etc. Here, again, queries prompted by possible modes of failure and directed to these specialists should develop the necessary corrective action after a coordinated design concept review. This coordination must "permit effective communication and proper liaison scheduling, be to the point, and be adequately funded and recorded" (Reference 16). The cost of this approach, when successful, undoubtedly will be less than the consequences of another launch and flight failure.

The focal point of this approach to the reliability reassessment of sounding rockets, then, is to design reliability into the rocket by designing out assumed or known modes of failure. These would be the modes of failure which, for the most part, already have been experienced in the past. Appendix D, a failures study chart, has been developed to present a fast rundown on a particular failure, the assumed failure modes, and the corrective action taken, with consequences.

Certainly, employing the above systematic approach should increase one's confidence in the success of subsequent sounding rocket launches and flights. In the final analysis, the success or failure of a sounding rocket mission is a reflection, not on the sounding rocket itself, but on the adequacy of the prelaunch effort and judgment expended.

(Manuscript received May 19, 1964)

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*Serial number of abstract appearing in NASA publication, "Reliability Abstracts & Technical Reviews," First Annual Volume, 1961-1962.

†Code number of abstract appearing in abstract publication issued by the Chemical Propulsion Information Agency of the Applied Physics Laboratory, Johns Hopkins University.

Appendix A

The Thinning Grain Structure Collapse Theory

This theory assumes that a peculiar combination of factors causes solid rocket motor blows during flight when the motor operates satisfactorily until just prior to burnout. These factors may on the one hand tend to reduce the throat area, and on the other to suddenly increase the propellant surface area. Loose components such as the resonance rod assembly, spring, and grain splinters would tend to block the throat. Increased surface area could be produced by a sudden collapse of the thinning grain structure prior to burnout. Various forces acting on the grain structure could account for the grain collapse:

1. The vehicle's acceleration;
2. The compressive force of the spring, were one used, to immobilize the grain;
3. The whipping action of resonance rods against thin web propellant;
4. Incipient combustion instability.

The exact mechanism by which this grain collapse is achieved may be "hinted at" in the present literature which discusses how the integrity of propellant grain structures is adversely affected (References 17-19).

It is the grain geometry or the distribution of the propellant weight which most markedly determines the ability of the grain structure to resist buckling and collapse. This in turn determines whether the critical burning surface area has been exceeded and whether a blow will occur. The extent to which the critical burning surface is approached may very well decide the fate of a particular motor. In short, a premature collapse of the grain structure results in a blow because of the unusually large amount of exposed propellant surface area inside the operating chamber.

Appendix B

Sustainer Trouble-Shooting Layout

Sustainer Trouble-Shooting Layout*

- Command signal mechanism → Was separating charge fired? → To sever interstage structure?
  - → Was succeeding stage ignited? → To force expended stage to separate by exhausting directly into the interstage compartment?
- ↓ Igniter resistance (amp/ohm)
  - → Fluctuations below required amperage?
  - → Electrical source reliable?
- ↓ 4 squibs/parallel
- ↓ Initiator powder → Blackpowder + Proprietary powder → Tests/Naval Propellant Plant†
  - → Degradation w/time? Affected by humid conditions?
    - → What was nature of conditioning prior to launch?
- ↓ Pellets
- ↓ Solid grain propellant
  - → Effective at all altitudes up to 200,000 feet
    - → Attitude of vehicle at time of malfunction?
    - → Test of igniters at sea level and desired altitude.
    - → Test of entire unit at sea level and desired altitude.
    - → Comparison of altitude test conditions w/malfunction conditions.
  - → Solid grain propellant insensitive to igniter?‡

*Discussion: The sequence of necessary events is shown on the extreme left starting with the operation of the command signal mechanism and ending with the sustained combustion of the solid grain propellant. Appropriate questions and applicable references for further study are inserted along this sequence in the attempt to identify the point at which the sequence was broken. In this particular case, in answer to the question "Was the separating charge fired?" the answer is "No" since the vehicle prematurely broke up before this stage of the sequence.

†JANAF 1959, Vol. 7, p. 4.

‡JANAF 1959, Vol. 7, p. 55.

Appendix C

Checklist of Failure Modes

(1) Rocket Motor Assembly*

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Improper assembly	Dimensional discrepancy Inadvertent omission of component Low thread count Mismatched units			
Unsoldered wire				
Bolt failure	Under- or over-torqued Structural failure Overheated † Without locking device			
Excessive temperature of motor at high altitudes	Vacuum insulation at high altitudes reduces the heat discharge to possibly overheat critical components			5
Improper torquing	Loose assembly of components	Torque test	Torque wrench	(‡)
O-ring difficulties	Damaged Missing Improperly inserted Poor material			(‡)
Leak				
Faulty weld	Imperfections Crack in weld	Burnthrough at weld X ray Zyglo**		
Design problems				
Materials problems	O-ring failure Gas retained in material after inspection with gas Contamination as a result of processing Faulty material Uncured plastic Material imperfections Improper choice of materials			
Improper modifications				

*Discussion: The failure modes are listed under: (1) Rocket motor assembly, (2) Igniter, (3) Propellant, (4) Liner, (5) Rocket motor case, (6) Resonance rods, (7) Nozzle, and (8) Forward and aft enclosures.

As additional failure modes are known, they would be inserted in the appropriate list with any appropriate comments, detection mode employed, corrective action taken, and referenced for further detailed information.

The growing list of failure modes would be used to pinpoint more readily the plausible failure modes for a specific motor failure.

†Although thrust reversal, thrust vector control (TVC), and safe-arm systems are not fully included in this initial listing, inadequate protection of bolts from the jetavator blowback caused the failure of a TVC system.

‡Hisler, A., "Naval Propellant Plant Travel Report," Goddard Space Flight Center, August 9, 1963. Liaison with F. Portner and V. Hart.

**Zyglo technique based on use of dye penetrant; rolled welds permit poor detection.

(2) Igniter

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Broken circuit	Externally and internally		Electrical continuity check	
Igniter blast	Igniter charge detonation Cracked grain Excessive ignition peaks			20
High altitude non-ignition	Insufficient pressure at ignition altitude to ignite blackpowder			(†)
	Pressure differential great enough to cause structural damage to igniter housing			5
Igniter pellet breakup	Tendency of pellets to crumble			(†)
Insufficient confinement*			Reinforced igniter housing or igniter basket	(†)
Igniter boss weld leak				20
Defective squib seal				
Excessive igniter peak pressure	(Igniter blast)			
Presence of water				
Outside amperage ignition range				
Insufficient initiator charge				
Detonation of igniter charge	(Comparable to igniter blast)			
Low heat concentration of igniter gases				

*Related to high altitude malfunction.
†Hisler, *op. cit.*

(3) Propellant

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Insensitive grain surface	Silicone adhered to grain surface upon mold release of grain to change mixture ratio at surface	Chemical analysis of grain surface	As appropriate	(*)
Propellant softening on aging	Softened propellant underwent viscous flow into nozzle	Hardness test		(*)
Poor inhibition	Inhibitor absorbed nitroglycerine (NG)	Chemical analysis for NG in inhibitor surface		(*)
	Delamination of inhibitor			(*)
	Breakup of grain surface because of pressure differential behind grain (gas seepage) and within combustion zone†			(*)
Grain shrinkage	Increased brittleness of grain and inhibitor, usually below loading temperature and on aging			21, (*)
Deformation	During aging, storage, flight pressurization			
Excessive propellant burning rate				
Grain breakup	Caused by ignition blast			
Heterogeneous propellant	Cracks‡ may propagate to surface on pressurization as a result of:	Non-destructive inspection:		22, 23
	Temperature aging	Ultrasonic		21
	Curve shrinkage	Radiographic		
	Ignition conditions	Isotopic		
	Early burning phase	Visual: use of probe		
	Malhandling	Chemical analysis		24
	Moisture			
	Voids			
	Flaws			
	Presence of water			

*Hisler, *op. cit.*

†Burnthrough at forward end related to differential pressure and poor inhibition.

‡Grain cracking as a result of temperature cycling.

(3) Propellant (Continued)

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Grain restriction failure	Insufficient insulation**			
Sagging grain	Poor grain suspension may lead to cracked grains at lower temperatures and propellant liner separation			(††)
Combustion instability	Initiated by:			
	Blackpowder charge			25
	Ineffective or missing resonance rods			
	Absence of aluminum in propellant			
	Poor propellant mounting			26
Firing at propellant brittle point	To produce:			
	Uneven web burning + premature grain breakup			25
	Excessive pressure and severe pressure oscillations			
Brittle failure of propellant				25
Critical L/D value of grain	Instability level affected by grain temperature and material lot variations			27
Burning rate instability	Dependent on propellant formulation	Batch test	Change burning rate inhibition	

**Propellant-liner interrelation.

††Miller, *op. cit.* (see footnote on p. 1).

(4) Liner

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Faulty liner bonding	Poor bonding agent			28
	Thermal contraction below ambient temperature of loading*			6, 29
Insulation failure	Insufficient insulation			
	Problem of:			
	Design			
	Proper material selection			
	Adequate thickness			
	Presence of water†	Chemical analysis		26
	Improper insulation			
	Insulation porosity			
	Adverse effect of diffusing ingredient from propellant	Chemical analysis		29
	Damaged insulation			
	Fast liner ablation			
	Liner separation on aging			
	Retention of gas in insulation after dye technique inspection	Chemical analysis		

*Grain shrinkage and faulty liner bonding related.
†To degrade propellant.

(5) Rocket Motor Case

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Corrosion weakened case	Out-of-round case allowed water to collect in upright position to rust case w/time			(*)
Structural failure	Case improperly heat-treated	Hardness test Metallurgical study	Close adherence to required heat-treat technique	6
Burnthrough	Result of premature heating of case			6, 30

*Hisler, *op. cit.*

(6) Resonance Rods

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Nozzle blockage	Force of spring, holding grain against aft end, too strong			
Grain breakup	Force of spring, to hold grain against aft end, too weak			
	Whiplike action of rods		Possible use of hydraulic system to reduce shock damage	(*)
Missing or loose rods				31

*Hisler, *op. cit.*

(7) Nozzle - Exit Cone, Components, and Throat

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Design problem	Poor throat reinforcement			32
Improper assembly				
Delamination				
Improper clearances and gaps	Caused by differential thermal expansion			33
	Exhaust gases flow into gaps and clearances to penetrate nozzle component interfaces			34
Port restriction	By freed or flowing potting material			
Chamber overpressurization				
Porous condition of carbon throat insert				
Reduced material thickness				
Reduced nozzle throat area				35
Severe erosion and/or fracture				6

(7) Nozzle - Exit Cone, Components, and Throat (Continued)

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Exit cone burnthrough				
Nozzle ejection				
Relative position of throat w/respect to chamber	Insertion of extension tube between chamber and throat may eliminate unstable burning. This also is a good fix for the above exhaust gas erosion failure mode. (Anglewise, the throat-chamber position may give rise to thrust misalignment.)			36, 37
Structural failure				

(8) Aft Closure

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Overtorquing of aft closure bolts				
Rupture				
Burnthrough	Caused by internal insulation failure and/or gas leak			

(9) Forward Closure

Failure Mode	Comment	Detection Mode	Corrective Action	Reference
Rupture				
Burnthrough	Caused by insulation failure and/or gas leak			

Appendix D

Rocket Failures Study Chart

Rocket Failures Study Chart*

Possible Modes of Failure	Special Considerations and Comments	Corrective Action			Consequences and Conclusions	References
		Possible	Critique	Selected		
Higher G level of sounding rockets	Weakens thinning grain structure					24
High compressive force of grain immobilizing spring	Weakens grain structure	Recommend new spring compressive force specification: 850+25 lb				21, 24
Longitudinal stringers in material induced initial longitudinal case failure	Stringers found in recovered damaged case	Tighter quality control on case material				(†)
Broken or missing or loose resonance rods	Promote combustion instability and uneven grain burning	Inspect for this condition prior to launch - prepare checklist				30
Large amount of propellant in chamber at time of grain collapse	Result of premature collapse of weakened grain structure					21, 24
Severe air transportation conditions	Fang of modified Ajax launcher damaged					
Whipping action of resonance rods	Prematurely collapses thinning grain structure	Stiffen rods to reduce vibration amplitude				24
Spring weight on grain magnified by acceleration	Increases forces applied to thinning grain structure	Reduce spring weight				24
Grain structure undercut by sharp edge	Reduces undercut structural strength of thinning grain structure	Chamfer inner-step contour of case				

*This chart could be expanded to record significant information as to the date, place, and nature of the failure. A running account could then be kept of corrective action as proposed, criticized, selected, and reported in followup reports (Reference 38).

†Hisler, *op. cit.*

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