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A NIKE FAILURE STUDY

by
Abrom Hisler

March 1966

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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Abstract

Sporadic Nike-Apache vehicle flight failures were viewed with concern prior to the first flight of the Nike boosted Aerobee 350 vehicle. The ensuing failure study, incorporating a functional sequence approach to reliability finally assessed the Nike malfunctions as induced by combustion instability and the "delta p" approach is advanced as a result.

Nike assembly precautions were taken to avoid combustion instability failure modes as pinpointed by this "delta p" hypothesis. On June 18, 1965, the first attempt by GSFC to launch the complete Aerobee 350 sounding rocket was a total success.

Author

A NIKE FAILURE STUDY

On 20 July 1963, six Nike Apache vehicles were launched in a sounding rocket eclipse program at Fort Churchill. The first two failed in flight at about the burnout time of the first (Nike) stage. The others went on to provide excellent information about the sun and ionosphere.

This report presents the findings from an investigation of these and similar motor failures.

The failures were significant for two reasons. The first obviously reflected on the unreliability of reputedly reliable motors. The other concerned the use of a Nike booster for the Aerobee 350 sustainer under development at the time.

Fortunately, parts of one of the failed units were recovered. The two units which failed were serial numbers 44098 and 44100. As a lead to understanding the nature of the two Nike failures, it was assumed that serial number 44099 would also contain the unknown failure mode because of some faulty assembly procedure common to all three. Rocket motors S/N 44097 and 44101 had flown successfully as did many of the other units within this particular Radford lot, RAD-SR-11-62.

The failure study was then conducted against the Nike life cycle background of:

1. rocket motor design
2. development program
3. production
4. assembly
5. delivery (storage and handling)
6. prelaunch inspection
7. launch attempt
8. recovered parts examination

The rocket motor design was reviewed employing the functional sequence approach (1). By considering the function of each component of the motor in sequential order (Appendix A), possible modes of failure could be identified (Appendix B) and would serve as critical inspection points during motor assembly.

An attempt was made to uncover past trouble areas which might have occurred during the original Nike development program, and which might be repeating as failure modes. However, no comprehensive report was to be found summarizing all the problems faced in developing the Nike although the Alleghany Ballistic Laboratory at Cumberland, Maryland, was consulted for this purpose.

A visit was made to Radford Arsenal, Virginia, to develop a greater familiarity with present Nike production methods and techniques so as to better understand Radford's quality control effort.

With the interest engendered as indicated above in Nike unit, S/N 44099, arrangements were made to inspect this unit in terms of an inspection plan prepared by Radford (Appendix C). This unit meanwhile had traveled to the Thumba Rocket Launching site in Trivandrum, India. When returned to this country, the exterior of the wooden container indicated it had received rough handling. Here then was a unit which had gone half way around the world and had aroused a high degree of curiosity as to its condition, especially since it might possibly contain an assembly faux pas common to the two units which had failed at Churchill.

Concurrent with these plans, a "Rocket Failure Study Chart - Nike 2.5DS59.000" was developed to list all possible modes of failure as they evolved during the study (Appendix D). Additional possible modes of failure, as uncovered, were entered on this chart.

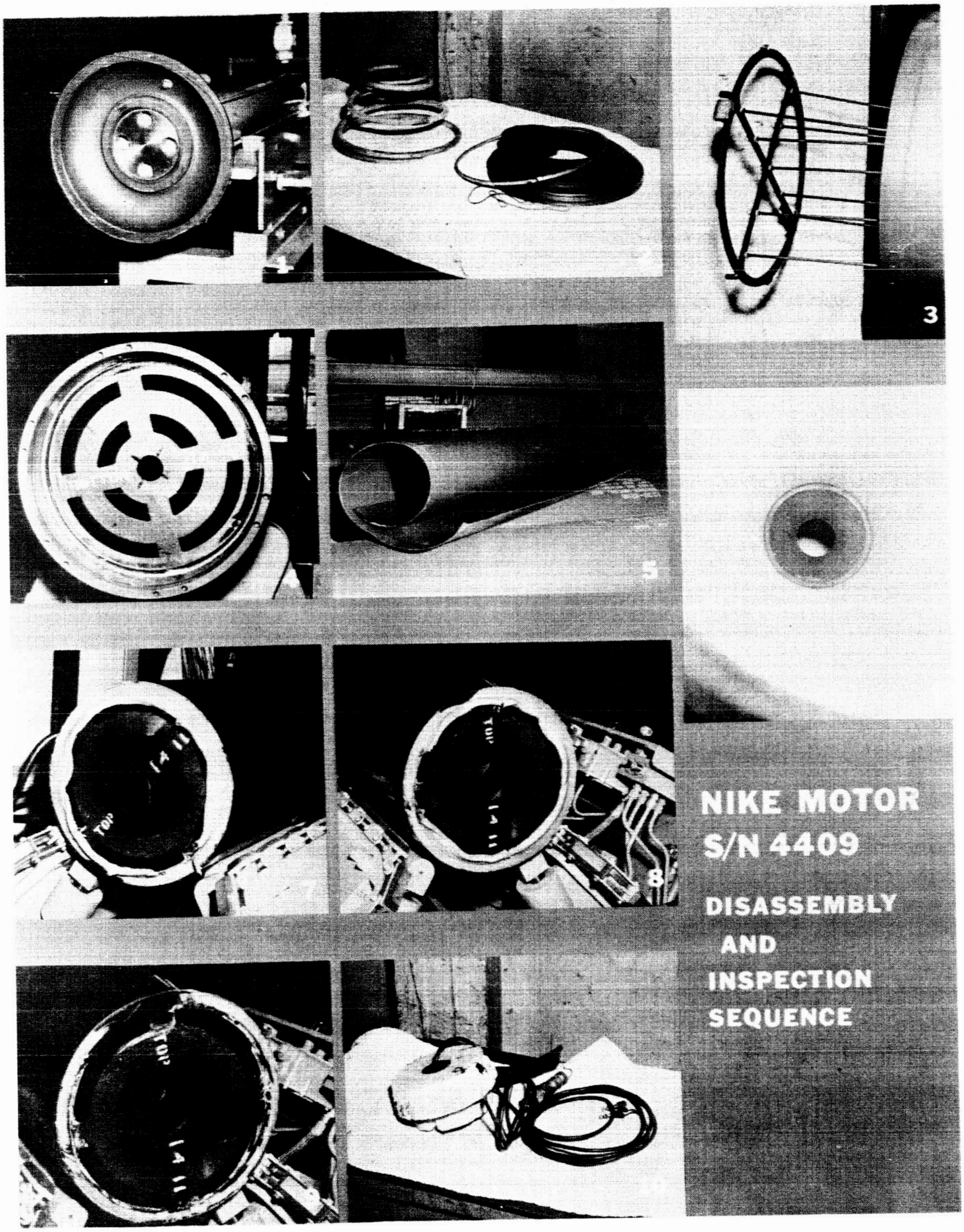
Upon disassembly and inspection of the S/N 44099 unit, the following discrepancies and possible indications of modes of failure were noted:

1. three inadequately torqued resonance rods; they were not finger-tight

2. grain undercut at the forward end: possibly reducing the structural integrity of the grain near burnout

3. poorly applied sealing compound at the aft end of the grain (in the 11:00 position of Figure 1): possibly permitting leakage (and flow) of otherwise stationary hot gases to the aft end of the motor along the insulation coated metal wall.

The composite photograph, Figure 1, may help to show the various stages of disassembly of the S/N 44099 unit along with the noted discrepancies. Sequentially



3
5
TOP
1 4 11
7
TOP
1 4 11
8
NIKE MOTOR
S/N 4409
DISASSEMBLY
AND
INSPECTION
SEQUENCE
TOP
1 4 11

Figure 1

it shows the forward head as removed (photo #1), then the removal of the shipping plug (replaced by the igniter prior to firing), the snap ring, and the spring which immobilizes the propellant grain (photo #2), the resonance rod assembly partially withdrawn from the grain (photo #3), the undercut forward end of the grain (photo #4), the template paper to protect the flamastic coating during grain loading and conveniently slide the propellant grain into the chamber case (photo #5), views of the sealing compound, as found, applied to the aft end of the grain (photos #7 and #8), a portion of the sealing compound removed to determine whether the unchamfired chill ring had cut into the aft end of the grain* (photo 9), and the nozzle closure with electrical harness (photo #10).

As a result of this disassembly and inspection, it was found necessary to update the quality control for the resonance rod assembly to:

1. Replace the now obsolete rubber grommet specification with that for the Belleville springs.

2. Properly torque the nuts of Ordnance Corps Drawing 8025087 so that the Belleville springs are under adequate compression.

Metallurgical examination of the recovered chamber remnants of one of the units indicated (2) that "the steel was dirty as shown by the amount of inclusions present in the structure. These inclusions could serve as stress risers and become failure initiation sites." These inclusions or "stringers" tended to reduce the homogeneity and strength of the steel.

To complete the S/N 44099 unit assessment, the original grain was satisfactorily static fired in a heavy wall test chamber motorcase. The 44099 unit, with a new replacement grain, then performed satisfactorily on NASA flight 12.02 GT (a boosted dummy Aerobee 350 sustainer).

At this point in time, the Rocket Failures Study Chart led to the Nike booster defects contribution theory, Figure 2. This theory assumes the probability of failure of a Nike unit is a product of the probability of occurrence of each of the possible failure modes ($P_t = x_1, x_2, x_3, \ldots$). During tailoff, it was assumed that gas leaking past the seal compound, combustion instability arising from loose resonance rods, high g forces of sounding rockets, and grain undercutting by the unchamfired chill ring and the resonance rod spider would all tend to weaken the grain structure.

*It had not done so.

NIKE BOOSTER DEFECTS CONTRIBUTION THEORY

$(P_f = X_1 X_2 X_3 \ldots)$

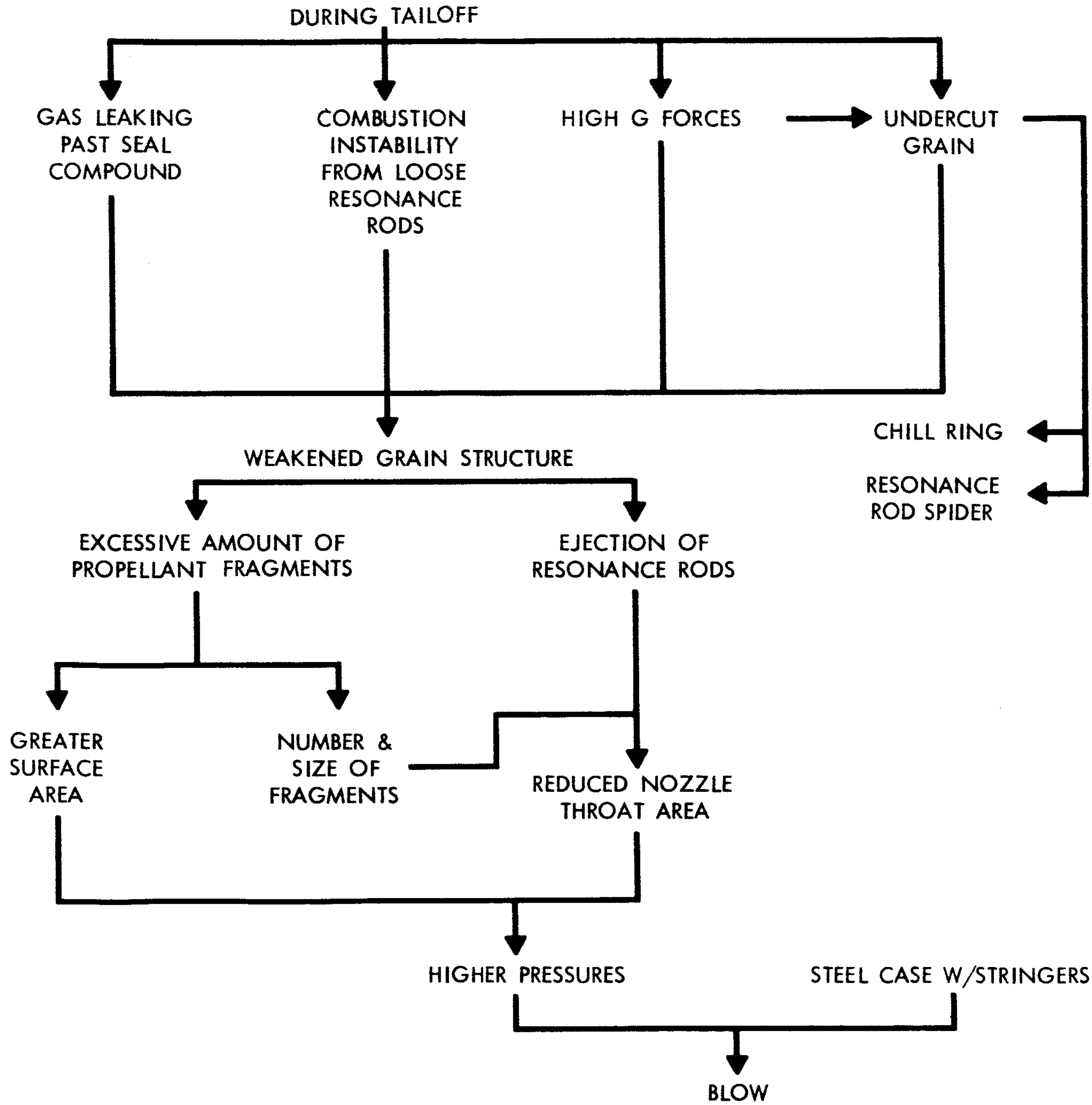


Figure 2

Later, on 24 November 1964, a first stage Nike M-5 malfunctioned after approximately 1.4 seconds of flight of a Nike Javelin at Eglin AFB (3). It was possible to recover the first stage fin assembly, a few pieces of the motor case, the M-5 nozzle, the interstage, the Nike head cap, and approximately 300 to 400 pounds of propellant. The situation here reminded one of the two Nike failures at Fort Churchill in July 1963. On investigating the November 1964 malfunction, it was concluded (3), on the basis of rippled grain surface evidence, that unstable burning had occurred in some of the channel chambers of the multi-channeled single grain. This observation has led to the "delta p" approach to combustion instability (Appendix E).

In preparation for the first series of flight tests of the complete Aerobee 350 sounding vehicle (17.01 - 17.04), a total of four Nike units were then disassembled and inspected. Inspection results of these units and the previous S/N 44099 are shown on Table 1. It would seem that the four motors had been previously disassembled and reassembled at Umatilla (Ordnance Depot, Hermiston, Oregon) without the quality control and assembly equipment available at Radford. As a result, the template paper had not been properly installed, the seal compound was dry, and three of the four grains were delaminated. The improperly installed template paper and dry seal compound would undoubtedly have created gas leakage problems. Grain delaminations would also have lead to possible Nike blowups.

After appropriate hole pattern modification of each of the four chamber cases for adaptation to Aerobee 350, the four grains were replaced by new ones (PR 47448) and reassembled in accordance with Radford quality control.

On 18 June 1965, the first attempt by GSFC to launch the complete Aerobee 350 sounding rocket was a total success. (4). The Nike boost motor had operated faultlessly.

TABLE 1. INSPECTION AT RADFORD ARSENAL OF NIKE BOOSTERS FOR AEROBEE 350 VEHICLES

Date of Inspection	10-12 March 1964	25 March 1965	25 March 1965	25 March 1965	25 March 1965
Unit No.	44099	8559	3333	8612	2239
Lot No.		RAD-271	RAD-2-22	RAD-271	RAD-2-11
Grain No.		8724	3482	8758	2298
Inspection Findings					
(1) Presence of Igniters	No	No	No	No	No
(2) Clothes Pin in Nozzle		X			
(3) Loose Flakes of Flamastic at Head End		X			
(4) Loose Resonance Rods in Sliding Condition - Nuts not Adequately Torqued	3 loose resonance rods	one loose rod			
(5) Condition of Grain		good			blemish on beaker surface
(6) Grain-Beaker Delamination			edge delamination	1/4" delamination to edge of grain	very slight edge delamination
(7) Uneven Application of Seal Compound	X	X			
(8) Foreign Matter in Nozzle			X		
(9) Template Paper Improperly Installed			X	X	
(10) Masking Tape on Template Paper			X		
(11) Dried Seal Compound			X		
(12) Template Paper Seal				X	
(13) Poor Assembly and Q C Technique		X	X	X	X
Disposition of Motor (see notes below)	1	2	2	2	2

1. The original grain was satisfactorily static fired; the 44099 unit with replaced grain performed satisfactorily on 12.02 GT.
2. These units received hole pattern modification of the chamber case required for the Aerobee 350; all four grains were replaced by new grains (P. R. No. 47448) and all four M24 igniters for these four units will have original igniter cartridge replaced by a hermetically sealed cartridge (8031023/P.R. No. 47458).

REFERENCES

1. "Sounding Rocket Reliability Reassessment" - Abrom Hisler, NASA TN D-2222, November 1964.

2. "Examination of Failed Nike Booster - Carl R. Johnson and John G. Grimsley, GSFC, 14 October 1963.

3. Private communication, "Failure of Nike M-5 at Eglin AFB", Mr. R. B. Jenkins/Space General Corporation to Mr. A. Hisler/Goddard Space Flight Center, January 13, 1965.

4. "Aerobee 350 Heralded as Scientific Workhorse", W. S. Beller, Missiles and Rockets, p. 26, September 27, 1965.

Appendix A

TO : Flight Performance Section Files DATE: 22 April 1965

FROM : Mr. Abrom Hisler
Flight Performance Section

SUBJECT : THE FUNCTIONAL SEQUENCE APPROACH TO NIKE RELIABILITY

REFERENCE : Sounding Rocket Reliability Reassessment, A. Hisler, NASA TN D-2222, Nov. 1964, p. 4

Use of the necessary sequence of events to run down modes of failure was suggested in Appendix B of the above reference. Its application to the Nike solid propellant rocket motor was attempted and will be here presented.

"The Nike Motor Components' Assembly", Attachment A, was prepared to develop the necessary level of familiarity. "A Functional Sequence of Nike Motor Operation", Attachment B, also attached, then followed. With the latter attachment, it is then possible to attempt to relate inspection findings and flight mishaps (see attached Inspection at Radford Arsenal of Nike Boosters for Aerobee 350 Vehicles, Table I).

Applicable functional sequence stages of Attachment B will be considered.

8. The Wallops procedure of opening the hermetic sealed cans and then taping them closed may introduce moisture at this point and possibly prevent igniter charge ignition.

10. Grain delaminations and blemishes may produce an excessive burning surface area to bring on a blow.

11(a). It is assumed that the resonance rods must vibrate properly to reduce local pressure gradients within the motor. Otherwise there will be uneven burning of the propellant to produce local hot spots and finally motor gas leakage at these points. If the resonance rods are not properly torqued, it is again assumed they cannot vibrate properly.

11(b). Leakage at the forward end of the motor is avoided by the 0-ring (8025016) and the gasket (8025103).

12(a). Leakage at the aft end of the motor must be avoided to prevent recirculation of combustion gases past the seam sealing compound (MIL-P-8116). Such gas circulation would erode the grain beaker and create local hot spots past the flamastic coating. There would be a race between this beaker erosion to create critical burning surface areas and eventual over-pressurization, and local heating to burn a hole through the motor body (8030044) leading to combustion gas leakage and eventual flame extinguishment.

To avoid the above, it is necessary that the seam sealing compound be uniformly applied. No dried sealing compound can be tolerated, and the template paper must not be allowed to "bunch up" at the aft end of the grain to act as a very unsatisfactory seal.

The flamastic coating may not stand up too well with time as loose flamastic coatings were noted on a ten year old motor.

Abrom Hisler

NIKE MOTOR COMPONENTS' ASSEMBLY - ATTACHMENT A

By referring to the appropriate drawing (Ordnance Corps., Dept. of the Army, Redstone Arsenal) it is possible to readily follow the steps of Nike motor assembly.

1. XM69 Igniter (8031024) - This igniter replaces the M24 and M65 igniters.

   a) The igniter cartridge (8031023) is assembled to the igniter head (8025059) via six washers (8025045), 2 nuts (MS 35649-62), and two self-locking nuts (MS 2-365-632A)

   b) The igniter cartridge (8031023) is hermetically sealed and consists of the

      1) cup (8031021) with two external connections with shorting wire prior to use

      2) cap (8031022)

   c) The cup (8031021) and cap (8031022) as a unit contain the explosive composition and internal wiring harness (8021026)

d) The internal wiring harness (8031026) lead out thru the igniter head (8025059) to the igniter harness assembly (8025066) attached to the igniter head (8025059) via the spring clip (8034509). Electrical wiring leads from the igniter harness assembly (8025066) thru one pressure sealed connection on the head assembly (8025012) to the interior of the rocket motor assembly. The harness assembly (803004) continues the electrical circuit from the inside of the head assembly (8025012) through the grain (8025090) thru the nozzle closure assembly (8030041) to permit igniter initiation from the aft end of the motor.

2. Integral nozzle-chamber body (803004) - Motor assembly is performed within this body after the flamastic coating has been applied and suitably dried. It consists of the following steps:

a) Insertion of template paper to protect the flamastic coating and reduce the coefficient of friction as the grain is slid into the chamber (8030044).

b) Insertion of the grain (8025090) after uniformly applying the seam sealing compound (Specification MIL-P-8116) and taping existing holes in the forward end of the body (8030044)

c) Thread harness assembly (8030004) thru grain and secure to nozzle closure assembly (8030041) previously assembled to nozzle in a) above

d) Insertion of resonance rod assembly (8025087) after properly torquing each of the nine resonance rods finger-tight

e) Mounting the spring (8025098) with the large base contacting the resonance rod assembly (8025087)

f) Pressing the head assembly (8025012) against the spring (8025098) after connecting the harness assembly (8030004) to the underside of the head assembly (8025012) electrical connector and after removing the tape over the holes in the forward end of the body (8030044), and after assembly of the lubricated "0" ring (8025016) to the head assembly (8025012)

g) Fix the snap ring (8025082) in position and release the pressure on the head assembly (8025012)

h) Assemble gasket (8025103) followed by shipping closure (8025014) to head assembly (8025012)

i) Prior to use, the XM69 igniter (8031024) replaces the shipping closure (8025014) but the gasket (8025103) remains

A FUNCTIONAL SEQUENCE OF NIKE MOTOR OPERATION
ATTACHMENT B

1. Electrical firing pulse
2. Thru harness external to motor
3. Thru harness assembly (8030004)
4. From inside to outside of head assembly (8025012)
5. To harness assembly (8025066)
6. To igniter cartridge (8031023)
7. Thru internal wiring harness (8031026)
8. To explosive composition (Note 2, 8031023)
9. Ignition of igniter charge
10. Initiate burning at surface of grain (8025090)
11. Generate combustion gases
    a) within grain
    b) at forward and aft end of motor
12. Travel of combustion gases
    a) to position between grain beaker and flamastic coating of motor body (803004)
    b) toward nozzle and out

Appendix B

POSSIBLE MODES OF FAILURE/FUNCTIONAL SEQUENCE APPROACH

1. Electrical continuity/continuity check

2. Proper combustion gas sealing in terms of:

   a) 0-ring (8025016)

   b) Gasket (8025103)

   c) Uniform application of seam sealing compound (MIL-P-8116)

   d) Proper use of template paper to avoid the sealing mode of failure

   e) No leakage past the electrical connection and pressure tap in the head assembly (8025012)/hydrostatic test

3. No grain delamination or anomaly

4. Properly torqued resonance rods; use of Belleville springs

5. Spring force within specified limits

To better understand the above critical items, reference to the Redstone Arsenal general assembly drawing no. 8030045 of the M-5 Nike rocket motor is suggested.

Appendix C

SCOPE OF WORK

INSPECTION OF A NASA NIKE ROCKET MOTOR FROM LOT RAD SR-11-62

The purpose of this inspection procedure is to determine if any condition or combination of conditions exist which could cause the malfunction of a Nike Rocket motor. This program shall utilize one M-5 Nike Rocket motor and shall consist of the following phases.

1. Visual, Dimensional, and Electrical Inspections

   a) Prior to opening the shipping and storage container, the exterior of the container will be inspected for the following:

      1) Evidence of structural damage

      2) Condition of the M24 igniter

   b) Upon removal of the M-5 Rocket Motor from the container, the following inspections will be made:

      1) Evidence of damage to the rocket motor

      2) Hydrostatic test stamp missing

   c) The M-5 unit will be disassembled and the following measurements and inspections will be made during or after disassembly:

      1) Propellant grain immobilizer spring improperly positioned

      2) Resonance rod assembly improperly installed

      3) Seam sealing compound missing

      4) Flamemastic coating chipped or cracked

      5) Condition of motor head "0" ring

   d) The M-5 propellant grain will be inspected for the following:

      1) Inhibitor or propellant cut, gouged, or damaged

2) Defective bonding of propellant and inhibitor

3) Inhibitor delamination

e) The metal parts will be inspected for the following:

1) Brinell hardness test on the motor chamber, motor head, and resonance rod support plate

2) Compression strength of immobilizer spring

3) Diameter of nozzle throat

4) Major outside diameter of head

5) Width and thickness of snap ring

6) Diameter of snap ring groove in head

7) Diameter of "0" ring groove

8) Inside diameter of forward end of motor body

9) Depth of snap ring groove in motor body

2. <u>Hydrostatic Test of Motor Chamber and Head</u>

The M-5 motor chamber and head will be hydrostatically tested at a pressure of 1625 (+50 -0) psig for a minimum of three minutes.

3. <u>Reconditioning and Reloading for Shipment</u>

a) Reconditioning of metal parts

1) The inside of the M-5 chamber will be coated with Flamemastic

2) The metal parts will be cleaned and painted

b) The M-5 Rocket motor will be reloaded, utilizing its original components, and will be held for shipping instructions.

Appendix D

ROCKET FAILURES STUDY CHART - NIKE 2.5 DS 59,000

Possible Modes of Failure	Special Considerations and Comments	Corrective Action			Consequences and Conclusions	References
		Possible	Critique	Selected		
Higher g level of sounding rockets	To weaken thinning grain structure					3
High compressive force of grain immobilizing spring	To weaken grain structure	Recommend new spring compressive force specification: 850 ± 25 lb.	Grain undercut by resonance rod spider		Reduce compression force to prevent undercutting grain	2, 3
Longitudinal stringers in material induced initial longitudinal case failure	Stringers found in recovered damaged case	Tighter quality control on case material		Prepare material specification on allowable stringer concentration	Incorporate paragraph 3.4 of MIL-S-18729B method A of ASTM-E-45 into material specs	1
Broken or missing or loose resonance rods	This would promote combustion instability and uneven grain burning	Inspect for this condition prior to launch-prepare check list		Torque rod assembly within allowable range		5
Large amount of propellant in chamber at time of grain collapse	As a result of premature collapse of weakened grain structure					2, 3
Severe air transportation conditions	Fang of modified Ajax launcher damaged					
Whipping action of resonance rods	To prematurely collapse thinning grain structure	Stiffen rods to reduce vibration amplitude				3
Spring weight on grain magnified by acceleration	To increase forces applied to thinning grain structure	Reduce spring weight	Spring weight is only 17 lbs.			3
Grain structure undercut by sharp edge	To reduce undercut structural strength of thinning grain structure	Chamfer chill ring of GSFC D7-087				
Resonance rods ejected to critically reduce throat area		Calculate effect of throat area reduced by total area rods. Reduce rod area or increase throat area	Via: $\dot{w} = C_w P_c A_t$ pressure increase would not be consequential		There is no need to prevent resonance rod from being ejected	3

Possible Modes of Failure	Special Considerations and Comments	Corrective Action			Consequences and Conclusions	References
		Possible	Critique	Selected		
Common assembly error	S/N 44098 & 44100	Inspect S/N 44099	Recommend simultaneous inspection of another unit for 350 first flight test		(1) Three of S/N 44099 resonance rods loosely assembled (2) Resonance rod spider undercut grain (3) Seal compound not adequately spread	3, 4, 6
Temperature extremes in transport planes	Thermal shock would damage grain	Maintain proper plane storage temperature	Had thermal shock occurred, there would have been immediate failure			
Leakage of gas to aft end of inhibitor	This would occur if the seal material were poorly applied. Grain structure collapse would then occur	Search for better technique of applying seal material				

References:

1. Examination of Failed Nike Booster by Carl R. Johnson & John G. Grimsley, 10-14-63
2. Patteson of Radford Ordnance Plant Correspondence of 22 October 1963
3. A. Hisler Trip Report to Radford Arsenal, 14-16 August 1963
4. A. Hisler Trip Report to ABL, 6 September 1963
5. NASA-Langley Launch Station Inspection Check List
6. Cost Estimate and Scope of Work to Inspect M & L Rocket Motor, 19 November 1963

Appendix E

THE "delta P" APPROACH TO COMBUSTION INSTABILITY

At the operating chamber pressure regime of a solid propellant rocket motor, it is assumed that the ratio of inertial to viscous forces plays a decisive role in determining the magnitude of the effective throat area.

Where this ratio is sufficiently high, the effective throat area approaches the design value. Where it is low, swirl flow is assumed to exist at the nozzle throat. In this respect, Swithenbank (1) has suggested "that the effect of swirl on nozzle flow is the predominant factor in the severe irregular burning that arises from traveling tangential modes---".

If the inertial/viscous forces ratio is too low, then instability prevails. Here it is further assumed that there is a periodic weight accumulation of gases in the free volume of the solid motor chamber so that the weight rate of flow of gases discharged through the exhaust nozzle also varies periodically (2). The weight rate of propellant consumption remains constant for the most part but does reflect increments in the chamber pressure.

With the effective throat area less than the design value, and the weight rate of gases in the free volume increasing, the chamber pressure increases to generally improve the mixing of combustion gases within the chamber. This changes the heat transfer pattern within the chamber to increase heat transfer toward and past the nozzle throat. In effect, annular layers of swirl flow at the throat are sheared off until the minimum pressure value for a particular pressure cycle is reached and the motor then momentarily operates at near design value of the throat area. Once this has occurred, the chamber pressure again rises as the swirl condition returns to again reduce the effective throat area and the cycle starts anew.

To maintain an adequate effective throat area so that the rate of gas discharge equals the rate of gas generation, additional energy must be provided so that the required inertial/viscous ratio is maintained. One suggested approach is to increase the pressure drop across the length of the motor by either increasing the pressure in the forward end of the chamber and/or reducing the pressure in the aft end of the chamber. In this respect, gas leakage in the forward end of the Nike motor, past the seal compound, may very well have reduced the pressure drop across the length of the chamber to the point where it caused combustion instability in that duct of the propellant grain where the rate of combustion gas accumulation was greatest. Another way to provide this additional energy is to inject a relatively higher velocity central core stream at the forward end of the chamber. The latter concept has been incorporated into the "purge motor", designed to purge combustion chambers of their instability. This motor is presently under patent application study.

In either case, it is assumed that the pressure drop (delta p) across the length of the chamber has been increased and hence the "delta p" approach.

The inertial/viscous force ratio, of course, is nothing more than the Reynolds number where the critical value is assumed to lie at the upper portion of the transition zone between laminar and turbulent flow. The above may be more than conjecture; a recent parametric study of rocket instability has found various types of Reynolds number similarity parameters to be significant (3).

Although the linear velocity corresponds to a Mach of 1 at the throat, and this velocity in the "x" direction can be assumed to be constant during combustion instability, the "y" and "z" orthogonal components of velocity do vary. With increasing chamber pressure during combustion instability, the resultant velocity may be increased slightly above a critical value during a pressure cycle to change the flow regime. A decided jump in the level of turbulence would then change the heat transfer pattern as suggested above to reduce swirl flow at the throat with the attendant increase in effective throat area and subsequent reduction in chamber pressure.

The above suggests that combustion instability is simply an instance of intermittent turbulence where the necessary turbulence level is <u>not</u> maintained. Intermittent turbulence occurs at a specific head where transitions between laminar and turbulent flow continue indefinitely (4).

If combustion stability is indeed a special case of intermittent turbulence, then raising the head (delta p) across the length of the chamber should bypass this intermittent happenstance.

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1. Swithenbank, J. and Sotter, G., "Vortex Generation in Solid Propellant Rockets", AIAA J. 2, p. 1301 (1964).

2. Zucrow, M. J., Aircraft & Missile Propulsion (John Wiley & Son, Inc., 1958), Vol. II, p. 480.

3. Zucrow, M. J., Parametric Study of Rocket Instability, Final Report, Grant AF-AF/SR 62-360, February 17, 1965, Purdue University, Lafayette, Indiana - AD 614 657.

4. Ginzburg, I. P., Applied Fluid Dynamics, NASA TT F-94, 1963, p. 53.