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COMPILATION OF ROCKET SPIN DATA

FINAL REPORT, VOLUME II
LITERATURE SURVEY

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FINAL REPORT

COMPILATION OF ROCKET SPIN DATA

VOLUME II: LITERATURE SURVEY

by

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Prepared under Contract No. NAS1-6833

for NASA Langley Research Center

PREFACE

Under Contract No. NAS1-6833 with the NASA Langley Research Center, the Emerson Electric Company has conducted a program to compile and evaluate all available data relating to the effects of (spin) acceleration on solid propellant rocket motor performance. This compilation of Rocket Spin Data (CRSD) program was initiated in November 1966 and completed in August 1968.

The CRSD program was directed by Mr. Leo J. Manda of Emerson Electric, with assistance from Mr. John E. Mosier, particularly with the computer programs generated during the course of this study. The program effort was monitored by Mr. Melvin H. Lucy of NASA Langley, who also provided a great deal of assistance with the data acquisition effort.

ABSTRACT

Data compiled from more than 200 reports of motor development tests and research studies indicate that a solid propellant rocket motor operating in a spin environment can exhibit gross deviations from static performance, depending upon spin rate, propellant formulation, and motor configuration. The usual increases in operating pressure and reductions in burn time experienced under spin are shown to be functions of both (centrifugal) acceleration effects on the combustion process and spin effects on combustion chamber and nozzle gas dynamics. Analytical attempts to predict these performance anomalies have shown qualitative agreement with experimental trends, but generally fail to provide quantitative estimates of the effects of the many complex phenomena involved in the gas evolution and flow processes.

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SECTION I

INTRODUCTION

For a number of years, the NASA and other Government agencies have been instrumental in developing solid propellant rocket motors which are spun to provide dynamic stability or to reduce dispersion due to thrust misalignment. Prior to the use of metal additives in these propellants, no serious problems attributed to the spin environment had been encountered in vehicles of interest to the NASA, although definite spin sensitivity had been noted in a number of spin-stabilized tactical rocket motors. However, with the use of aluminum and other metal additives in the more recent propellant formulations, various motor performance anomalies have been experienced with motors subjected to even low spin rates.

Recognizing that a considerable amount of data pertinent to the effects of spin on solid propellant motor performance has been generated by Government agencies and contractors, the NASA Langley Research Center has contracted the Emerson Electric Co. to compile and evaluate this data in order to provide: (1) an improved basis for dealing with the problems associated with motors operating in this environment; and (2) guidance for future research efforts in this area.

The results of this Compilation of Rocket Spin Data (CRSD) program are presented in this and two additional volumes of the CRSD final report. These volumes are organized according to:

Volume I - Acceptation Test Facilities: describes the various spin and centrifuge test facilities available for testing solid propellant rocket motors in acceleration environments.

Volume II - Literature Survey: summarizes the results of the extensive CRSD literature survey, documenting the acceleration effects experienced in various motor development programs and specifying the current state of the art in acceleration studies.

Volume III - Data Evaluation and Recommendations: examines the test data obtained from the various Government agencies and contractors and recommends promising areas for future research activities.

This second volume of the CRSD final report is divided into two primary areas of interest: (1) Motor Performance Data; and (2) Research Studies. The motor performance summaries include data obtained with 26 different motors operating in radial acceleration environments as high as 30,000 G's. The research studies encompass the efforts of some 25 organizations investigating (radial) acceleration effects on solid propellant motor performance.

SECTION II

MOTOR PERFORMANCE DATA

Since the primary objective of any motor development program is to assure the satisfactory performance of the vehicle, a number of design changes are frequently incorporated (often simultaneously) in a given motor if it does not function properly. As a result, no standard of comparison is provided, thereby effectively precluding quantitative estimates of the effects of different variables on performance anomalies. Thus it is most difficult to quantify the effects of a spin environment on motor performance from the motor development test results presented herein. However, a qualitative evaluation of these results indicates that (centrifugal) accelerations of more than 10-20 G's directed perpendicularly into the burning surface of metallized solid propellants will generally:

(1) Increase ignition delay time
(2) Increase motor operating pressure
(3) Decrease burn time
(4) Extend the tailoff burning period
(5) Increase motor burnout mass and thermal protection requirements through the deposition of aluminum (oxide) on the chamber/ nozzle walls.

Effects (2) and (3) above, may be directly attributed to an acceleration-induced increase in the apparent propellant burning rate and/or surface area, which yields higher mass generation rates in the spin environment.

In addition to the above, motors incorporating end-burning grains and the usual converging-diverging nozzle are subjected to severe centerline coning of the propellant surface in a spin environment. The cause of this phenomenon has not yet been determined. However, the effect has generally been reduced or effectively eliminated by modifying the nozzle configuration.

The test results obtained from approximately 100 reports documenting the static and spin tests performed during 26 different motor development programs are summarized in this section. These results and the reference documents are presented individually for each motor, arranged alphabetically. As indicated in Table II-1, motors operating at spin rates producing centrifugal accelerations from 0.15 to 35,000 G's have been investigated.

TABLE II-1: Motor Performance Summaries

Motor	Maximum Accel. (G's)	Propellant Type	Percent Metal	Source	Effects
Alcor	26-66	CTPB	16	Aerojet	Burn time reduced 3-5%; case heating
BE-3	10-27	CMDB	21	Hercules	Burn time reduced 4%
Black Brant	0.5-35	POUR	5	Bristol Aeros.	Slight modification of tailoff
BOMROC (B)	0-12K	FL	20	NOTS	Reduced burn time
BOMROC (S)	13K-16K	FL	5	NOTS	Centerline coning eliminated with "nozzle cap"
CYGNUS-15	195	POSUL	0.9	NASA/Thiokol	None
		POUR	17.2	Aerojet	Thermal failure of case; strain anomalies
HYDAC	100	POCARB	16	Lockheed	Burn time reduced 11%; severe case heating
JPL-SR-28-3	4-9	POUR	16	JPL	None
M7A2B1	600-30K	POSUL	0	Thiokol	Burn time reduced 26%
NOTS 100	10	POUR	17.7	Goodrich	Reduced burn time
NOTS 551	4-30	POUR	17.7	NOTS	Severe heating and nozzle failure; redesign
RAP	12K	FL	5	NOTS	Burn time reduced 10%
SVM-1	3.6	CTPB	15	Aerojet	None
TE-364	6.5	CTPB	16	Thiokol	Ignition delay time increased 100%
TE-388	40	PBAA	18	Thiokol	Burn time reduced 6%; pressure increased 20%

TABLE II-1: Motor Performance Summaries (contd.)

Motor	Maximum Accel. (G's)	Propellant Type	Percent Metal	Source	Effects
TE-442	60		16	Thiokol	Progressive burning; pressure increased 10%
TE-M-444	6	CTPB	16	Thiokol	
TE-M-458	0.15	POUR	13	Thiokol	None
TE-M-466/467	6K-35K			Thiokol	Grain design modified to reduce spin sensitivity
TE-M-479	1.4	CTPB	16	Thiokol	
TM-3	40	PBAN	16	UTC	Burn time reduced 28%; pressure increased 57%
WASP (S)	0-16K	PVC	1.0	Atlantic R.	Significant strain effects on burning
WASP (B)	16K	PVC	1.0	Atlantic R.	Apparent 30% burn rate increase at periphery
WASP (S)	16K	PVC	0	Atlantic R.	Vortex spoiler eliminated center-line coning
X-248	135	DB	3	Hercules	Pressure increased 82%; case failure
X-258	10	CMDB	20	Hercules	Burn time reduced 9%; case heating
X-259	38	CMDB	20	Hercules	Burn time reduced 7%
XM-85	10	POUR	12	Atlantic R.	Burn time reduced 9-11%; case heating
XSR57-UT-1	12	PBAN		UTC	Inconsistent test results

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Alcor

Aerojet-General Corporation's Alcor 1A and 1B motors were designed for the Athena third-stage propulsion. Both units use a 16% aluminized carboxy-terminated polybutadiene propellant (ANB-3066, Type III) in a case-bonded six-point star grain configuration. These motors differ primarily in that: (A) the 1A motor case is 4130 steel, while the 1B case is fabricated of welded titanium; and (B) the 1B nominally contains 5 LB_m less propellant.

The following results were obtained in tests reported in (1) - (7):

Reference	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Motor	1A	1A	1A	1A	1B	1B	1B
Spin Rate (RPM)	0	300	480	305	300	300	187
Max. Accel. (G's)	0	26	66	27	26	26	10
Burn time (SEC)	23.8	24.3	23.1	23.0	23.4	24.3	24.3
Max. Pressure (PSI)	533	518	556	555	516	520	518

As indicated, there is apparently no monotonic variation in motor ballistics with acceleration level in these tests. Moreover, it is noted that the pressure histories in (6) and (7) are essentially identical, even though the acceleration level in (6) is more than twice that in (7). However, more than normal motor case heating was noted in (2) along the line of the star points, and motor case burnthrough was experienced in (3). In addition, comparison of the predicted and actual pressure histories obtained with (2) and (3) indicates 3.5% and 5.3% reductions in burn time and 2.4% and 7.8% increases in maximum pressure, respectively.

References

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(2) D. R. JOHNSON: "Interior Ballistics Report on Motor STVD-3, ALCOR 1A"; SRO: 64:5280: M:795; 15 September 1964.

(3) G. LEE: "Interior Ballistics Report On Motor STVD-4, ALCOR 1A"; SRO: 64:5270: M:829; 5 October 1964.

(4) L. R. BAHOR and R. M. BROOKSBANK: "Performance of the Aerojet-General Corporation Alcor 1A Solid-Propellant Rocket Motor Under the Combined Effects of Rotational Spin and Simulated Altitude"; AEDC-TR-66-236; December 1966; (U).

(5) G. LEE: "Interior Ballistics Report on Motor STV-092, ALCOR-LB"; SRO: 66:5270: M:126; 3 June 1966.

(6) L. R. BAHOR: "Performance of the Aerojet-General Corporation ALCOR-1B Solid-Propellant Rocket Motor Under the Combined Effects of Rotational Spin and Simulated Altitude"; AEDC-TR-66-186; October 1966; AD-489777; (U).

(7) L. R. BAHOR and R. M. BROOKSBANK: "Performance of the Aerojet-General Corporation ALCOR 1B Solid-Propellant Rocket Motor (S/N STV-117)

under the Combined Effects of Rotational Spin and Simulated Altitude"; AEDC-TR-67-50; (U)

(8) M. H. LUCY, G. B. NORTHAM and R. L. SWAIN: "Rocket Motor Spin Data Summary"; Symposium on the Behavior of Propellants Under Acceleration Fields; China Lake, California; NOTS TP3770; June 1965; AD-363903; (C).

(9) H. L. MERRYMAN and D. W. WHITE: "Altitude Ballistic Performance, Heat Flux, and Ignition Shock Data of an AGC ALCOR 1B Solid-Propellant Rocket Motor Fired in a Simulated In-Flight Ignition Environment"; AEDC-TR-68-55; March 1968; (U).

BE-3

The BE-3 motor, produced by Hercules Powder Company for the fourth stage of the Athena system, uses a 21% aluminized composite-modified double-base propellant (DDP-80) in a nearly spherical grain configuration.

In (1) - (4), motor burn time is seen to vary from 8.7 to 9.3 SEC in static firings, while (5) indicates a variation from 8.5 - 8.7 SEC in a series of five spin tests at 300 - 600 RPM (23 - 90 G's). Thus the spin environment would seem to cause an average reduction in burn time of approximately 4.3%.

References

(1) C. F. NOKES Jr.: "Altitude Testing of Hercules Powder Company BE-3 Rocket Motors (Phase III - Surveillance Round Firings)"; AEDC-TDR-62-222; January 1963; AD-333984; (C).

(2) A. A. CIMINO and D. W. WHITE: "An Investigation of Rocket Motor Heat Transfer to a Surrounding Spacecraft Structure at Simulated Altitude Conditions"; AEDC-TDR-63-79; May 1963; AD-336250; (C).

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(4) M. A. NELIUS: "An Investigation of the Effects of Storage Time on the Performance of a Hercules Powder Company BE-3-A2 Rocket Motor"; September 1964; AD-353414; (C).

(5) L. E. FOLSOM: "Dynamic Spin Firing of the BE-3-A4 Athena Motor"; Bulletin of the Second Meeting, ICRPG Solid Propellant Rocket Static Test Working Group; CPIA Publication No. 58; September 1964; (C).

(6) "Static Firing Test Report: BE-3-A8 Athena Fourth Stage Rocket Motor"; Hercules Incorporated (Bacchus) Document No. H230-12-10-2; 15 March 1968; (U).

Black Brant III

The Black Brant III is produced by Bristol Aerospace Corporation for the NASA Goddard Space Flight Center. This motor uses a 5% aluminized polyurethane propellant (A24RX5) in a six-point star grain configuration.

Spin tests conducted at the NASA Langley Research Center indicate that a spin environment varying from 60-500 RPM (.5-35 G's) during firing produces essentially no effect on motor ballistics other than a slight modification of tailoff characteristics (1).

In (2), telemetered flight-test pressure data indicates that one motor subjected to 0-300 RPM operated at a combustion pressure about 7.6% higher than a comparable static firing, while another motor subjected to 0-360 RPM operated at a pressure about 6.5% lower than the static test. However, the validity of this telemetered data is subject to some question because the pressure-time integrals for these three tests also vary by about the same percentages.

References

(1) M. H. LUCY: "Spin Acceleration Effects on Some Full-Scale Solid Rockets"; AIAA Sounding Rocket Vehicle Technology Specialist Conference; Williamsburg, Virginia; 1 March 1967; (U).

(2) L. H. TOUGH: Private Correspondence; 22 December 1967; (U).

BOMROC

The dual-thrust BOMROC motor is currently being developed by the Naval Weapons Center (formerly NOTS) using a 20% aluminized fluorocarbon propellant (PL 6301) for the boost motor and a 5% aluminized fluorocarbon propellant (PL 6677) for the sustainer. This spin-stabilized motor is subjected to radial accelerations from 0 to 12,000 G's during boost and 13,000-16,000 G's during sustain.

The development history of both the radial-burning boost motor and end-burning sustain motor is outlined in (1). Methods of eliminating the severe centerline coning problems initially evidenced in the sustainer are discussed, along with the various testing techniques employed to evaluate motor performance in the spin environment. It is noted that the use of a "nozzle entrance cap" has provided an essentially neutral-burning sustainer. However, significant ballistic effects are noted with the boost motor, even with the multi-nozzle configuration employed.

Reference

(1) D. W. CARPENTER, J. A. YEAKEY and R. W. FEIST: "Spin Stabilized Bombardment Rocket (BOMROC)"; Presented at ICRPG/AIAA Solid Propulsion Conference; Washington, D. W.; July 1966; CPIA Publication No. 111, Volume II; pp. 439-483; (C)

CYGNUS-15

The Cygnus-15 motor has been developed by NASA for the fourth stage of the Trailblazer II re-entry test vehicle. Propellants manufactured by NASA, Thiokol Chemical Corporation, and Aerojet-General Corporation have been used during the course of this motor development. The NASA formulation (also produced by Thiokol) is a .9% aluminized polysulfide composite, NASA BF-117B. The Aerojet propellant is a 17.2% aluminized polyurethane composite, ANP-2986.

As indicated in (1) - (3), no ballistic or thermal anomalies were noted at radial accelerations up to 195 G's with either the NASA or Thiokol BF-117B propellant. However, as noted in (3), the more heavily aluminized ANP-2986 formulation resulted in the thermal failure of flight-weight motor cases. Moreover, (3) also notes the possibility of strain-induced anomalies, deduced from the reproducible differences between pressure histories obtained in flight-weight or heavywall motor cases.

References

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(2) L. BAHOR and R. M. BROOKSBANK: "An Investigation of the NASA CYGNUS-15 Solid Propellant Rocket Motor Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TR-65-115; June 1965; AD-464378: (U)

(3) M. H. LUCY, G. B. NORTHAM and R. L. SWAIN: "Rocket Motor Spin Data Summary"; Symposium on the Behavior of Propellants Under Acceleration Fields; China Lake, California; NOTS TP3770; June 1965; AD-363903; (C)

HYDAC

Lockheed Propulsion Company's HYDAC I and II motors have been used as the upper stage of a number of probe vehicles. The II configuration is a re-designed version of the I, and contains the same 16% aluminized polycarbutene propellant.

The 100-G spin test of the HYDAC I motor reported in (1) and (4) resulted in an 11% decrease in burn time and a 14% increase in average operating pressure compared to static tests, in addition to severe motor case heating. After modification, a similar spin test yielded a comparable reduction in burn time, but an average pressure over burn time only 3% greater than static. However, measured pressures were generally 13-20% greater than predicted.

Telemetered pressure data obtained on a HYDAC I flight test conducted 13 October 1964 indicated motor performance essentially equivalent to static test results until a nozzle (thermal) failure terminated combustion approximately 0.5 SEC prior to anticipated burn time. However, similar data obtained on a 17 February 1966 flight test of the HYDAC II indicated a pressure history very similar to the spin test results reported in (2).

References

(1) L. COBB: "Report on Static Spin Test of HYDAC Motor H22-1 on 10 September 1964"; 9 November 1964; (Contract No. N123(61756)35313A (PMR); (U).

(2) M. H. LUCY: "Static Spin Test of Modified HYDAC Motor H25-18, S/N 16"; 21 January 1965; (U).

(3) M. H. LUCY, G. B. NORTHAM and R. L. SWAIN: "Rocket Motor Spin Data Summary"; Symposium on the Behavior of Propellants Under Acceleration Fields; China Lake, California; NOTS TP3770; June 1965; AD-363903; (C).

(4) M. H. LUCY: "Spin Acceleration Effects on Some Full-Scale Solid Rockets"; AIAA Sounding Rocket Vehicle Technology Specialist Conference; Williamsburg, Virginia; 1 March 1967; (U).

JPL-SR-28-3

The JPL-SR-28-3 motor is produced by the Jet Propulsion Laboratory for the Applications Technology Satellite. Designated as the JPL SR-28-1 prior to a change in motor case material from steel to titanium, this motor uses a 16% aluminized polyurethane composite propellant (JPL-540) in a cylindrically perforated grain configuration.

As indicated in (1) - (6), tests performed at both 100 RPM (4 G's) and 150 RPM (8.7 G's) indicated essentially no deviations from static ballistic performace. However, it was noted that the aluminum oxide deposits found in the nozzles of static firings were not evidenced in the spin tests.

References

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(2) A. A. CIMINO and C. W. STEVENSON: "Altitude Testing of a JPL-SR-28-1 Apogee Rocket Motor for the Advanced Technological Satellite Spacecraft (Preliminary Test Phase - Part II)"; AEDC-TDR-64-259; December 1964; AD-355495; (C).

(3) "Applications Technology Satellite"; Quarterly Progress Report No. 3; SSD 5103R; (Contract NAS5-3823) 1 December 1964 through 28 February 1965; (U).

(4) M. A. NELIUS and C. W. STEVENSON: "Results of Testing Two JPL-SR-28-1 Solid Propellant Rocket Motors (S/N's P-14 and P-15) Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TR-65-186; September 1965; AD-470354; (U).

(5) R. G. ANDERSON: "Applications Technology Satellite (ATS) Apogee Rocket Motor"; Paper presented at the ICRPG/AIAA Solid Propulsion Conference; Washington, D.C.; July 1966; CPIA Publication No. 111, Volume 1; pp. 483-556.

(6) A. A. CIMINO and C. W. STEVENSON: "Results of the Qualification Test of Eight JPL-SR-28-3 Rocket Motors at Simulated Altitude"; AEDC-TR-66-221; November 1966; AD-802218; (U).

M7A2B1

The M7A2B1, as produced by the Thiokol Chemical Corporation for use as the Honest John spin rocket, employs a 5-point "star" grain composed of a non-aluminized polysulfide composite propellant.

With four canted nozzles used to provide radial accelerations varying from 625 to approximately 30,000 G's over the burning interval, calculated flight-test motor performance appeared to yield a 26% reduction in burn time and a 40% increase in maximum pressure compared to static tests.

References

(1) T. T. TSUKIDA, R. B. DILLINGER, and I. F. WITCOSKY: "Rearward Firing 3.0 Inch Spinner Rocket"; NOTS TP 3456; May 1966; (C).

NOTS 100

The NOTS 100 spherical motor incorporates a 17.7% aluminized polyurethane propellant designated as E-107. This propellant was originally produced by B. F. Goodrich, and has subsequently been manufactured by various sources.

Spin tests conducted at approximately 9.5 G's radial acceleration produced a slightly higher average thrust and shorter burn time in (2) than that measured in (1), although the nozzle throat diameter had been increased by approximately 28%. Further tests reported in (3) indicate significant differences in motor response to the same acceleration environment. Also as noted in (3), propellant aging effects and insufficient propellant/liner bond strength are thought to compound the problem. This propellant is currently undergoing extensive acceleration testing at the NASA Langley Research Center.

References

(1) M. A. NELIUS: "Results of Testing Two NOTS-100B Spherical Rocket Motors Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TDR-64-102; May 1964; AD-350338; (C).

(2) D. W. WHITE: "Results of Testing a NOTS 100B (S/N 59) Rocket Motor Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TR-65-15; January 1965; AD-356465; (C).

(3) M. H. LUCY, G. B. NORTHAM and R. L. SWAIN: "Rocket Motor Spin Data Summary"; Symposium on the Behavior of Propellants Under Acceleration Fields; China Lake, California; NOTS TP3770; June 1965; AD-363903; (C).

NOTS 551

The NOTS 551 motor incorporates a slightly modified version (E-107M) of the 17.7% aluminized polyurethane propellant (E-107) used in the NOTS 100 spherical motor.

After experiencing severe motor case heating and nozzle failure during a 45-G spin test (1), the 551A motor was redesigned primarily to eliminate the thermal problems (551B). In addition, 18 subscale (2.7:1) motors were tested at spin rates calculated to provide the same radial accelerations as the full-scale motor in an effort to predict motor performance (2), (3). However, subsequent full-scale test results reported in (3) indicate measured pressures approximately 11-15% lower than predicted for a radial acceleration profile varying from 4-30 G's over the burning interval.

References

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(2) J. D. ANDREWS and V. D. BURKLAND: "Technical History and Development of the NOTS Mod 551B Rocket Motor"; NOTS IDP 2567; March 1966; (C).

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(4) M. H. LUCY: "Spin Acceleration Effects on Some Full-Scale Solid Rockets"; AIAA Sounding Rocket Vehicle Technology Specialist Conference; Williamsburg, Virginia; 1 March 1967; (U).

RAP

The RAP motor currently being developed by the Naval Weapons Center (formerly NOTS) uses the same 5% aluminized fluorocarbon propellant (PL 6677) as is employed in the NWC BOMROC motor. The end-burning RAP motor is subjected to radial accelerations as high as 12,000 G's and axial accelerations up to 50,000 G's.

The development history of this motor is briefly outlined in (1), which also discusses a number of the methods used in an attempt to eliminate the severe centerline coning problems experienced in the spin environment. Of these, a "nozzle diffuser plate" similar to the "nozzle entrance cap" used in the BOMROC motor has been found to provide an essentially neutral thrust history, but with a burning time approximately 10% shorter than that obtained in static tests.

References

(1) R. B. DILLINGER: "Rocket Assisted Projectile (RAP) Propulsion Systems Design"; Presented at ICRPG/AIAA Solid Propulsion Conference; Washington, D.C.; July 1966; CPIA Publication No. 111, Volume II; pp. 415-437; (C).

SVM-1

Aerojet-General Corporation's SVM-1 motor was designed for the INTELSAT II spacecraft. This motor uses a 15% aluminized carboxy-terminated polybutadiene propellant (ANB-3066) in a neutral-burning conocyl grain configuration.

An AEDC spin test of this motor at 3.6 G's radial acceleration (2) indicated essentially no performance deviations from previously reported static tests (1).

References

(1) "Hughes HS-303A Apogee Motor Program Final Report"; Report No. 8608-01F; Aerojet-General Corporation; Sacramento, California.

(2) A. A. CIMINO and C. W. STEVENSON: "Altitude Evaluation of the Intelsat II Communications Spacecraft Apogee Motor in the Spin Mode at an Environmental Temperature of 55°F"; AEDC-TR-67-43; June 1967; AD-654269; (U).

TE-364

The Thiokol Chemical Corporation (Elkton) TE-364 motor was initially designed as the main retrograde motor for the Surveyor spacecraft (TE-364-1). The basic motor configuration was later modified for use as the third-stage propulsion unit for the Improved Delta vehicle (TE-M-364-3) by adding approximately 17% more propellant. Heavywall test units were employed in both the original development program (TE-359) and in the modification program (TE-T-359-3,4). In addition, the Delta development effort included 8 subscale tests (TE-T-470) to determine the effects of the anticipated 6.5-G spin environment on the performance of the 16% aluminized carboxy-terminated polybutadiene propellant (TPH-3062).

The static test results obtained with the Surveyor motor are summarized in (1) - (3). This application of the TE-364 motor had no spin requirement.

Both the static and spin test results obtained with the Delta motor are summarized in (4) and (5), from which it is seen that the only apparent effect of the 6.5-G spin environment on motor performance is an increase in average ignition delay time from .125 SEC to .285 SEC (5). In the subscale tests (5), it is shown that decreasing the aluminum particle size from 30 to 5 microns has no apparent effect on spin sensitivity (or the lack thereof) at this low an acceleration level.

References

(1) L. R. BAHOR and A. L. CANNELL: "Altitude Test of a Thiokol TE-364-1 Surveyor Retrograde Rocket Motor"; AEDC-TDR-63-157; August 1963; AD-339234; (C).

(2) A. F. DOMAL: "Altitude Performance Evaluation of the Main Retrograde Thrust Rocket for the Surveyor Lunar Spacecraft (Thrust Vector Excursion Analysis) (Summary of Six TE-364-1 Firings)"; AEDC-TR-65-77; May 1965; AD-360118; (C).

(3) A. F. DOMAL: "Altitude Performance Evaluation of the Main Retrograde Thrust Rocket for the Surveyor Lunar Spacecraft (Summary of Nine TE-364 Firings)"; AEDC-TR-65-244; December 1965; AD-367768; (C).

(4) A. A. CIMINO and C. W. STEVENSON: "Altitude Performance Evaluation of a Thiokol TE-T-359-3 Solid-Propellant Rocket Motor Spinning at 112 RPM"; AEDC-TR-66-75; April 1966; AD-371271; (C).

(5) "Delta Third-Stage Feasibility Program Final Report"; Thiokol Elkton Report No. E78-66: Volume I; Volume II, Part I; and Volume II, Part II; 28 July 1966; (C).

TE-388

The TE-388 motor designed by Thiokol Chemical Corporation (Elkton) for the Iroquois vehicle uses an 18% aluminized PBAA propellant (TPH-3117) in a cylindrically perforated grain burning on both ends.

As summarized in (1), static test performance indicates a chamber pressure rising from 500 PSI at ignition to 770 PSI at burnout over a burning interval of approximately 7.1 SEC. When subjected to a constant spin rate of 600 RPM (17-40 G's radial acceleration), operating pressure varies from an initial 475 PSI to 920 PSI at burnout over a foreshortened burning interval of 6.7 SEC (2), (3).

References

(1) R. M. BROOKSBANK and M. A. NELIUS: "Altitude Testing of a Thiokol TE-M-388 Solid-Propellant Rocket Motor"; AEDC-TR-65-12; January 1965; AD-455483; (U).

(2) M. H. LUCY: "Static Spin Test of Thiokol Chemical Corporation TE-388 Iroquois Motor"; NASA Langley Research Center Rocket Group File Test Report; 10 October 1966; (U).

(3) M. H. LUCY: "Spin Acceleration Effects on Some Full-Scale Solid Rockets"; AIAA Sounding Rocket Vehicle Technology Specialist Conference; Williamsburg, Virginia; 1 March 1967; (U).

TE-442

The Thiokol Chemical Corporation (Elkton) TE-442 motor incorporates a 16% aluminized propellant in an 8-point "star" spherical grain configuration.

A brief reference to TE-442 motor performance in (2) indicates that maximum operating pressure was increased about 10% in a 60-G spin environment. Although this effect was negated by increasing the nozzle throat size to reduce combustion pressure (1), comparison of a representative static pressure history with two dynamic firings indicates a basic change in the overall combustion process toward more progressive burning approaching burnout.

References

(1) C. E. MORGAN: "TE-422 Motor Data Sheets"; Thiokol Elkton letter to G. B. Northam, Langley Research Center; 4 November 1964; (U).

(2) "Delta Third-Stage Feasibility Program Final Report"; Thiokol Elkton Report No. E78-66; Volume II, Part I; 28 July 1966; (C).

TE-M-444

The TE-M-444 spherical motor was designed by Thiokol Chemical Corporation (Elkton) for MIT Lincoln Laboratory. This motor uses the same 16% aluminized carboxy-terminated polybutadiene propellant (TPH 3062) as is employed in the TE-364 series motors.

A single 6.1-G radial acceleration spin test is reported in (1), with no reference to, or comparison with, previous static or spin firings.

References

(1) L. R. BAHOR: "Results of Testing the Thiokol TE-M-444 Solid Propellant Rocket Motor Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TDR-64-269; December 1964; AD-355574; (C).

TE-M-458

The Thiokol Chemical Corporation (Elkton) TE-M-458 was designed to provide retrograde thrust for the NASA Anchored Interplanetary Monitoring Platform. This spherical motor uses a 13% aluminized polyurethane propellant (TPG-3129) in an 8-point "star" grain configuration.

Two tests performed at 0.15-G radial acceleration (1) indicate no perceptible effect of the spin environment on motor performance.

References

(1) A. A. CIMINO and C. W. STEVENSON: "Altitude Performance Evaluation of Two AIMP Retrograde Motors (TE-M-458) on a Spacecraft Spinning at 28 RPM"; AEDC-TR-66-8; February 1966; AD-369226; (C).

TE-M-466/467

The Thiokol Chemical Corporation (Elkton) TE-M-466/467 motors were designed for the Nortronics Non-Linear Dispensing System. Two aluminized propellants (TP-H-3132 and TP-H-3123) were used during the course of this development program. Both propellants were significantly affected by the spin environment, which produced radial accelerations varying from 6,000 G's at ignition to 35,000 G's at burnout.

In an effort to reduce the severe effects of the spin environment noted with the 3132 propellant, the 3123 formulation (with a lower aluminum content) was employed in a few limited tests. However, the remainder of the program was completed with the original propellant when these tests proved unsuccessful.

In order to decrease motor performance sensitivity to the spin environment, the grain design was altered to minimize the amount of propellant surface normal to the (radial) acceleration vector. Although clearly demonstrating that this approach is indeed feasible, the grain design thus evolved could not produce satisfactory motor performance. After a series of six grain modificiations, satisfactory performance was achieved.

References

(1) "Final Development Report, Phase I, Nonlinear Dispensing System Rocket Motor"; Report No. E41-66; 11 May 1966; (U).

TE-M-479

The TE-M-479 spherical motor was designed by Thiokol Chemical Corporation (Elkton) to be used as the apogee kick motor for the Radio Astronomy Explorer spacecraft. This motor uses the same 16% aluminized carboxy-terminated polybutadiene propellant (TPH-3062) as is employed in the TE-M-444 and TE-364 series motors.

Two spin tests at 1.4-G's radial acceleration are reported in (1), with no reference to previous static or spin test firing results.

References

(1) J. E. HARRIS and D. E. WHITE: "Evaluation of Two Radio Astronomy Explorer Spacecraft Apogee Kick Motors Tested in the Spin Mode at Simulated Altitude Conditions"; AEDC-TR-67-127; July 1967; AD-817821; (U).

TM-3

The TM-3 motor was designed by United Technology Center for the Air Force SSC development of the FW-4S motor. The UTC version of this motor uses a 16% aluminized PBAN propellant (UTC UTP-3096) in an essentially cylindrical grain configuration with one radial slot. The XSR-57-UT-1 was also designed as the FW-4S motor.

Test results reported in (1) indicate a 10% reduction in normal burn time and a 14% increase in maximum operating pressure at 10 G's radial acceleration, and a 28% reduction in burn time and 57% increase in maximum pressure at a radial acceleration of 40 G's.

References

(1) M. H. LUCY, G. B. NORTHAM and R. L. SWAIN: "Rocket Motor Spin Data Summary"; Symposium on the Behavior of Propellants Under Acceleration Fields; China Lake, California; NOTS TP3770; June 1965; AD-363903; (C).

WASP

As developed by Emerson Electric for the U. S. Army Missile Command, the spin-stabilized WASP rocket motor incorporated separate spin, boost, and sustain propulsion systems.

The initial motor design used two end-burning grains of a non-aluminized polysulfide propellant for the spin motor, a five-point "star" configuration of the same propellant for the boost motor, and an end-burning alkyd-resin styrene composite for the sustain motor. All propellants were supplied by Bermite Powder Company.

As reported in (1), boost thrust measurements obtained at radial acceleration levels decaying from about 7000 G's to zero at burnout gave no positive indications of any significant effect of the spin environment on motor performance.

The revised WASP motor design incorporated a cylindrically perforated grain of 1% aluminized polyvinyl chloride propellant (Arcite 386M) for the spin motor, a 6-point "star" configuration of the same propellant for the boost motor, and an end-burning non-aluminized polyvinyl chloride composite (Arcite 377A) for the sustain motor. The sustain motor also incorporated a vortex spoiler in the nozzle entrance section, patterned after those developed at the Naval Weapons Center (NOTS). All propellants were supplied by Atlantic Research Corporation.

As reported in (2), the effects of radial accelerations increasing from 0 to approximately 16,000 G's on spin motor performance were found to be primarily a result of propellant/case structural interactions, with some burn rate amplification due to combustion effects also likely, but undefined (4).

In order to achieve simultaneous burnout of both the struts and periphery of the boost grain at 16,000 G's, the peripheral web thickness was increased about 30% during this development program. Whether the apparent 30% increase in burn rate under spin was primarily due to alumina centrifugation (4) or preferential peripheral ignition of the grain under spin (2) was not resolved.

With the vortex spoiler incorporated in the sustainer nozzle, the end-burning sustain motor was essentially neutral burning (2), (4). However, a concurrent test program conducted at Redstone Arsenal (3) with the same non-aluminized propellant indicated severe centerline coning of the grain at radial accelerations of only 3500 G's when the vortex spoiler was not incorporated in the nozzle.

References

(1) T. F. HOEKEL and L. J. MANDA: "The Influence of the Spin Environment on the WASP Booster Performance"; Symposium on the Behavior of Propellants Under Acceleration Fields; Naval Ordance Test Station; NOTS TP3770; June 1965; AD-363903; (C).

(2) "Final Report - WASP Advanced Development Program"; Volume I; Emerson Electric Report No. 2030; February 1966; AD-373484; (C).

(3) D. R. ULLOTH and W. D. GUTHRIE: "A Study of Vortex Effects in Spinning Rocket Motors"; Report RK-TR-66-8; April 1966; AD-374624; (C).

(4) P. W. SERBU, ET AL: "WASP Motor Development Program"; presented at ICRPG/AIAA Solid Propulsion Meeting, Washington, D. C.; 19-21 July 1966; CPIA Publication No. 111; Volume II; pp. 485-507; AD-373908; (C).

X-248

The X-248 motor developed by Hercules Powder Company has been used on the Altair I, Thor-Able, Scout, Deta, Shotput, Argo D4, Caleb, Transit-TIROS, Atlas-Able, Trailblazer II, and Javelin vehicles. This motor uses a 3% aluminized cast double-base propellant (BUU) in a finocyl grain configuration.

In spin tests conducted at ABL (1), a 45% increase in maximum pressure and 14% decrease in burn time were observed at a radial acceleration approaching 74 G's; and an 82% increase in maximum pressure, followed by case failure, occurred at approximately 135 G's. Subsequently, spin tests performed at the NASA Langley Research Center (2), (3) indicated; (A) no significant performance changes at 15 G's; (B) a 24% increase in maximum pressure and 14% decrease in burn time at 63 G's; and (C) a 34% increase in maximum pressure and 10% decrease in burn time at 92 G's. From the data presented in (3), it is seen that no spin effects are evident in either (B) or (C) before approximately 55% of normal burn time has elapsed, at which time combustion pressure increases quite rapidly to the maximum values noted. An extensive series of centrifuge tests of the BUU propellant is currently in progress at NASA Langley.

References

(1) W. B. HELBERT Jr., G. H. MOODY, and M. G. PORTER; "JATO X-248 Performance Data"; ABL Dev. 1244; 1959.

(2) M. H. LUCY, G. B. NORTHAM and R. L. SWAIN: "Rocket Motor Spin Data Summary"; Symposium on the Behavior of Propellants Under Acceleration Fields; China Lake, California; NOTS TP3770; June 1965; AD-363903; (C).

(3) L. J. BEMENT: "Report of LRC X-248 Test Firings and Upgrading Techniques"; NASA Langley Research Center; 1966.

X-258

The X-258 (Altair II) motor produced by Hercules Powder Company as a replacement for the X-248 has been used on both the Scout and SLV-1D vehicles. This motor uses a 20% aluminized composite-modified double-base propellant in a finocyl grain configuration (10). Functioning as the fourth stage of the Scout, the X-258 is subjected to radial accelerations of approximately 10 G's.

After (3) indicated that the sources of motor failure observed in (1) and (2) had been corrected, the spin tests described in (4) and (5) indicated a consistent 7% increase in maximum pressure and 9% reduction in burn time compared to static firings. In addition, case discoloration due to thermal effects was observed in these and subsequent spin tests. The ballistic data for all X-258 firings conducted from 7/16/61 to 6/22/63 are summarized in (6).

Centrifuge tests of a homologue of the X-258 propellant formulation are described in (7). Values of the mass flow coefficient (C_D) obtained from these tests at different orientations of the acceleration vector with respect to the end-burning propellant surface are given below.

Motor Number	#1	#2
40 G's Away From Surface	.00741	.00734
Static	.00692	.00660
40 G's Into Surface	.00637	.0054C

With a 5% difference in measured values of C_D (implying a 10% difference in combustion temperature) at static conditions, the validity of this data is questionable. Nevertheless, accepting the results at face value indicates 12.8% and 19.2% decrease in combustion temperature with acceleration directed away from the surface, and 18.0% and 6.4% increases in temperature with acceleration toward the surface. However, (16) indicates that the combustion efficiency of this propellant is strongly influenced by operating pressure, particularly at pressures near 400 PSI. With no pressure data given in (7), the influence of this parameter on the apparent "acceleration effects" cannot be evaluated.

Flight test data presented in (12) indicates a burn time approximately 5% longer than that recorded in static spin tests (4) and (5), thereby advancing the possibility that in-flight longitudinal accelerations may tend to reduce the effects of radial acceleration noted in static spin tests. However, later flight test data from (17) indicates a burn time essentially equivalent to those observed in the ground spin tests.

The results of a fairly extensive X-258 propellant research program are reported in (16). In this program, two modifications (P2 and P3) of the X-258 propellant (P1) were also studied in an effort to better define the potential significance of propellant variables in determining the effects of acceleration on motor performance. The differences in propellant formulation are given by:

P1 = the X-258 propellant
P2 = P1 with smaller oxidizer particles
P3 = P1 with larger aluminum particles

In summary, the results of this program have indicated:

(A) Combustion efficiency decreased linearly with pressure from 1000 to 400 PSI, then sharply declined below 400 PSI. From observation of the burning surface, it is concluded that this decline is a result of a change in the aluminum combustion process.

(B) At a given acceleration level, the P3 propellant left about 3 times as much residue in a 40-LB_m test motor as did the P1 propellant.

(C) Longitudinal accelerations yielded a pressure trace essentially equivalent to that obtained statically.

(D) Radial accelerations produced an increase in operating pressure and a decrease in burn time.

(E) Combined radial and longitudinal accelerations yielded a better approximation to the theoretical pressure history than did the static firings.

(F) The rate of change of burn rate with strain level was found to be a function of pressure level.

References

(1) H. G. DAVIS and M. A. NELIUS: "Simulated Altitude Testing of an X-258 B-1 Solid-Propellant Rocket Motor." AEDC-TDR-62-216, November 1962; AD-333135; (C).

(2) L. R. BAHOR and M. A. NELIUS: "Altitude Testing of Two HPC-ABL X-258 B-1 Solid-Propellant Rocket Motors." AEDC-TDR-63-62; April 1963; AD-335487; (C).

(3) L. R. BAHOR and M. A. NELIUS: "Simulated Altitude Testing of HPC-ABL X-258 B-1 (S/N RH-45) Solid-Propellant Rocket Motor." AEDC-TDR-63-105, May 1963; (C).

(4) M. A. NELIUS and D. W. WHITE: "Results of Testing the HPC-ABL X-258 B-1 Solid-Propellant Rocket Motor (S/N RH-47) Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TDR-64-41; March 1964; AD-433216; (U).

(5) M. A. NELIUS and D. W. WHITE: "Results of Testing Two HPC-ABL X-258 (S/N RH56, 58) Solid-Propellant Rocket Motors Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TDR-64-97; May 1964; AD-440108; (U).

(6) J. F. WOOD: "X-258 Data Summary Report"; Hercules Powder Company, Report No. ABL/I-24; May 1964; (U).

(7) "Analysis of the Performance of the X-258 Altair III"; Hercules Powder Company, Report No. 044845; August 21, 1964; (U).

(8) R. M. BROOKSBANK and D. W. WHITE: "Results of Testing the HPC-ABL X-258 E-2 (S/N RH 100) Solid-Propellant Rocket Motor Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TDR-64-255; December 1964; AD-452606; (U).

(9) J. E. HARRIS, M. A. NELIUS, and C. W. STEVENSON: "Results of Testing Two HPC-ABL X-258 E-4 (S/N's RH 106 and RH 105) Solid-Propellant Rocket Motors Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TR-65-71; April 1965; AD-461205; (U).

(10) M. H. LUCY, G. B. NORTHAM and R. L. SWAIN: "Rocket Motor Spin Data Summary"; Symposium on the Behavior of Propellants Under Acceleration Fields; China Lake, California; NOTS TP3770; June 1965; AD-363903; (C).

(11) J. M. PELTON and J. F. WOOD, Jr.: "X-258 Development Program Final Report"; Hercules Powder Company, Report No. ABL/R-57; July 1965; (U).

(12) D. DEMBROW: "Performance of X-258 Third-Stage Motor Delta 21"; NASA TM-X-55566; July 1965; (U).

(13) A. A. CIMINO and J. E. HARRIS: "Results of Testing Two HPC-ABL X-258 E-6 Solid-Propellant Rocket Motors (S/N's RH 123 and RH 128) Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TR-65-189; September 1965; AD-470355; (U).

(14) T. F. OWENS, J. PASKIND, M. B. RUBIN and C. K. WHITNEY: "Scout Motor Performance Analysis and Prediction Study (PAPS)"; NASA CR-336; (Contract No.'s NAS1-3683 through NAS1-3686); December 1965; (U).

(15) P. JOHNSON and J. M. PELTON: "Postfiring Report of X-258 Motors RH 105 and RH 106"; Hercules Powder Company, Report No. ABL/X-142; March 1966; (U).

(16) K. B. KRAMER: "X-258 Propellant Characterization Study Final Report"; (Contract No. NASW-1241); May 1966; NASA CR 66096; (C).

(17) J. E. SCHMIDT: "Performance of X-258 Third-Stage Motor on Delta 36"; NASA TN-D-4050; July 1967; (U).

X-259

The X-259 (Antares II) motor produced by Hercules Powder Company for the third stage of the Scout has also been designated for use on the Project Fire vehicle. This motor uses a 20% aluminized composite-modified double-base propellant in a finocyl grain configuration (1). The propellant is essentially the same as that used in the X-258, but incorporates more finely ground oxidizer particles to achieve a burning rate approximately 14% higher than that of the X-258 (2), (3).

Spin tests at 200 and 300 RPM (16.5 and 38 G's, respectively) reported in (1) indicated essentially no effects of the 200 RPM environment on motor performance, but a 7% reduction in burn time and an 11% increase in operating pressure (during the latter burning phase) at 300 RPM. Test results reported in (3) indicate that static performance was apparently unaffected by (10-G) radial, (25-G) longitudinal, or combined acceleration environments.

References

(1) M. H. LUCY, G. B. NORTHAM and R. L. SWAIN: "Rocket Motor Spin Data Summary"; Symposium on the Behavior of Propellants Under Acceleration Fields; China Lake, California; NOTS TP3770; June 1965; AD-363903; (C).

(2) T. F. OWENS, J. PASKIND, M. B. RUBIN, and C. K. WHITNEY: "Scout Motor Performance Analysis and Prediction Study (PAPS)"; NASA CR-336; December 1965; (U).

(3) K. B. KRAMER: "X-258 Propellant Characterization Study Final Report"; (Contract No. NASW-1241); May 1966; NASA CR 66096; (C).

XM-85

The XM-85 is produced by Atlantic Research Corporation for use as the fourth-stage propulsion unit on the Air Force Standard Launch Vehicle (SLV-1B). The XM-85 motor configuration is identical to that of the NOTS 100A, but uses a 12% metallized polyurethane propellant formulation (Arcane 35H) in place of the 17.7% aluminized E-107 propellant originally incorporated.

Spin tests performed at radial accelerations of approximately 9.5 G's yielded burn times approximately 9% (4), 11% (5), and 3% (6) less than the average of three static firings reported in (1). In addition, the maximum thrust increased about 16-17% in the spin environment. Moreover, thermal effects due to the centrifugation of metallic residues were noted near the motor equator in the three spin firings.

References

(1) A. A. CIMINO and D. W. WHITE: "Simulated Altitude Tests of Three Atlantic Research Corporation XM-85 Solid-Propellant Rocket Motors"; AEDC-TDR-63-111; June 1963; AD-337585; (C).

(2) A. A. CIMINO and D. W. WHITE: "Simulated Altitude Test of an Atlantic Research Corporation SM-85 Solid-Propellant Rocket Motor (S/N 38)"; AEDC-TDR-63-144; July 1963; AD-338942; (C).

(3) A. A. CIMINO: "Simulated Altitude Test of Atlantic Research Corporation XM-85 Solid-Propellant Rocket Motor (S/N T1-3) Spinning at 200 RPM"; AEDC-TDR-64-122; June 1964; AD-350756; (C).

(4) A. A. CIMINO and C. W. STEVENSON: "Simulated Altitude Test of an Atlantic Research Corporation XM-85 Solid-Propellant Rocket Motor (S/N T1-5) Spinning at 200 RPM"; AEDC-TR-65-16; January 1965; AD-356816; (C).

(5) A. A. CIMINO and C. W. STEVENSON: "Simulated Altitude Test of an Atlantic Research Corporation XM-85 Solid Propellant Rocket Motor (S/N T1-2) Spinning at 200 RPM"; AEDC-TR-65-56; April 1965; AD-358781; (C).

(6) D. W. WHITE: "Results of Testing an Atlantic Research Corporation XM-85 Solid-Propellant Rocket Motor Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-65-96; May 1965; AD-360773; (C).

(7) M. H. LUCY, G. B. NORTHAM, and R. L. SWAIN: "Rocket Motor Spin Data Summary"; Symposium on the Behavior of Propellants Under Acceleration Fields; Naval Ordnance Test Station; NOTS TP3770; June 1965; AD-363903; (C).

XSR 57-UT-1

The XSR 57-UT-1 rocket motor has been developed by United Technology Center (UTC) as the Scout fourth-stage propulsion unit. This motor incorporates an aluminized polybutadiene acrylonitrile (PBAN) propellant (UTP-3096A) in a case-bonded, transversely slotted tube grain configuration.

The results of a series of developmental tests performed at spin rates from 0-210 RPM (0-12 G's radial accelerations) are reported in (2) and summarized below.

Temperature (°F)	77	77	77	35	35	35
Max. Acceleration (G's)	0	9.8	12.0	0	5.3	7.0
Burn Rate (IN/SEC)	.228	.252	.259	.218	.226	.228
Burn Rate Ratio	1.00	1.10	1.14	1.00	1.04	1.05
Burn Time (SEC)	32.9	29.9	29.3	33.8	33.5	33.2
Avg. Pressure (PSI)	636	657	692	598	595	620

Additional tests performed at 70-80 °F are reported in (3) and (4) and summarized below.

Max. Acceleration (G's)	0	11	11	11	11
Burn Rate (IN/SEC)	.247	.258	.258	.262	.277
Burn Rate Ratio	1.0	1.045	1.045	1.06	1.12
Action Time (SEC)	31.5	31.3	31.0	30.8	29.5
Avg. Pressure (PSI)	655	658	665	664	704

As indicated, the average static burn rate is 8% higher than that measured at 77 °F in the preceeding test series (with the same nozzle throat diameter). Moreover, the burn rate under spin is found to vary about 8% at a constant acceleration level. No explanation is offered for these phenomena.

References

(1) D. W. WHITE: "Results of Testing UTC XSR 57-UT-1 Solid-Propellant Rocket Motors Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TR-65-47; March 1965; AD-460198; (U).

(2) C. M. FREY: "Fourth-Stage Scout Rocket Motor Program Development Test Report"; UTC-2100-DTR; 16 March 1965; AD-464839; (U).

(3) D. W. WHITE and J. E. HARRIS: "Results of Testing UTC SXR 57-UT-1 Solid-Propellant Rocket Motors Under the Combined Effects of Simulated Altitude and Rotational Spin"; AEDC-TR-65-150; July 1965; AD-466559; (U).

(4) C. M. FREY: "Fourth-Stage Scout Rocket Motor Preliminary Flight Rating Test Report"; UTC 2100 - PFRTR; 3 June 1965; AD-473466; (U).

(5) J. E. HARRIS and D. W. WHITE: "Simulation of the De-Spin Event of the UTC XSR 57-UT-1 Solid-Propellant Rocket Motor (S/N 30104)"; AEDC-TR-66-87; February 1966; AD-483144L; (U).

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SECTION III

RESEARCH STUDIES

The "research studies" discussed herein include all those spin-oriented activities which are either not specifically directed to the development of a particular motor, or which represent extensions of such development efforts to include more basic investigations of observed spin phenomena.

Since the performance of a solid propellant rocket motor operating in a spin environment can be significantly influenced both by the effects of centrifugal acceleration on the combustion process and by the effects of the induced swirl flow on chamber and nozzle gas dynamics, these two areas of interest form the primary bases of discussion. In general, the literature published on each of these topics is reviewed chronologically, with all references cited ( ) contained in Section IV of this report, along with a brief abstract of each document.

Combustion Phenomena

Some of the earliest indications of the effects of an acceleration environment on the combustion process were provided by Ordahl and Wall in 1955.

After noting a power loss in the Sidewinder gas generator under acceleration, Ordahl (46) conducted a number of limited centrifuge tests of the N-4, N-5, X-9, PL 777, and JPN double-base propellants at accelerations up to 50 G's directed into, away from, and parallel to the propellant surface. With acceleration into the burning surface, the following effects were noted:

- N-4: No apparent effect at 30 G's.
- N-5: Pressure decreased 20-25% at 30 G's.
- X-9: Pressure decreased in proportion to the magnitude of the acceleration, with a reduction of approximately 30% measured at 50 G's.
- PL 777: Pressure increased 35-40% at 30 G's.
- JPN: Inconclusive results due to nozzle erosion.

No explanation is attempted for the differences in acceleration sensitivity observed.

The behavior of the non-metallized T-24 (TRX-109) polysulfide composite propellant under high axial and radial accelerations was examined by Wall (92) in a series of 3C static and 42 dynamic firings. The test vehicle was gun-launched in the dynamic tests, achieving spin rates of 26,000 RPM at the muzzle and 54,000 RPM (109,000 G's) at burnout. Four grain configurations providing (propellant surface)/(nozzle throat) area ratios of 150, 200, 250, and 300 were tested. However, only 3 dynamic tests were performed for any given area ratio, and 36% of these tests yielded no useful results. Nevertheless, the acceleration environment resulted in an apparent 135-165% increase in propellant burn rate, with this burn rate amplification apparently increasing with decreasing grain complexity. This conclusion is "quantified" in (93) by correlating burn rate augmentation with a measure of grain complexity termed the "configuration factor" x, where $X = A_c/A_x$, A_x = grain port area, and A_c is the area of a circular cavity with a perimeter equal to the propellant surface area per unit length. However, this generalization must be regarded as tentative at best, primarily because of: the limited sample size; a relatively high percentage of test failures; and the usual inaccuracies inherent in deriving pressure-time histories from vehicle distance-time measurements. Moreover, it is interesting to note that nozzle vortex choking should also tend to increase with decreasing grain complexity.

With the exception of brief notes by Butts, Goldshine, Stiefel, etc. (54) relative to gas generator performance under acceleration, no further studies of acceleration effects on combustion were published until 1960, when Redel began the experimental study for Edwards AFB outlined in (69). The results of this study are summarized in (73), with intermediate results presented in (70) - (74). From the quantity and quality of data generated during this investigation of four solid propellants (OMAX 452 ammonium nitrate composite, N-5 double-base, TPL-3014 polysulfide composite, and GCR-524 aluminized PBAA), it is validly concluded that ignition is facilitated with acceleration toward the propellant surface and made more difficult with acceleration away from or parallel to the surface. Any further conclusions are subject to restrictions of: inhibitor/bonding failure, inadequate isolation of significant variables, and insufficient sample sizes.

An investigation of the effects of acceleration on the performance of 4 double-base propellants (ARP, ARW, CIA, and DQO) was initiated at Hercules ABL by Eirich (14) in 1961. The results of this study (extended to include 2 CMDB formulations (CYH and DDP) and a BPY gas generator propellant) are summarized below from the test data reported in (17) for 40-G accelerations directed either toward (t) or away from (a) the surface of an end-burning grain.

Propellant	$\bar{P}$ (static)	$\bar{P}$ (t)	$\bar{P}$ (a)
ARP	1110	1148	----
ARP	636	656	682
ARW	834	848	---
ARW	284	307	---
CIA	No valid data		
DQO	1265	1437	1240
CYH	562	503	513
DDP	No valid data		
BPY	334	625	333

As indicated, performance variations are generally insignificant, particularly in view of the fact that a number of the acceleration tests represent single motor firings. However, acceleration toward the propellant surface is seen to cause considerable increases in burning rate and average pressure with the DQO and BPY formulations.

In view of the fact that propellant strain may increase appreciably with motor case expansion under spin, Coy's 1961 study of the influence of strain on the burning rates of two polyurethane formulations (23) may be significant in determining one factor contributing to the increased burning rates usually observed in a spin environment. In this study, the 1000 PSI burning rates of both an aluminized and non-aluminized polyurethane were found to increase 1.2-1.5% per percent of strain. Similar results were obtained by Saylak (88), who investigated 4 different types of propellants and found widely varying response to strain, but a generally consistent increase in burning rate with strain level, which was most pronounced with a plastisol formulation. In addition, Saylak was able to correlate this increase in burning rate with a "volumetric change index" based on Poisson's ratio.

An increased interest in spin/acceleration effects on motor performance began to be evidenced throughout Government and industry in 1963, and has generally continued to the present.

In (18), Sutphin reports the results obtained in testing a CMDB propellant (DDP-80) at an axial acceleration of 150 G's and at a lateral acceleration of 50 G's. No effects of the acceleration environments were apparent in the two tests performed at each orientation. Similar results were also obtained at UTC (102) with two composite propellants (UTX 1724 and UTX 2649) subjected to accelerations as high as 800 G's parallel to the propellant surface.

Meanwhile, centrifuge tests conducted by Thiokol Elkton (85) at ambient pressure indicated an increase in burn rate with acceleration level, up to 125% and 50% at 750 G's for medium-burning (TP-G-3016D) and fast-burning propellant formulations, respectively, for the acceleration directed into the burning surface. Conversely, slight reductions in rate were observed with acceleration directed out of the propellant surface.

The influence of spin on the performance of Army tactical motors was also recognized in 1963 at Redstone and Picatinny arsenals and Ballistic Research Laboratory.

Using flight-test data obtained with the XM-27 double-base propellant to establish a burn rate dependence on spin rate, Guthrie and Chen of Redstone derived a semi-empirical method of predicting motor performance for changes in grain design. As illustrated in (80), this approach was generally successful in approximating maximum operating pressure, but less adequate for duplicating the overall pressure-time histories.

A number of end-burning grains of an unspecified double-base propellant were examined by Vecchio and Harnett of Picatinny at spin rates up to 12,000 RPM (55). Test results obtained with these motors indicated increased spin sensitivity with both spin rate and conditioning temperature. Most significantly, this brief study is the first to note severe coning of the end-burning propellant surface under spin.

The results of a series of 100-G centrifuge tests of the XM-27 double-base propellant are summarized below from Redel's report (74) to the Ballistics Research Laboratory.

Direction of Acceleration	$\bar{P}/\bar{P}$ (static)	t/t (static)
(A) Toward	1.22	.95
(B) Away From	1.17	1.02
(C) Parallel To	1.07	1.00

As indicated, acceleration in any direction appears to increase combustion pressure, with no decrease in burn time in one instance (C), and 2% <u>increase</u> in another (B). Assuming constant propellant density and similar motor/grain geometries, this latter result would require an increase in combustion temperature of more than 40% with acceleration directed away from the propellant surface. Moreover, there is considerable discrepancy between these results and those published in (80) for the same propellant.

The Redel test program noted above was continued through 1964 with both centrifuge and spin tests of the HX-12, X-14, N-4, N-5, and JPN double-base propellants and a 2% aluminized composite propellant, C-505A. As summarized in (78) and (79), acceleration toward the surface was generally found to decrease the burning rates and average pressures measured with the double-base propellants, and increase these parameters with the composite. However, as noted previously in the discussion of Redel's 1960 test program, the validity of these results is again subject to limitations of small sample size and a relatively large number of inhibitor/bonding failures.

The acceleration studies performed prior to 1964 are summarized by Palm and Martin in (81), who also report the results of a test program performed at spin rates up to 10,000 RPM with AGJ double-base propellant. In these tests, the radial burning surface is inhibited to varying degrees to reduce the burn rate amplification experienced under spin. Although some success is evidenced with this technique, it is noted that results presented for 72% inhibition indicate both higher pressures and a longer burning time than obtained at 56%, with no change in grain/nozzle geometry.

Cylindrically perforated grains of an aluminized PBAA propellant (Thiokol's TPH-8126) and two aluminized polyurethane formulations (Aerojet's ANP 2969 and ANP 3063) were tested at axial and lateral accelerations up to 200 G's by Landau and Cegielski in 1964. The results of these tests reported in (8) indicate no effect of the acceleration environments on motor performance. Similar results are also reported by Horton (90) for both cylindrically perforated and "star" grains of a PBAA propellant tested at axial accelerations up to 100 G's, and by Iwanciow and Lawerence (103) for cylindrical grains of two 16% aluminized propellants (UTX-1724-16 and UTX 2649) at axial accelerations up to 800 G's. However, some apparent degradation of characteristic velocity is noted in the latter tests conducted at UTC.

On the other hand, end-burning tests of AHH double-base propellant performed by Harnett and Olstein (56) at spin rates up to 12,000 RPM again indicated severe centerline coning of the propellant surface, increasing with increasing spin rate. However, satisfactory motor performance was achieved by modifying the nozzle configuration.

In contrast, spin tests of 1.5 IN diameter end-burning grains of ARP double-base propellant reported by Dickinson and Lechelt (20) indicated no apparent effects of spin rates of 17,000 and 23,400 RPM on motor performance, nor any centerline coning of the grain.

Two rather significant events mark 1965 as something of a "year of transition" with respect to the study of acceleration effects on motor performance. The first of these is the industry-wide recognition of the importance of spin phenomena in determining deviations from static performance, as exemplified at the Naval Weapons Center (NOTS) Symposium on the Behavior of Propellants Under Acceleration Fields. The second is the initiation of controlled studies of acceleration effects at the NASA-Langley Research Center and United Technology Center.

The NOTS symposium included papers presented by NOTS personnel (49), (50), and (51), and by Aerojet (2), Picatinny (57), Redstone (82), Redel (78), UTC (104), and Lockheed Propulsion (42), among others.

In tests of 6 different end-burning flourocarbon propellant formulations performed by Abernathy and Rodgers at spin rates up to 15,000 RPM (49), post-firing residue deposits of up to 39% of the initial propellant mass were measured with some of the heavier metallized propellants. In addition, significant degradations in specific impulse were noted as tabulated below.

Propellant	I_s(9000 RPM)/I_s (static)
PL 6301	.943
PL 6307	.931
PL 6608	.905
PL 6610	.900
PL 6306	.887
PL 6615	.684

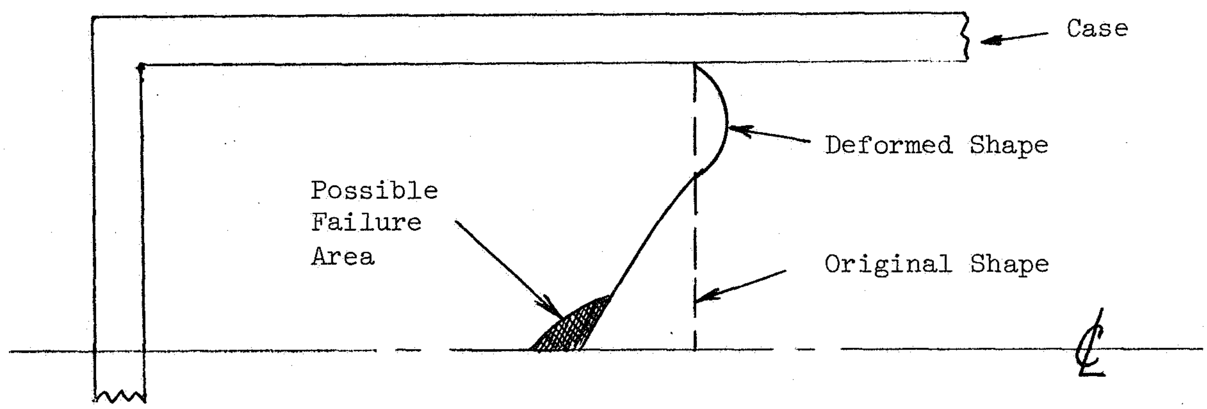
Additional tests of the (20% Al flourocarbon) PL 6301 and (5% Al flourocarbon) PL 6610 are reported by Dillinger and Feist in (51), along with results obtained with ANP-3095 (15% Al polyurethane), C-55A (17% Al PBAA), and E-107 (18% Al polyurethane). In general, spin thrust increased and burn time decreased compared to static firings, with widely varying results obtained as a function of both the propellant type and nozzle configuration. Centerline coning was evidenced in all end-burning firings incorporating single nozzles, both by post-firing examination of the head-end inhibitors and by x-ray movies taken during firing. For those motors incorporating dual nozzles, minor coning was observed in line with each nozzle. However, this effect was largely eliminated through the use of "vortex spoilers" in the convergent sections of the single nozzles.

The influence of propellant structural properties on spin sensitivity was investigated by both Bischel of NOTS (50) and Bernard and Karnesky of Aerojet (2).

Using propellants with moduli varying from 500 to 50,000 PSI, Bernard and Karnesky tested end-burning grains at 9400 RPM. The only apparent difference in response to this environment was evidenced by an increase in the time required to initiate deviations from static thrust (which were large with all samples) with increasing propellant modulus.

Bischel used solid cylindrical grains in non-firing tests to establish the failure mode and spin rates required to initiate failure with the PL 6301, PL 6306, PL 6608, ANP-3095, E-107, and C-55A propellants. In all instances except two, failure was initiated with centerline cracks which subsequently spread radially. One of the exceptions involved an anisotropic grain (with minimum properties in the radial direction) which exhibited cylindrical cracking. In the other, centerline dishing produced a permanent set in the grain surface without cracking.

A qualitative consideration of the behavior noted by Bischel indicates that the deformation of the free surface of the grain under spin will be a function of grain length and diameter, Poisson's ratio, and case rigidity. If the propellant has the usual Poisson's ratio near 0.5, grain deformation is due to volume conservation arising from both case deformation and the centrifugal force on the grain.



The grain deformation arising from case expansion under spin will be relatively insensitive to propellant modulus. However, that produced by centrifugal force (which causes the propellant to extrude axially) is a function of the grain modulus. Therefore, with a given case deflection, grain deformation under spin should decrease with increasing modulus.

The presentations by Picatinny Arsenal (57), Redel (78), and Redstone Arsenal (82) at the NOTS symposium are essentially reiterations of the results previously published in (56), (77), and (80) and (81), respectively. Similarly, the data presented by Iwanciow and Lawrence of UTC (104) reiterates that published in (102), but also includes the results of a limited series of spin tests performed with an aluminized PBAN at centrifugal accelerations up to 45 G's. Noting that the thrust histories obtained with this motor were increasingly progressive with increasing spin rate, the time-average burn rates were found to increase almost linearly with acceleration level, to an r(spin)/r(static) of 1.7-2.0 at 45 G's.

Tests conducted by Bernard of LPC (42) using an 8% aluminized PBAA propellant (LPC 571) indicated no consistent effect of spin rates up to 11,000 RPM (7600 G's) on the performance of a test motor equipped with a single nozzle, but did exhibit holes bored in the head closure, with bore depth proportional to spin rate. However, when the same propellant was flight tested at more than 24,000 RPM in a motor equipped with 9 nozzles, no boring of the head closure was evidenced.

The data presented at the NOTS symposium (along with that published by other sources) is reviewed by Dunn in (5), who also presents the results of a number of acceleration experiments conducted at Boeing. In these tests of two fast-burning propellants (UTC's CTPB UTP-7464 with 12% Al, and a 14% Al Thiokol formulation), there were no appreciable effects of accelerations up to 360 G's (directed either into or out of the propellant surface) on the performance of either propellant.

A series of controlled studies of the effects of acceleration on propellant combustion was initiated at the NASA-Langley Research Center in 1964/65, with some of the initial results of this study published by Northam in (33). In these tests of a 16% aluminized PBAA propellant at accelerations up to 300 G's, both the base burn rate and pressure exponent (as determined from the average burn rates of a 0.5 IN web propellant slab) were significantly affected by acceleration directed normally (90°) into the propellant surface. However, accelerations up to 200 G's directed at angles up to 60° into the surface did not appear to affect motor performance. The increases in burn rate and pressure exponent measured under normal acceleration (a_n) were able to be expressed according to:

$$(a_n < 80 \text{ G's}):\quad r = (.293 + 4.8 \times 10^{-6}(a_n)^2)(P/500)^{(.326 + .014\, a_n)}$$

$$(a_n > 100 \text{ G's}):\quad r = (.331 + 1.22 \times 10^{-4} a_n)(P/500)^{.40}$$

Simultaneously, a program specifically directed to study the effects of spin on motor performance was initiated at United Technology Center (UTC) under Navy sponsorship. The results of this first of three UTC spin study programs are reported in (105) - (108).

Tests of a 16% aluminized PBAN propellant reported in (105) indicate an 85% increase in the burn rate of a cylindrical grain subjected to radial (centrifugal) accelerations of 50 G's (900 RPM). In addition, a simplified analysis of motor gas dynamics concludes that the gas flow in a typical spinning motor would not be significantly affected by rotation.

The test motor to be used throughout the remainder of UTC's spin studies is described in (106). The 4.5 IN outside diameter cylindrical grain with tapered end surfaces is designed for neutral burning with a (constant) propellant surface area of 86.5 IN^2. With a 0.6 IN web thickness, the radial acceleration at a constant spin rate increases by 36% over the burning interval. Without mentioning the previous quarter's conclusion that the effects of motor rotation on nozzle flow would not be significant, the use of Mager's analysis (3) to estimate the effects of rotation on mass efflux indicates potential flow rate reductions of as much as 60% for the sample cases cited.

UTC's previous analysis of cylindrical combustion chamber gas dynamics is extended in (107) to include viscous effects on the radial velocity and pressure distributions for incompressible flow. Typically, a central core of rotational flow is surrounded by a region of irrotational flow, with a maximum rotational gas velocity at the interface of these regions. The extent of the core region is a function of Reynolds number, as given below.

Reynolds Number	Core Radius / Wall Radius	Max. Velocity / Wall Velocity
10**6	.0027	317.
10**5	.0075	101.
10**4	.023	32.
10**3	.07	9.9
10**2	.23	3.2
10**1	.72	1.1

From the calculated pressure distributions also given, one example indicates a 77% pressure gradient across a 6 IN chamber rotating at 1500 RPM.

The overall results of this initial UTC spin study are summarized in (108), which includes both the spin test results obtained with the basic PBAN propellant formulation (and various modifications thereof) and a theoretical model for burn rate augmentation under acceleration.

The theoretical analysis of burn rate augmentation is based upon the postulation that increases in burn rate under acceleration are primarily due to an increase in heat transfer to the propellant surface arising from the retention of hot particles at the surface by centrifugal force. This analysis concludes that: (A) no augmentation is possible with non-metallized formulations; (B) a particle will be retained at the propellant surface until it is burnt to a critical size, determined by the equilibrium between aerodynamic drag and centrifugal forces; (C) achieving a state of equilibrium augmentation requires a finite time; and (D) augmentation should be a function of both initial particle size and percent of metals loading. Although the experimental results did lend some support to this theory, the discrepancies between actual results and theoretical predictions generally indicated that this model is not adequate for predicting acceleration effects on burning rate.

Numerous modifications to a basic UTC PBAN propellant (A, below) were used for the spin test program. The various propellant formulations are enumerated below:

(A) 16% PBAN binder
16% Aluminum (Al) - 47 micron mass median particle diameter
68% Ammonium Perchlorate (AP) - primarily 400 micron

(B) 16% PBAN
16% Al - 8 micron
68% AP - 400 micron

(C) 16% PBAN
16% Al - 47 micron (?)
68% AP - 190 micron
Burn Rate Catalyst

(D) 16% PBAN
16% Al - closely controlled to 43-61 micron
68% AP - 400 micron (?)

(E) (?)% PBAN
8% Al - 47 micron (?)
(?)% AP - 400 micron (?)

(F) 16% PBAN
16% Tungsten - 12-20 micron
68% AP - 400 micron (?)

(G) (?)% PBAN
(?)% AP

The results of these tests are reproduced in Figures 3-1 and 3-2. As indicated in Figure 3-1, the control propellant (A) is significantly affected by acceleration, yielding burn rates at 100 G's approximately twice those measured statically. In addition, the burn rate augmentation is seen to be highly time- and/or web-dependent. However, spin sensitivity is considerably reduced by reducing the size of the aluminum particles (B), but even more significantly by reducing the size of the oxidizer particles (C). From Figure 3-2 it is seen that close control of aluminum particle size (D) yields essentially the same results observed with the control propellant. In addition, halving the percentage of aluminum (E) is seen to produce almost exactly the same results as reducing the aluminum particle size from 47 to 8 microns (B, Figure 3-1). Essentially no burn rate augmentation was observed with the non-aluminized propellant formulation at accelerations up to the 100-G maximum test capability.

From the results of this initial UTC spin study program, it is concluded that spin effects on burning rate are a function of: acceleration level; percent of metals loading; metal particle size; and oxidizer particle size. One of the most significant findings of this study is that there is an apparent upper limit on burn rate augmentation under acceleration, and in some instances a decrease in rate with time over the burning interval for the propellants tested.

A concurrent UTC study of spin effects on hybrid motor performance (111) indicates that fuel regression rates are initially reduced under spin to a minimum level, and subsequently increased with increasing spin rate. Beyond the minimum regression rate, the rate augmentation (r/r_o) is given by:

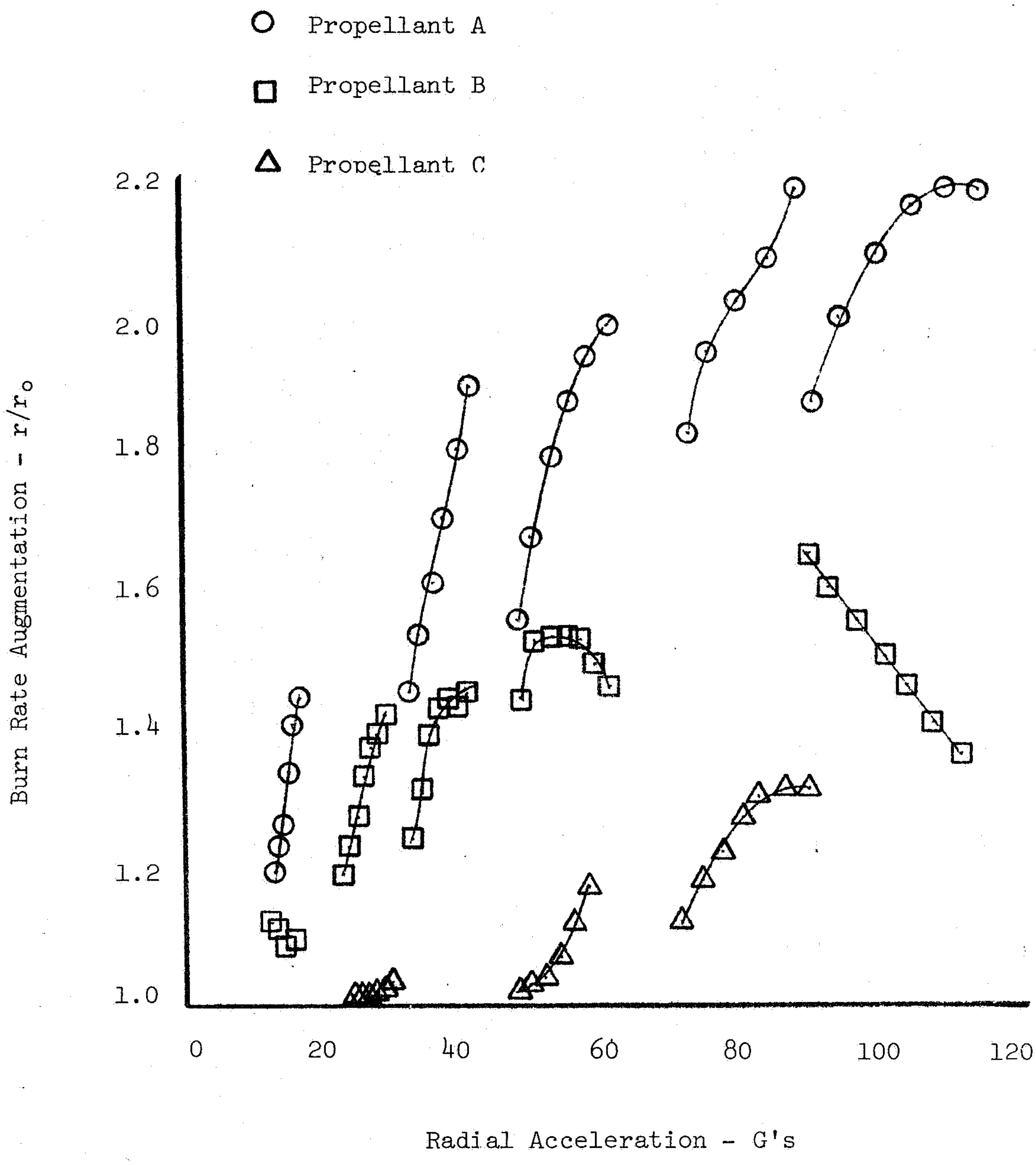


FIGURE 3-1: Burn Rate Augmentation Data from (108) UTC PBAN Composite Propellants A, B, C

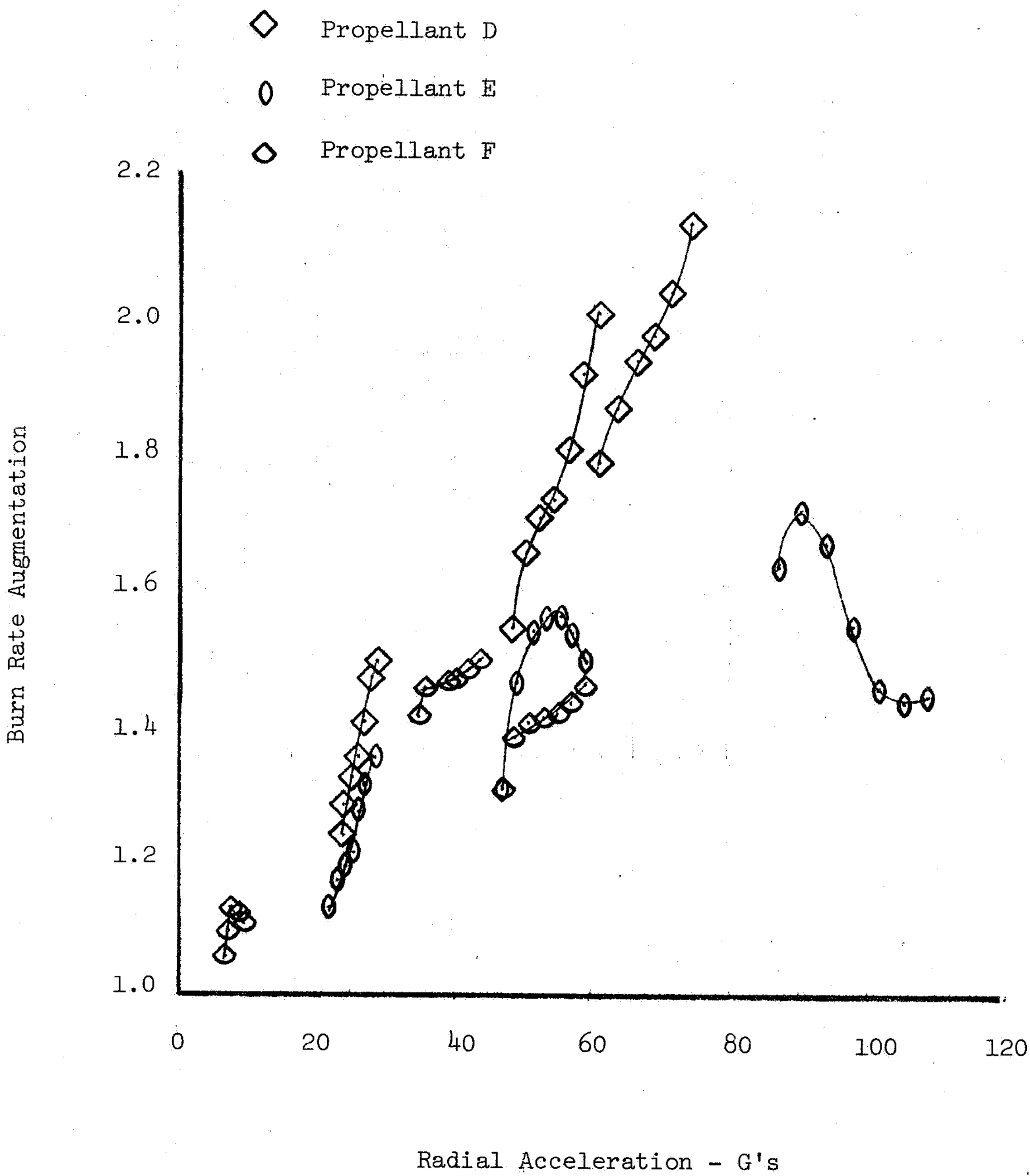


FIGURE 3-2: Burn Rate Augmentation Data from (108) UTC PBAN Composite Propellants D, E, F

$$r/r_o = .87\ [1 + 2.4 \times 10^{-6} (PDW/2\ G_o)^2]^{.25}$$

where P = chamber pressure, PSIA
D = (cylindrical) fuel port diameter, IN
W = angular velocity, RAD/SEC

As in the UTC study discussed previously, a reduction in burn rate augmentation with reduced ammonium perchlorate particle size was also reported by Hercules (21) for a 20% aluminized composite-modified double-base propellant.

Again confirming results previously obtained by Picatinny Arsenal and the Naval Weapons Center, Guthrie and Ulloth of Redstone Arsenal noted severe centerline coning of a 40mm diameter end-burning grain subjected to spin rates up to 12,000 RPM. Extinguished grains recovered after nozzle ejection indicated that the depth of coning was proportional to spin rate. However, various nozzle baffle arrangements were shown to significantly reduce the effects of the gas vortexing phenomena to which this coning is attributed (83).

In another series of closely controlled experiments, conducted at the Naval Postgraduate School (43, 44), Anderson investigated the effects of acceleration up to 2000 G's on the burning rates of three families of composite propellants: polyurethane (PU), carboxy-terminated polybutadiene (CTPB), and PBAN. The various modifications of these propellants used in Anderson's centrifuge strand tests are enumerated below:

X101: 30% PU
70% AP

X102: 27% PU
63% AP
10% Al - 6.3 micron

X103: 25% PU
57% AP
18% Al - 6.3 micron

X104: 25% PU
57% AP
18% Al - 31 micron

The oxidizer mass median particle diameter in all X100 series propellants was 195 microns.

X200: 14% CTPB
69% AP - trimodal
17% Al - 7.1 micron

X301: 20% PBAN
80% AP

X302: 19% PBAN
77% AP
4% Al - 14 micron

X303: 16% PBAN
68% AP
16% Al - 14 micron

X304: 16% PBAN
68% AP
16% Al - 47 micron

The oxidizer used in all X300 series propellants was a bimodal blend of 2/3 as received (190 micron) and 1/3 ground to 9 microns. It is noted that the X304 formulation should be quite comparable to UTC's propellant (C), above.

Although considerable burn rate augmentation was measured with the non-aluminized X101 propellant when the nichrome ignition wire was allowed to fall and remain on the burning surface, essentially no augmentation was measured with this propellant at accelerations up to 200 G's when the wire remained intact. In a number of instances, combustion ceased immediately after ignition at the higher acceleration levels, depending upon chamber pressure. Notably, the burn rate augmentation measured with the X101 formulation at 1500 PSI was greater than that of any of the three aluminized members of this series.

The burn rate augmentation measured with the CTPB propellant was found to be essentially independent of pressure level, and given empirically by:

$$r/r_o = 1 + .028\ (G)^{.30}$$

Contrary to the UTC hypothesis reviewed previously, the burn rate of the non-aluminized PBAN propellant was significantly increased at acceleration levels greater than 200 G's. Moreover, at these higher accelerations, the disposition of the ignition wire did not appear to influence the burn rate augmentation, as was the case with the X101 formulation.

Because of the generally large time dependency exhibited by the UTC propellant "C" burn rate augmentation, comparison of these spin test results with those obtained with the generally comparable X304 propellant is rather difficult. However, it appears that the burn rate augmentations measured in the centrifuge strand tests are generally higher than those obtained by UTC at accelerations lower than 50 G's, and lower at accelerations greater than 50 G's.

In another effort to generate a theoretical model for burn rate augmentation, R. Glick of Thiokol Huntsville used Summerfield's granular diffusion theory (120) as a basis for predicting the influence of acceleration on burning rate (94). The trends predicted by the model generated for metallized propellants were generally in qualitative agreement with those observed for base burn rate and pressure exponent variations with acceleration. However, the non-metallized model exhibited a number of important discrepancies with experimental data, notably an inverted burn rate augmentation pressure dependency, no upper bound on augmentation with acceleration (as observed by Anderson), and an immediate increase in burn rate with acceleration (whereas both Anderson and UTC observed essentially no augmentation at accelerations less than 100 G's).

The second UTC spin study was initiated in March 1966, with results presented in (112) - (115).

In addition to postulating that aluminum surface flooding may be the cause of the reduced burn rate augmentations noted at some of the higher (100-G) acceleration levels, (112) presents spin test data obtained using a propellant with "finer AP powder" (than the control propellant A, above). Burn rate augmentations measured with this formulation were 12-22% higher than those obtained with UTC propellant C (above) at 20-30 G's, and 2-16% higher at 40-50 G's. Significantly, this formulation did not include the burn rate catalyst incorporated in C, and therefore had a lower base burn rate than the earlier formulation.

An investigation of the effect of combustion pressure on burn rate augmentation published in (113) indicated that the augmentation experienced at a given acceleration level increased considerably with an increase in design operating pressure from 185 to 600 PSI. However, when the design pressure was increased to 1150 PSI, the burn rate initially increased markedly to a maximum value, and subsequently decreased rapidly to a final value considerably below that observed at ignition. Moreover, the postfiring slag deposits in the motor changed significantly from the small globules obtained in lower-pressure firings to a continuous layer at high pressure.

Spin tests of various modifications of the control propellant (A, above) reported in (114) reaffirm previous indications that burn rate augmentation is reduced with both smaller Al and AP particles. Additional tests conducted using dichromated aluminum also indicate reductions in augmentation, which are attributed to the decreased tendency to form agglomerates at the burning surface.

In addition to summarizing the results obtained during this second UTC spin study, (115) presents data acquired for essentially constant centrifugal acceleration (at the propellant surface), produced by decreasing the motor spin rate during the burning interval. The results of these tests were found to be quite reproducible, and indicated: (a) a 27% increase in burn rate augmentation over the burning interval for the control propellant; and (b) an 8% increase in augmentation, followed by an 8% decrease to essentially the initial value, with propellant (B) containing 8 micron aluminum in place of the 47 micron of the control propellant.

In describing the Picatinny Arsenal facility used for interrupted-burning tests of a 107mm motor (58), Clark and Femia present limited data obtained during spin tests of the AHH double-base propellant. Using split grains, deeply pocked areas were observed axially along the length of each grain half, with an 83% metallic lead residue removed from the bottom of the pits. However, the surface of a cylindrically perforated grain also tested was found to be quite regular, and only slightly pitted. In addition, the surfaces of the CP grains located opposite the dual nozzles used on these test motors were found to be badly scalloped.

All available acceleration studies published prior to May 1967 are abstracted by Manda in (13), who also presents detailed reviews of selected references.

Expanding the initial NASA-sponsored effort under which Glick's model for burn rate augmentation was generated (94, 95), a study was initiated at Thiokol Huntsville in April 1967 to: (a) analyze the flow in circumferential slots under spin; (b) develop a grain regression analysis to predict motor ballistics under spin; (c) determine the heat transfer at the head closure of a spinning motor; and (d) review and revise Glick's burning rate augmentation models. The results of this study as presented in (97) - (100) indicate: (A) a computer program is available for studying the effects of spin rate, slot geometry, particle size and density, and particle evolution location on the retention of metal (oxide) particles in a slot, along with determining the influence of spin on slot gas dynamics; (B) a computerized grain regression analysis is available for predicting the internal ballistics of a motor under spin, given the sensitivity of the propellant to both the magnitude and direction of acceleration; (C) a considerable increase in nozzle heat transfer can be anticipated under spin, with a threefold increase predicted at an example nozzle throat section operating at 10,000 RPM; and (D) the assumed metal agglomeration mechanism is critical to predicting the burn rate augmentation for metallized propellants, and inclusion of the concept of a critical particle radius (dependent upon the relative magnitudes of the viscous and inertia forces) has improved the ability of the model to correlate the experimental data generated by Anderson (43).

The third Navy-sponsored UTC spin study was initiated in May 1967 with the objectives of: (A) developing an apparatus to photograph a solid propellant burning surface under acceleration; (B) conducting motor extinction tests under spin to determine whether the transient burn rate augmentation noted previously might be caused by uneven surface regression; (C) quantifying the influence of the base burn rate on propellant spin sensitivity; and (D) investigating the gas dynamics associated with an end-burning grain operating in a spin environment. The results of these studies are presented in (116) - (119).

As outlined in (116), the centrifuge to be used for the photographic studies is capable of accelerations of more than 600 G's. In addition, the spin test fixture previously used is to be modified to extend maximum acceleration capability from 200 G's to more than 400 G's. Initial studies of the requirements for cold-flow simulations of end-burning grain gas dynamics indicate that a cold-flow apparatus operating at 65 PSIA and 3000 RPM would simulate the performance of a typical motor operating at 1000 PSIA and 12,000 RPM, based upon similarity of Reynolds number and tangential Mach number. Preliminary results obtained with such a cold-flow apparatus indicate the presence of a high-speed vortex a short distance downstream of a porous plate rotating in a chamber. This vortex has a rotational rate approximately an order of magnitude greater than the rotational speed of the plate.

The review of previous studies (33, 43, 108, and 115) of acceleration phenomena presented in (117) concludes that the burning rate of a metallized composite propellant operating in a (spin) acceleration environment can be affected by:

(A) <u>The magnitude and direction of the acceleration vector with respect to the burning surface</u>: Acceleration directed normally into the surface generally increases the burning rate, whereas acceleration parallel to and normally out of the surface usually does not affect burning rate. Moreover, a number of propellants appear to exhibit a threshold level beyond which burn rate is very sensitive to acceleration, up to certain levels where the burn rate augmentation becomes asymptotic (or in some cases decreases) with further acceleration.

(B) Burn time and/or web thickness: In a number of UTC experiments, burn rate augmentation was found to either increase to a maximum and then decrease, or decrease monotonically, over the burning interval. Whether this effect is primarily a function of time or the amount of web consumed has not been resolved.

(C) Pressure level: Increasing motor operating pressures below 1000 PSI have generally been found to increase burn rate augmentation, although the test results reported by different investigators indicate widely varying response to changes in pressure.

(D) Base burn rate: Burn rate augmentation at a given acceleration level has generally been found to decrease with increasing base (unaccelerated) burn rate.

(E) Metal content and particle size: Experiments conducted by both UTC and the Naval Postgraduate School (NPS) have indicated that non-metallized propellants are generally insensitive to accelerations up to approximately 100 G's. The acceleration sensitivity of metallized formulations can be reduced by reducing either the percent of metals loading or the metal particle size. The significance of conduction phenomena has been demonstrated by the appreciable augmentation experienced using non-reactive metals.

(F) Oxidizer particle size: Reduction of oxidizer particle size has been shown to be a very effective means of reducing burn rate augmentation with acceleration. This phenomenon is attributed to a reduction in aluminum agglomerate size with reduced oxidizer size.

(G) Binder type: Although burn rate augmentation has qualitatively been found to be a function of binder type, the influence of this parameter has not as yet been the subject of systematic experiment.

In addition to the above, results of cold-flow smoke tracer tests conducted with a simulated end-burning grain indicate that the flow through a porous plate moves radially inward toward the centerline of a spinning motor, with rotation rates downstream of the plate significantly higher than that of the plate. However, these results may be influenced to an unknown degree by the fact that the smoke injection velocity was 30 FT/SEC compared to an air velocity of 5 FT/SEC from the plate.

A new UTC model for burn rate augmentation with metallized propellants is presented in (118). With the premise that erosive burning beneath metal globules is the primary cause of burn rate augmentation, this model successfully predicts experimental augmentation trends, notably the reduction in augmentation at higher acceleration levels attributed to aluminum surface flooding. However, one rather serious qualification on the applicability of this model is the required knowledge of globule size.

Extension of the UTC spin capability to provide test data at centrifugal accelerations up to 400 G's has indicated that: (A) the control propellant (A, above) is subject to decreasing augmentation with time at accelerations greater than 200 G's; and (B) the non-aluminized formulation yields a burn rate augmentation of approximately 30% at 400 G's.

Results of the continuing NASA-Langley acceleration studies are reported by Lucy and Northam in (35). Using primarily a PBAA propellant, these test indicate: (A) decreasing burn rate augmentation with decreasing aluminum particle size; (B) increasing augmentation with percent aluminum at accelerations less than 150 G's, but a reversed correlation at higher accelerations; and (C) a highly transitional dependence of augmentation on propellant orientation at acceleration vector angles of 75-90° to the burning surface. Additional comparisons of Langley centrifuge slab motor data with that obtained from NPS strand tests and UTC spin tests indicate significant difference in calculated values of burn rate augmentation, depending on the test technique employed.

The results of what may be the most significant investigation of acceleration phenomena undertaken to date have recently been published by Sturm of the Naval Postgraduate School (45). This study was primarily concerned with identifying the significant parameters affecting burn rate augmentation experienced with: (A) non-metallized propellants; (B) aluminized propellants with nominal base burning rates; and (C) aluminized propellants with very fast base burn rates. The matrix of propellant formulations tested is given in Table III-1.

Non-Metallized Propellants

The burn rates of the three non-metallized formulations were increased by accelerations greater than 50 G's directed normal and into the propellant burning surface. However, accelerations directed normal and out of the surface had no effect on the burning rate. No burn rate time dependence was indicated by the average rates calculated for 1.0 IN and 2.1 IN strands. Increasing the pressure from 500 to 1000 PSIA increased the acceleration sensitivity of these propellants, as did preheating the strands from 21°C to 54°C.

A mathematical model which attributes the increase in burning rate to the retention of the fine AP oxidizer particles on the propellant surface was developed and successfully employed to correlate the experimental results obtained during the course of this study. This model, based upon Fenn's phalanx flame combustion model (122), suggests that acceleration effects can be minimized by: (A) decreasing the weight percentage of the fine AP particles (W_o) in multi-modal propellants; and (B) increasing the base burn rate of the propellant with burning rate catalysts. The use of a high percentage of fine oxidizer particles will have the advantageous effect of increasing the base burn rate, but the disadvantageous effect of increasing W_o. The net effect on the acceleration sensitivity of the propellant will depend on the relative magnitudes of these two effects.

Table III-1: Compositions of Propellant Formulations Tested by Sturm at NPS

10.6 micron Al	14.0								15.0	
28 micron Al				5.0	15.0		15.0			15.0
9 micron AP		19.62	34.0	16.83	11.26	17.32	27.15	19.62	11.26	11.26
68 micron AP	68.0									
94 micron AP		59.38	45.0	58.22	55.89	57.73	40.0			
200 micron AP								59.38	55.89	55.89
9.3 micron Al_2O_3						5.0				
PBAN Binder	18.0	21.0	21.0	19.95	17.85	19.95	17.85	21.0	17.85	17.85

Metallized Propellants

The tests of the six aluminized propellant formulations have indicated: (A) Accelerations normal and into the burning surface of the nominal burning rate propellants were found to affect their burning rates; (B) The burning rate of an individual strand was found to decrease with increasing distance burned; (C) The acceleration sensitivity of these propellants exhibited no consistent pressure dependency; (D) An increased initial temperature was not found to affect the acceleration sensitivity of the single propellant so tested; and (E) The primary factor affecting the relative acceleration sensitivities of these propellants was the amount of aluminum and/or aluminum oxide retained in the spent inhibitor cases. There was an inverse relationship between the burn rate augmentation experienced by a propellant and the percentage of the original aluminum retained on the surface of the propellant. This inverse relationship can be explained by postulating at least two distinct modes of augmentation: (a) a relatively fast combustion mode in which distinct agglomerates determine the overall propellant burning rate; and (b) a slower combustion mode in which the surface of the propellant is covered with a continuous "flood" of aluminum (oxide). Those propellants which "flood" most quickly after ignition experience the least burn rate augmentation and greatest aluminum retention, whereas those propellants which tend to remain in the discrete agglomerate combustion mode experience the greatest augmentation and least aluminum retention.

Aluminum particle size was found to be the primary factor affecting aluminum retention. Increasing the aluminum size from 10.6 to 28 microns in otherwise similar formulations decreased the amount of aluminum retained on the propellant surface. Moreover, increasing both the size of the coarse AP particles and the weight percentage of the fine AP particles reduced the amount of aluminum retention. However, no consistent pressure or base burn rate dependence was noted with the amount of aluminum retained. Once the surfaces of the five propellants became "flooded", they burned at essentially equal absolute burning rates, depending to some degree on the size of the coarse AP particles in the propellants.

One formulation using aluminum oxide in place of aluminum was found to exhibit a greater acceleration sensitivity than the analogous aluminized propellant, thereby suggesting that heat transfer is a significant mechanism in the overall augmentation phenomenon.

Fast Burning Propellants

Accelerations up to 100 G's yielded essentially no burn rate augmentation with two fast-burning formulations tested at 1000 and 1500 PSIA, thereby indicating that the use of very small AP particles in conjunction with burn rate catalysts is an effective method of minimizing burn rate augmentation.

Combustion Models

The burn rate augmentation models proposed by Crowe (109) and Glick (94) do not adequately predict the relative acceleration sensitivities of the basic series of aluminized propellants tested herein. The results of this investigation suggest that any new model must account for both the unsteady accumulation of aluminum (oxide) on the propellant surface and the heat transfer from the flame zone to the propellant surface through the low thermal resistance agglomerates on the propellant surface.

From the above review of more than 80 published studies of (spin) acceleration effects on solid propellant performance, it is immediately obvious that the behavior of composite propellants under acceleration has been far better characterized than that of the double-base propellants, due primarily to a lack of controlled effort to investigate the latter. However, after more than four years of relatively intensive investigation (conducted primarily at United Technology Center, the Naval Postgraduate School, and the NASA-Langley Research Center), the understanding of the complex phenomena involved in determining composite propellant sensitivity to acceleration may best be described as rudimentary. Without question, this result is due primarily to a lack of understanding of the basic process of solid propellant combustion.

Although the influence of various propellant formulation variables (i.e., metal mass loading and particle size and oxidizer particle size) on acceleration sensitivity can generally be predicted qualitatively, quantitative estimates of the influence of these parameters are generally beyond the scope of current capabilities. However, significant progress toward this goal has been achieved by Sturm of the NPS with his non-metallized combustion model, and to a lesser extent by Willoughby of UTC with his erosive burning model for metallized propellants. In both of these efforts, it is significant that effectively microscopic combustion characteristics of the propellant ingredients are required to effect predictions of the macroscopic acceleration sensitivity. Unfortunately, this type of data is generally unavailable. Thus the designer of a solid propellant rocket motor which is to be subjected to potentially significant accelerations is currently left little choice but to test the proposed propellant formulation in an acceleration environment closely approximating both the magnitude and direction of that anticipated.

On the other hand, acceleration test devices are seen to be potentially powerful tools for use in developing an improved understanding of the basic solid propellant combustion process itself. (For example, Sturm's success in correlating the acceleration test data obtained with non-metallized propellants has lent considerable credence to Fenn's phalanx flame combustion model, upon which Sturm based his theory that non-metallized burn rate augmentation is primarily a function of oxidizer particle retention at the propellant surface.) To this end, a centrifuge device would seem most appropriate, primarily because the potentially significant gas vortexing phenomena associated with spinning rocket motors is eliminated from consideration.

Gas Dynamics

Although a number of investigators have attempted to define the effects of (spin) acceleration on rocket motor gas dynamics, the extreme complexity of the phenomena involved has generally precluded the development of satisfactory analyses. However, various simplifications of the general three-dimensional viscous flow problem under consideration have been used to allow at least qualitative predictions of motor behavior, particularly with regard to the reduction in nozzle efflux capability under spin.

Axial Acceleration

In 1962, Wu and Pottsepp analyzed the homentropic flow in a nozzle subjected to a constant acceleration. As indicated in (7), an example acceleration of 100 G's transposes the sonic point upstream such that the Mach number at the geometric throat is 1.013, and motor thrust is increased approximately 1%.

A similar analysis reported by Thiokol Elkton in (85) also concludes that motor performance will be slightly enhanced by acceleration, and interprets the effect of acceleration as an effective increase in flow area over the actual geometric area of the nozzle.

In 1966, Ehlers employed the method of characteristics to evaluate the effects of axial acceleration on solid propellant combustion through the influence on nozzle characteristics (6). The results of this analysis indicate reductions in both operating pressure and mass generation rate with increasing acceleration.

Although it is most difficult to divorce the effects of "axial" acceleration from those due to the combustion process and Coriolis acceleration experienced in centrifuge tests, most experimental data obtained to date would seem to indicate that the mass flow coefficient (C_D) increases slightly with acceleration. If valid, this result would imply a reduction in combustion pressure and/or effective nozzle throat area in an axial acceleration environment.

Spin Studies

Studies of spin effects on motor gas dynamics can be generally classified according to whether the source flow is primarily rotational or irrotational. The flow evolved from the surface of an end-burning grain is seen to be rotational. That is, the tangential gas velocity (V) is directly proportional to radial position (r) and spin rate(w):

[1] $$V \text{ (rotational)} = wr$$

On the other hand, the flow emanating from the surface of a radial-burning cylindrical grain of radius r_o may be considered irrotational. That is, the tangential gas velocity at any radius across the chamber is inversely proportional to radial position:

[2] $$V \text{ (irrotational)} = wr_o^2/r$$

Obviously, the typical solid propellant grain configuration will involve a combination of both phenomena. However, most investigators have confined their studies to one or the other of the two limiting cases, due to the extreme complexities involved in attempting to find meaningful analytic solutions to even these simplified flow models.

Rotational Flow

The initial analysis of the effect of spin on nozzle gas dynamics with an end-burning grain was published by Bastress in (40), and reiterated in (41). Assuming constant total velocity at any nozzle section and no radial variations in gas properties, Bastress employs a "spinning coordinate system" to yield the axial velocity (U) distribution at the nozzle throat section (*) given by:

[3]
$$\mathcal{U}_*^2 = \frac{2g\gamma R T_o}{\gamma - 1}\left(1 - \frac{T_*}{T_o}\right) - w^2\left[\left(\frac{R_o}{R_*}\right)^2 - 1\right]^2 r^2$$

where g = gravitational constant
γ = specific heat ratio of propellant gases
R = gas constant
T_o= stagnation temperature
T_*= nozzle throat temperature = $2T_o/(\gamma + 1)$
R_o= combustion chamber radius
R_*= nozzle throat radius

With the assumption of constant gas properties across the throat section, [3] obviously predicts a reduction in nozzle efflux capability under spin, with a resultant increase in motor operating pressure. This trend has definitely been observed in a number of spinning rocket motor firings.

With a similar objective, Manda also analyzed the flow from an end-burning grain through a nozzle, based upon the assumptions of conservation of angular momentum in uniformly contracting streamtubes (11). While pointing out that the results of (40,41) are not consistent with the conservation of energy from the grain surface to the nozzle throat section, (11) yields the following expression for the axial velocity distribution at the throat:

[4]
$$\mathcal{U}_*^2 = \frac{2g\gamma R T_o}{\gamma - 1}\left(1 - \frac{T_*}{T_o}\right) - W^2\left(\frac{R_o}{R_*}\right)^2\left[\left(\frac{R_o}{R_*}\right)^2 - 1\right] r^2$$

where T_*/T_o is evaluated as a function of the required momentum balance in the radial direction (i.e., $dP/dr = \rho V^2/gr$) as:

[5]
$$\frac{T_*}{T_o} = \frac{2}{\gamma+1} + \frac{(\gamma-1)W^2}{2g\gamma R T_o}\left(\frac{R_o}{R_*}\right)^4 r^2$$

With [5], the complete expression for the axial velocity distribution is given by:

[6]
$$\mathcal{U}_*^2 = \frac{2g\gamma R T_o}{\gamma+1} - W^2\left(\frac{R_o}{R_*}\right)^2\left[2\left(\frac{R_o}{R_*}\right)^2 - 1\right] r^2$$

Commenting on the results presented in (11), M. K. King presents a third analysis of the same phenomenon in (4), based upon the required choking of the mass flux per unit area at the nozzle throat section. However, as is pointed out in (12), King's results fail to satisfy the requisite radial momentum balance, whereas it can be shown that the analysis of (11) can satisfy King's choking criterion if a smoothly rounded nozzle approach section is assumed.

In a further comment on the results reported in (40), (11), and (4), W. S. King presents yet another analysis of the rotational flow problem (123), which indicates that nozzle efflux capability under spin can be either increased or reduced, depending upon whether stagnation conditions are taken at the grain centerline or periphery, respectively. However, the inclusion of a term which apparently destroys the non-dimensional nature of King's equation #19 for the ratio of mass flow with spin to that without spin lends some doubt as to the validity of the results reported herein.

In July 1964, the Purdue University Jet Propulsion Center (JPC) initiated a comprehensive analytical and cold-gas experimental study of spin effects on the gas dynamics associated with simulated end-burning and cylindrical-burning grain configurations. Sponsored by the U. S. Army Missile Command (Redstone Arsenal), this study has continued to the present, with interim results reported in (59) - (68).

In (61), Norton outlines the bases upon which an inviscid analysis of rotational flow is founded, and presents the results of a computer program generated to accomplish this analysis. One example case indicates that the throat area of a nozzle with an initial contraction ratio of 12:1 would have to increase by approximately 70% to maintain design mass flow and chamber pressure at a spin rate of 1875 RPM.

The JPC cold-gas spin test fixture is described by Farquhar in (62). With inserts used to simulate either end-burning or radial-burning grains, this fixture is designed to provide a spin capability of more than 12,000 RPM with a 6 IN motor. Preliminary tests conducted at speeds up to 3500 RPM indicated increasing total pressures with radius using an axially directed total pressure probe.

Additional experimental studies reported in (63) indicated that the perforated disk used for the end-burning "grain" was not simulating the rotational gas flow anticipated from such a surface, thereby requiring a system of upstream baffles to more equally distribute the flow. The analytic results reported herein indicated that neither of two simplified flow models considered to date adequately describes the gas dynamics in an end-burning motor, and proposes a more complete inviscid model to accomplish this task.

A portion of the large volume of literature dealing with various aspects of vortex flows is reviewed in (64), with special emphasis on those articles which might be applicable to rocket motor gas dynamics. The topics considered herein include: compressible (rotational and irrotational) vortex flows in nozzles; viscous boundary layers with vortex flows in nozzles and near rotating disks; and vortex breakdown and backflow. Some of the conclusions drawn from this study include: recirculating viscous flow patterns may be established between the fore and aft ends of a combustion chamber; the boundary layer can transport significant portions of the mass from one area of the flow field to another; and backflow patterns may be established in a nozzle, particularly if the ratio of tangential velocity to axial velocity becomes much larger than 1.0.

Whereas (64) primarily emphasized the theoretical aspects of numerous vortex flow studies, the concurrent experimental results obtained in many of these are reviewed in (65). This report also reviews the results obtained by the NPS, UTC, and others in attempting to define the effects of acceleration on propellant combustion. Not surprisingly, the authors conclude that the three problems of primary concern in developing an understanding of spin effects on motor performance are: (A) the mechanism(s) controlling coning in end-burning motors; (B) definition of the effects of acceleration on the combustion process; and (C) definition of chamber and nozzle gas dynamics in a spin environment.

Results obtained using Norton's improved model for adiabatic inviscid flow from a rotational source are presented in (66), along with experimental data obtained in cold-flow tests of a spinning porous plate. Using air at 30 PSIA and a 6 IN diameter plate, significant reductions in mass flow were obtained in these experiments, increasing with both the rotational speed of the plate and nozzle (chamber/throat) area contraction ratio. Ratios of the mass flow rate under spin ($\dot{m}$) to that obtained without spin ($\dot{m}_o$) are given below for the maximum plate speed of 10,000 RPM.

$\frac{A\ (\text{chamber})}{A\ (\text{throat})}$	$\frac{\dot{m}}{\dot{m}_o}$
144	.915
256	.815
516	.715
1024	.642

Similar results reported by Farquhar in (67) also indicate significant reduction in nozzle efflux capability with increasing spin rate and nozzle contraction ratio. Using the original JPC spin test fixture and simulated end-burning grain, the following test data was obtained at a spin rate of 10,000 RPM.

$\frac{A\ (\text{chamber})}{A\ (\text{throat})}$	$\frac{\dot{m}}{\dot{m}_o}$
39.3	.973
78.5	.930
214.0	.899

Additional tests conducted by Farquhar at a constant contraction ratio of 78.5 indicate that the reduction in mass flow under spin is essentially independent of mass flow rate (for flows varying from 2.0 to 3.6 LBm/SEC). From these results, Farquhar concludes that the vortex choking phenomenon is primarily a function of the ratic of the angular velocity of the gas to the axial velocity of the gas in the motor chamber. However, this conclusion seems most difficult to rationalize from the data presented. The axial velocity at the "grain" face should be directly proportional to flow rate, whereas the tangential velocity should be a function only of radial position and spin rate. Therefore, if the mass flow reduction is essentially independent of flow rate (i.e., of axial velocity), this phenomenon would then seem to be a function only of spin rate (i.e., of tangential velocity), and not of the ratio of these velocities.

As summarized in (68), the overall results of the JPC investigation of swirling flows obtained using simulated end-burning and radial-burning "grains" indicate:

(A) Swirling flow reduces nozzle efflux capability.
(B) The flow reduction obtained with swirl is strongly dependent on: [1] the nature of the induced swirl (rotational vs. irrotational); [2] the swirl strength (i.e., motor spin rate); and [3] nozzle contraction ratio.
(C) The flow reduction with swirl is apparently unaffected by: [1] mass flow rate; [2] chamber pressure; or [3] distance between the "grain" surface and the nozzle.
(D) The percentage of mass flow reduction appears to approach a limit (for a given contraction ratio), beyond which further increases in swirl intensity have negligible effect on the mass flow rate.
(E) Norton's viscous analyses of both the rotational and irrotational flow fields are closely corroborated by experiment up to the point of the limiting flow reduction (D, above). This phenomenon has not been predicted, nor do the authors indicate a firm qualitative understanding of the reason(s) for its existence.

With the recent cessation of the Purdue JPC swirling flow studies, the Navy-sponsored spin research program at United Technology Center (UTC) represents the only effort to study rotational gas dynamics known to be currently active. The results of this effort to date are summarized in (116) - (119).

In (116), UTC states without proof that cold-flow similarity to typical solid rocket motor performance requires:

[7] $$\rho_c a_c D/\mu_c = \rho a D/\mu$$

and

[8] $$V_c/a_c = V/a$$

where a = speed of sound in the chamber
μ = gas viscosity
and the subscript c refers to the "cold" flow apparatus. Obviously, [7] is a Reynolds number, and [8] a "tangential" Mach number. Using these criteria, UTC deduces that actual flow conditions can be simulated by $P_c/P = 0.065$, and $w_c/w = 0.25$. If valid, this conclusion indicates that the Purdue JPC tests were overspun by a factor of 4.0.

Experimental test results reported in (116) indicate the presence of a high-speed (irrotational-type) vortex immediately downstream of the rotating plate used to simulate the surface of an end-burning grain, with the strength of the vortex apparently a function of both plate speed and upstream pressure. Where the radial pressure gradient across the chamber radius should be approximately 0.1 PSI for pure rotational flow at 3280 RPM, gradients of 1.5 and 4.5 PSI were measured at upstream pressures of 28.0 and 65.5 PSIA, respectively.

The visual observations of flow patterns in the chamber reported in (117) confirm previous indications of the existence of a high-speed vortex in the chamber, and qualitatively indicate the presence of recirculating flow in the chamber at larger "grain"-nozzle separation distances. Unfortunately, the validity of the smoke-tracer flow visualization may be influenced to an unknown degree by the fact that a smoke injection velocity of 30 FT/SEC was used in conjunction with an axial velocity of only 5 FT/SEC through the porous plate used to simulate an end-burning grain.

From Batchelor's analysis (124) of the stream function for incompressible ideal flow with axial symmetry, (118) indicates that upstream flow near the outer wall of a converging channel may be predicted analytically, and outlines an approach to be used in this attempt.

Irrotational Flow

The essentially irrotational flow which would be characteristic of that found in a combustion chamber containing a radial-burning grain was first analyzed by Mager (3), who showed that significant reduction in nozzle efflux capability could be experienced with swirling flow. Neglecting radial velocities and assuming uniform axial velocities at any nozzle cross section, Mager predicts a vacuum core at the nozzle centerline, whose diameter is found to be a function of nozzle contraction ratio and tangential velocity. The nozzle efflux capability is reduced by the presence of this vacuum core, as is indicated in Figure 3-3, which gives the ratio of flow rate with spin ($\dot{m}$) to that obtained statically ($\dot{m}_o$) as a function of the swirl factor (α_*), determined by:

V_o = tangential velocity ($R_o w$) at the grain surface (R_o)
a_o = speed of sound at chamber conditions
R_* = nozzle throat radius

Mager's results (originally published only for γ = 1.4) were extended by Glick and Kilgore (96) to include specific heat ratios varying from 1.10 to 1.28. As indicated in Figure 3-3, values of γ realized in most rocket motors will yield greater reductions in mass flow rate than those realized in comparable cold-gas tests.

Although Mager's analysis would be strictly applicable only to radial-burning cylindrical grain configurations, the conservation of angular momentum (which forms the basis for this analysis) would seem to indicate that the R_oV_o terms in the swirl factor could equivalently be replaced by 0.5 $w\oint rdr$ (taken over the burning surface) to approximate the mass flow reduction for non-cylindrical grain configurations.

Norton's analysis (68) of a basically irrotational flow field modified to include a viscous core (rather than Mager's vacuum core) represents the only known effort to improve Mager's original analysis, published in 1961. The results of both of these

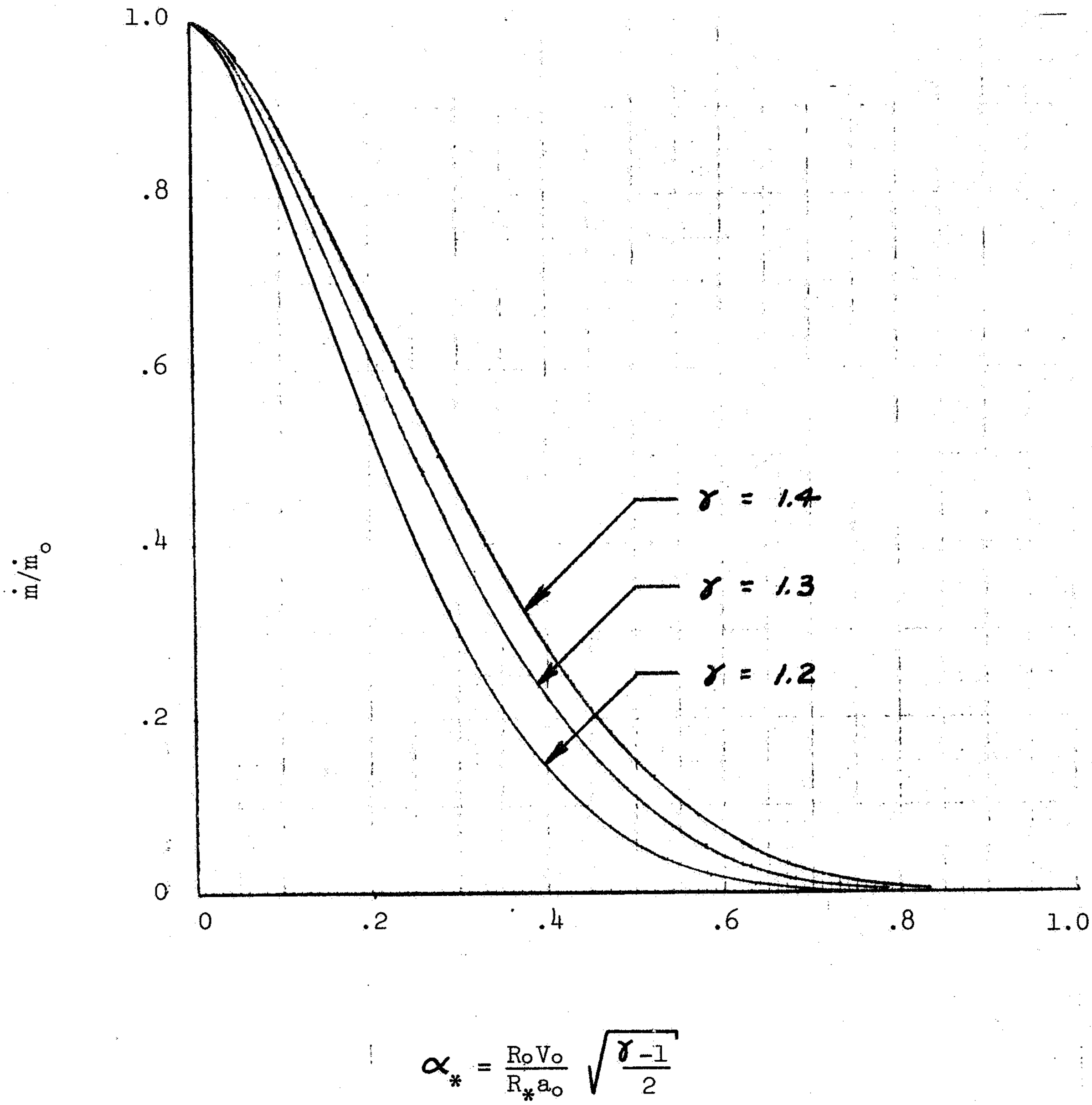


FIGURE 3-3: Mass Flow Reduction with Irrotational Swirl, from (3)

analyses are compared with experimental data obtained with the Purdue JPC simulated radial-burning "grain" in Figure 3-4. As indicated, both analytical predictions agree quite closely with the experimental data, obtained with a port-to-throat area ratio of 44.4:1. However, the viscous analysis appears somewhat more representative at the higher swirl magnitudes, where the stronger vortex would be more susceptible to viscous dissipation due to the larger velocity gradients.

Rather than employing a spin apparatus, Aerojet used tangential injection of air to determine the effects of swirl on the gas dynamics of a simulated cylindrical "grain". Significant reductions in nozzle efflux in this "spin" environment are reported in (1).

Perhaps the most extensive series of "irrotational" swirling flow experiments was initiated by Massier at the Jet Propulsion Laboratory (JPL) in 1963 using Argon. As reported in (25) and (27) - (30), Massier also used tangential gas injection to achieve swirling flow.

Comparisons of nozzle heating rates with and without swirl reported in (25) indicate heating rates with swirl varying from approximately twice that of the non-swirl case at the nozzle inlet to equivalent rates at the throat section.

Alternately using both pressure taps and thermocouples at the head end of the simulated "combustion" chamber, Massier reports considerable stagnation pressure and temperature gradients across the chamber in (27). Stagnation pressure increased from 2.0 PSIA at the chamber centerline to 15 PSIA at a radius equal to the nozzle throat radius (0.16 IN), and subsequently remained essentially constant out to the chamber radius of 0.975 IN. Stagnation temperature increased from 505 °R at a radius of 0.10 IN, and subsequently decayed asymptotically to 530 °R at the chamber wall. As reported by numerous other investigators, the flow field in the chamber was characterized by a region of irrotational flow surrounding a central core of rotational flow.

With a reduction in stagnation pressure (at the chamber wall) from 15.2 PSIA to 2 PSIA, the maximum tangential velocity in the "combustion" chamber decreased from 675 FT/SEC at a radius of 0.04 IN to 390 FT/SEC at 0.10 IN (28). Additional tests performed with (chamber wall) stagnation pressures up to 30 PSIA indicated a constant reduction in mass flow rate to approximately 69% of no-swirl values. Extrapolating Mager's predictions (Figure 3-3) to a value of $\gamma = 1.67$ indicates that a mass flow reduction of 64% would be anticipated for the calculated swirl coefficient of 0.28.

Values of thrust calculated in (29) by integrating the static pressure distributions across the chamber end wall and along the length of the nozzle indicated that the simulated spin rate of approximately 10,000 RPM would cause a 20% reduction in thrust compared to no-spin values.

In addition to the above studies of basically irrotational flows applied to simulated rocket motors (chambers incorporating converging-diverging nozzles, with nozzle geometries similar to those found in rockets), the results of numerous vortex-tube studies may also be applicable to the problem of determining the effects of a spin environment on the chamber and nozzle gas dynamics associated with internal-burning solid propellant rocket motors. A bibliography of more than 100 of these

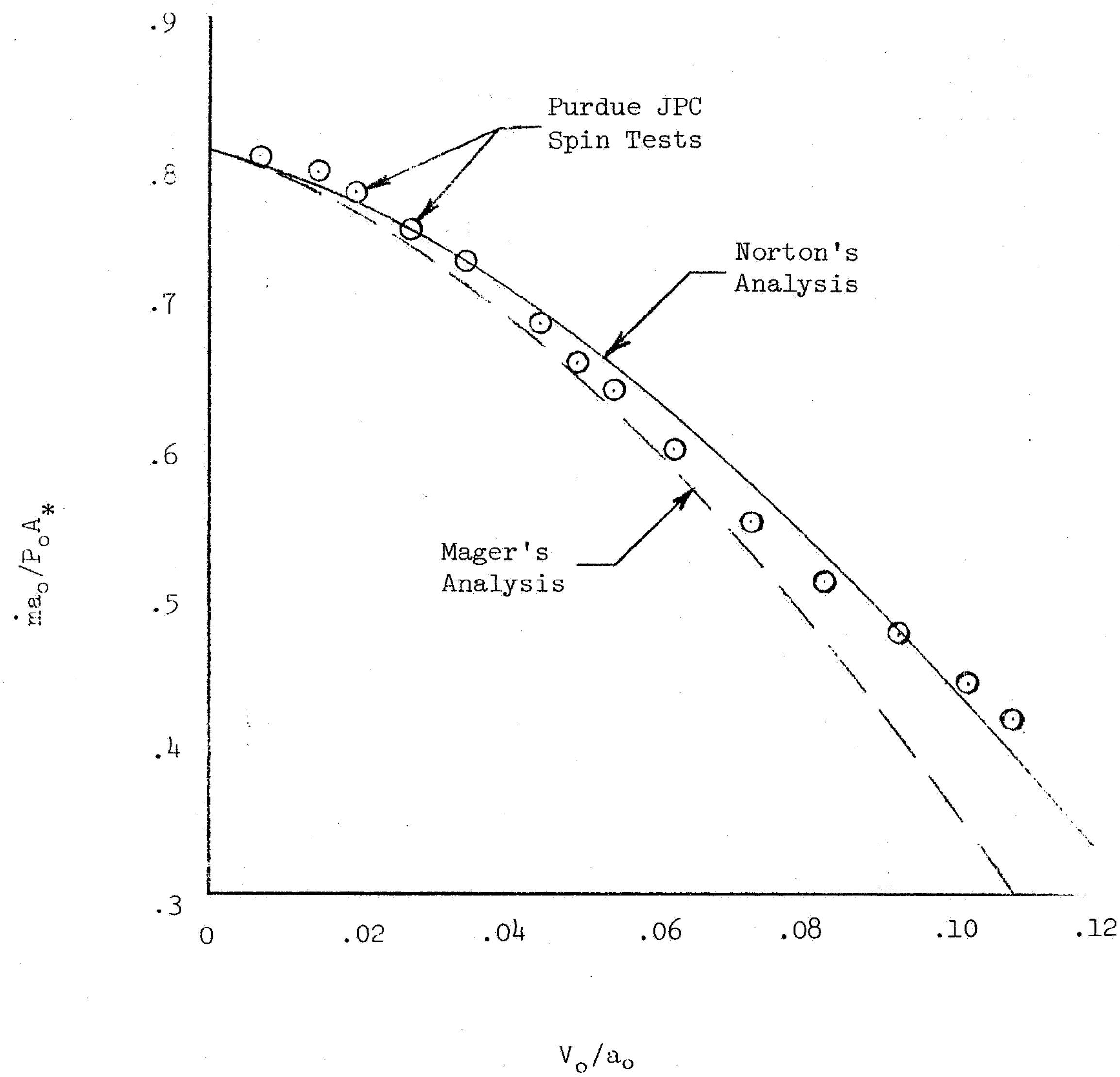


FIGURE 3-4: Comparison of Mager's Inviscid Analysis with Norton's Viscous Analysis and JPC Test Data

publications is presented in (13), along with brief abstracts of selected references. Of these, Roschke's 1966 flow-visualization study of incompressible vortices (31) graphically illustrates the extreme complexity of the flow fields developed with swirling flow. Using dye injection in a water vortex tube, test results obtained with planar endwalls clearly indicated: (A) the pronounced transient and three-dimensional nature of the flow; and (B) the strong influence of tube aspect ratio (L/D) and endwall configuration on the flow patterns. In general, the diameter of the vortex core decreased with increasing L/D, and endwall boundary layer effects were found to dominate the flow patterns observed at smaller values of L/D. Turbulence appeared to increase with both L/D and mass flow rate, except in the core, where no turbulence was observed. Both the axial and radial secondary flows increased with non-planar (conical, canted, and hemispherical) endwall configurations. Moreover, these secondary flows were found to occupy a larger radial domain (i.e., were less confined to the core region) with the non-planar endwalls.

Combustion Instability

The complexity of flow phenomena evidenced in the above reviews of cold-flow tests performed to simulate the gas dynamics of spinning rocket motors may be further complicated by the interesting possibility that spin may tend to enhance the tendency toward tangential-mode combustion instability in an actual motor.

In (37), Maslen and Moore predict the possibility of strong transverse waves in a cylindrical chamber, and suggest that, if the combustion process is able to provide the energy required to drive an oscillation in any mode, the largest amplitudes will tend to occur in those modes having small inherent damping. That is, transverse oscillations will likely be more severe than longitudinal because the latter are subject to shock losses. The authors further indicate that, depending on geometric considerations, the spinning mode is more likely to occur than a standing or "sloshing" mode. Such a spinning mode would be accompanied by a quasi-steady flow in a direction opposite that of the wave propagation, which tends to develop into a steady wheel-flow propagation.

The predictions of (37) were qualitatively verified in a number of combustion instability experiments conducted by Landsbaum and Spaid of JPL (24). In these tests, motors restrained by heavy chains were found to rotate in the test stand during periods of unstable burning. Assuming that the torque required to effect such rotation was provided by friction drag at the propellant surface, rotational gas velocities on the order of 1600 FT/SEC at this surface were calculated.

In (84), Swithenbank and Sotter report visual observation of vortex combustion instability using combustion chambers equipped with Plexiglas windows. The authors also indicate that this mode of instability can be readily triggered using tangential injection of nitrogen, and persists after the nitrogen flow has been shut off.

Combustion instability experiments at NASA Lewis reported in (38) indicate severe overpressurization of a small radial-burning motor when gases from a solid-propellant gas generator were injected tangentially into the motor chamber. Comparison of the pressure histories obtained with and without the injectant indicated that the vortex generated with injection caused an effective reduction in nozzle throat area of approximately 50%. However, this effect was eliminated through the use of a radially drilled ring inserted in the chamber.

To date, the studies of "spin" effects on solid propellant rocket motor gas dynamics have firmly established that nozzle efflux capability can be significantly reduced in a spin environment, depending on the nature of the swirling flow upstream of the nozzle entrance section. Beyond this, progress toward developing a comprehensive understanding of spinning gas dynamics might best be described as incremental, primarily because of the extreme complexity of the generally three-dimensional (and often unsteady) flow phenomena involved.

In addition to reducing nozzle efflux capability (with an attendant increase in operating pressure), a spin environment may also cause a significant increase in head closure heat transfer with an internal-burning grain, or severe centerline coning of an end-burning grain. The augmented heat transfer at the motor head closure is currently being studied at Thiokol Huntsville, and the mechanisms by which the rotational flow emanating from an end-burning grain might be transformed to develop a highly erosive centerline core are currently under investigation at United Technology Center.

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SECTION IV

RESEARCH REFERENCES

All references cited in Section III of this report are compiled herein, along with an abstract of each document. These publications are listed alphabetically according to the (corporate or Government) agency by which the data was generated, and chronologically under each agency.

AEROJET GENERAL CORPORATION

(1) "Study of High Effective Area Ratio Nozzles for Spacecraft Engines"; Report No. NAS-7-136-F, Volume I; June 1964; (U).

Cold gas tests of a nozzle incorporating swirling flow (achieved by the tangential injection of air in the "combustion" chamber) yielded mass flow rates considerably less than one-dimensional values compared on the basis of measured static pressure at the "grain" radius. Radial pressure distributions measured at the head closure were in close agreement with theoretical predictions for a free vortex.

(2) R. E. BERNARD and A. L. KARNESKY: "Spin Effects on Rocket Motor Performance"; Symposium on the Behavior of Propellants Under Acceleration Fields; Naval Ordnance Test Station; NOTS TP3770; June 1965; AD-363903; (C).

The influence of propellant structural capacity in determining motor response to a spin environment was evaluated in end-burning motor firings at 9400 RPM. Propellants with moduli of 500, 5200, 12,000, and 80,000 PSI were ignited statically and spun to test speed in approximately 6 SEC. The only apparent effect was that the time required to initiate deviations from static thrust histories appeared to increase with propellant modulus. Additional tests were also performed with a motor fabricated with dual nozzles and a baffle separating the chamber in halves. Centerline coning effects were not eliminated, but occurred in the center of each half.

AEROSPACE CORPORATION

(3) A. MAGER: "Approximate Solution of Isentropic Swirling Flow Through a Nozzle"; ARS Journal; Volume 31, No. 8; August 1961; pp. 1140-48; (U).

An analysis applicable to determining the reduction in nozzle efflux capacity with spinning cylindrically perforated grains indicates potentially large reductions in effective throat area. It is noted that equation 20 (page 1145) is in error. The bracketed term should be raised to the 0.5 power.

RESEARCH REFERENCES

ATLANTIC RESEARCH CORPORATION

(4) M. K. KING: "Comment on 'Spin Effects on Rocket Nozzle Performance'"; AIAA Journal of Spacecraft and Rockets; Volume 3, No. 12; December 1966; pp. 1812-1813; (U).

This attempt to apply one-dimensional analysis to the flow through a nozzle from an end-burning grain fails to satisfy the requisite force (momentum) balance in the radial direction.

BOEING COMPANY

(5) B. M. DUNN: "The Effect of Acceleration on the Burning Rate of Solid Propellants"; Boeing Report No. D2-36403-1; October 1965; (C).

In addition to reviewing and summarizing the acceleration studies of some 30 authors, this report presents the results of centrifuge tests of two fast-burning propellants. These tests indicate essentially no significant effects of ±360 G's acceleration on propellant performance at 2000-2500 PSI.

(6) F. E. EHLERS: "Influence of Acceleration on Combustion in a Rocket Engine"; Boeing Company, Scientific Research Laboratories, Mathematical Note - 470; June 1966; (U).

The method of characteristics is used to evaluate the influence of high axial acceleration on nozzle gas dynamics and the attendant effects on solid propellant combustion. The results indicate a reduction in operating pressure and mass generation rate with acceleration, increasing with propellant (burning rate) pressure exponent.

DOUGLAS AIRCRAFT CORPORATION

(7) J. C. WU and L. POTTSEPP: "Flow of a Compressible Fluid in an Accelerating Nozzle"; Douglas Report No. SM-38824; 6 April 1962; AD-274803; (U).

By means of a one-dimensional analysis, it is shown that nozzle acceleration serves to choke the nozzle upstream of the geometric throat. For a 100-G acceleration example, the Mach number at the throat is increased to 1.013.

DOUGLAS AIRCRAFT CORPORATION (contd.)

(8) Z. H. LANDAU and J. M. CEGIELSKI: "The Ballistic Behavior of Solid Propellant Rocket Grains in a High Acceleration Environment"; Douglas Paper No. 1783; May 1964; (U).

Cylindrically perforated grains of aluminized propellant were centrifuge tested under accelerations as high as 200 G's. No effects were apparent in firings directed either parallel to or perpendicular to the centrifuge axis. These rather limited results are generalized to conclude that combustion effects are not the primary source of the acceleration - induced phenomena noted by other sources.

(9) Z. H. LANDAU and J. M. CEGIELSKI: "Ballistic Behavior of Solid Propellant Grains Under High Acceleration"; AIAA Journal of Spacecraft and Rockets; Volume 2, No. 3: May-June 1965; (U).

A condensed version of Douglas Paper No. 1783.

(10) T. J. SCHWEITZER: "Proposal to Perform a Compilation of Rocket Spin Data"; DAC Report No. DAC 590206-P; May 1966; (U).

Swirling flow through the motor/nozzle is considered to be the primary cause of solid motor spin sensitivity. "All available pressure rise data was correlated within a few percent" by multiplying Mager's isentropic swirl strength (3) by $(L_*/33Rg)^2$, where L_* is an effective characteristics motor chamber length and Rg is the propellant burning surface radius of gyration.

EMERSON ELECTRIC COMPANY

(11) L. J. MANDA: "Spin Effects on Rocket Nozzle Performance"; AIAA Journal of Spacecraft and Rockets; Volume 3, No. 11; November 1966; pp. 1695-1696; (U).

An idealized analysis of the flow from a spinning end-burning grain through a nozzle indicates that the spin effects considerable radial variations in gas properties at the nozzle throat. These density and velocity gradients cause a reduction in the flow capacity of the nozzle.

EMERSON ELECTRIC COMPANY (contd.)

(12) L. J. MANDA: "Reply by Author to M. K. King"; AIAA Journal of Spacecraft and Rockets; Volume 3, No. 12; December 1966; pp. 1813-1814; (U).

A discussion of the discrepancies between the author's analysis of spin effects on nozzle performance and that offered by King (4) indicates that King's analysis fails to satisfy the required radial momentum balance.

(13) L. J. MANDA: "Compilation of Spin Data Program Technical Summary No. 2 - Reference Bibliography"; Emerson Electric Report No. 2122-2; 31 May 1967; (U).

This report abstracts more than 200 documents dealing with acceleration effects and presents detailed reviews of a number of the more significant studies. An additional 100 references to vortex flow phenomena are also included.

HERCULES INCORPORATED

(14) M. D. EIRICH: "Acceleration Effects on Propellant Burning"; ABL/QPR-27; April 1961; Page 79; AD-322640; (C).

A program to study centrifuge - induced acceleration effects on double-base and CMDB propellants was initiated with the fabrication of 6" diameter end-burning grains. A quench system is incorporated to allow partial burning studies.

(15) M. D. EIRICH and A. M. JACOBS: "Acceleration Effects on Propellant Burning"; ABL/QPR-29; July 1961; Page 115: AD-324111; (C).

Centrifuge firings under a 40-G acceleration directed into the propellant surface produced negligible variations in ARP and ARW burning characteristics. However, comparable accelerations produced a 9-13% increase in operating pressure (12-13% in burning rate) with DQO propellant.

(16) M. D. EIRICH: "Acceleration Effects on Propellant Burning"; ABL/QPR-33; January 1962; Page 17; AD-331078; (C).

Centrifuge firings of CYH propellant resulted in more severe throat erosion than that noted in static tests. Tests of BPY propellant with acceleration directed into the surface yielded average pressures 100% higher than those measured in static tests.

HERCULES INCORPORATED (contd.)

(17) M. D. EIRICH: "Acceleration Effects on Propellant Burning"; Hercules Powder Company Report No. ABL/EPA-8; October 1962; (C).

Seven double-base and composite-modified double-base propellants were tested in the ABL centrifuge at accelerations of 40 G's directed both into and away from the 6 IN diameter end-burning propellant surface. Effects noted with acceleration toward the surface varied from none to severe overpressurization, depending upon the type of propellant. No significant effects were apparent with acceleration away from the surface.

(18) J. A. SUTPHIN: "The Effects of High Acceleration on the Ballistic Parameters of a Typical CMDB Propellant"; Hercules Powder Company (Kenvil) Final Report U9413; April 24, 1963; (U).

Centrifuge tests of a composite-modified double-base propellant (DDP-80) at 150 G's axial and 50 G's lateral acceleration indicated essentially no effect of acceleration on the performance of a five-spoke wagonwheel grain configuration.

(19) E. J. SKURZYNSKI: "Effects of Acceleration on Propellant Burning Rate"; Private Correspondence; 28 May 1964; (C).

Various acceleration studies performed by ABL and others are summarized without conclusions. In many instances, the large effects reported at low acceleration levels (less than 50 G's) would seem to indicate: (A) poor data acquisition; (B) inadequate isolation of significant variables; or (C) that double-base propellants are much more sensitive to acceleration effects than are the composites.

(20) B. B. DICKINSON and R. H. LECHELT: "Investigations into the Effect of High Radial Accelerations on the Ballistics of Double-Base Propellants"; Hercules Powder Company (Kenvil) Final Report RI 703; April 13, 1965; (U).

Spin tests of ARP propellant in end-burning, internal-burning, and internal/external-burning grain configurations at radial accelerations up to 8000 G's (23,400 RPM) generally indicate no effect of the spin environment on propellant performance.

HERCULES INCORPORATED (contd.)

(21) "X-258 Propellant Characterization Study Final Report"; (Contract No. NASW-1241); May 1966; NASA CR 66096; (C).

Propellant characterization studies performed for the X-258 (type A), X-259 (type B), and an experimental propellant (type C) indicated the following:

(A) The burning rate increased about 5% under a 5-10 G radial acceleration, but reverted to static values when a 25-G axial acceleration was superimposed on the radial.
(B) No effects of radial acceleration were evident in this test series, which used more finely ground AP particles than (A).
(C) This propellant, using more finely ground Al particles than (A), exhibited a significant increase in burn rate, and decrease in operating pressure, under radial acceleration. This anomaly is attributed to a decrease in Al combustion efficiency resulting in a degradation of characteristic velocity. The mass of metallic residue obtained from spinning test motors in this series was approximately four times that obtained with propellant (A).

(22) R. R. MILLER: "Some Factors Affecting the Combustion of Aluminum in Solid Propellants"; ICRPG Second Combustion Conference; CPIA Publication No. 105; May 1966; AD-484561; (U).

This study of aluminum agglomerate size and combustion efficiency has yielded a model for the agglomerization mechanism which gives an agglomerate distribution equation found to be in good agreement with experimental data for both composite and double-base propellants. Agglomerate size is found to be a function of both propellant composition and combustion pressure.

JET PROPULSION LABORATORY

(23) J. COY: "Influence of Strain on Burning Rate"; JPL Quarterly Summary Report 38-4; 15 July 1961; (C).

Polyurethane propellants subjected to strains of 5 and 10% were found to exhibit increases in 1000 PSI burn rate of 7.4 and 11.6%, respectively, in one instance, and 4.2 and 8.5% in another.

JET PROPULSION LABORATORY (contd.)

(24) LANDSBAUM and SPAID: "Experimental Studies of Unstable Combustion in Solid-Propellant Rocket Motors"; JPL Technical Report No. 32-146; 4 August 1961; (U).

Motors with case-bonded tubular grains were found to rotate in the test stand during combustion instability experiments, thus indicating the presence of large tangential gas velocities at the propellant surface during periods of unstable burning.

(25) P. F. MASSIER: "Heat Transfer to Convergent-Divergent Nozzles from Ionized Argon"; JPL Space Programs Summary No. 37-24; Volume IV; 31 December 1963; pp. 105-108; (U).

Nozzle heating rates obtained with tangential injection of argon are compared to those realized with radial injection. The swirl component induced by tangential injection was found to increase the heating rate, with the effects thus produced diminishing along the length of the nozzle.

(26) G. A. FLANDRO: "Roll Torque and Normal Force Generation in Accoustically Unstable Rocket Motors"; AIAA Journal; Volume 2, No. 7; July 1964; pp. 1303-1306; (U).

In order to estimate roll torques generated during combustion instability, acoustic streaming theory is used to calculate vortex strength for the first traveling tangential mode. Although qualitative agreement between theory and experiment is claimed, measured torques are usually several times larger than predicted.

(27) P. F. MASSIER: "Axisymmetric Steady Flow of a Swirling Compressible Fluid Through a Convergent-Divergent Nozzle Without External Heat Transfer"; JPL Space Programs Summary No. 37-33; Volume IV, 30 June 1965; pp. 133-41; (U).

The combination of analysis and experimental results indicate that the swirling flow established in a "combustion chamber" by tangential injection of the gas consists of a rotational core surrounded by a potential vortex. Measurements taken at the head closure indicated increases in both stagnation pressure (7.5:1) and stagnation temperature (1.05:1) from the centerline out to a radius equal to the nozzle throat radius.

JET PROPULSION LABORATORY (contd.)

(28) P. F. MASSIER: "Swirling Flow of Argon Through an Axisymmetric Convergent-Divergent Nozzle"; JPL Space Programs Summary No. 37-34; Volume IV, 31 August 1965; pp. 149-57; (U).

The work initiated in (27) was extended to include measurements at a (head closure wall) stagnation pressure of 2.0 PSIA in addition to those obtained at 15.2 PSIA. Significant reductions in swirl angle, circulation, and angular momentum were measured along the length of the nozzle. In addition, mass flow rates with swirl were reduced to about 75% of those obtained without swirl, based upon stagnation pressure measurements at the outer chamber radius.

(29) P. F. MASSIER: "Thrust Comparisons for Swirling and Non-Swirling Flows of Argon Through a Convergent-Divergent Nozzle as Determined From Wall Pressure Measurements"; JPL Space Programs Summary No. 37-35; Volume IV; 31 October 1965; pp. 161-65; (U).

The static pressure distribution along the length of a converging-diverging nozzle was integrated to ascertain the thrust developed. With a tangential velocity 9.2 times the axial velocity at the wall of the nozzle inlet, the thrust developed with swirling flow was approximately 80% of that developed without swirl.

(30) P. F. MASSIER: "Static Pressure Drop Along the Wall of a Constant-Diameter Duct Which Contains a Decaying Swirling Flow of Argon"; JPL Space Programs Summary No. 37-36; Volume IV; (U).

Experimental results obtained for a pressure-drop parameter as a function of Reynolds number based on distance of fluid travel indicate that the pressure loss is a function of: (A) wall friction; (B) shear stresses in the mainstream resulting from the vortex velocity distribution; (C) the mainstream velocity change resulting from the developing boundary layer; and (D) the nozzle configuration.

(31) E. J. ROSCHKE: "Flow Visualization Studies of a Confined, Jet-Driven Water Vortex"; JPL Technical Report No. 32-1004; September 1966; (U).

Dye-injection studies performed in a 4 IN diameter vortex tube clearly indicate: (1) the pronounced three-dimensional nature of the flow; (2) the strong influence of tube L/D on the flow patterns; (3) the significance of end-wall configuration and boundary layer effects; and (4) the significant disturbances arising from inserting probes in the flow.

RESEARCH REFERENCES

NASA-LANGLEY RESEARCH CENTER

(32) C. W. MARTZ and R. L. SWAIN: "Experimental and Analytical Study of Rolling-Velocity Amplification During the Thrusting Process for Two 10 Inch-Diameter Spherical Rocket Motors in Free Flight"; NASA TM X-75; September 1959; (C).

Two spherical motors were flight tested to measure "spin-up" or roll rate amplification due to transfer of angular momentum from the swirling exhaust gases to the interior grain surfaces. A heavywall motor showed an increase in spin rate of about 10%, while a lightweight motor showed an increase of 19%. A theoretical model for predicting the spin-up is also presented.

(33) G. B. NORTHAM: "An Investigation of the Effects of Acceleration on the Combustion Characteristics of an Aluminized Composite Solid Propellant"; Master's Thesis; Department of Mechanical Engineering; Virginia Polytechnic Institute; June 1965; (U).

Slabs of 16% aluminized PBAA propellant were tested on the Langley centrifuge under accelerations as high as 300 G's directed at angles of 0°, 30°, 60°, and 90° into the propellant surface. At 90° and 500 PSI, the burn rate increased about 25% over the 0-300 G acceleration spectrum, as did the amount of post-firing residue. No effects on either burn rate or residue were noted at accelerations up to 200 G's oriented at angles other than 90° into the propellant surface.

(34) G. B. NORTHAM: "An Experimental Investigation of the Effects of Acceleration on the Combustion Characteristics of an Aluminized Composite Solid Propellant"; ICRPG/AIAA Solid Propulsion Conference, Washington, D.C.; July 1966; CPIA Publication No. 111, Volume II; AD-373908; (C).

A condensation of the results presented in Northam's M. S. thesis (33).

(35) M. H. LUCY and G. B. NORTHAM: "On the Effects of Acceleration Upon Solid Rocket Performance"; ICRPG/AIAA Solid Propulsion Conference, Atlantic City, J.J.; June 4-6, 1968.

Tests performed with double-base, polyurethane, and polybutadiene propellants to determine the influence of binder type, percent aluminum, and aluminum particle size on propellant sensitivity to acceleration are discussed, along with the results of interrupted-burning tests performed at various acceleration levels and orientations to the burning surface.

NASA-LANGLEY RESEARCH CENTER (contd.)

(36) M. H. LUCY: "NASA-Langley Centrifuge Acceleration Data"; Unpublished.

Numerous centrifuge tests of the 3% aluminized BUU double-base propellant are currently being analyzed to quantify observed effects of accelerations up to 300 G's on burn rate. Preliminary results indicate that the burn rate amplification under acceleration is apparently time-dependent.

NASA-LEWIS RESEARCH CENTER

(37) S. H. MASLEN and F. K. MOORE: "On Strong Transverse Waves Without Shocks in a Circular Cylinder"; Journal of the Aeronautical Sciences; Volume 23; June 1956; pp. 583-593; (U).

This study of large-amplitude tangential pressure waves in a circular cylinder indicates that strong shock-free waves can occur in transverse modes, contrary to results obtained for a plane mode, wherein acoustic waves progressively steepen into shocks. The possibility of strong tangential waves suggests that extremely violent waves may be produced by interaction with a suitable energy source (combustion).

(38) C. FEILER, M. HEIDMANN, and L. POVINELLI: "Experimental Investigation of Transverse-Mode Solid-Propellant Combustion Instability in a Vortex Burner"; NASA TN D-3708; November 1966; (U).

The onset and cessation of transverse-mode combustion instability induced by tangential gas injection in a two-dimensional circular combustor was characterized by the tangential Mach number and chamber pressure. The tangential flow caused pressures 2-3 times higher than would be anticipated simply from the increased mass addition, indicating that the swirling flow caused significant nozzle blockage. These experimental results were explained by calculations for the propellant response based on a wave-amplification mechanism arising from preferential energy addition with flow biasing.

(39) L. POVINELLI: "Particulate Damping in Solid-Propellant Combustion Instability"; NASA TM X-52252; AIAA Fifth Aerospace Sciences Meeting; January 1967; (U).

Transverse-mode instability tests performed in the vortex burner of (38) with aluminum added to both the primary propellant and the injectant gases indicate that aluminum suppresses instability by acting as a sound attenuator in the gas phase rather than by altering the driving or response of the propellants.

RESEARCH REFERENCES

A. D. LITTLE

(40) D. S. ALLAN, E. K. BASTRESS, and D. A. KNAPTON: Design Studies of a 105mm Gun-Boosted Rocket; Report No. C-64868; January 1963; AD-336539; (C).

This attempt to employ a rotating coordinate system to analyze the flow from a spinning end-burning grain through a nozzle fails to satisfy the requisite energy balance between the grain surface and nozzle throat.

(41) E. K. BASTRESS: "Internal Ballistics of Spinning Solid-Propellant Rockets"; AIAA Journal of Spacecraft and Rockets; Volume 2, No. 3; May-June 1965; pp. 455-457; (U).

A condensation of the results presented in (40).

LOCKHEED PROPULSION COMPANY

(42) C. W. BERNARD: "Lockheed Propulsion Company Spin Effects Experience"; Symposium on the Behavior of Propellants Under Acceleration Fields; NOTS TP3770; June 1965; AD-363903; (C).

Test motors with single nozzles fired under spin rates up to 11,000 RPM evidenced considerable erosion of the head closure, proportional to spin rate. However, full-scale flight tests of motors with nine nozzles experienced no erosion though spinning at 25,000 RPM.

NAVAL POSTGRADUATE SCHOOL

(43) J. B. ANDERSON: "An Investigation of the Effect of Acceleration on the Burning Rate of Composite Propellants"; Ph.D. Thesis for Naval Postgraduate School; NPS-57RV7071A; August 1966; AD-819847; (U).

Propellants with polyurethane, CTPB, and PBAN binder systems were examined in centrifuge strand-burning tests at accelerations up to 2000 G's. The burning rates of all compositions were affected by acceleration, and in many instances by the presence of the nichrome ignition wire. Effects ranged from a fourfold increase in burning rate to extinguishment immediately after ignition.

NAVAL POSTGRADUATE SCHOOL (contd.)

(44) J. B. ANDERSON and R. E. REICHENBACH: "An Investigation of the Effect of Acceleration on the Burning Rate of Composite Propellants"; ICRPG/AIAA Second Solid Propulsion Conference; June 6-8, 1967; (U).

Essentially a condensed version of Anderson's Ph.D. thesis (43).

(45) E. J. STURM: "A Study of the Burning Rates of Composite Solid Propellants in Acceleration Fields"; Ph.D. Thesis for NPS; March 1968; (U).

Centrifuge strand tests at pressures of 500, 1000, and 1500 PSI and accelerations up to 1000 G's indicate that propellant sensitivity to acceleration depends upon the basic burn rate of the formulation and the oxidizer and aluminum weight percentages and particle sizes. In addition, a theoretical model was developed which successfully correlates the data obtained for non-metallized propellants operating in acceleration environments.

NAVAL WEAPONS CENTER (formerly Naval Ordnance Test Station)

(46) D. D. ORDAHL: "Some Problems Inherent in the Design and Development of Small Solid Propellant Auxiliary Power Units"; Bulletin of 11th JANAF Solid Propellant Group (Volume II), May 1955; (C).

Centrifuge tests of five double-base propellants at accelerations up to 50 G's indicated widely varying effects on motor performance.

(47) J. E. CRUMP: "Photographic Survey of Aluminum Combustion in Solid Propellants"; Proceedings of the First ICRPG Combustion Instability Conference; CPIA Publication No. 68 (Volume I); January 1965; AD-458060; (U).

From the aluminum agglomeration observed during the combustion process, it is concluded that the size of the agglomerates formed should be a function of the size of the binder pockets in the propellant, and therefore of the size of the ammonium perchlorate.

NAVAL WEAPONS CENTER (contd.)

(48) J. E. CRUMP: "Surface Characteristics of Quenched Samples of Composite-Aluminum Propellants"; Proceedings of the First ICRPG Combustion Instability Conference; CPIA Publication No. 68 (Volume I); January 1965; AD-458060; (U).

High-speed motion pictures of the propellant quenching process indicate that the expansion wave created during quench removes almost all aluminum agglomerates from the propellant surface. Subsequent stero-microscopic studies of the propellant surface after quench indicated that the surfaces of all propellants studied were almost completely covered with aluminum, in a form apparently identical to that in the unburned propellant. From this observation, it is concluded that the binder and ammonium perchlorate pyrolize away, leaving the aluminum behind to ignite later. In addition, the surface of the quenched samples was found to be very rough, with the roughness increasing with combustion pressure.

(49) C. W. ABERNATHY and C. R. RODGERS: "Fluorocarbon Propellant Performance in an Acceleration Field"; Symposium on the Behavior of Propellants Under Acceleration Fields: NOTS TP3770; June 1965; AD-363903; (C).

Tests of various fluorocarbon propellant formulations at spin rates up to 15,000 RPM yielded post-firing residue deposits of as much as 30% of the initial propellant weight, depending upon metal additive. Comparable degradations in impulse were also noted.

(50) K. H. BISCHEL: "Propellant Structural Problems in Spinning Motors"; Symposium on the Behavior of Propellants Under Acceleration Fields; NOTS TP3770; June 1965; AD-363903; (C)

Various propellant formulations in end-burning grain configurations were spin-tested without firing to determine structural adequacy. Although failures were initiated at different spin rates depending upon the propellant, these failures generally consisted of cracks starting at the center of the grain and spreading radially.

NAVAL WEAPONS CENTER (contd.)

(51) R. B. DILLINGER and R. W. FEIST: "Spin Effects on the Internal Ballistics of Solid Propellant Rocket Motors"; Symposium on the Behavior of Propellants Under Acceleration Fields; NOTS TP3770; June 1965; AD-363903; (C).

End-burning and internal-burning motors incorporating a variety of propellants were tested at spin rates up to 12,000 RPM. Recovered grains and x-ray movies taken during the tests gave evidence of both centerline coning and edge rounding under spin. Coning and ballistic anomalies experienced under spin were reduced or eliminated by various nozzle modifications.

(52) "Aluminum Particle Combustion Progress Report for 1 Apr. 1964 - 30 June 1965"; Technical Progress Report No. 415; April 1966; AD-632606; (U).

The results of a number of theoretical and experimental investigations of aluminum particle combustion are compiled in this review of the current (1966) state of knowledge in this field.

(53) J. E. CRUMP: "Aluminum Combustion in Composite Propellants"; ICRPG Second Combustion Conference; Los Angeles, California; November 1966; CPIA Publication No. 105; pp. 331-353; (U).

This study shows that the size of aluminum agglomerates formed during the combustion of composite propellants is determined by the size of the oxidizer particles rather than by the original size of the aluminum. However, the agglomerate size is found to decrease as the aluminum concentration decreases. In addition, the agglomeration is apparently unaffected by the type of binder.

OLIN-MATHIESON

(54) P. G. BUTTS and J. C. BARR: "Developments in the Application of Rubber Base Ammonium Nitrate Propellants to Solid Propellant Gas Generation"; Bulletin of the 15th Meeting of the JANAF Solid Propellant Group (Volume V); June 1959; (C).

Some problems attendant to the operation of gas generators at pressures below 650 PSI with accelerations of 75 G's are briefly noted.

RESEARCH REFERENCES

PICATINNY ARSENAL (U. S. Army Munitions Command)

(55) R. VECCHIO and S. HARNETT: "Static Spin Testing of Solid Propellant Rockets"; Bulletin of the First Meeting of ICRPG Working Group on Static Testing; CPIA Publication No. 24; 16-18 October 1963; (C).

This description of a test stand used for spin testing small-diameter motors at rates up to 30,000 RPM includes a limited number of the results obtained with end-burning grains of different composition. Both centerline coning and ignition difficulties were evidenced in some tests under spin, but no effects were noted in others.

(56) S. HARNETT and M. OLSTEIN: "The Effect of Spin on the Internal Ballistics of End-Burning Rocket Propellants"; Picatinny Arsenal Technical Memo Report No. 1555; October 1964; AD-357261; (C).

Dynamic tests of a 3 IN diameter end-burner at spin rates up to 12,000 RPM yielded large deviations from static test results. Various baffle arrangements were subsequently examined in an effort to eliminate centerline coning and pressure variations.

(57) S. HARNETT and M. OLSTEIN: "Effects of Spin on End-Burning Solid Double-Base Propellant Grains"; Symposium on the Behavior of Propellants Under Acceleration Fields; NOTS TP3770; June 1965; AD-363903; (C).

Essentially a reprint of (56).

(58) W. G. CLARK and F. C. FEMIA: "Interrupted Burning of Rocket Propellants Under High Spin Rates"; Bulletin of the Fifth Meeting of the Solid Propellant Rocket Static Test Working Group; CPIA Publication No. 161; December 1967; (C).

Primarily concerned with test equipment and methods, this qualitative discussion of the results achieved with internal-burning motors operating at 9600 RPM indicates a definite time-dependent pocking of the grain surface with some grains, apparently the result of lead deposition. In addition, the interrupted-burning technique is shown to be a valuable means of determining surface progression in a spin environment.

PURDUE UNIVERSITY (Jet Propulsion Center)

(59) J. D. HOFFMAN et al: "Investigation of High Acceleration on the Interior Ballistics of Solid Propellant Rocket Motors"; Monthly Progress Reports on Contract NOS. DA-01-021-AMC 428 (Z) D4-13612, DA-01-021-AMC 12864 (Z), DA-01-021-AMC 15257 (Z), and DA-AH01-67-C-2215; July 1964 to Present; (U).

This combined analytical and cold-gas experimental study has attempted to define the effects of spin on the gas dynamics associated with simulated end-burning and cylindrical-burning grain geometries.

(60) J. D. HOFFMAN: "Investigation of Acceleration Effects in Spinning Motors"; Symposium on the Behavior of Propellants Under Acceleration Fields; NOTS TP3770; June 1965; AD-363903; (C).

Outlines the tasks to be performed for (59).

(61) D. J. NORTON: "An Analytic Study of the Effects of Rotation on the Performance of Solid Propellant Rocket Motors"; Report No. TM-66-8; 6 April 1966; pp. 293-316; (U).

The initial theoretical models developed to analyze the rotational flow from an end-burning grain are discussed. Preliminary results obtained with these models indicate a definite reduction in nozzle efflux capability.

(62) B. W. FARQUHAR: "An Experimental Study of the Effects of Rotation on Spin Stabilized Rocket Motors"; Report No. TM-66-8; 6 April 1966; pp. 317-334; (U).

The design and fabrication of a 6 IN diameter cold gas (air) test motor is described, including anticipated modifications to extend the current 3500 RPM rotation speed capability to 12,000 RPM.

(63) B. W. FARQUHAR, J. D. HOFFMAN, D. J. NORTON: "Investigation of High Acceleration on the Interior Ballistics of Solid Propellant Rocket Motors"; Report No. F-66-10; December 1966; AD-651110; (U).

This updated summary of the work previously reported in (61) and (62) discusses: (A) the analytical results obtained using simplified theoretical models, and the basis for a more comprehensive analytical approach; and (B) the problems attendant to the fabrication of the experimental test motor and instrumentation.

PURDUE UNIVERSITY (contd.)

(64) D. J. NORTON, B. W. FARQUHAR, and J. D. HOFFMAN: "Analytical Studies of the Interior Ballistics of Spin Stabilized Rocket Motors - A Literature Survey"; Report No. TM-67-1; January 1967; (U).

This report presents a survey of literature pertinent to contained rotating flows, with emphasis on applications to the study of the internal ballistics of spinning rocket motors. Analytical models describing acceleration effects on solid propellant burning rates are also reviewed.

(65) B. W. FARQUHAR, D. J. NORTON, and J. D. HOFFMAN: "Experimental Studies of the Interior Ballistics of Spinning Rocket Motors"; Purdue University Jet Propulsion Center Report No. TM-67-2C; January 1967; (C).

Complementing JPC Report No. TM-67-1, this document reviews: experimental studies of various types of (cold-gas) swirling flows; results obtained in spin tests of a variety of solid propellants (composite, double-base, etc.) in different motor configurations; and a few of the facilities currently available for spin testing.

(66) D. J. NORTON: "The Analysis of Rotating Flow in Solid Propellant Rocket Motors"; Report No. TM-67-3; pp. 52-60; April 1967; (U).

An analytical method for determining requisite nozzle throat size for end-burning rocket motors is presented, along with an outline for anticipated studies of a simulated internal-burning grain geometry.

(67) B. W. FARQUHAR: "An Experimental Cold-Flow Study of the Internal Ballistics of Spinning Solid Propellant Rocket Motors"; Report No. TM-67-3; pp. 61-67; April 1967; (U).

Data obtained with a simulated end-burning grain operating at rotational speeds up to 13,000 RPM indicated that the mass flow reduction experienced in a spin environment is primarily a function of the ratio of the angular velocity of the gas to the axial velocity of the gas in the motor chamber.

PURDUE UNIVERSITY (contd.)

(68) B. W. FARQUHAR, D. J. NORTON and J. D. HOFFMAN: "An Experimental Investigation of Swirling Flow in Nozzles"; Report No. TM-67-8; January 1968; (U).

The results presented indicate that "vortex choking" (mass flow reduction in a spin environment) is influenced by: the type of vortex generated in the chamber; the nozzle contraction ratio; and the rotational speed of the motor. However, this choking phenomenon appears to approach a limiting value, beyond which the mass flow remains essentially constant.

REDEL

(69) "An Investigation of the Effects of Acceleration on the Burning Characteristics of Solid Propellants"; Report No. KPR-1; 1 February 1960; AD-315309 (C).

A program to investigate the effects of accelerations up to 100 G's on solid propellant burning is outlined. Sample propellant types are to include composite, double-base, and CMDB, with and without aluminum.

(70) "An Investigation of the Effects of Acceleration on the Burning Characteristics of Solid Propellant"; Report No. KPR-2; 1 May 1960; (C).

Interrupted burning tests of a polysulfide propellant (Thiokol BF 117) gave inconclusive results.

(71) "An Investigation of the Effects of Acceleration on the Burning Characteristics of Solid Propellants"; Report No. KPR-3; 1 August 1960; AD-318830; (C).

Tests of an OMAX gas generator propellant yielded considerable variations from static behavior under centrifuge and coaxial spin accelerations of 100 G's. Both ignition and equilibrium burning were significantly affected by both the magnitude and direction of the acceleration vector with respect to the propellant surface.

REDEL (contd.)

(72) "An Investigation of the Effects of Acceleration on the Burning Characteristics of Solid Propellants"; Report No. KPR-4; 1 November 1960; AD-321063; (C).

Limited centrifuge tests of a double-base propellant at 50 and 100 G's indicated reductions in burn rate with acceleration toward the surface and increased rates with the acceleration away from the surface. Additional tests of a polysulfide composite propellant yielded increased burning rates with acceleration to either direction.

(73) "An Investigation of the Effects of Acceleration on the Burning Characteristics of Solid Propellants"; Report No. KPR-5; 1 February 1961; (C).

Tests of an aluminized ammonium perchlorate propellant (GCR-524) indicate that the burn rate is increased by acceleration away from the burning surface and decreased by acceleration into the surface. Ignition and repeatability problems encountered during these tests render the results somewhat questionable.

(74) "An Investigation to Characterize the Effects of Acceleration on the Burning of Gun-Boosted Rocket Propellant"; Report No. VML-6; May 1963; AD-345926; (C).

Accelerations of 100 G's were shown to influence both the ignition and equilibrium burning of a double-base propellant. Pressure measurements obtained while firing perforated grains under spin and end-burning grains at various orientations to the acceleration vector were consistently 7-22% higher than those measured statically.

(75) "An Investigation to Characterize the Effects of Acceleration on the Burning of Gun-Boosted Rocket Propellant"; Final Report No. VML-14; 1 March 1964; AD-356358; (C).

Tests of the HX-12 and JPN double-base propellants under 100-G accelerations indicated that higher chamber pressures amplify the increase in burning rate measured with acceleration away from the surface. On the other hand, increased pressure tended to reduce the decrease in burning rate evidenced with acceleration into the surface.

(76) "An Investigation to Characterize the Effects of Acceleration on the Burning of Gun-Boosted Rockets"; Redel Corporation VML-15; May 1964; (C).

Cylindrically perforated grains of N-5 propellant exhibited large increases in combustion pressure (approximately 2:1) when spin tested at 10,000 RPM.

REDEL (contd.)

(77) "An Investigation to Characterize the Effects of Acceleration on the Burning of Gun-Boosted Rocket Propellants"; Report No. VML-21; 15 December 1964; AD-358267; (C).

Two double-base propellants (N-4 and N-5) were tested at 10,000 RPM in grain configurations which provided for: (A) radial burning; and (B) dual end burning with an inhibited cylindrical port. Following nozzle ejection due to excessive chamber pressures under spin, nozzle (throat) size was varied to allow operation at normal pressure. In some instances of nozzle ejection with the dual end-burning grains, propellant/inhibitor structural failure was noted along the internal port.

(78) J. W. DE DAPPER and W. DROBOT: "Experimental Investigation of the Influence of High Spin Rates (10,000 rpm) on the Combustion of N-4 and N-5 Propellants"; Symposium on the Behavior of Propellants Under Acceleration Fields: NOTS TP3770; June 1965; AD-363903; (C).

Essentially a reproduction of (77).

(79) J. W. DE DAPPER and W. DROBOT: "The Effect of Acceleration on the Burning Rates of Selected Propellants"; CPIA Publication No. 83; August 1965; pp. 101-127; (C).

The results presented in (69)-(77) are summarized, indicating widely variant responses to acceleration environments up to 200 G's. Double-base propellant testing was emphasized, with large differences in performance noted among the various formulations. The inconsistent results obtained precluded any generalization of these results to deduce causal mechanisms.

REDSTONE ARSENAL (U. S. Army Missile Command)

(80) W. D. GUTHRIE and E. C. M. CHEN: "Effects of Acceleration on Burning Rates of Solid Propellants"; Report RK-TR-63-22; 1 October 1963; (C).

A semi-empirical method of estimating the effects of acceleration on motor performance uses experimental burn rate/acceleration data in combination with "zoned" surface area regression to estimate chamber pressure histories.

REDSTONE ARSENAL (contd.)

(81) T. E. MARTIN and E. J. PALM: "The Effect of Acceleration on the Combustion of Propellants"; Fourth Meeting of TCCP Panel 0-6, A Review of the Work in the United States on the Effect of Acceleration on Propellant Combustion; August 1964; (C).

This brief review of the Army/Navy/Air Force acceleration work prior to 1964 also includes the results of a MICOM test program to investigate the effects of inhibiting varying amounts of propellant surface on motor performance under spin.

(82) W. D. GUTHRIE: "Some Techniques to Design Rocket Motors to Spinning Environment"; Symposium on the Behavior of Propellants Under Acceleration Fields; NOTS TP3770; June 1965; AD-363903; (C).

This qualitative discussion of the spin effects noted with three different rocket systems indicates the possibility of potentially severe overpressurization when operating in a spin environment.

(83) W. D. GUTHRIE and D. R. ULLOTH: "A Study of Vortex Effects in Spinning Rocket Motors"; Report RK-TR-66-8; April 1966; AD-374624; (C).

Spin tests of a 40mm end-burning motor at rates up to 12,000 RPM indicate severe centerline coning of grains extinguished at nozzle ejection, with the amount of coning proportional to spin rate. Various nozzle baffles were investigated to reduce the vortexing phenomena.

SHEFFIELD UNIVERSITY

(84) G. SOTTER and J. SWITHENBANK: "Vortex Generation in Solid Propellant Rockets"; AIAA Journal; Volume 2, No. 7; July 1964.

Acoustic streaming theory is modified and used to predict the effects arising from vortices generated in solid propellant rocket motors during periods of combustion instability. With a qualitative consideration of combustion heat release on vortex generation, it is shown that large torques are possible within propellant cavities and that significant radial pressure gradients will be experienced with the presence of the vortices.

THIOKOL CHEMICAL CORPORATION (ELKTON DIVISION)

(85) "Chemical Approaches to Rapid Burning Propellants"; Report No. E71-63, Volumes I, II, and III; 7 June 1963; AD-338226, -338248, and -338198; (C).

Volume II (AD-338248): Limited ambient-pressure centrifuge tests of medium- and fast-burning propellants indicate 125% and 50% increases, respectively, in burning rates at accelerations of approximately 750 G's. In addition, an analysis of acceleration effects on one-dimensional gas dynamics concludes that motor performance will be slightly improved under acceleration.

(86) "Evaluation of Solid Rocket Motor Ballistic Properties Under High 'G' Environments"; Volumes I and II; Report E93-63; (RTD-TDR-63-1054) June 1963; Volume II AD-337640; (C).

Volume I: Not available.
Volume II: Classified propellant properties are presented in this volume in order that Volume I may be unclassified.

(87) "A Research Study to Advance the State-of-the-Art of Solid Propellant Grain Design"; Summary Report E92-63; (RTD-TDR-63-1049) October 1963; AD-420826; (U).

Strain levels up to 12% were used to evaluate the effect of strain on the burning rate of an HA/MAPO, an HB/Epoxy, a polyurethane, and a plastisol propellant. Effects were found to vary considerably with formulation, with increases as high as 39% (at 500 PSI) and 26% (at 1000 PSI) measured with one composition at a 10% strain level. In addition, the burn rate pressure dependency (exponent) also appeared to vary from static values under strain.

(88) D. SAYLAK: "The Effects of Strain on the Burning Rate of Solid Propellants"; Bulletin of the Second Meeting of the ICRPG Working Group on Mechanical Behavior; CPIA Publication No. 27; October 1963; p. 423; (U).

A condensation of the results reported in (87).

(89) J. G. HORTON: "Experimental Evaluation of Solid Propellant Rocket Motors Under Acceleration Loads"; AIAA Preprint No. 64-133; Presented at the AIAA Solid Propellant Rocket Conference, Palo Alto, California; 29-31 January 1964; (U).

Centrifuge tests of both star and cylindrically perforated PBAA grains indicated no effects of axial accelerations as high as 100 G's on propellant performance.

THIOKOL ELKTON (contd.)

(90) J. G. HORTON: "Experimental Evaluation of Solid Propellant Rocket Motors Under Acceleration Loads"; AIAA Journal of Spacecraft and Rockets; Volume I, No. 6; November-December 1964; pp. 673-5; (U).

A condensation of results reported in (89).

(91) W. G. ANDREWS, J. W. EDWARDS, and D. R. REED: "Some Observations on Ballistic Anomalies and Spin Stabilization"; Proceedings of the American Astronautical Society 1967 National Meetings; June 1967; (U).

The deviations from static performance usually experienced in a spin environment are briefly discussed.

THIOKOL CHEMICAL CORPORATION (HUNTSVILLE DIVISION)

(92) R. H. WALL: "Interior Ballistic and Grain Design Studies of a Spin-Stabilized Gun-Boosted Rocket Using a Polysulfide Perchlorate Propellant"; Bulletin of the 11th JANAF Solid Propellant Meeting; May 1955; (C).

Gun-launched rounds with four different non-aluminized propellant grain designs were used to evaluate the effects of high radial and axial accelerations on motor performance. Data obtained from a reduction of vehicle distance - time measurements indicated a 135-165% increase in burn rate under acceleration, with no apparent change in propellant pressure exponent.

(93) J. M. MURPHY and R. H. WALL: "Effects of Grain Configuration Upon the Burning Rate of a Spinning Rocket Motor"; AIAA Journal of Spacecraft and Rockets; Volume 3, No. 2; February 1966; (U).

The results of Wall's 1955 study (92) are "quantified" by correlating burn rate augmentation with a measure of grain configuration complexity.

(94) R. L. GLICK: "An Analytical Study of the Effects of Radial Acceleration Upon the Combustion Mechanism of Solid Propellant"; Thiokol Rpt. No. 42-66; NASA Rpt. No. 66218; December 1966; (U).

This theoretical study of spin effects on the internal ballistics of a rocket motor containing a cylindrically perforated grain concludes that motor performance is primarily a function of swirl effects on nozzle gas dynamics and acceleration effects on propellant burning rate.

THIOKOL HUNTSVILLE (contd.)

(95) L. H. CAVENY, R. L. GLICK, and B. K. HODGE: "Effect of Acceleration on the Burning Rate of Composite Propellants"; Reprint of a paper presented at the AIAA Third Propulsion Joint Specialist Conference, Washington, D.C.; 17-21 July 1967; (Control No. U-67-4465); (U).

Essentially a condensation of the results presented in (94). However the theory for non-metallized propellants has been modified slightly to allow better prediction of effects noted at high acceleration levels.

(96) R. L. GLICK and M. S. KILGORE: "Effect of Specific Heat Ratio on Mass Flow for Swirling Nozzle Flow"; AIAA Journal of Spacecraft and Rockets; Volume IV, No. 8; August 1967; pp. 1098-1099; (U).

The numerical results presented in Mager's analysis (3) are expanded to include values for specific heat ratios varying from 1.10 to 1.28.

(97) G. F. MAGNUM: "A Study of the Effects of Radial Acceleration Upon the Combustion Mechanism of Solid Propellants"; First Quarterly Technical Summary Letter, Contract NAS1-7034; April-June 1967; (U).

This report indicates that the four phases of this study for NASA-Langley will include: (A) an analysis of the flow in circumferential slots under spin; (B) a grain regression analysis to predict burning surface under spin; (C) a theoretical study of the heat transfer at the head closure of a spinning motor; and (D) review and revision of the burning rate models presented in (94). In addition to documenting some of the preliminary results obtained in programs (A), (B), and (D), this report also presents a review of the current technology available for predicting the internal ballistics of spinning rocket motors.

THIOKOL HUNTSVILLE (contd.)

(98) G. F. MAGNUM: "A Study of the Effects of Radial Acceleration Upon the Combustion Mechanism of Solid Propellants"; Second Quarterly Technical Summary Letter, Contract NAS1-7034; July-September 1967; (U).

(A) A computer program to predict the state of the gas at the slot exit is being written.
(B) A computerized technique for calculating the regression of a "star" grain and resulting chamber pressure history under spin has been developed using Northam's results for acceleration sensitivity as a function of the angle of the acceleration vector with respect to the propellant surface (33).
(C) An analysis of nozzle convective heating is being developed using a semi-empirical approach rather than an integral boundary layer method.
(D) Data obtained from Anderson's study (43) indicates that the pitting parameter of (94) must be modified for metallized propellants.

(99) G. F. MAGNUM: "A Study of the Effects of Radial Acceleration Upon the Combustion Mechanism of Solid Propellants"; Third Quarterly Technical Summary Letter, Contract NAS1-7034; October-December 1967; (U).

(A) A computer program is being written to study the effects of spin rate, slot geometry, particle size, particle density, and initial location of the particle on the retention of metal (oxide) in a slot under spin.
(C) The nozzle heating analysis predicts increased heating rates under spin, with those calculated for a sample case at 10,000 RPM approximately three times higher than the static results at the nozzle throat section.
(D) A modification of the particle retention/rejection criterion for the metallized burn rate model of (94) indicates a marked improvement in ability to correlate the results of Anderson's experiments (43).

(100) B. K. HODGE and R. H. WHITESIDES: "Theoretical Study of Ballistics and Heat Transfer in Spinning Solid Propellant Rocket Motors"; Final Report, Contract NAS1-7034; NASA CR 66639; July 1968; (U).

RESEARCH REFERENCES

UNITED AIRCRAFT CORPORATION

(101) R. W. HALE, B. V. JOHNSON, F. S. OWEN, and A. TRAVERS: "Experimental Investigation of Characteristics of Confined Jet-Driven Vortex Flows"; UAC Research Laboratories Report R-2494-2; November 1961; AD-328502; (C).

Experimental measurements of both water and air flows in a vortex tube indicate: (A) good agreement with theoretically predicted radial flow in the end-wall boundary layer; and (B) that the secondary radial flow in this boundary layer is of the same magnitude as the total flow.

UNITED TECHNOLOGY CENTER

(102) J. FEEMSTER: "High Acceleration Rocket Motor Development Program"; UTC Report No. 2034-FR; 6 May 1963; AD-338916; (C).

Tests of two different composite propellants under centrifuge accelerations as high as 800 G's parallel to the burning surface yielded no significant deviations from static behavior.

(103) B. L. IWANCIOW, W. J. LAWRENCE, and J. MERTENS: "The Effect of Acceleration on Solid Composite Propellant Combustion"; AIAA Paper No. 64-227; presented at the First AIAA Annual Meeting, Washington, D.C.; 29 June - 2 July 1964; (U).

Micromotors with cylindrical port grains were fired on a centrifuge with the acceleration vector aligned with the thrust axis. The acceleration had no apparent effect on the burning rate for either the aluminized or the non-aluminized composites studied. However, a degradation in characteristic velocity with increasing acceleration was noted for both propellants. This degradation could not be attributed to combustion inefficiency, and was therefore assumed to be the result of coriolis acceleration forces acting on the nozzle efflux.

(104) B. L. IWANCIOW and W. J. LAWRENCE: "The Effects of Acceleration on Solid Propellant Combustion"; Symposium on the Behavior of Propellants Under Acceleration Fields; NOTS TP3770; June 1965; AD-363903; (C).

The results of the axial acceleration tests reported in (102) are summarized, along with limited results obtained with an aluminized PBAN formulation spun to 900 RPM (45 G's). These spin tests indicated more than 100% increases in burn rate at a radial acceleration of 45 G's.

UNITED TECHNOLOGY CENTER (contd.)

(105) C. T. CROWE and P. G. WILLOUGHBY: "Investigation of Particle Growth and Ballistic Effects on Solid-Propellant Rockets"; UTC 2128-QT1; 30 April 1965; AD-462937; (U).

In addition to presenting a brief review of the effects of rotation on motor characteristics, an analysis of spin effects on nozzle flow concludes that the gas flow in a typical rocket nozzle is not significantly affected by rotation.

(106) C. T. CROWE and P. G. WILLOUGHBY: "Investigation of Particle Growth and Ballistic Effects on Solid-Propellant Rockets"; UTC 2128-QT2; 28 July 1965; AD-467102; (U).

From a preliminary analysis of acceleration effects on the heat transferred between the flame zone and the propellant surface, it is concluded that acceleration will not affect the gas-phase heat transfer. Mager's analysis (3) is used to estimate the effects of rotation on the nozzle efflux from a cylindrically perforated grain.

(107) C. T. CROWE and P. G. WILLOUGHBY: "Investigation of Particle Growth and Ballistic Effects on Solid-Propellant Rockets"; UTC-2128 - QT3; October 29, 1965; AD-473426; (U).

Spin tests performed with both aluminized and non-aluminized PBAN formulations indicated no burn rate augmentation with the non-aluminized composition at radial accelerations up to 100 G's, and a 110% increase in burn rate with the aluminized propellant. A significant reduction in burn rate amplification is noted with a reduction in aluminum particle size.

(108) C. T. CROWE and P. G. WILLOUGHBY: "Investigation of Particle Growth and Ballistic Effects on Solid-Propellant Rockets"; UTC-2128-FR; 15 June 1966; AD-486262; (U).

Spin tests of PBAN formulations with various combinations of aluminum and ammonium perchlorate particle sizes indicate that acceleration effects on burn rate may be significantly more sensitive to AP size than to Al.

(109) C. T. CROWE and P. G. WILLOUGHBY: "Effect of Spin on the Internal Ballistics of a Solid-Propellant Motor"; AIAA Paper No. 66-523; June 1966; (U).

A condensation of the spin acceleration studies presented in (105) - (108).

UNITED TECHNOLOGY CENTER (contd.)

(110) C. T. CROWE and P. G. WILLOUGHBY: "A Study of Particle Growth in a Rocket Nozzle"; AIAA Paper No. 66-639; June 1966; (U).

A condensation of the particle growth studies reported in (105) - (108).

(111) D. R. MATTHEWS: "Analytical and Experimental Program to Determine Effect of Spin on Hybrid Rocket Internal Ballistics"; UTC 2189 MLR 6; 10 August 1966.

Experimental data obtained with a spinning hybrid motor indicates that the effects of acceleration on (fuel) regression rates may be either positive or negative, depending upon the acceleration level.

(112) J. K. BURCHARD and P. G. WILLOUGHBY: "Investigation of Performance Losses and Ballistic Effects in Solid Propellant Rockets"; UTC 2197-QTR1; 30 June 1966; (U).

An analytical and experimental program to study the internal ballistics of spinning rocket motors is outlined. The results of experiments to measure the dependence of acceleration effects on propellant composition indicate that the use of finer oxidizer powder reduces the burn rate sensitivity to acceleration. It is also shown that the burning rate of a fast-burning propellant containing acicular aluminum is not affected by accelerations as high as 75 G's.

(113) J. K. BURCHARD and P. G. WILLOUGHBY: "Investigation of Performance Losses and Ballistic Effects in Solid Propellant Rockets"; UTC-2197-QTR-2; 30 September 1966; AD-804186; (U).

A consideration of the effects of viscosity on the degradation of angular momentum indicates negligible viscous effects. However, a cold-gas experimental program is recommended to fully resolve the complex interactions of chamber/nozzle gas dynamics in an end-burning rocket motor. In addition, an experimental evaluation of the effects of chamber pressure on burn rate augmentation under spin indicates the possibility of a significant change in the combustion mechanism at higher pressure levels.

(114) J. K. BURCHARD and P. G. WILLOUGHBY: "Investigation of Performance Losses and Ballistic Effects in Solid Propellant Rockets"; UTC-2197-QTR-3; 30 December 1966; AD-804925; (U).

Important discrepancies in experimental data obtained with cylindrically perforated grains raise doubt as to the validity of the results reported herein, as well as those reported previously in (108) and (113).

UNITED TECHNOLOGY CENTER (contd.)

(115) J. K. BURCHARD and P. G. WILLOUGHBY: "Investigation of Performance Losses and Ballistic Effects in Solid-Propellant Rockets"; UTC-2197-FR; (Contract No. NOw 66-0444-C); 14 April 1967; AD-815115; (U).

The effects of propellant formulation parameters (oxidizer particle size, static burning rate, binder formulation, and the form and type of aluminum) on the propellant response to an acceleration environment are enumerated. In addition, an analytical investigation of the vortex flow in spinning end-burning motors indicates that viscous effects are of little importance in determining the nature of the swirl motion.

(116) P. G. WILLOUGHBY: "Investigation of Internal Ballistics Effects in Spinning Rocket Motors"; UTC-2281-QTR1; 30 August 1967; (U).

The third UTC/Navy program investigating spin effects on propellant combustion is outlined. The studies performed under this contract will include: photographing a burning propellant surface under acceleration; motor extinction tests; examination of the effects of base burn rate on acceleration sensitivity; and cold-gas studies of simulated end-burning grains. An analysis of cold-gas flow similarity parameters indicates that a chamber pressure of 65 PSI and spin rate of 3000 RPM can be used to simulate a motor operating at 1000 PSI and a spin rate of 12000 RPM. Initial results of a number of cold-gas experiments indicate that a potential-type vortex is apparently formed in the chamber above the surface of the "grain".

(117) P. G. WILLOUGHBY: "Investigation of Internal Ballistics Effects in Spinning Rocket Motors"; UTC-2281-QTR2; 30 November 1967; (U).

Previous results obtained by UTC and other sources are reviewed in a "state-of-the-art" summary of observed propellant performance sensitivity to acceleration vector direction, burning time, pressure level, base burn rate, metal loading, oxidizer size, and binder type. In addition, analytic models currently proposed for determining acceleration effects on combustion are discussed. Smoke tracer photographs obtained in the simulated end-burner cold-gas experiments seem to confirm previous indications of the existence of a potential-type vortex above the surface of the "grain".

UNITED TECHNOLOGY CENTER (contd.)

(118) P. G. WILLOUGHBY: "Investigation of Internal Ballistic Effects in Spinning Rocket Motors"; UTC-2281-QTR3; 29 February 1968; (U).

A new theoretical model for burn rate augmentation presented in this report is seen to provide at least a qualitative explanation for many of the phenomena observed in an acceleration environment, including the reduction in burn rate amplification experienced at some of the higher acceleration levels.

(119) P. G. WILLOUGHBY: "Investigation of Internal Ballistic Effects in Spinning Rocket Motors"; UTC-2281-FR; to be published in June 1968.

MISCELLANEOUS SOURCES

(120) M. SUMMERFIELD, G. S. SUTHERLAND, M. J. WEBB, H. J. TABACK, and K. P. HALL: "Burning Mechanism of Ammonium Perchlorate Propellants"; Progress in Astronautics and Rocketry: Solid-Propellant Rocket Research; Academic Press; New York; 1960; pp. 227-259; (U).

Using a one-dimensional combustion model to develop the "granular diffusion flame" theory of composite propellant burning, a two-component burn rate dependence on combustion pressure is identified. Comparison of theoretical results with measurements obtained with an ammonium perchlorate/ polystyrene propellant indicates good agreement with the predicted pressure dependence. (Three additional papers on steady-state burning mechanisms are also presented in this volume.)

(121) W. M. FASSEL, C. A. PAPP, D. L. HILDENBRANK and R. P. SERNKA: "The Experimental Nature of the Combustion of Metallic Powders"; Progress in Astronautics and Rocketry: Solid-Propellant Rocket Research; Academic Press; New York; 1960; pp. 259-269; (U).

Combustion products gathered from metal burning studies of a variety of metals and alloys indicated that, regardless of initial particle shape, the products formed were predominantly hollow spheres of oxide, sometimes containing spherical droplets of the original metal. Droplet size was found to decrease with more complete combustion. (Four additional papers on the combustion of metals are also presented in this volume.)

MISCELLANEOUS SOURCES (contd.)

(122) J. B. FENN: "A Phalanx Flame Model for the Combustion of Composite Solid Propellants"; Project Squid Technical Report No. PR-114-P; University of Virginia; April 1967; (U).

A new model for the combustion of composite propellants represents the flame as burning at the interfacial region between streams of fuel and oxidant generated by the vaporization of each of these solid components. The interface between the two solid phases receives the greatest heat flux from the reaction zone, and vaporization occurs most rapidly near the interface. The reaction zone is a "phalanx" which spearheads the attack of hot reaction gases on the solid. This model provides a rational physical explanation for many qualitative observations of solid propellant combustion, and successfully correlates the pressure dependence of burning rates.

(123) W. S. KING: "On Swirling Nozzle Flows"; AIAA Journal of Spacecraft and Rockets; Volume IV, No. 10; October 1967; pp. 1404-1405; (U).

This examination of the equations of motion for the axisymmetric, inviscid flow of an ideal gas swirling through a nozzle concludes that the mass flux under spin can be either greater or less than the static flow rate, depending upon the stagnation conditions selected for comparison.

(124) G. K. BATCHELOR: "An Introduction to Fluid Mechanics"; Chapter 7; Cambridge University Press; 1967; (U).